

US008363649B2

# (12) United States Patent Konda

#### $(54)$ FULLY CONNECTED GENERALIZED MULTI-LINK MULTI-STAGE NETWORKS

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- $(73)$ Assignee: Konda Technologies Inc., San Jose, CA  $(1)$ S
- Notice: Subject to any disclaimer, the term of this  $(* )$ patent is extended or adjusted under 35 U.S.C. 154(b) by 297 days.

This patent is subject to a terminal disclaimer.

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### **Related U.S. Application Data**

- $(60)$ Provisional application No. 60/940,389, filed on May 25, 2007, provisional application No. 60/940,391, filed on May 25, 2007, provisional application No. 60/940,392, filed on May 25, 2007.
- $(51)$  Int. Cl. H04L 12/50  $(2006.01)$

### **US 8,363,649 B2**  $(10)$  Patent No.:

### \*Jan. 29, 2013 (45) Date of Patent:

- U.S. Cl. ......... 370/388; 370/390; 370/419; 370/413  $(52)$
- $(58)$ Field of Classification Search .................. 370/388, 370/389, 395.4, 462

See application file for complete search history.

#### $(56)$ **References Cited**

## **U.S. PATENT DOCUMENTS**



\* cited by examiner

Primary Examiner - Dang Ton Assistant Examiner - Mohamed Kamara

#### $(57)$ **ABSTRACT**

A generalized multi-link multi-stage network comprising  $(2 \times \log_d N) - 1$  stages is operated in strictly nonblocking manner for unicast, also in rearrangeably nonblocking manner for arbitrary fan-out multicast when  $s \ge 2$ , and in strictly nonblocking manner for arbitrary fan-out multicast when  $s \ge 3$ , includes an input stage having N/d switches with each of them having d inlet links and sxd outgoing links connecting to second stage switches, an output stage having N/d switches with each of them having d outlet links and sxd incoming links connecting from switches in the penultimate stage. The network also has  $(2 \times \log_d N) - 3$  middle stages with each middle stage having N/d switches, and each switch in the middle stage has sxd incoming links connecting from the switches in its immediate preceding stage, and sxd outgoing links connecting to the switches in its immediate succeeding stage. Also each multicast connection is set up by use of at most two outgoing links from the input stage switch.

### 22 Claims, 125 Drawing Sheets



# FLEX LOGIX EXHIBIT 1019





















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**Sheet 76 of 125** 

















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FIG.8A



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#### FULLY CONNECTED GENERALIZED MULTI-LINK MULTI-STAGE NETWORKS

### CROSS REFERENCE TO REL ATED APPLICATIONS

This application is related to and claims priority of the PCT Application Serial No. PCT/US08/64604 entitled "FULLY CONNECTED GENERALIZED MULTI-LINK MULTI-STAGE NETWORKS" by Venkat Konda assigned to the 10 same assignee as the current application, filed May 22, 2008, he U.S. Provisional Patent Application Ser. No. 60/940,389 entitled "FULLY CONNECTED GENERALIZED REAR-RANGEABLY NONBLOCKING MULTI-LINK MULTI-STAGE NETWORKS" by Venkat Konda assigned to the 15 same assignee as the current application, filed May 25, 2007, he U.S. Provisional Patent Application Ser. No. 60/940,391 entitled "FULLY CONNECTED GENERALIZED FOLDED MULTI-STAGE NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed 20 May 25, 2007 and the U.S. Provisional Patent Application Ser. No. 60/940,392 entitled "FULLY CONNECTED GEN-ERALIZED STRICTLY NONBLOCKING MULTI-LINK MULTI-STAGE NETWORKS" by Venkat Konda assigned to  $h_{\text{F}}$  is the same assignee as the current application, filed May 25, 25<br>2007

2007.<br>This application is related to and incorporates by reference in its entirety the U.S. application Ser. No. 12/530,207 entitled "FULLY CONNECTED GENERALIZED MULTI-STAGE NETWORKS" by Venkat Konda assigned to the 30 same assignee as the current application, filed Sep. 6, 2009, he PCT Application Serial No. PCT/US08/56064 entitled "FULLY CONNECTED GENERALIZED MULTI-STAGE NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed Mar. 6, 2008, the U.S. Provisional Patent Application Ser. No. 60/905,526 entitled "LARGE SCALE CROSSPOINT REDUCTION WITH NONBLOCKING UNICAST & MULTICAST IN ARBITRARILY LARGE MULTI-STAGE NETWORKS" by Venkat Konda assigned to the same assignee as the current 40 application, filed Mar. 6, 2007, and the U.S. Provisional Patent Application Ser. No. 60/940,383 entitled "FULLY CONNECTED GENERALIZED MULTI-STAGE NET-WORKS" by Venkat Konda assigned to the same assignee as he current application, filed May 25, 2007. STAGE: WET WORKEN'' by Vensita Kenda assignation the the constrained in the 10.8 Previously and the 107 of 20740 MM (mediation Sec. No. 609004589<br>
the U.S. Previously Page 127 of 20710 CINERALIZED REAGARE. RANGERS (No. 20

This application is related to and incorporates by reference in its entirety the U.S. patent application Ser. No. 12/601,273 entitled "FULLY CONNECTED GENERALIZED BUT-TERFLY FAT TREE NETWORKS"by Venkat Konda assigned to the same assignee as the current application filed 50 concurrently, the PCT Application Serial No. PCT/US08/ 64603 entitled "FULLY CONNECTED GENERALIZED BUTTERFLY FAT TREE NETWORKS"by Venkat Konda assigned to the same assignee as the current application, filed May 22, 2008, the U.S. Provisional Patent Application Ser. No. 60/940,387 entitled "FULLY CONNECTED GENER-ALIZED BUTTERFLY FAT TREE NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed May 25, 2007, and the U.S. Provisional Patent Application Ser. No. 60/940,390 entitled "FULLY CON- 60 NECTED GENERALIZED MULTI-LINK BUTTERFLY FAT TREE NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed May 25, 2007.

This application is related to and incorporates by reference in its entirety the U.S. patent application Ser. No. 12/601,275 65 entitled ""VLSILAYOUTS OF FULLY CONNECTED GEN-ERALIZED NETWORKS" by Venkat Konda assigned to the

same assignee as the current application filed concurrently, the PCT Application Serial No. PCT/US08/64605 entitled "VLSI LAYOUTS OF FULLY CONNECTED GENERAL-IZED NETWORKS"by Venkat Konda assigned to the same assignee as the current application, filed May 22, 2008, and the U.S. Provisional Patent Application Ser. No. 60/940,394 entitled "VLSI LAYOUTS OF FULLY CONNECTED GEN-ERALIZED NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed May 25, 2007.

This application is related to and incorporates by reference in its entirety the U.S. Provisional Patent Application Ser. No.  $61/252,603$  entitled "VLSI LAYOUTS OF FULLY CON-NECTED NETWORKS WITH LOCALITY EXPLOITA-TION" by Venkat Konda assigned to the same assignee as the current application, filed Oct. 16, 2009.

This application is related to and incorporates by reference in its entirety the U.S. Provisional Patent Application Ser. No. 61/252,609 entitled "VLSI LAYOUTS OF FULLY CON-NECTED GENERALIZED AND PYRAMID NET-WORKS"byVenkat Konda assigned to the same assignee as the current application, filed Oct. 16, 2009.

#### BACKGROUND OF INVENTION

Clos switching network, Benes switching network, and Cantor switching network are a network of switches configured as a multi-stage network so that fewer switching points are necessary to implement connections between its inlet links (also called "inputs") and outlet links (also called "outputs") than would be required by a single stage (e.g. crossbar) switch having the same number of inputs and outputs. Clos and Benes networks are very popularly used in digital crossconnects, switch fabrics and parallel computer systems. However Clos and Benes networks may block some of the connection requests.

There are generally three types of nonblocking networks: strictly nonblocking; wide sense nonblocking; and rearrangeably nonblocking (See V. E. Benes, "Mathematical Theory of Connecting Networks and Telephone Traffic' Academic Press, <sup>1965</sup> that is incorporated by reference, as background). In a rearrangeably nonblocking network, a connection path is guaranteed as a result of the networks ability to rearrange prior connections as new incoming calls are received. In strictly nonblocking network, for any connection request from an inlet link to some set of outlet links, it is always possible to provide a connection path through the network to satisfy the request without disturbing other existing connections, and ifmore than one such path is available, any path can be selected without being concerned about realization of future potential connection requests. In wide-sense nonblocking networks, it is also always possible to provide a connection path through the network to satisfy the request without disturbing other existing connections, but in this case the path used to satisfy the connection request must be carefully selected so as to maintain the nonblocking connecting capability for future potential connection requests.

Butterfly Networks, Banyan Networks, Batcher-Banyan Networks, Baseline Networks, Delta Networks, Omega Networks and Flip networks have been widely studied particularly for self routing packet switching applications. Also Benes Networks with radix of two have been widely studied<br>and it is known that Benes Networks of radix two are shown and it is known that Benes Networks of radix two are shown to be built with back to back baseline networks which are rearrangeably nonblocking for unicast connections.

U.S.Pat. No. 5,451,936 entitled "Non-blocking Broadcast Network" granted to Yang et al. is incorporated by reference herein as background of the invention. This patent describes

a number of well known nonblocking multi-stage switching network designs in the background section at column 1, line 22 to column 3, 59. An article by Y. Yang, and G. M., Masson entitled, "Non-blocking Broadcast Switching Networks" IEEETransactions on Computers, Vol. 40, No. 9, September 1991 that is incorporated by reference as background indicates that if the number of switches in the middle stage, m, of a three-stage network satisfies the relation m $\geq$ min((n-1)(x+  $r^{1/x}$ )) where  $1 \le x \le \min(n-1,r)$ , the resulting network is nonblocking for multicast assignments. In the relation, r is the number of switches in the input stage, and n is the number of inlet links in each input switch.

USS. Pat. No. 6,885,669 entitled "Rearrangeably Nonblocking Multicast Multi-stage Networks" by Konda showed hat three-stage Clos network is rearrangeably nonblocking for arbitrary fan-out multicast connections when  $m \ge 2 \times n$ . And U.S. Pat. No. 6,868,084 entitled "Strictly Nonblocking Multicast Multi-stage Networks" by Konda showed that three-stage Clos network is strictly nonblocking for arbitrary  $_{20}$ fan-out multicast connections when  $m \geq 3 \times n-1$ .

In general multi-stage networks for stages of more than hree and radix of more than two are not well studied. An article by Charles Clos entitled "A Study of Non-Blocking Switching Networks" The Bell Systems Technical Journal, Volume XXXII, January 1953, No. 1, pp. 406-424 showed a way of constructing large multi-stage networks by recursive substitution with a crosspoint complexity of  $d^2 \times N \times (log_d)$ N)<sup>2.58</sup> for strictly nonblocking unicast network. Similarly USS.Pat. No. 6,885,669 entitled "Rearrangeably Nonblock- <sup>30</sup> ing Multicast Multi-stage Networks" by Konda showed a way of constructing large multi-stage networks by recursive substitution for rearrangeably nonblocking multicast network. An article by D. G. Cantor entitled "On Non-Blocking Switching Networks" 1: pp. 367-377, 1972 by John Wiley and Sons, Inc., showed a way of constructing large multistage networks with a crosspoint complexity of  $d^2 \times N \times (\log_d)$ N)<sup>2</sup> for strictly nonblocking unicast, (by using  $log_dN$  number of Benes Networks for  $d=2$ ) and without counting the crosspoints in multiplexers and demultiplexers. Jonathan Turner  $40$ studied the cascaded Benes Networks with radices larger than two, for nonblocking multicast with 10 times the crosspoint complexity of that of nonblocking unicast for a network of size N=256. three-stage Clos network is strictly nonblocking for arbitrary  $_{20}$  for any extraction of the mean and is stage a more for a from the forest<br>and fan-out multicast connections when m<sup>22</sup>*Sxn*=1. In general antiticastige 25 UES 8,3-63.649 B2<br>
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The crosspoint complexity of all these networks is prohibi-  $45$ tively large to implement the interconnect for multicast connections particularly in field programmable gate array (PGA) devices, programmable logic devices (PLDs), field programmable interconnect Chips (FPICs), digital crossconnects, switch fabrics and parallel computer systems.

#### SUMMARY OF INVENTION

A generalized multi-link multi-stage network comprising  $(2 \times \log_d N)$ –1 stages is operated in strictly nonblocking man- 55 ner for unicast includes an input stage having N/d switches with each of them having  $d$  inlet links and  $2\times d$  outgoing links connecting to second stage switches, an output stage having  $N/d$  switches with each of them having d outlet links and  $2 \times d$ incoming links connecting from switches in the penultimate stage. The network also has  $(2 \times \log_d N)$ –3 middle stages with each middle stage having N/d switches, and each switch in the middle stage has 2xd incoming links connecting from the switches in its immediate preceding stage, and 2xd outgoing links connecting to the switches in its immediate succeeding stage. Also the same generalized multi-link multi-stage network is operated in rearrangeably nonblocking manner for

arbitrary fan-out multicast and each multicast connection is set up by use of at most two outgoing links from the input stage switch.

A generalized multi-link multi-stage network comprising  $(2 \times \log_a N)$ –1 stages is operated in strictly nonblocking manner for multicast includes an input stage having N/d switches with each of them having d inlet links and 3xd outgoing links connecting to second stage switches, an output stage having N/d switches with each of them having d outlet links and  $3\times d$ incoming links connecting from switches in the penultimate stage. The network also has  $(2 \times \log_a N)$ –3 middle stages with each middle stage having N/d switches, and each switch inthe middle stage has 3xd incoming links connecting from the switches in its immediate preceding stage, and 3xd outgoing links connecting to the switches in its immediate succeeding stage.

#### BRIEF DESCRIPTION OF DRAWINGS

FIG. 1A is a diagram 100A of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having inverse Benes connection topology of five stages with  $N=8$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network forarbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1B is a diagram 100B of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with N=8, d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1C is a diagram 100C of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1D is a diagram 100D of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with N=8, d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1E is a diagram 100E of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N=8$ ,  $d=2$  and  $s=2$ , strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1F is a diagram 100F of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having Baseline connection topology of five stages with  $N=8$ ,  $d=2$  and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1G is a diagram 100G of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with N=8, d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1H is a diagram 100H of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1] is a diagram 100] of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently back-to-back Butterfly networks) of five stages with  $N=8$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1J is a diagram 100J of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary 20 fan-out multicast connections, in accordance with the invention.

FIG. 1K is a diagram 100K of a general symmetrical multilink multi-stage network  $V_{mlink}(N, d, s)$  with  $(2 \times \log_d N)-1$ stages with s=2, strictly nonblocking network for unicast 25 connections and rearrangeably nonblocking network forarbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1A1is <sup>a</sup> diagram 100A1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having 30 multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1B1 is a diagram 100B1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast con-40 nections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1C1 is a diagram 100C1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having 45 an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1D1 is <sup>a</sup> diagram 100D1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1E1 is <sup>a</sup> diagram 100E1 of an exemplary asymmetrical multi-link multi-stage network  $V_{\text{min}k}(N_1, N_2, d, s)$  (hav- $\frac{1}{2}$  and the connection topology called flip network and also known 60 as inverse shuffle exchange network) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention. nesina mpehage hailit using hasekis-bank Banjan Mekanis Mekan

FIG. 1F1 is a diagram 100F1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having Baseline connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=2$ , strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1G1 is a diagram 100G1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1H1 is <sup>a</sup> diagram 100H1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 111 is a diagram 10011 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently backto-back Butterfly networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1J1 is a diagram 100J1 of an exemplary asymmetrical exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1K1 is a diagram 100K1 of a general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages with N<sub>1</sub>=p\*N<sub>2</sub> and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1A2 is a diagram 100A2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=2$ , strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1B2 is a diagram 100B2 of an exemplary asymmetri-50 cal multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=2$ , strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1C2 is a diagram 100C2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1D2 is a diagram 100D2 of an exemplary asymmetri-65 cal multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1E2 is a diagram 100E2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(\bar{N}_1, N_2, d, s)$  (hav- 5 ing a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1F2 is a diagram 100F2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having Baseline connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking 15 network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1G2 is a diagram 100G2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having 20 an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1H2 is a diagram 100H2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblock- 30 multi-link multi-stage network  $V_{mlink}(N, d, s)$  having inverse ing network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 112 is adiagram 10012 of an exemplary asymmetrical multi-link multi-stage network  $V_{\text{min}k}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently backto-back Butterfly networks) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=2$ , strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in 40 accordance with the invention. nombelsking nutwork for antitrapy the out multitiest connections. In accordance with the investion of  $1/2$  is a diagonal 100P2 of an example propagation and the investion of 2007 of 2007 of 2007 of 102 of 2008 of 2008 of

FIG. 1J2 is a diagram 100J2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , d=2 and s=2, strictly nonblocking 45 network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 1K2 is a diagram 100K2 of a general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages with  $N_2=p^*N_1$  and s=2, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connecions, in accordance with the invention.

FIG. 2A is a diagram 200A of an exemplary symmetrical folded multi-link multi-stage network  $V_{\text{fold-link}}(N, d, s)$  having inverse Benes connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=2$  with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out 60 multicast connections, in accordance with the invention.

FIG. 2B is a diagram 200B of a general symmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N, d, 2)$  with  $(2 \times \log_d N) - 1$  stages strictly nonblocking network for unicast connections and rearrangeably nonblocking network forarbirary fan-out multicast connections in accordance with the invention.

FIG.2C is <sup>a</sup> diagram 200C of an exemplary asymmetrical folded multi-link multi-stage network  $V_{fold-mlink}(N_1,N_2,d, 2)$ having inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where p=3, and d=2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 2D is a diagram 200D of a general asymmetrical folded multi-link multi-stage network  $\mathrm{V}_{\mathit{fold-mlink}}(N_1, N_2, d, 2)$ with  $N_2=p^*N_1$  and with  $(2 \times \log_d N)-1$  stages strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections in accordance with the invention.

FIG.2E is <sup>a</sup> diagram 200E of an exemplary asymmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1,N_2,d, 2)$ having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where p=3, and d=2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

25 with  $N_1=p*N_2$  and with  $(2xlog_d N)-1$  stages strictly non-FIG. 2F is a diagram 200F of a general asymmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1, N_2, d, 2)$ blocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections in accordance with the invention.

FIG. 3A is a diagram 300A of an exemplary symmetrical Benes connection topology of five stages with  $N=8$ ,  $d=2$  and s=3, strictly nonblocking network for arbitrary fan-out mullicast connections, in accordancewith the invention.

FIG.3B is <sup>a</sup> diagram 300B of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with N=8, d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3C is <sup>a</sup> diagram 300C of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with N=8, d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3D is <sup>a</sup> diagram 300D of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3E is <sup>a</sup> diagram 300E of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with N=8,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fanout multicast connections, in accordance with the invention.

FIG.3F is <sup>a</sup> diagram 300F of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having Baseline connection topology of five stages with  $N=8$ , d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3G is <sup>a</sup> diagram 300G of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with N=8, d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3H is <sup>a</sup> diagram 300H of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 31 is a diagram 3001 of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently back-to-back Butterfly networks) of five stages with  $N=8$ , d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3J is a diagram 300J of an exemplary symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$ and s=3, strictly nonblocking network for arbitrary fan-out  $_{15}$ multicast connections, in accordance with the invention.

FIG. 3K is a diagram 300K of a general symmetrical multilink multi-stage network  $V_{mlink}(N, d, s)$  with  $(2 \times \log_d N)-1$ stages with s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the inven- 20 tion.

FIG. 3A1is <sup>a</sup> diagram 300A1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p^*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking 25 network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3B1 is <sup>a</sup> diagram 300B1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega  $30$ Networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fanout multicast connections.

FIG. 3C1 is a diagram 300C1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having 35 an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

nce with the invention.<br>FIG. <mark>3D1</mark> is a diagram **300D1** of an exemplary asymmetri- 40 cal multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3E1 is a diagram 300E1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly non-50 cal multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (havblocking network for arbitrary fan-out multicast connections, in accordance with the invention. strengt measure and matter than the measure of the measure of the measure of the measure counter for an accordance with the measure of the complete counter of the complete counter of the complete of the complete counter o

FIG. 3F1 is a diagram 300F1 of an exemplary asymmetrical multi-link multi-stage network  $V_{\text{min}k}(N_1,N_2,d,s)$  having Baseline connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3G1 is a diagram 300G1 of an exemplary asymmetrical multi-link multi-stage network  $V_{\textit{mink}}(N_1,N_2,d,s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3H1 is a diagram 300H1 of an exemplary asymmetri- 65 cal multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,

 $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 311 is a diagram 30011 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently backto-back Butterfly networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3J1 is a diagram 300J1 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3K1 is a diagram 300K1 of a general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages with N<sub>1</sub>=p<sup>\*</sup>N<sub>2</sub> and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3A2 is a diagram 300A2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3B2 is a diagram 300B2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3C2 is a diagram 300C2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3D2is <sup>a</sup> diagram 300D2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3E2 is a diagram 300E2 of an exemplary asymmetriing a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.3F2 is a diagram 300F2 of an exemplary asymmetrical multi-link multi-stage network  $\mathbf{V}_{mlink}(\mathbf{N}_1,\mathbf{N}_2,\mathbf{d}, \mathbf{s})$  having Baseline connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3G2 is a diagram 300G2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

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FIG. 3H2 is a diagram 300H2 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where p=3, d=2 and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG.312 is a diagram 30012 of an exemplary asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently back-10 to-back Butterfly networks) of five stages with  $N_2=8$ ,  $N_1=p^*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 3J2 is a diagram 300J2 of an exemplary asymmetrical 15 multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=3$ , strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

TIG. 3K2 is a diagram 300K2 of a general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_d N) - 1$  stages with  $N_2 = p^*N_1$  and s=3, strictly nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4A is a diagram 400A of an exemplary symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  having inverse<br>Benes connection topology of five stages with N=8, d=2 and s—2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably non-30 blocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4A1 is a diagram 400A1 of an exemplary symmetrical folded multi-stage network  $V_{fold}(N, d, 2)$  having Omega connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=2$  with 35 exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4A2 is a diagram 400A2 ofan exemplary symmetrical 40 folded multi-stage network  $V_{fold}(N, d, 2)$  having nearest neighbor connection topology of five stages with N=8, d=2 and s=2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4B is a diagram 400B of a general symmetrical folded multi-stage network  $V_{fold}(N, d, 2)$  with  $(2 \times \log_d N)-1$  stages strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out 50 multicast connections in accordance with the invention.

FIG.4C is a diagram 400C of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  having inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where p=3, and d=2 with exemplary multicast 55 connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbirary fan-out multicast connections, in accordance with the invention. works or hacken based bath Newtork are equivalently has<br>the based bath Newtorks of  $\theta$  of the stages with N<sub>2</sub>-8, Newtorks of 200<br>M<sub>3</sub>-8, Newtorks are  $P_2$ , where  $P_2$ , a where  $P_2$ , a where  $P_2$ , a where  $P_2$ , a wh

venuon.<br>FIG. <mark>4C1</mark> is a diagram **400C1** of an exemplary asymmetri- 60 cal folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  having Omega connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , and d=2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbirary fan-out multicast connections, in accordance with the invention.

FIG. 4C2 is a diagram 400C2 of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  having nearest neighbor connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where  $p=3$ , and d=2 with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4D is a diagram 400D of a general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  with  $N_2=p*N_1$ and with  $(2 \times \log_d N)-1$  stages strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections in accordance with the invention.

FIG.4E is <sup>a</sup> diagram 400E of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1,N_2,\bar{d}, 2)$  having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , and  $d=2$  with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

25 Omega connection topology of five stages with  $N_2=8$ , FIG. 4E1 is a diagram 400E1 of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  having  $N_1=p*N_2=24$ , where  $p=3$ , and  $d=2$  with exemplary multicast connections, strictly nonblocking, network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4E2 is a diagram 400E2 of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  having nearest neighbor connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , and  $d=2$  with exemplary multicast connections, strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections, in accordance with the invention.

FIG. 4F is a diagram 400F of a general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 2)$  with  $N_1=p*N_2$ and with  $(2 \times \log_d N)-1$  stages strictly nonblocking network for unicast connections and rearrangeably nonblocking network for arbitrary fan-out multicast connections in accordance with the invention.

FIG.5A is <sup>a</sup> diagram 500A of an exemplary symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  having inverse Benes connection topology of five stages with  $N=8$ , d=2 and s=1 with exemplary unicast connections rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 5Bis a diagram 500B ofa general symmetrical folded multi-stage network  $V_{fold}(N, d, 1)$  with  $(2 \times \log_d N) - 1$  stages rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 5C is a diagram 500C of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 1)$  having inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where p=3, and d=2 with exemplary unicast connections rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 5D is a diagram 500D of a general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 1)$  with  $N_2=p*N_1$ and with  $(2 \times \log_d N)-1$  stages rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 5E is a diagram 500E of an exemplary asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, 1)$  having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ , and d=2 with exemplary unicast connections rearrangeably nonblocking network for unicast connections, in accordancewith the invention.

FIG. 5F is a diagram 500F of a general asymmetrical 5 folded multi-stage network  $V_{fold}(N_1, N_2, d, 1)$  with  $N_1=p*N_2$ and with  $(2 \times \log_d N) - 1$  stages rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 6A is a diagram 600A of an exemplary symmetrical 10 multi-stage network  $V(N, d, s)$  having inverse Benes connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6B is a diagram 600B of an exemplary symmetrical 15 multi-stage network  $V(N, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6C is a diagram 600C of an exemplary symmetrical 20 multi-stage network  $V(N, d, s)$  having an exemplary connection topology of five stages with N=8, d=2 and s=1, rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG.6D is <sup>a</sup> diagram 600D of an exemplary symmetrical 25 multi-stage network  $V(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6E is a diagram 600E of an exemplary symmetrical 30 multi-stage network  $V(N, d, s)$  (having a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6F is a diagram 600F of an exemplary symmetrical 35 multi-stage network V(N, d, s) having Baseline connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6G is a diagram 600G of an exemplary symmetrical multi-stage network  $V(N, d, s)$  having an exemplary connec-  $40$ tion topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG.6H is <sup>a</sup> diagram 600H of an exemplary symmetrical multi-stage network  $V(N, d, s)$  having an exemplary connec-  $45$ tion topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6I is a diagram 600I of an exemplary symmetrical multi-stage network V(N, d, s) (having a connection topology 50 multi-stage network  $V(N_1, N_2, d, s)$  with  $(2 \times \log_d N) - 1$  stages built using back-to-back Banyan Networks or back-to-back Delta Networks or equivalently back-to-back Butterfly networks) of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections. PIG. 6. A is a diagony 6600-A of an examplary symmetrical to<br>multi-stage network V(N, d, s) having inverse Denes connection<br>tion tropology of two stages with N=R, d=2 and s=1, rear-<br>network behavior and the method. The s

FIG. 6J is a diagram 600J of an exemplary symmetrical 55 multi-stage network  $V(N, d, s)$  having an exemplary connection topology of five stages with  $N=8$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6K is a diagram 600K of a general symmetrical multistage network  $V(N, d, s)$  with  $(2xlog_d N)-1$  stages with s=1, 60 rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 6A1 is a diagram 600A1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having inverse Benes connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  65 where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6B1 is a diagram 600B1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where p=3, d=2 and s=1, rearrangeably nonblocking network for unicast connections.

FIG. 6C1 is a diagram 600C1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6D1 is <sup>a</sup> diagram 600D1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6E1 is a diagram 600E1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology called flip network and also knownasinverse shuffle exchange network) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG.6F1 is a diagram 600F1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having Baseline connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6G1 is a diagram 600G1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6H1 is <sup>a</sup> diagram 600H1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p^*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 611 is a diagram 60011 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or backto-back Delta Networks or equivalently back-to-back Butterfly networks) of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$  where p=3, d=2 and s=1, rearrangeably nonblocking network for unicast connections.

FIG. 6J1 is a diagram 600J1 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_1=8$ ,  $N_2=p*N_1=24$ where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6K1 is a diagram 600K1 of a general asymmetrical with  $N_1=p*N_2$ , and s=1, rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 6A2 is a diagram 600A2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having inverse Benes connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6B2 is a diagram 600B2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Omega Networks) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where p=3, d=2 and s=1, rearrangeably nonblocking network for unicast connections.

FIG. 6C2 is a diagram 600C2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

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FIG. 6D2 is a diagram 600D2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections, in accordance with the invention.

FIG. 6E2 is a diagram 600E2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology called flip network and also known as inverse shuffle exchange network) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network  $10$ for unicast connections.

FIG. 6F2 is a diagram 600F2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having Baseline connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network 15 for unicast connections.

FIG. 6G2 is a diagram 600G2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network 20 for unicast connections, in accordance with the invention.

FIG. 6H2 is a diagram 600H2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network 25 for unicast connections, in accordance with the invention.

FIG.612 is adiagram 60012 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  (having a connection topology built using back-to-back Banyan Networks or backto-back Delta Networks or equivalently back-to-back Butter- <sup>30</sup> fly networks) of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where p=3, d=2 and s=1, rearrangeably nonblocking network for unicast connections.

FIG. 6J2 is a diagram 600J2 of an exemplary asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  having an exemplary connection topology of five stages with  $N_2=8$ ,  $N_1=p*N_2=24$ , where  $p=3$ ,  $d=2$  and  $s=1$ , rearrangeably nonblocking network for unicast connections.

FIG. 6K2 is a diagram 600K2 of a general asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  with  $(2 \times \log_a N) - 1$  stages 40 with  $N_2=p*N_1$  and s=1, rearrangeably nonblocking network for unicast connections in accordance with the invention.

FIG. 7A is high-level flowchart of a scheduling method according to the invention, used to set up the multicast connections in all the networks disclosed in this invention.

FIG. 8A1 is a diagram 800A1 of an exemplary prior art implementation of a two by two switch; FIG. 8A2 is a diagram 800A2 for programmable integrated circuit prior art implementation of the diagram 800A1 of FIG. 8A1; FIG. 8A3 is a diagram 800A3 for one-time programmable integrated circuit prior art implementation of the diagram 800A1 of FIG. 8A1; FIG. 8A4 is a diagram 800A4 for integrated circuit placement and route implementation of the diagram 800A1 of FIG. 8A1. where  $\eta = 3$ , d  $\dot{2}$  and s 1, nearrangeably noinbecking new<br>or Fig. That is the strength and the strength in the strength for the<br>interactions, in accordance with the invention. FIG. 6112 is a diagram 600112 of an exa

#### DETAILED DESCRIPTION OF THE INVENTION

The present invention is concerned with the design and operation oflarge scale crosspoint reduction using arbitrarily large multi-link multi-stage switching networks for broadcast, unicast and multicast connections. Particularly multilink multi-stage networks with stages more than three and radices greater than or equal to two offer large scale crosspoint reduction when configured with optimal links as disclosed in this invention.

When a transmitting device simultaneously sends information to more than one receiving device, the one-to-many connection required between the transmitting device and the receiving devices is called a multicast connection. A set of multicast connections is efferred to as a multicast assignment.<br>When a transmitting device sends information to one receiving device, the one-to-one connection required between the transmitting device and the receiving device is called unicast connection. When a transmitting device simultaneously sends information to all the available receiving devices, the one-to-all connection required between the transmitting device and the receiving devices is called a broadcast connection.

In general, a multicast connection is meant to be one-tomanyconnection, which includes unicast and broadcast connections. A multicast assignment in a switching network is nonblocking if any of the available inlet links can always be connected to any of the available outlet links.

In certain multi-link multi-stage networks, folded multilink multi-stage networks, and folded multi-stage networks of the type described herein, any connection request of arbitrary fan-out, i.e. from an inlet link to an outlet link or to a set of outlet links of the network, can be satisfied without blocking if necessary by rearranging some of the previous connection requests. In certain other multi-link multi-stage networks of the type described herein, any connection request of arbitrary fan-out, i.e. from an inlet link to an outlet link or to a set of outlet links of the network, can be satisfied without blocking with never needing to rearrange any of the previous connection requests.

In certain multi-link multi-stage networks, folded multilink multi-stage networks, and folded multi-stage networks of the type described herein, any connection request of unicast from an inlet link to an outlet link of the network, can be satisfied without blocking if necessary by rearranging some of the previous connection requests. In certain other multilink multi-stage networks of the type described herein, any connection request of unicast from an inlet link to an outlet link of the network, can be satisfied without blocking with never needing to rearrange any of the previous connection requests.

Nonblocking configurations for other types of networks with numerous connection topologies and scheduling methods are disclosed as follows:

1) Strictly and rearrangeably nonblocking for arbitrary fan-out multicast and unicast for generalized multi-stage net-45 works  $V(N_1, N_2, d, s)$  with numerous connection topologies and the scheduling methodsare described in detail in the U.S. application Ser. No. 12/530,207 that is incorporated by reference above.

2) Strictly and rearrangeably nonblocking for arbitrary fan-out multicast and unicast for generalized butterfly fat tree networks  $V_{bnf}(N_1, N_2, d, s)$  with numerous connection topologies and the scheduling methods are described in detail in PCT Application Serial No. PCT/US08/64603 that is incorporated by reference above.

3) Strictly and rearrangeably nonblocking for arbitrary fan-out multicast and unicast for generalized multi-link butterfly fat tree networks  $V_{mlink-bf}$ (N<sub>1</sub>, N<sub>2</sub>, d, s) with numerous connection topologies and the scheduling methods are described in detail in PCT Application Serial No. PCT/US08/ 64603 that is incorporated by reference above.

4) VLSI layouts of generalized multi-stage networks  $V(N_1,$ N<sub>2</sub>, d, s), generalized folded multi-stage networks  $V_{fold}(N_1, N_2)$  $N_2$ , d, s), generalized butterfly fat tree networks  $V_{b,n}(N_1, N_2,$ d, s), generalized multi-link multi-stage networks  $V_{mlink}(N_1, ...)$  $N_2$ , d, s), generalized folded multi-link multi-stage networks  $V_{\text{fold-mlink}}(N_1, N_2, d, s)$ , generalized multi-link butterfly fat tree networks  $V_{mlink-bf}(N_1, N_2, d, s)$ , and generalized hypercube networks  $V_{\text{hcube}}(N_1, N_2, d, s)$  for s=1, 2,3 or any number in general, are described in detail in the PCT Application Serial No. PCT/US08/64605 that is incorporated by reference above.

5) VLSI layouts of numerous types of multi-stage networks  $5$ with locality exploitation are described in U.S. Provisional Patent Application Ser. No. 61/252,603 that is incorporated by reference above.

6) VLSI layouts of numerous types of multistage pyramid networks are described in U.S. Provisional Patent Application Ser. No. 61/252,609 that is incorporated by reference above.

RNB Multi-Link Multi-Stage Embodiments:

Symmetric RNB Embodiments:

15 Referring to FIG. 1A, in one embodiment, an exemplary symmetrical multi-link multi-stage network 100A with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches [S1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four 25 switches MS(1,1)-MS(1,4), middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS$  $(3,4).$ 

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage  $130$ , middle stage  $_{40}$ 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable 45 N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d, The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1-OS4 can be denoted in general with the notation 50 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 2d\*2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. A symmetric multi-link multi-stage network can be 55 represented with the notation  $V_{mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the mput switch of outlet hinks of each output switch, and s is the<br>ratio of number of outgoing links from each input switch to 60 the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same. a commention between configurable logic blocks, between an  $24$  of any single and output stage 120 via middle stages 130,<br>140, any that a different interaction and the stages 130, and 140, and 1450 is above where input as

Each of the N/d input switches IS1-IS4 are connected to 65 exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch

 $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$ 4)).

Each of the N/d middle switches  $MS(1,1)$ -MS $(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2×d links (for example the links  $ML(1,1)$  and  $ML(1,$ 2) are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links  $ML(1,7)$  and  $ML(1,8)$  are connected to the middle switch MS(1,1) from input switch IS2) and also are connected to exactly d switches in middle stage 140 through  $2 \times d$  links (for example the links ML $(2,1)$  and ML $(2,$ 2) are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch MS(1,1) to middle switch MS(2, 3)).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,11)$  and  $ML(2,12)$  are connected to the middle switch MS(2,1) from middle switch MS(1,3)) andalso are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,3)$ ).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,11)$  and  $ML(3,12)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from Middle switch MS(3,1), and the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$  and  $ML(4,$ 2), and output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,7)$  and  $ML(4,8)$ .

Finally the connection topology of the network 100A shownin FIG. 1A is knownto be back to back inverse Benes connection topology.

Referring to FIG. 1B, in another embodiment of network  $V_{mlink}(N, d, s)$ , an exemplary symmetrical multi-link multistage network 100B with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of tour, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)-MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle

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stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1-OS4 can be denoted in general with the notation 15 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 2d\*2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The symmetric multi-link multi-stage network of 20 FIG. 1B is also the network of the type  $V_{link}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input 25 switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to 30 exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$ 4)).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2×d links (for example the links  $ML(1,1)$  and  $ML(1,$ 2) are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links ML(1,9) and ML(1,10) are con- 40 nected to the middle switch  $MS(1,1)$  from input switch IS3) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$ are connected from middle switch  $MS(1,1)$  to middle switch MS(2,2)).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example 50 the links  $ML(2,1)$  and  $ML(2,2)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,9)$  and  $ML(2,10)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links 55 (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,2)$ ). switches. The symmetric mutil-infarmulti-mutil-strange network of 2013 is also the network of the type  $V_{\rm gas}/N_4$  d, s), where N represents the total namber of rine the symmetric finite symmetric finite witch responses t

Similarly each of the N/d middle switches MS(3,1)-MS(3, 60 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,9)$  and  $ML(3,10)$  are connected to the middle switch 65  $MS(3,1)$  from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 2xd

links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from Middle switch MS(3,1), and the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$  and  $ML(4,$ 2), and output switch OS1 is also connected from middle switch  $MS(3,3)$  through the links  $ML(4,9)$  and  $ML(4,10)$ .

Finally the connection topology of the network 100B shown in FIG. 1B is known to be back to back Omega connection topology.

Referring to FIG. 1C, in another embodiment of network  $V_{mlink}$ (N, d, s), an exemplary symmetrical multi-link multistage network 100C with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1-OS4 can be denoted in general with the notation 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 2d\*2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The symmetric multi-link multi-stage network of FIG. 1C is also the network of the type  $V_{mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of cach input switch or outlet links of cach output switch, and <sup>s</sup> is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$ 4)).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links (for example the links  $ML(1,1)$  and  $ML(1,1)$ 2) are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links  $ML(1,15)$  and  $ML(1,16)$  are con- 5 nected to the middle switch MS(1,1) from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  10 are connected from middle switch MS(1,1) to middle switch MS(2,2)).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example 15 the links  $ML(2,1)$  and  $ML(2,2)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,15)$  and  $ML(2,16)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,4)$ ) and also are connected  $\alpha$  exactly d switches in middle stage 150 through 2xd links 20 (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,2)$ ).

Similarly each of the N/d middle switches  $MS(3,1)$ -MS(3, 25 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links ML(3,15) and ML(3,16) are connected to the middle switch  $30\,4$ ) in the middle stage 140 are connected from exactly d<br>ML(3,15) and ML(3,16) are connected to the middle switch  $30\,4$ ) in the middle stage 140 are connecte  $MS(3,1)$  from middle switch  $MS(2,4)$  and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch MS(3,1), and the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output 35 4) in the middle stage 150 are connected from exactly d switch OS2 from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links ML(4,1) and ML(4, 40 from exactly 2xd switches in middle stage 150 through 2xd switches in middle stage 150 through 2xd 2), and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,15)$  and  $ML(4,16)$ .

Finally the connection topology of the network 100C shown in FIG. 1C is hereinafter called nearest neighbor connection topology.

Similar to network 100A ofFIG. 1A, 100B ofFIG. 1B, and 100C ofFIG.IC,referring to FIG. 1D, FIG. 1E, FIG. 1F, FIG. 1G, FIG. 1H, FIG. 1] and FIG. 1J with exemplary symmetrical multi-link multi-stage networks 100D, 100E, 100F, 100G, 100H,1001, and 100J respectively with five stages oftwenty 50 switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches 55 IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ -MS  $(1,4)$ , middle stage  $140$  consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four 60 by four switches MS(3,1)-MS(3,4). middle swind MS(2,1), and the link of 112,24) and the link of 112,24) and the link of 12,24) and the link of 12,24) and the link of 12,24) and 100 smiths and 200 smiths and 200 smiths and 200 smiths and 200 smiths and 200

Such networks can also be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

The networks 100D, 100E, 100F, 100G, 100H, 100I and 100J ofFIG. 1D, FIG. 1E, FIG. 1F, FIG. 1G, FIG. 1H, FIG. 1, and FIG. 1J are also embodiments of symmetric multi-link multi-stage network can be represented with the notation  $V_{link}$  (N, d, s), where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Just like networks of 100A, 100B and 100C, for all the networks 100D, 100E, 100F, 100G, 100H, 100] and 100] of FIG. 1D, FIG. 1E, FIG. 1F, FIG. 1G, FIG. 1H, FIG. 11, and FIG. 1J, each of the N/d input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ switches in middle stage 130 through 2xd links and also are connected to exactly d switches in middle stage 150 through 2xd links.

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ switches in middle stage 140 through 2xd links and also are connected to exactly d output switches in output stage 120 through 2xd links.

Each of the N/d output switches OS1-OS4 are connected links.

In all the ten embodiments of FIG. 1A to FIG. 1J the connection topology is different. That is the way the links  $ML(1,1)-ML(1,16)$ ,  $ML(2,1)-ML(2,16)$ ,  $ML(3,1)-ML(3,$ 16), and  $ML(4,1)$ - $ML(4,16)$  are connected between the respective stages is different. Even though only ten embodiments are illustrated, in general, the network  $V_{mlink}(N, d, s)$ can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{mlink}(N, d, d)$ s) may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{mlink}$ (N, d, s) network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N, d, s)$  can be built. The ten embodiments of FIG. 1A to FIG. 1J are only three examples of network  $V_{mlink}$ (N, d, 8).

In all the ten embodiments of FIG. 1A to FIG. 1J, each of the links ML(1,1)-ML(1,16), ML(2.1)-ML(2,16), ML(3,1)-  $ML(3,16)$  and  $ML(4,1)$ - $ML(4,16)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The

 $10$ 

middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and MS(3,1)-MS(3,4) are referred to as middle switches or middle ports.

In the example illustrated in FIG. 1A (or in FIG. 1B to FIG. 1J), <sup>a</sup> fan-out offour is possibleto satisfy <sup>a</sup> multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection requestissatisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the  $_{15}$ network 100A (or 100B to 100J), to be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In 20 case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, 25 the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output  $~^{30}$ stage switches to satisfy the connection request. Generalized Symmetric RNB Embodiments:

Network 100K of FIG. 1K is an example of general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  with  $(2 \times \log_a N)-1$  stages. The general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$ according to the current invention. Also the general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$ according to the current invention. (And in the example of FIG. 1K, s=2), The general symmetrical multi-link multistage network  $V_{mlink}(N, d, s)$  with  $(2 \times \log_d N)-1$  stages has d inlet links for each of N/d input switches IS1-IS(N/d) (for example the links IL1-IL(d) to the input switch IS1) and  $2 \times d$ outgoing links for each ofN/d input switches IS1-IS(N/d)(for example the links  $ML(1,1)-ML(1,2d)$  to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS( $N/d$ ) (for example the links OL1-OL $(d)$  to the output switch OS1) and 2xd incoming links for cach of N/d output switches OS1-OS(N/d) (for example  $ML(2\times Log_d$ N-2,1)-ML $(2 \times \text{Log}_d N - 2,2 \times d)$  to the output switch OS1). a broadcast connection requests depending on the example. In 2016<br>a case of a unicarat connection request, a fun-out of one is used,<br>i.e. a single middle stage switch in middle stage 110 is used to<br>starisfy the request. M 40

Each of the N/d input switches IS1-IS(N/d) are connected to exactly d switches in middle stage 130 through 2xd links.  $\frac{55}{20}$ 

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,N/d)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the N/d middle switches

$$
MS(\text{Log}_d N - 1, 1) - MS(\text{Log}_d N - 1, \frac{N}{d})
$$

24

through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_A N-1)$  through 2xd links.

Similarly each of the N/d middle switches

$$
MS(2 \times Log_d N - 3, 1) - MS(2 \times Log_d N - 3, \frac{N}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$ N-5) through 2xd links and also are connected to exactly d output switches in output stage 120 through 2xd links.

Each of the N/d output switches OS1-OS(N/d) are connected from exactly d switches in middle stage 130+10\*  $(2*Log<sub>a</sub>N-4)$  through 2xd links.

As described before, again the connection topology of a general  $V_{mlink}(N, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{mlink}(N, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N, d, s)$  can be built. The embodiments of FIG. 1A to FIG. 1J are ten examples of network  $V_{mlink}(N, d, s)$ .

The general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical multi-link multistage network  $V_{mlink}(N, d, s)$  can be operated in strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention.

60 tions of the first type Every switch in the multi-link multi-stage networks discussed herein has multicast capability. In a  $V_{mlink}(N, d, s)$ network, if a network inlet link is to be connected to more than one outlet link on the same output switch, then it is only necessary for the corresponding input switch to have one path to that output switch. This follows because that path can be multicast within the output switch to as many outlet links as necessary. Multicast assignments can therefore be described in terms of connections between input switches and output switches. An existing connection or a new connection from an input switch to r' output switches is said to have fan-out r'.If all multicast assignments of a first type, wherein any inlet link of an input switch is to be connected in an output switch to at most one outlet link are realizable, then multicast assignments of a second type, wherein any inlet link of each input switch is to be connected to more than one outlet link in the same output switch, can also be realized. For this reason, the following discussion is limited to general multicast connec-

$$
\left(\text{with fan-out } r', 1 \le r' \le \frac{N}{d}\right)
$$

in the middle stage  $130+10*(\text{Log}_d N-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}-3)$ 

with fan-out 
$$
r'
$$
,  $1 \leq r'$ 

although the samediscussion is applicable to the second type.

 $\overline{\mathbf{S}}$ 

To characterize a multicast assignment, for each inlet link

$$
i \in \Big\{1, 2, \ldots, \frac{N}{d}\Big\},\
$$

let I<sub>i</sub>=O, where

$$
O\subset \Big\{1,\,2,\,\ldots\,\ ,\,\frac{N}{d}\Big\},
$$

denote the subset of output switches to which inlet link i is to 15 be connected in the multicast assignment. For example, the network of FIG. 1C shows an exemplary five-stage network, namely  $V_{mlink}(8,2,2)$ , with the following multicast assignment  $I_1 = \{2,4\}$  and all other  $I_i = \{\phi$  for j=[2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into <sup>20</sup> that the connection  $I_1$  fans out in the first stage switch IS1 into <sup>20</sup> middle switches  $MS(1,1)$  and  $MS(1,2)$  in middle stage 130, and fans out in middle switches  $MS(1,1)$  and  $MS(1,2)$  only once into middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and MS(2,3) only once into middle switches MS(3,2) and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches MS(3,2) and MS(3,4) only once into output switches OS2 and OS4 in output stage 120. <sup>30</sup> Finally the connection I, fans out once in the output stage switch OS2 into outlet link OL3 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle <sup>35</sup> stage 130.

Asymmetric RNB  $(N_2>N_1)$  Embodiments:

Referring to FIG. 1A1, in one embodiment, an exemplary Referring to FIO. 1A1, in the emboddle and exemptary<br>asymmetrical multi-link multi-stage network 100A1 with 40 five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by eight switches MS(3,1)- MS(3,4).  $\phi \propto \{1, 2, \ldots, \frac{N}{d}\}$ .<br>
denote the subset of conjunt switches to which indet link it is to be conserved in the multicest is signament. For example, the multicest signament is conserved in the multicest of the subset

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches [S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_1}{d}$ 

where  $N_i$  is the total number of inlet links or and  $N_i$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N$ , where  $p > 1$ . The number of middle switches in each middle stage is  $_{10}$  denoted by

 $\frac{N_1}{d}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation  $(d+d_2)*d_2$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 2d\*2d. The size of each switch in the last middle stage can be denoted as 2d\*(d+ d,). <sup>A</sup> switch as used herein can be either <sup>a</sup> crossbarswitch,or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1- IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.<br>Each of the

 $\frac{N_1}{d}$ 

input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through 2xd links(for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$ through the links  $ML(1,3)$  and  $ML(1,4)$ .

Each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch MS(1,1) from input switch IS1, and the links  $ML(1,7)$  and  $ML(1,8)$  are connected to the middle switch MS(1,1) from input switch IS2) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch MS(1,1) to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ).

 $\overline{a}$ 

40

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch MS(2,1) from middle switch  $MS(1,1)$ , and the links  $ML(2,11)$  and  $ML(2,12)$  are connected to the middle switch MS(2,1) from middle switch  $MS(1,3)$ ) and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $_{15}$  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,3)). fixouga? So that Glorentagne leminas MLZ,43 and NLLZ,<br>
2) are extrosched to the middle swinch NS(2,1) from niddle<br>
swich NS(2,1) and nide to swinch of 2013<br>
cytical base of 10 of 10 of 211) and MLZ (2,13) and also are con

Similarly each of the

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,$ 2) are connected to the middle switch MS(3,1) from middle switch MS(2,1), and the links ML(3,11) and ML(3,12) are  $30$  switches IS1-IS4 and output switches OS1-OS4 are crossbare switch MS(2,1), and the links ML(3,11) and ML(3,12) are  $30$  switches IS1-IS4 and output switches OS1 connected to the middle switch MS(3,1) from middle switch  $MS(2,3)$ ) and also are connected to exactly

output switches in output stage 120 through d+d, links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from Middle switch  $MS(3,1)$ ; the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ; the links  $ML(4,5)$  and  $ML(4,6)$ are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; and the links  $ML(4,7)$  and  $ML(4,8)$  are connected to output switch OS4 from middle switch MS(3,1)).

 $\frac{d+d_2}{2}$ 

Each of the

$$
\frac{N_1}{d}
$$

output switches OS1-OS4 are connected from exactly

$$
\frac{d+d_2}{2}
$$

switches in middle stage 150 through  $d+d_2$  links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  60 through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is also connected from middle switch MS(3,2) through the links  $ML(4,9)$  and  $ML(4,10)$ ; output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,17)$  and  $ML(4,18)$ ; and output switch OS1 is also connected from  $65$ middle switch  $MS(3,4)$  through the links  $ML(4,25)$  and  $ML(4,26)$ .

Finally the connection topology of the network 100A1 shown in FIG. 1A1 is known to be back to back inverse Benes connection topology.

Referring to FIG. 1B1, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 100B1 with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by eight switches MS(3,1)-  $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

where 
$$
N_1
$$
 is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N$ , where  $p > 1$ .  
The number of middle switches in each middle stage is denoted by

$$
\frac{N_1}{d}
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation  $(d+d_2)*d_2$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 2d\*2d. The size of each switch in the last middle stage can be denoted as 2d\*(d+  $d_2$ ). A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d repre-

 $\overline{\mathbf{S}}$ 

20

sents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

Each of the

 $\frac{N_1}{d}$ 

input switches [S1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch MS(1,1) through the links ML(1,1), ML(1,2), and also to middle switch MS(1,2)  $_{15}$ through the links  $ML(1,3)$  and  $ML(1,4)$ .

Each of the

$$
\frac{N_1}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through  $2 \times d$  25 links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch MS(1,1) from input switch IS1, and the links  $ML(1,9)$  and  $ML(1,10)$  are connected to the middle switch  $MS(1,1)$  from input switch IS3) and also are middle switch  $MS(1,1)$  from input switch  $1SS$ ) and also are<br>connected to exactly d switches in middle stage 140 through  $30$ 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the



middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2, 45)$ 2) are connected to the middle switch MS(2,1) from middle switch MS $(1,1)$ , and the links ML $(2,9)$  and ML $(2,10)$  are connected to the middle switch MS(2,1) from middle switch  $MS(1,3)$ ) and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,2)). input awiebles IS1.154 are connected to exactly 2xd awitels<br>in middle stage 181<br>of the middle stage 130 directions with IS1 is counseled to middle with<br>b MS(11) through the small clusts (for 200 middle with NS(12) in the<br>

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2×d links (for example the links ML $(3,1)$  and ML $(3, 65)$ 2) are connected to the middle switch MS(3,1) from middle switch  $MS(2,1)$ , and the links  $ML(3,9)$  and  $ML(3,10)$  are

connected to the middle switch  $MS(3,1)$  from middle switch MS(2,3)) and also are connected to exactly

$$
\frac{d+d_2}{2}
$$

output switches in output stage 120 through d+d, links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch MS(3,1); the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ; the links  $ML(4,5)$  and  $ML(4,6)$ are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; and the links  $ML(4,7)$  and  $ML(4,8)$  are connected to output switch OS4 from middle switch MS(3,1)). Eachofthe

$$
-\frac{N_1}{d}
$$

output switches OS1-OS4 are connected from exactly

$$
\frac{d+d_2}{2}
$$

switches in middle stage 150 through  $d+d_2$  links (for example output switch OS1 is connected from middle switch  $MS(3,1)$ through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links ML(4,9) and ML(4,10); output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,17)$  and ML(4,18); and output switch OS1 is also connected from middle switch MS(3,4) through the links ML(4,25) and ML(4,26)).

40 connection topology. Finally the connection topology of the network 100B1 shown in FIG. 1B1 is known to be back to back Omega

Referring to FIG. 1C1, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 100C1 with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches MS(1,1)-MS(1,4), middle stage 140 consists of four, four by four switches  $MS(2,1)$ -MS $(2,4)$ , and middle stage 150 consists of four, four by eight switches MS(3,1)-  $MS(3,4)$ .

60 stage 150. Such a network can be operated in rearrangeably Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar  $\overline{5}$ 

25

switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_1}{I}$ 

where  $N_i$  is the total number of inlet links or and  $N_i$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p*N$ , where  $p>1$ .  $10$ The number of middle switches in each middle stage is denoted by

 $\frac{N_1}{d}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and cach output switch OS1- OS4 can be denoted in general with the notation  $(d+d_2)*d_2$ , 20 where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 2d"2d. The size of each switch in the last middle stage can be denoted as  $2d^*(d+)$ d,). A switch as used herein can be either a crossbar switch, or  $20 \frac{30}{2}$ a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where N, represents the total number of inlet links of all input switches (for example the links IL1- IL8), Nrepresents the total numberofoutlet links ofall output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. OS4 can be denoted in general with the notation  $(444_3)^6d_3$ , 20<br>where<br>where<br> $d_2 = N_2 \times \frac{d}{N_1} = p \times d$ .<br>The size of each switch in any of the middle stages excepting<br>the last middle stage can be denoted as 2d<sup>2</sup>(d +<br>a). 40

Each of the

$$
\frac{l_1}{l}
$$

input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch MS(1,1) through the  $_{50}$ links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$ through the links  $ML(1,3)$  and  $ML(1,4)$ .

Each of the

$$
\frac{1}{\epsilon}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through  $2 \times d$  60 links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch MS(1,1) from input switch IS1, and the links  $ML(1,15)$  and  $ML(1,16)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch

 $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ). Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2×d links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,15)$  and  $ML(2,16)$  are  $_{15}$  connected to the middle switch MS(2,1) from middle switch  $MS(1,4)$  and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,2)).

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2×d links (for example the links  $ML(3,1)$  and  $ML(3,$ 2) are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,15)$  and  $ML(3,16)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,4)$ ) and also are connected to exactly

$$
\frac{d+d_2}{2}
$$

output switches in output stage  $120$  through d+d<sub>2</sub> links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch  $MS(3,1)$ ; the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ; the links  $ML(4,5)$  and  $ML(4,6)$ are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; and the links  $ML(4,7)$  and  $ML(4,8)$  are connected to output switch OS4 from middle switch MS(3,1)).<br>Each of the

# $\frac{N_{1}}{d}$

output switches OS1-OS4 are connected from exactly

$$
\frac{d+d_2}{2}
$$

switches in middle stage 150 through d+d, links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,9)$  and  $ML(4,10)$ ; output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,17)$  and ML(4,18); and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,25)$  and ML(4,26)).

Finally the connection topology of the network 100C1 shown in FIG. 1C1 is hereinafter called nearest neighbor <sup>5</sup> connection topology.

Similar to network 100A1 of FIG. 1A1, 100B1 of FIG. 1B1, and 100C1 of FIG. 1C1, referring to FIG. 1D1, FIG. 1E1, FIG. 1F1, FIG. 1G1, FIG. 11, FIG. <sup>111</sup> and FIG. 1J1  $10$ with exemplary asymmetrical multi-link multi-stage networks 100D1, 100E1, 100F1, 100G1, 100H1, 10011, and 100J1 respectively with five stages of twenty switches for satisfying communication requests, such assetting upatelesatisfying communication requests, such as setting up a tele-<br>phone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output <sup>15</sup> stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS(3,4)$ .

Such networks can also be operated in strictly non-blocking manner for unicast connections, because the switches in he input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rear-<br>rangeably non-blocking manner for multicast connections, <sup>30</sup> because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. 25

The networks 100D1, 100E1, 100F1, 100G1, 100H1. <sup>35</sup> 10011 and 10031 ofFIG. 1D1, FIG. 1E1, FIG. 1F1, FIG. 1G1, FIG. 1H1, FIG. 111, and FIG. 1J1 are also embodiments of asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where N, represents the total number of inlet links of all input switches (for example the links IL1-IL8), N<sub>2</sub> represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. rangeably non-blocking manner for multicast connections,  $\frac{1}{2}$  once the multical connection in the multistage 143 or exists for an out state of the are for which and there are four witches in each of middle stage 143

Just like networks of 100A1, 100B1 and 100C1, for all the networks 100D1, 100E1, 100F1, 100G1, 100H1, 10011 and 100J1 ofFIG. 1D1, FIG. 1E1, FIG. 1F1, FIG. 1G1, FIG. 1H1, FIG. 111, and FIG. 1J1, each of the

$$
\frac{N_1}{d}
$$

input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through 2xd links.

Each of the

$$
-\frac{N}{a}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

34

 $\frac{N_1}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links and also are connected to exactly d switches in middle stage 150 through 2xd links.

Similarly each of the

Similarly each of the

 $\frac{N_1}{d}$ 

20 through 2xd links and also are connected to exactly middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140

$$
\frac{d+d_2}{2}
$$

output switches in output stage  $120$  through  $d+d<sub>2</sub>$  links. Each of the

 $\frac{N_1}{d}$ 

output switches OS1-OS4 are connected from exactly

$$
\frac{d+d_2}{2}
$$

40 switches in middle stage 150 through  $d+d_2$  links.

In all the ten embodiments of FIG. 1A1 to FIG. 1J1 the connection topology is different. That is the way the links  $ML(1,1)-ML(1,16)$ ,  $ML(2,1)-ML(2,16)$ ,  $ML(3,1)-ML(3,$ 16), and  $ML(4,1)$ - $ML(4,16)$  are connected between the respective stages is different. Even though only ten embodiments are illustrated, in general, the network  $V_{mlink}(N_1,N_2,d,$ s) can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{mlink}$  $(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental propertyof <sup>a</sup> valid connection topology of the  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$  can be built. The ten embodiments of FIG. 1A1 to FIG. 1J1 are only three examples of network  $V_{mlink}(N_1, N_2, d, s)$ .

In all the ten embodiments ofFIG. 1A1 to FIG. 1J1, each of the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,16)$ ,  $ML(3,1)$ - $ML(3,16)$  and  $ML(4,1)$ - $ML(4,16)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The

outlet links for each of

middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and MS(3,1)-MS(3,4) are referred to as middle switches or middle ports.

In the example illustrated in FIG. 1A1 (or in FIG. 1B1 to FIG. 1J1), a fan-out of four is possible to satisfy a multicast  $\frac{5}{3}$ connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network  $100A1$  (or  $100B1$  to  $100J1$ ), to  $15$ be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In 20 case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, 25 the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output <sup>30</sup> stage switches to satisfy the connection request. Generalized Asymmetric RNB  $(N_2>N_1)$  Embodiments: is need. The specific middle experience for an expose that are closed.<br>In inside stage 134 or line procedure and the control is mixed as the small solution in that are control to the small solution and the small solution

Network 100K1 of FIG. 1K1 is an example of general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, ...)$ d, s) with  $(2 \times \log_a N_1) - 1$  stages where N<sub>2</sub>>N<sub>1</sub> and N<sub>2</sub>=p\*N, 35 where  $p>1$ . In network 100K1 of FIG. 1K1,  $N_1=N$  and  $N_2=p*N$ . The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \geq 2$  according to the nononocking manner for municast when  $s \equiv z$  according to the current invention. Also the general asymmetrical multi-link  $40$ multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention. (And in the example of FIG.  $1K1$ , s=2). The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times log_d N_1) - 1$  stages has d inlet links 45 for each of

input switches  $IS1$ -IS( $N_1/d$ ) (for example the links IL1-IL(d) to the input switch  $IS1$ ) and  $2 \times d$  outgoing links for each of

 $\frac{N_1}{N_2}$ 

input switches IS1-IS(N<sub>1</sub>/d) (for example the links ML(1,1)- $\epsilon$ <sub>60</sub>  $ML(1,2d)$  to the input switch IS1). There are  $d_2$ 

(where 
$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d
$$
)

36

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example the links OL1- $OL(p * d)$  to the output switch OS1) and  $d+d$ ,  $(=d+p \times d)$ incoming links for each of

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$  $N_1-2,1$ )-ML $(2\times Log_dN_1-2, d+d_2)$  to the output switch OS1). Each of the

 $\frac{N_1}{d}$ 

input switches  $IS1-IS(N/d)$  are connected to exactly 2xd switches in middle stage 130 through 2xd links. Each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(1,1)$ - $MS(1,N_1/d)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches

$$
MS(\text{Log}_{d}N_1 - 1, 1) - MS(\text{Log}_{d}N_1 - 1, \frac{N_1}{d})
$$

 $_{50}$  in the middle stage 130+10\*(Log<sub>d</sub>N<sub>1</sub>-2) are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d N_1-1)$  through 2xd links,

Similarly each of the

 $N_1$ 

middle switches

$$
MS(2 \times Log_d N_1 - 3, 1) - MS(2 \times Log_d N_1 - 3, \frac{N_1}{d})
$$
$\overline{\mathbf{S}}$ 

(3,4).

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log_{d})$  $N<sub>1</sub>$ -5) through 2xd links and also are connected to exactly

$$
\frac{d+d_2}{2}
$$

output switches in output stage  $120$  through d+d<sub>2</sub> links. Each of the

output switches  $OS1-OS(N_1/d)$  are connected from exactly

$$
\frac{d+d_2}{2}
$$

switches in middle stage  $130+10*(2*Log_{d} N_{1}-4)$  through d+d, links

As described before, again the connection topology of a 25 general  $V_{mlink}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{mlink}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The 30 applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$ can be built. The embodiments of FIG. 1A1 to FIG, 1J1 are ten examples of network  $V_{mlink}(N_1, N_2, d, s)$  for s=2 and  $N_2 > N_1$ . origin waviories in computating 140 turespectral to the reader of t

The general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably non-40 blocking manner for multicast when s=2 according to the current invention. Also the general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if s=2 according to the current invention.

For example, the network of FIG. 1C1 shows an exemplary five-stage network, namely  $V_{mlink}(8,24,2,2)$ , with the following multicast assignment  $I_1 = \{1,4\}$  and all other  $I_i = \phi$  for j=[2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,2)$  50 in middle stage 130, and fans out in middle switches  $MS(1,1)$ and  $MS(1,2)$  only once into middle switches  $MS(2,1)$  and MS(2,3) respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and  $MS(2,3)$  only once into middle switches  $MS(3,1)$  and 55  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches MS(3,1) and MS(3,4) only once into output switches OS1 and OS4 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage switch OS1 into outlet link OL2 and in the output stage switch OS4 twice into the outlet links OL20 and OL23. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

Asymmetric RNB  $(N_1 > N_2)$  Embodiments:

Referring to FIG. 1A2, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 100A2 with 38

five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of

four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage  $150$  consists of four, four by four switches MS $(3,1)$ -MS

20 non-blocking manner for multicast connections, because the Such a network can be operated in strictly non-blocking  $_{15}$  manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably switches in the input stage 110 are of size six by cight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_2}{d}$ 

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
\frac{N_2}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1^*(d+d_1)$  and each output switch OS1-OS4 can be denoted in general with the notation  $(2\times d^*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as 2d\*2d. The size of each switch in the first middle stage can be denoted as  $(d+d_1)$ \*2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where N, represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch.

 $\frac{N_2}{d}$ 

39

input switches IS1-IS4 are connected to exactly

$$
\frac{d+d_1}{2}
$$

switches in middle stage 130 through  $d+d_1$  links (for example input switch IS1 is connected to middle switch MS(1,1)  $_{15}$ through the links  $ML(1,1)$ ,  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$ and  $ML(1,4)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,5)$ ,  $ML(1,6)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$  20 through the links  $ML(1,7)$  and  $ML(1,8)$ ).

Each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

 $\frac{d+d_1}{2}$ 

input switches through  $d+d_1$  links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,9)$  and  $ML(1,$ 10) are connected to the middle switch  $MS(1,1)$  from input switch IS2; the links ML(1,17) and ML(1,18) are connected 40 to the middle switch MS(1,1) from input switch IS3; and the links  $ML(1,25)$  and  $ML(1,26)$  are connected to the middle switch MS(1,1) from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ).  $\frac{x+4}{x+4}$ <br>
switches in middle stage 150 through d-d, links (for example<br>
input wisted). It is a connected to middle witch DMS(1.1) is connected to middle witch DMS(1.4) in put witch ISI is some absolution of the links

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch  $MS(2,1)$  from middle switch MS(1,1), and the links ML(2,11) and ML(2,12) are  $\overline{60}$ connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and 65  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,3)).

40

 $\frac{N_2}{N_1}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2×d links (for example the links  $ML(3,1)$  and  $ML(3,1)$ 2) are connected to the middle switch MS(3,1) from middle switch  $MS(2,1)$ , and the links  $ML(3,11)$  and  $ML(3,12)$  are connected to the middle switch  $MS(3,1)$  from middle switch MS(2,3)) and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch  $MS(3,1)$ ; and the links  $ML(4,3)$  and ML(4,4) are connected to output switch OS2 from middle switch MS(3,1)).

Each of the

Similarly each of the



30 output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$ through the links  $ML(4,1)$  and  $ML(4,2)$ ; and output switch  $OS1$  is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,7)$  and  $ML(4,8)$ ).

Finally the connection topology of the network 100A2<br>shown in FIG. 1A2 is known to be back to back inverse Benes connection topology.

Referring to FIG. 1B2, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 100B2 with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)-MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ -MS  $(3,4).$ 

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

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where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

 $\frac{N_2}{d}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1^*(d+d_1)$  and each output switch OS1-O84 can be denoted in general with the notation  $(2\times d*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting  $_{20}$ the first middle stage can be denoted as 2d\*2d. The size of each switch in the first middle stage can be denoted as (d+  $d_1$ <sup>\*</sup>2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric  $_{25}$ multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8),  $d_{30}$ represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch. The size of each input switch [S1-154 can be denoted in <sup>10</sup><br>
gott CaVi the nonlined  $A^2(4+4)$  and each orapt awitich condition<br>
(2xd\*d), where<br>
(2xd\*d), where<br>  $(2x+4)$ , where<br>  $(2x+4)$ , where<br>  $(3x+4)$ , where<br>  $(4x-4)$ 

Each of the



input switches [S1-IS4 are connected to exactly

 $\frac{d+ d_1}{d}$ 

switches in middle stage  $130$  through d+d<sub>1</sub> links (for example input switch IS1 is connected to middle switch  $MS(1,1)$ through the links  $ML(1,1)$ ,  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$ and  $ML(1,4)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,5)$ ,  $ML(1,6)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$ through the links  $ML(1,7)$  and  $ML(1,8)$ .<br>Each of the

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130  $^{60}$ are connected from exactly

$$
\frac{d+d_1}{2}
$$

input switches through  $d+d_1$  links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,9)$  and  $ML(1,$ 10) are connected to the middle switch  $MS(1,1)$  from input switch IS2; the links  $ML(1,17)$  and  $ML(1,18)$  are connected to the middle switch MS(1,1) from input switch IS3; and the links  $ML(1,25)$  and  $ML(1,26)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the



middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2×d links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch MS(2,1) from middle switch  $MS(1,1)$ , and the links  $ML(2,9)$  and  $ML(2,10)$  are connected to the middle switch MS(2,1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,2)).

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,$ 2) are connected to the middle switch MS(3,1) from middle switch  $MS(2,1)$ , and the links  $ML(3,9)$  and  $ML(3,10)$  are connected to the middle switch MS(3,1) from middle switch MS(2,3)) and also are connected to exactly d output switches in output stage  $120$  through  $2 \times d$  links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch  $MS(3,1)$ ; and the links  $ML(4,3)$  and ML(4,4) are connected to output switch OS2 from middle switch MS(3,1)).

Each of the

40

 $\frac{N_2}{N_1}$ 

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$  and  $ML(4,2)$ ; and output switch OS1 is also connected from middle switch  $MS(3,3)$  through the links  $ML(4,9)$  and  $ML(4,10)$ ).

Finally the connection topology of the network 100B2 shown in FIG. 1B2 is known to be back to back Omega 65 connection topology.

Referring to FIG. 1C2, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 100C2 with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four,  $5$ six by eight switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches MS(1,1)-MS(1,4), middle stage 140 consists of  $10\,$ four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ -MS  $(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the  $_{15}$ input stage  $110$  are of size six by eight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by cight, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input 25 switches [S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage  $120$  can be denoted in general with the variable

$$
\frac{N_2}{d},
$$

where N<sub>1</sub> is the total number of inlet links or and N<sub>2</sub> is the total  $\frac{1}{35}$ number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
\frac{N_2}{d}
$$

The size of each input switch IS1-IS4 can be denoted in The size of each input switch is  $1 - 1$ , and each output switch  $45$ <br>general with the notation  $d_1^*(d+d_1)$  and each output switch  $45$ OS1-O84 can be denoted in general with the notation  $(2\times d*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $2d*2d$ . The size of  $55$ each switch in the first middle stage can be denoted as (d+  $d_1$ <sup>\*</sup>2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the 60 notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , 65 and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch. non-blocking manner for multicast connections, because the 20<br>non-blocking in another simple and the matter and the switches in the interpret and of middle stage 130 and nickle single (10 and middle stage 130 and middle s

Each of the

 $N_2$  $\overline{d}$ 

44

input switches IS1-IS4 are connected to exactly

$$
\frac{d+d_1}{2}
$$

switches in middle stage 130 through  $d+d_1$  links (for example input switch IS1 is connected to middle switch  $MS(1,1)$ through the links  $ML(1,1)$ ,  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$ and  $ML(1,4)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,5)$ ,  $ML(1,6)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$ through the links  $ML(1,7)$  and  $ML(1,8)$ ).<br>Each of the

$$
\frac{N_2}{d}
$$

30 middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

$$
\frac{d+d_1}{2}
$$

40 switch IS2; the links  $ML(1,17)$  and  $ML(1,18)$  are connected input switches through  $d+d_1$  links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,9)$  and  $ML(1,$ 10) are connected to the middle switch MS(1,1) from input to the middle switch  $MS(1,1)$  from input switch IS3; and the links  $ML(1,25)$  and  $ML(1,26)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the

 $\frac{N_2}{N}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2×d links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch MS(2,1) from middle switch  $MS(1,1)$ , and the links  $ML(2,15)$  and  $ML(2,16)$  are connected to the middle switch MS(2,1) from middle switch MS(1,4)) and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,2)).

25

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,1)$ 2) are connected to the middle switch MS(3,1) from middle switch  $MS(2,1)$ , and the links  $ML(3,15)$  and  $ML(3,16)$  are connected to the middle switch MS(3,1) from middle switch MS(2,4)) and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links 15  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch  $MS(3,1)$ ; and the links  $ML(4,3)$  and ML(4,4) are connected to output switch OS2 from middle switch MS(3,1)).

Each of the

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$ through the links  $ML(4,1)$  and  $ML(4,2)$ ; and output switch through the links ML(4,1) and ML(4,2); and output switch<br>OS1 is also connected from middle switch MS(3,4) through  $_{30}$  middle switches MS(1,1)-MS(1,4) in the middle stage 130 the links  $ML(4,15)$  and  $ML(4,16)$ .

Finally the connection topology of the network 100C2 shown in FIG. 1C2 is hereinafter called nearest neighbor connection topology.

Similar to network 100A2 of FIG. 1A2, 100B2 of FIG. 1B2, and 100C2 of FIG. 1C2, referring to FIG. 1D2, FIG. 1E2, FIG. 1F2, FIG. 1G2, FIG. 1H2, FIG. 112 and FIG. 1J2 with exemplary asymmetrical multi-link multi-stage networks 100D2, 100E2, 100F2, 100G2, 100H2, 10012, and 100J2 respectively with five stages of twenty switches for 40 satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shownwhere input stage 110 consists of four, six by eight switches IS1-IS4 45 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four 50 by four switches  $MS(3,1)$ - $MS(3,4)$ . Each of the  $\frac{m_1}{4}$ <br>
comput wwitches OSI-OS4 are connected from exactly  $\frac{3}{4}$ <br>
comput wwitches in middle stage 150 through 2xd links (for example<br>
comput witch OSI is connected from middle switch MS(3,1)<br>
through

Such networks can also be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four 55 switches in cach of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage  $120$  are of size four by two, 60 and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

The networks 100D2, 100E2, 100F2, 100G2, 100H2, 10012 and 100J2 ofFIG. 1D2, FIG. 1E2, FIG. 1F2, FIG. 1G2, FIG. 1H2, FIG. 1I2, and FIG. 1J2 are also embodiments of 65 asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  rep-

resents the total numberofinlet links ofall input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of outgoing links where  $N_1 > N_2$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Just like networks of  $100A2$ ,  $100B2$  and  $100C2$ , for all the networks 100D2, 100E2, 100F2, 100G2, 100H2, 10012 and

10032 ofFIG. 1D2, FIG. 1E2, FIG. 1F2, FIG. 1G2, FIG. 1H2, FIG. 112, and FIG. 1J2, each of the

$$
\frac{N_2}{d}
$$

input switches IS1-IS4 are connected to exactly

 $\frac{d+d_2}{d_2}$ 

switches in middle stage  $130$  through d+d<sub>2</sub> links. Each of the

 $\frac{N_2}{4}$ 

are connected from exactly

$$
\frac{d+d_2}{2}
$$

input switches through  $d+d_2$  links and also are connected to exactly d switches in middle stage 140 through 2xd links. Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links and also are connected to exactly d switches in middle stage 150 through 2xd links.

Similarly each of the

## $\frac{N_2}{N_1}$

middle switches MS(3,1)-MS(3.4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links and also are connected to exactly d output switches in output stage 120 through 2xd links.

Each of the

## $\frac{N_2}{d}$

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 2xd links.

In all the ten embodiments of FIG. 1A2 to FIG. 1J2 the connection topology is different. That is the way the links  $ML(1,1)-ML(1,16)$ ,  $ML(2,1)-ML(2,16)$ ,  $ML(3,1)-ML(3,$ 16), and  $ML(4,1)$ - $ML(4,16)$  are connected between the respective stages is different. Even though only ten embodiments are illustrated, in general, the network  $V_{mlink}(N_1, N_2, d,$ s) can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{mlink}$  $(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes 10 that the fundamental property of a valid connection topology of the  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$  can be built. The ten embodi- 15 ments of FIG. 1A2 to FIG. 1J2 are only three examples of network $\mathbf{V}_{\textit{mlink}}(\mathbf{N}_1, \mathbf{N}_2, \mathbf{d}, \mathbf{s}).$ 

In all the ten embodiments ofFIG. 1A2 to FIG. 132, each of the links ML(1,1)-ML(1,16), ML(2,1)-ML(2,16), ML(3,1)-  $ML(3,16)$  and  $ML(4,1)$ - $ML(4,16)$  are either available for use 20 by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1- OS4 are also referred to as the network output ports. The 25 output stage 120 is often referred to as the last stage. The middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and  $MS(3,1)$ - $MS(3,4)$  are referred to as middle switches or middle ports.

In the example illustrated in FIG. 1A2 (or in FIG. 1B2 to <sup>30</sup> FIG. 1J2), a fan-out of four is possible to satisfy a multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two 35 is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle 40 switches permits the network 100A2 (or 100B2 to 100J2), to be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be Interest connection request, a multicast connection request or 45 a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the  $\frac{1}{20}$  input switches IS1-IS(N<sub>2</sub>/d) are connected to exactly fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request. Generalized Asymmetric RNB  $(N_2>N_1)$  Embodiments: ML(3,160 and ML (4,15)-ML(4,160 are either avoidable for two  $20$ <br>by a new connection or not avoilable if currently used by an<br>existing connection. The input switches IS1-1S4 are also<br>estimal conference of the state. The

Network 1001K2 of FIG. 1K2 is an example of general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, 60)$ d, s) with  $(2 \times \log_d N_2)$ -1 stages where  $N_1 > N_2$  and  $N_1 = p^*N_2$ where p>1. In network 100K2 of FIG. 1 $\overline{K2}$ , N<sub>2</sub>=N and  $N_1=p*N$ . The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the 65 current invention. Also the general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in

strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention. (And in the example of FIG.  $1K2$ ,  $s=2$ ). The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_a N_2) - 1$  stages has  $d_1$  (where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

inlet links for each of

$$
\frac{N_2}{d}
$$

input switches  $IS1$ -IS(N<sub>2</sub>/d) (for example the links IL1-IL  $(p * d)$  to the input switch IS1) and  $d+d_1$  (=d+p×d) outgoing links for each of

$$
\frac{N_2}{d}
$$

input switches IS1-IS( $N_2/d$ ) (for example the links ML(1,1)- $ML(1,(d+p*d))$  to the input switch IS1). There are d outlet links for each of



output switches  $OS1-OS(N<sub>2</sub>/d)$  (for example the links OL1- $OL(d)$  to the output switch  $OS1$ ) and 2xd incoming links for each of

 $\frac{N_2}{d}$ 

output switches  $OS1-OS(N_2/d)$  (for example  $ML(2\times Log_d)$  $N_2$ 2,1)-ML(2xLog<sub>d</sub>  $N_2$ -2,2xd) to the output switch OS1).<br>Each of the

 $\frac{N_2}{4}$ 

$$
\frac{d+d_1}{2}
$$

switches in middle stage  $130$  through d+d<sub>1</sub> links. Each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(1,1)-MS(1,N_2/d)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(\text{Log}_{d}N_{2}-1, 1) - MS\left(\text{Log}_{d}N_{2}-1, \frac{N_{2}}{d}\right)
$$

in the middle stage  $130+10*(\text{Log}_A N_2-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_2-3)$  15 through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d N_2-1)$  through 2xd links.

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(2 \times Log_d N_2 - 3, 1) - MS \bigg( 2 \times Log_d N_2 - 3, \frac{N_2}{d} \bigg)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log_{d})$ N,-5) through 2xd links and also are connected to exactly d output switches in output stage  $120$  through  $2 \times d$  links.

Each of the

$$
f_{\rm{max}}
$$

40

output switches  $OS1-OS(N_2/d)$  are connected from exactly d switches in middle stage  $130+10*(2*Log_a N_2-4)$  through  $2 \times d$  links.

As described before, again the connection topology of a general  $V_{mlink}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{mlink}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$ can be built. The embodiments of FIG. 1A2 to FIG. 1J2 are ten examples of network  $V_{mlink}(N_1, N_2, d, s)$  for s=2 and  $N_2 > N_1$ . AFSUog,  $N_{2} = 1.13 - 1.85[1.5y_{2} - 1. \frac{N_{2}}{2}]$ <br>
in the middle stope 130+10°(Log, N<sub>2</sub> - 2) are connected from<br>
exactly d switches in middle stope 130+10°(Log, N<sub>2</sub> -3) is<br>
through 2sd this was that and also are connecte

The general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in 65 strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention.

For example, the network of FIG. 1C2 shows an exemplary five-stage network, namely  $V_{mink}(8,24,2,2)$ , with the follow-<br>ing multicast assignment  $I_1 = \{1,4\}$  and all other  $I_j = \emptyset$  for j=[2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,4)$ in middle stage 130, and fans out in middle switches  $MS(1,1)$ and  $MS(1,4)$  only once into middle switches  $MS(2,1)$  and MS(2,4) respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ 10 and  $MS(2,4)$  only once into middle switches  $MS(3,1)$  and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches MS(3,1) and MS(3,4) only once into output switches OS1 and OS4in output stage 120. Finally the connection  $I_1$  fans out once in the output stage switch OS1 into outlet link OL1 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

20 Symmetric Folded RNB Embodiments:

ing that in the illustrations folded network  $V_{fold-mlink}(N_1, N_2, N_3)$ The folded multi-link multi-stage network  $V_{fold\_mlink}(N_1,$  $N<sub>2</sub>$ , d, s) disclosed, in the current invention, is topologically exactly the same as the multi-link multi-stage network  $V_{mlink}$  $(N_1, N_2, d, s)$ , disclosed in the current invention so far, except-

d, s) is shown as it is folded at middle stage  $130+10*(\text{Log}_d)$  $N_{2}$ –2). This is true for all the embodiments presented in the current invention.

30 symmetrical folded multi-link multi-stage network 200A Referring to FIG, 2A, in one embodiment, an exemplary with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle  $35$  stages 130,  $140$ , and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1-OS4 can be denoted in general with the notation 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 2d¥\*2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. A symmetric folded multi-link multi-stage network

can be represented with the notation  $V_{fold-mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from 5 each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to 10 exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$  $4)$ 

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links (for example the links  $ML(1,1)$  and  $ML(1,$ 2) are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links ML $(1,7)$  and ML $(1,8)$  are connected 20 to the middle switch MS(1,1) from input switch IS2) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2, 1)$ 3)).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2xd links (for example 30 the links  $ML(2,1)$  and  $ML(2,2)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,11)$  and  $ML(2,12)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links 35 (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,3)$ ).

Similarly each of the N/d middle switches MS(3,1)-MS(3, 40 4) in the middle stage 150 are connected from exactly d switches in middle stage <sup>140</sup> through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links ML(3,11) and ML(3,12) are connected to the middle switch  $45$  $MS(3,1)$  from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from Middle switch MS(3,1), and the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output 50 switch OS2 from middle switch MS(3,1)). Feach of the NKi (mpi winds) ISI-1848 are connected to the RNA (for example in the RNA (151) and MI (151) and MI (181) and MI (181

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$  and  $ML(4, 55)$ 2), and output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,7)$  and  $ML(4,8)$ ).

Finally the connection topology of the network 200A shown in FIG. 2A is known to be back to back inverse Benes connection topology.

In other embodiments the connection topology may be different from the network  $200A$  of FIG.  $2A$ . That is the way the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,16)$ ,  $ML(3,1)$ - $ML(3,16)$ , and  $ML(4,1)$ - $ML(4,16)$  are connected between the respective stages is different. Even though only one embodiment is illustrated, in general, the network  $V_{fold-mlink}(N, d, s)$ can comprise any arbitrary type of connection topology. For

52

example the connection topology of the network  $V_{fold-mlink}$ (N, d, s) may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{fold-mlink}(N, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold-mlink}(\vec{N}, \vec{d}, s)$  can be built. The embodiment of FIG. 2A is only one example of network  $V_{fold-mlink}(N, d, s)$ .

In the embodiment of FIG. 2A each of the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,16)$ ,  $ML(3,1)$ - $ML(3,16)$  and  $ML(4,1)$ -ML $(4,16)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4 are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The middle stage switches MS(1, 1)- $MS(1,4)$  and  $MS(2,1)$ - $MS(2,4)$  are referred to as middle switches or middle ports. The middle stage 130 is also referred to as root stage and middle stage switches MS(2,1)-  $MS(2,4)$  are referred to as root stage switches.

In the example illustrated in FIG. 2A, a fan-out of four is possible to satisfy a multicast connection request if input switch is 1S2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out oftwoisirrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network 200A, to be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. asingle middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request. Generalized Symmetric Folded RNB Embodiments:

Network 200B of FIG. 2B is an example of general symmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N,$ d, s) with  $(2 \times \log_d N)-1$  stages. The general symmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}$ (N, d, s) can be operated in strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention. (And in the example of FIG.  $2B$ ,  $s=2$ ). The general symmetrical folded multi-link multi-stage network  $V_{fold\_minh}(N, d, s)$ <br>with (2×log<sub>a</sub> N)–1 stages has d inlet links for each of N/d input switches IS1-IS(N/d) (for example the links IL1-IL(d) to the input switch IS1) and 2xd outgoing links for each of N/d input switches IS1-IS(N/d) (for example the links ML $(1, 1)$ 1)-ML(1,2d) to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS(N/d) (for example the links  $OL1-OL(d)$  to the output switch OS1) and  $2 \times d$ incoming links for each of N/d output switches OS1-OS(N/d) (for example  $ML(2 \times Log_d N-2,1)$ - $ML(2 \times Log_d N-2,2 \times d)$  to the output switch OS1).

Each of the N/d input switches  $IS1$ -IS(N/d) are connected to exactly d switches in middle stage 130 through 2xd links.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,N/d)$  in the middle stage 130 are connected from exactly d input switches through 2xd links and also are connected to exactly

d switches in middle stage 140 through 2xd links.

Similarly each of the N/d middle switches

$$
MS(\text{Log}_d N - 1, 1) - MS\left(\text{Log}_d N - 1, \frac{N}{d}\right)
$$

in the middle stage  $130+10*(\text{Log}_d \text{N}-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}-3)$ through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_{d} N-1)$  through  $2 \times d$ links. 20

Similarly each of the N/d middle switches

$$
MS(2 \times \text{Log}_d N - 3, 1) - MS\left(2 \times \text{Log}_d N - 3, \frac{N}{d}\right)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected 30 from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$ N-5) through 2xd links and also are connected to exactly d output switches in output stage 120 through 2xd links.

Each of the N/d output switches OS1-OS(N/d) are connected from exactly d switches in middle stage  $130+10*$  35  $(2 * Log<sub>d</sub> N-4)$  through 2xd links.

As described before, again the connection topology of a general  $V_{fold-mlink}(N, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{fold-mlink}(N, d, s)$  may be back to back inverse Benes 40 networks, back to back Omeganetworks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold-mlink}(N, d, s)$  network is,<br>when no connections are setup from any input link if any 45 output link should be reachable. Based on this property numerous embodiments of the network  $V_{fold\text{-}mlink}(N, d, s)$  can be built. The embodiment of FIG. 1A is one example of network  $V_{fold-minik}$ (N, d, s).<br>The general symmetrical folded multi-link multi-stage netswitch a foreign zon annotation and also are connected to exactly<br>dissimilately in the SM and S

work  $V_{fold\text{-}mlink}(N, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multilink multi-stage network  $V_{\text{fold-mlink}}(N, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to 55 the current invention.

Every switch in the folded multi-link multi-stage networks discussed herein has multicast capability. In a  $V_{fold-mlink}(N, d, d)$ s) network, if a network inlet link is to be connected to more than one outlet link on the same output switch, then it is only necessary for the corresponding input switch to have one path to that output switch. This follows because that path can be multicast within the output switch to as many outlet links as necessary. Multicast assignments can therefore be described in terms of connections between input switches and output switches. An existing connection or a new connection from an input switch to r' output switches is said to have fan-out r'. If

all multicast assignments of a first type, wherein any inlet link of an input switch is to be connected in an output switch to at most one outlet link are realizable, then multicast assignments of a second type, wherein any inlet link of each input switch is to be connected to more than one outlet link in the same output switch, can also be realized. For this reason, the following discussion is limited to general multicast connections of the first type

$$
\left(\text{with fan-out } r', 1 \le r' \le \frac{N}{d}\right)
$$

 $_{15}$  although the same discussion is applicable to the second type. To characterize a multicast assignment, for each inlet link

$$
i \in \bigg\{1, \, 2, \, \ldots \, , \, \frac{N}{d}\bigg\},
$$

let  $I<sub>i</sub>=O$ , where

25

 $O\subset\Bigg\{1,\,2,\,\ldots\,\,,\,\frac{N}{d}\Bigg\},$ 

denote the subset of output switches to which inlet link i is to be connected in the multicast assignment. For example, the network of FIG. 1C shows an exemplary five-stage network, namely  $V_{mink}(8,2,2)$ , with the following multicast assignment  $I_1$ ={2,4} and all other  $I_j$ = $\phi$  for j={2-8}. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,2)$  in middle stage 130, and fans out in middle switches  $MS(1,1)$  and  $MS(1,2)$  only once into middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and  $MS(2,3)$  only once into middle switches  $MS(3,2)$  and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,2)$  and  $MS(3,4)$  only once into output switches OS2 and OS4 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage switch OS2 into outlet link OL3 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

Asymmetric Folded RNB  $(N_2>N_1)$  Embodiments:

Referring to FIG. 2C, in one embodiment, an exemplary asymmetrical folded multi-link multi-stage network 200C with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, four by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by eight switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage  $110$  are of size two by four, the  $5$ switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input  $10$ switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_1}{d}$ 

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total  $_{20}$ number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

The size of each input switch IS1-IS4 can be denoted in <sup>30</sup> general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation  $(d+d_2)*d_2$ , where

$$
d_2=N_2\times \frac{d}{N_1}=p\times d.
$$

The size of each switch in any of the middle stages excepting 40 the last middle stage can be denoted as 2d\*2d. The size of each switch in the last middle stage can be denoted as  $2d^*(d+)$ d,). A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multilink multi-stage network can be represented with the notation  $V_{fold-mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. where N<sub>1</sub> is the total number of finite links or and N<sub>2</sub>+ site boton 2 on<br>mumber of coulde links and N<sub>2</sub>-N<sub>1</sub> and N<sub>2</sub>-P<sup>N</sup>N, where p>1.<br>
The number of middle switches in each middle stage is<br>
denoted by<br>
The size of e 45

Each of the

$$
\frac{N_1}{d}
$$

input switches [S1-IS4 are connected to exactly d switches in middle stage  $130$  through  $2\times d$  links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $65$  $ML(1,1)$ ,  $ML(1,2)$ , and also to middle switch  $MS(1,2)$ through the links  $ML(1,3)$  and  $ML(1,4)$ .

Each of the

 $\frac{N_1}{d}$ 

56

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 2xd links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch MS(1,1) from input switch IS1, and the links  $ML(1,7)$  and  $ML(1,8)$  are connected to the middle switch  $MS(1,1)$  from input switch IS2) and also are connected to exactly d switches in middle stage 140 through 2 $\times$ d links (for example the links ML $(2,1)$  and ML $(2,2)$  are <sup>15</sup> connected from middle switch MS $(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ). Similarly each of the



 $_{25}$  through 2xd links (for example the links ML(2,1) and ML(2, middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 2) are connected to the middle switch MS(2,1) from middle switch  $MS(1,1)$ , and the links  $ML(2,11)$  and  $ML(2,12)$  are connected to the middle switch MS(2,1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,3)).

Similarly each of the

### $\frac{N_1}{d}$

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2×d links (for example the links  $ML(3,1)$  and  $ML(3,$ 2) are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,11)$  and  $ML(3,12)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,3)$ ) and also are connected to exactly

 $rac{d+d_2}{dt}$ 

output switches in output stage  $120$  through d+d<sub>2</sub> links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from Middle switch  $MS(3,1)$ ; the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ; the links  $ML(4,5)$  and  $ML(4,6)$ are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; and the links  $ML(4,7)$  and  $ML(4,8)$  are connected to output switch OS4 from middle switch  $\overline{\text{MS}(3,1)}$ .<br>Each of the

 $\overline{\phantom{a}}$ 

output switches OS1-OS4 are connected from exactly

 $\frac{d+d_2}{d}$ 

switches in middle stage  $150$  through d+d<sub>2</sub> links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is also connected from middle switch MS(3,2) through the links  $ML(4,9)$  and  $ML(4,10)$ ; output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,17)$  and ML(4,18); and output switch OS1 is also connected from middle switch  $\overline{\text{MS}}(3,4)$  through the links  $\overline{\text{ML}}(4,25)$  and  $_{15}$ ML(4,26)).

Finally the connection topology of the network 200C<br>shown in FIG. 2C is known to be back to back inverse Benes connection topology.

In other embodiments the connection topology may be 20 different from the network  $200C$  of FIG.  $2C$ . That is the way the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,16)$ ,  $ML(3,1)$ - $ML(3,16)$ , and  $ML(4,1)$ - $ML(4,16)$  are connected between the respective stages is different. Even though only one embodirespective stages is different. Even though only one embodi-<br>ment is illustrated, in general, the network  $V_{fold\text{-}mlink}(N, d, s)$  25 multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  with can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold\text{-}mlink}$ (N, d, s) may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the  $V_{fold-mlink}(N, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold\_mlink}(N, d, s)$  can be built. The embodiment of FIG. 2C is only one example of network  $V_{\text{fold-mlink}}(N \, d, s)$ .

In the embodiment of FIG.  $2C$  each of the links ML(1,1)-ML(1,16), ML(2,1)-ML(2,16), ML(3,1)-ML(3,16) and  $ML(4,1)$ -ML $(4,16)$  are either available for use by a new connection or not available if currently used by an existing connection of not available in carrelary ased by an existing connection. The input switches IS1-IS4 are also referred to as the 40 network input ports. The input stage 110 is often referred to as he first stage. The output switches OS1-OS4 are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The middle stage switches  $MS(1, 1)$ 1)-MS(1,4) and MS(2,1)-MS(2,4) are referred to as middle 45 switches or middle ports. The middle stage 130 is also referred to as root stage and middle stage switches MS(2,1)- MS(2,4) are referred to as root stage switches. the lindamental property of a valid comection topology of 30<br>steps the le  $V_{\text{phif-coupl}}(N_{\text{eff}})$  of a valid connections are<br>setup from any input link all the output links should be reach-<br>should be reached on this propert

In the example illustrated in FIG. 2C, a fan-out of four is possible to satisfy a multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out oftwoisirrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network 200C, to be operated in rearrangeably nonblocking manner in accordance 60 with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, 65 i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-de-

scribed embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request.

Generalized Asymmetric Folded RNB  $(N_2>N_1)$  Embodiments:

Network 200D of FIG. 2D is an example of general asymmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1,$  $N_2$ , d, s) with  $(2 \times \log_d N_1) - 1$  stages where  $N_2 > N_1$  and  $N_2=p*N$ , where  $p>1$ . In network 200D of FIG. 2D,  $N_1=N$  and  $N_2=p*N$ . The general asymmetrical folded multi-link multistage network  $V_{fold-mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$ according to the current invention. Also the general asymmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1,$  $N_2$ , d, s) can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention. (And in the example of FIG. 2D, s=2). The general asymmetrical folded  $(2 \times \log_{4} N_{1})$ -1 stages has d inlet links for each of



input switches IS1-IS( $N_1/d$ ) (for example the links IL1-IL(d) to the input switch IS1) and 2xd outgoing links for each of

$$
\frac{N_1}{d}
$$

input switches IS1-IS( $N_1/d$ ) (for example the links ML(1,1)- $ML(1,2d)$  to the input switch IS1). There are  $d_2$ 

(where 
$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d
$$
)

outlet links for each of

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example the links OL1-OL( $p * d$ ) to the output switch OS1) and  $d+d_2$  (=d+pxd) incoming links for each of

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$  $N_1-2,1$ )-ML(2xLog<sub>d</sub> $N_1-2, d+d_2$ ) to the output switch OS1).

 $\overline{\phantom{a}}$ 

Each of the

 $\frac{N_1}{d}$ 

59

input switches IS1-IS( $N_1/d$ ) are connected to exactly 2xd switches in middle stage 130 through 2xd links.

Each of the

middle switches  $MS(1,1)-MS(1,N_1/d)$  in the middle stage 130 are connected fromexactly d input switches through 2xd links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(\text{Log}_d N_1 - 1, 1) - MS(\text{Log}_d N_1 - 1, \frac{N_1}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_1-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d N_1-1)$  through 2xd links. Each of the<br>  $\frac{N_1}{d}$ <br>
middle switches MS(1,1)-MS(1,N/d) in the middle stage 15<br>
10 are connected form exactly diagret witheless input<br>
Hulse and also are connected to exactly d switches in middle<br>
stage 140 through 2×

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(2 \times Log_d N_1 - 3, 1) - MS(2 \times Log_d N_1 - 3, \frac{N_1}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$  $N_1$ –5) through 2xd links and also are connected to exactly

$$
\frac{d+d_2}{2}
$$

output switches in output stage  $120$  through d+d<sub>2</sub> links. Each of the

$$
\frac{N_1}{d}
$$

output switches  $OS1-OS(N_1/d)$  are connected from exactly

 $\frac{d+d_2}{dt}$ 

switches in middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  through  $d+d$ , links.

20 this property numerous embodiments of the network As described before, again the connection topology of a general  $V_{fold-mlink}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold-mlink}$  $(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on  $V_{fold-mlink}(N_1, N_2, d, s)$  can be built. The embodiment of FIG. 1C is one example of network  $V_{fold-mlink}(N_1, N_2, d, s)$  for s=2 and  $N_2 > N_1$ .

25 work  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably  $30 \text{ ing to the current invention.}$ The general symmetrical folded multi-link multi-stage netnonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multilink multi-stage network  $V_{fold\text{-}mlink}$ (N<sub>1</sub>, N<sub>2</sub>, d, s) can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  accord-

For example, the network of FIG. 2C shows an exemplary five-stage network, namely  $V_{fold-mink}(8,24,2,2)$ , with the fol-<br>lowing multicast assignment  $I_1 = \{1,4\}$  and all other  $I_j = \emptyset$  for  $j=[2-8]$ . It should be noted that the connection I, fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and MS(1,2) in middle stage 130, and fans out in middle switches  $MS(1,1)$  and  $MS(1,2)$  only once into middle switches  $MS(2, 1)$ 1) and MS(2,3) respectively in middle stage 140.

 $40$  and MS(2,3) only once into middle switches MS(3,1) and Finally the connection  $I_1$  lans out once in the output stage<br>s switch OS1 into outlet link OL2 and in the output stage switch The connection  $I_1$  also fans out in middle switches  $MS(2,1)$  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,4)$  only once into output switches OS1 and OS4 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage OS4 twice into the outlet links OL20 and OL23. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

50 Asymmetric Folded RNB  $(N_1>N_2)$  Embodiments:

Referring to FIG. 2E, in one embodiment, an exemplary asymmetrical folded multi-link multi-stage network 200E with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data 55 call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, four by four switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by four switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output

40

stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage  $110$  are of size six by eight, the  $5$ switches in output stage 120 are of size four by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_2}{I}$ 

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
\frac{N_2}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1^*(d+d_1)$  and each output switch OS1-OS4 can be denoted in general with the notation <sup>30</sup>  $(2\times d^*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as 2d\*2d. The size of each switch in the first middle stage can be denoted as (d+  $d_1$ <sup>\*</sup>2d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multi-link multi-stage network can be represented with the notation  $V_{\mathit{fold-mlink}}(N_1,N_2,d,s),$  where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch SS 8.365.699 02<br>
SS 8.365.699 02<br>
N, and is a state ratio of number of to each output switch to the outlet links ofeach output switch. Each of the mmber of order links and N<sub>/</sub>>N<sub>3</sub> and N<sub>1</sub> - p<sup>a</sup>N<sub>3</sub>, where p>1. <sub>20</sub><br>
The manner of middle swiches in each middle stage is  $\frac{N}{2}$ .<br>
The size of each imple swiches in each middle stage is  $\frac{N_2}{2}$ .<br>
The size of ea

$$
\frac{N_2}{d}
$$

input switches IS1-IS4 are connected to exactly

$$
\frac{d+d_1}{2}
$$

switches in middle stage 130 through  $d+d_1$  links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  65 through the links  $ML(1,1)$ ,  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$ 

and  $ML(1,4)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,5)$ ,  $ML(1,6)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$ through the links  $ML(1,7)$  and  $ML(1,8)$ ).

Each of the

## $\frac{N_2}{d}$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

 $\frac{d+d_1}{2}$ 

input switches through d+d, links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,9)$  and  $ML(1,$ 10) are connected to the middle switch MS(1,1) from input switch IS2; the links  $ML(1,17)$  and  $ML(1,18)$  are connected to the middle switch  $MS(1,1)$  from input switch IS3; and the links  $ML(1,25)$  and  $ML(1,26)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,3)$  and  $ML(2,4)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ).

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 2×d links (for example the links  $ML(2,1)$  and  $ML(2,$ 2) are connected to the middle switch MS(2,1) from middle switch  $MS(1,1)$ , and the links  $ML(2,11)$  and  $ML(2,12)$  are connected to the middle switch MS(2,1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,3)$  and  $ML(3,4)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,3)).

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 2xd links (for example the links  $ML(3,1)$  and  $ML(3,$ 2) are connected to the middle switch MS(3,1) from middle switch  $MS(2,1)$ , and the links  $ML(3,11)$  and  $ML(3,12)$  are connected to the middle switch MS(3,1) from middle switch MS(2,3)) and also are connected to exactly d output switches in output stage 120 through 2xd links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switch OS1 from middle switch  $MS(3,1)$ ; and the links  $ML(4,3)$  and ML(4,4) are connected to output switch OS2 from middle switch  $MS(3,1)$ ).

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Each of the

 $\frac{N_2}{d}$ 

output switches OS1-OS4 are connected from exactly d switches in middle stage <sup>150</sup> through 2xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$  and  $ML(4,2)$ ; and output switch OS1 is also connected from middle switch MS(3,2) through the links  $ML(4,7)$  and  $ML(4,8)$ ).

Finally the connection topology of the network 200E shown in FIG. 2E is known to be back to back inverse Benes  $_{15}$ connection topology.

In other embodiments the connection topology may be different from the network 200E of FIG. 2E. That is the way the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,16)$ ,  $ML(3,1)$ -ML(3,16), and ML(4,1)-ML(4,16) are connected between the 20 respective stages is different. Even though only one embodiment is illustrated, in general, the network  $V_{fold\text{-}mlink}(N, d, s)$ can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold\text{-}mlink}$  $(N, d, s)$  may be back to back Benes networks, Delta Net- 25 works and many more combinations. The applicant notes that he fundamental property of a valid connection topology of the  $V_{fold\text{-}mlink}(N, d, s)$  network is, when no connections are setup fromany input link all the output links should be reachnetwork  $V_{fold\text{-}mlink}(N, d, s)$  can be built. The embodiment of network  $V_{fold\_mlink}(N, d, s)$  can be built. The embodiment of  $FIG. 2E$  is only one example of network  $V_{fold\_mlink}(N, d, s)$ .

 $I$ . 2E is only one example of network  $V_{fold-mlink}(N, d, s)$ .<br>In the embodiment of FIG. 2E each of the links ML(1,1)-ML(1,16), ML(2,1)-ML(2,16), ML(3,1)-ML(3,16) and  $ML(4,1)$ -ML $(4,16)$  are either available for use by a new con- 35 nection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as hefirst stage. The output switches OS1-OS4 are also referred o as the network output ports. The output stage 120 is often 40 referred to as the last stage. The middle stage switches  $MS(1,$ 1)- $MS(1,4)$  and  $MS(2,1)$ - $MS(2,4)$  are referred to as middle switches or middle ports. The middle stage 130 is also referred to as root stage and middle stage switches MS(2,1)- MS(2,4) are referred to as root stage switches.

In the example illustrated in FIG.  $2E$ , a fan-out of four is possible to satisfy a multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again 50 only a fan-out of two is used. The specific middle switches hat are chosen in middle stage 130 when selecting a fan-out oftwoisirrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more 55 han two middle switches permits the network 200E, to be operated in rearrangeably nonblocking manner in accordance with the invention. able. Based on this property numerous embodiments of the 30<br>encycle and the pair. The embodiment of FIG. 2E is early one example of network  $V_{664\pi\mu\sigma\mu\mu}(N, d, s)$ . In the mbodiment of FIG. 2E is each of the links ML(41.

The connection request of the type described above can be unicast connection request, a multicast connection request or  $\delta_0$  N<sub>2</sub>-2,1)-ML(2xLog<sub>d</sub>N<sub>2</sub>-2,2xd) to the output switch OS1). a broadcast connection request, depending on the example. In case of <sup>a</sup> unicast connection request, <sup>a</sup> fan-outof one is used, i.e. a single middle stage switch is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a net-

work (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request.

Generalized Asymmetric Folded RNB  $(N_2>N_1)$  Embodiments:

Network 200F of FIG. 2F is an example of general asymmetrical folded multi-link multi-stage network  $V_{fold-mlink}(N_1,$  $N_2$ , d, s) with  $(2 \times \log_d N_2) - 1$  stages where  $N_1 > N_2$  and  $N_1=p*N_2$  where p>1. In network 200F of FIG. 2F,  $N_2=N$  and  $N_1=p^*N$ . The general asymmetrical folded multi-link multistage network  $V_{fold-mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$ according to the current invention. Also the general asymmetrical folded multi-link multi-stage network  $V_{fold-mlink}(N_1,$  $N_2$ , d, s) can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention. (And in the example of FIG. 2F, s=2). The general asymmetrical folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  with  $(2 \times \log_d N_2)$ –1 stages has d, (where

$$
d_1=N_1\times\frac{d}{N_2}=p\times d
$$

inlet links for each of

$$
\frac{N_2}{d}
$$

input switches IS1-IS( $N_2/d$ ) (for example the links IL1-IL  $(p^*d)$  to the input switch IS1) and d+d,  $(=d+pxd)$  outgoing links for each of

 $\frac{N_2}{4}$ 

input switches IS1-IS(N<sub>2</sub>/d) (for example the links ML $(1,1)$ - $ML(1,(d+p*d))$  to the input switch IS1). There are d outlet links for each of

 $\frac{N_2}{d}$ 

output switches  $OS1-OS(N_2/d)$  (for example the links OL1-OL(d) to the output switch OS1) and 2xd incoming links for each of

 $\frac{N_2}{d}$ 

output switches  $OS1-OS(N_2/d)$  (for example  $ML(2\times Log_d)$ 

 $\frac{N_2}{d}$ 

input switches IS1-IS( $N_2/d$ ) are connected to exactly

 $\frac{d+d_1}{d}$ 

switches in middle stage  $130$  through d+d<sub>1</sub> links. Each of the

middle switches  $MS(1,1)$ - $MS(1,N_2/d)$  in the middle stage  $_{15}$ 130 are connected from exactly d input switches through  $2\times d$ links and also are connected to exactly d switches in middle stage 140 through 2xd links.

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(\text{Log}_d N_2 - 1, 1) - MS(\text{Log}_d N_2 - 1, \frac{N_2}{d})
$$

in the middle stage  $130+10*(\text{Log}_d \text{N}_2-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_2-3)$ through 2xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d N_2-1)$  through 2xd 35 stage 130. links.  $\frac{N_2}{d}$ <br>
middle switches MS(1.1)-MS(1.X<sub>2</sub>/d) in the middle stage 149<br>
are connected from exactly diaput switches in middle<br>
illuse and also are connected to exactly disputes witches in middle<br>
stage 140 through 2xd l

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(2 \times Log_d N_2 - 3, 1) - MS(2 \times Log_d N_2 - 3, \frac{N_2}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  are connected <sub>50</sub> from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$  $N_2$ –5) through 2xd links and also are connected to exactly d output switches in output stage  $120$  through  $2 \times d$  links.

Each of the

output switches OS1-OS( $N_2/d$ ) are connected from exactly d 60 switches in middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  through 2×d links.

As described before, again the connection topology of a general  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{\text{fold-mlink}}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back

to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold-mlink}$  $(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{\text{fold-mlink}}(N_1, N_2, d, s)$  can be built. The embodiment of FIG. 2F is one example of network  $V_{fold\text{-}mlink}(N_1, N_2, d, s)$  for s=2 and  $N_{2} > N_{1}$ .

The general symmetrical folded multi-link multi-stagenetwork  $V_{fold-mlink}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multilink multi-stage network  $V_{fold\text{-}mlink}^{\dagger}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention.

For example, the network of FIG. 2E shows an exemplary five-stage network, namely  $V_{fold-mink}$ (**8.24.2.**2), with the fol-<br>lowing multicast assignment  $I_1$ ={1,4} and all other  $I_1$ = $\phi$  for  $j=[2-8]$ . It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and MS(1,4) in middle stage 130, and fans out in middle switches  $MS(1,1)$  and  $MS(1,4)$  only once into middle switches  $MS(2,$ 1) and MS(2,4) respectively in middle stage 140.

25  $30$  Finally the connection  $I_1$  fans out once in the output stage The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and MS(2,4) only once into middle switches MS(3,1) and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,4)$  only once into output switches OS1 and OS4in output stage 120. switch OS1 into outlet link OL1 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle

SNB Multi-Link Multi-Stage Embodiments:

Symmetric SNB Embodiments:

40 stages of twenty switches for satisfying communication Referring to FIG. 3A, in one embodiment, an exemplary symmetrical multi-link multi-stage network 300A with five requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, twobysix switches IS1-IS4 and output stage <sup>120</sup> consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by six switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, six by six switches MS(2,1)-MS(2,4), and middle stage 150 consists of four, six by six switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage <sup>110</sup> are of size two by six, the switches in output stage 120 are of size six by two, and there are four switches in 55 each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and each output switch OS1-OS4 can be denoted in general with the notation 3d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 3d\*3d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. A symmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for  $5$ example the links IL1-IL8), d represents the inlet links of each<br>input switch or outlet links of each output switch, and s is the input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to exactly 3xd switches in middle stage 130 through  $3 \times d$  links  $15$ (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ).

 $L(1,5)$ , and ML $(1,6)$ ).<br>Each of the N/d middle switches MS(1,1)-MS(1,4) in the 20 middle stage 130 are connected from exactly d input switches through 3xd links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$  are connected to the middle switch  $MS(1,1)$ from input switch IS1, and the links  $ML(1,10)$ ,  $ML(1,11)$ , and ML(1,12) are connected to the middle switch MS(1,1) from 25 input switch IS2) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage <sup>130</sup> through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the 35 middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,16)$ ,  $ML(2,17)$ , and  $ML(2,18)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , 40 and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,4)$ ,  $ML(3,5)$ , and  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,3)).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3, 45)$ 4) in the middle stage 150 are connected from exactly d switches in middle stage <sup>140</sup> through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links ML $(3,16)$ , ML $(3,17)$ , and ML $(3,18)$  are connected to 50 the middle switch  $MS(3,1)$  from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 3xd links (for example the links  $ML(4,1)$ ,  $ML(4,$ 2), and  $ML(4,3)$  are connected to output switch OS1 from Middle switch  $MS(3,1)$ , and the links  $ML(4,10)$ ,  $ML(4,11)$ , and  $ML(4,12)$  are connected to output switch OS2 from middle switch MS(3,1)). M.I.(2,4), ML(2,6), and ML(2,6) are connected from middle switch NS(2,1). Winding weak of the N/a middle switch MS(2,1) MS(2, 3) MS(2, 3) Might page 140 or connected from exactly d 4) in the middle switch SM(2,1) MS(2,2)

Each of the N/d output switches OS1-OS4 are connected from exactly 3xd switches in middle stage 150 through 3xd inks (for example output switch OS1 is connected from 60 middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and ML(4,3), and output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,10)$ ,  $ML(4,$ 11) and ML(4,12)).

Finally the connection topology of the network 300A 65<br>shown in FIG. 3A is known to be back to back inverse Benes connection topology.

Referring to FIG. 3B, in another embodiment of network  $V_{mlink}$ (N, d, s), an exemplary symmetrical multi-link multistage network 300B with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage  $110$  consists of four, two by six switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by six switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, six by six switches MS(2,1)-MS (2,4), and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage  $110$  are of size two by six, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and each output switch OS1-OS4 can be denoted in general with the notation 3d<sup>\*</sup>d. Likewise, the size of each switch in any of the middle stages can be denoted as 3d\*3d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in tum may be a crossbar switch or a network of switches. The symmetric multi-link multi-stage network of FIG. 3B is also the network of the type  $V_{mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and <sup>s</sup> is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to exactly 3xd switches in middle stage 130 through 3xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 3xd links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$  are connected to the middle switch  $MS(1,1)$ from input switch IS1, and the links  $ML(1,13)$ ,  $ML(1,14)$ , and  $ML(1,15)$  are connected to the middle switch  $MS(1,1)$  from input switch IS3) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ ; and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,13)$ ,  $ML(2,14)$ , and  $ML(2,15)$  are connected to

the middle switch  $MS(2,1)$  from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,4)$ ,  $ML(3,5)$  and 5  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,2)).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ 4) in the middle stage 150 are connected from exactly d switches in middle stage <sup>140</sup> through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,13)$ ,  $ML(3,14)$ , and  $ML(3,15)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 3xd links (for example the links ML $(4,1)$ , ML $(4,$ 2), and  $ML(4,3)$  are connected to output switch OS1 from Middle switch  $MS(3,1)$ , and the links  $ML(4,4)$ ,  $ML(4.5)$ , and ML(4,6) are connected to output switch OS2 from middle switch MS(3,1)).

Lach of the N/d output switches OS1-OS4 are connected from exactly 3xd switches in middle stage 150 through 3xd inks (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and ML $(4,3)$ , and output switch OS1 is also connected from 25 middle switch  $MS(3,3)$  through the links  $ML(4,13)$ ,  $ML(4,$ 14), and ML(4,15)).

Finally the connection topology of the network 300B shown in FIG. 3B is known to be back to back Omega connection topology.

Referring to FIG. 3C, in another embodiment of network  $V_{mlink}$ (N, d, s), an exemplary symmetrical multi-link multistage network 300C with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 40 consists of four, six by six switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, six by six switches MS(2,1)-MS (2,4), and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking  $45$ manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. 55 The number of middle switches in cach middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and each output switch OS1-OS4 can be denoted in general with the notation 3d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as 3d\*3d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The symmetric multi-link multi-stage network of FIG. 3C is also the network of the type  $V_{mlink}(N, d, s)$ , where 65 N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the swinch MSS(11).<br>
Since The Notice Notice of the Notice of the Notice CS1-OS4 are connected<br>
from exactly 3xd switches in middle singe 150 through 3xd<br>
from exactly 3xd switch OS1 is connected from<br>
middle swinch MS(3.1) l

inlet links of each input switch or outlet links of each output switch, and <sup>s</sup> is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to exactly 3xd switches in middle stage 130 through 3xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected trom exactly d input switches through 3xd links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$  are connected to the middle switch  $MS(1,1)$ frominput switch IS1, and the links ML(1,22), ML(1,23), and  $ML(1,24)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,  $MI(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links ML(2,1), ML(2,2), and ML(2,3) are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,1)$ , and the links  $ML(2,22)$ ,  $ML(2,23)$ , and  $ML(2,24)$  are connected to the middle switch  $MS(2,1)$  from middle switch  $MS(1,4)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$ , and the links  $ML(3,4)$ ,  $ML(3,5)$ , and ML(3,6) are connected from middle switch MS(2,1) to middle switch MS(3,2)).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,3)$ 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,1)$ , and the links  $ML(3,22)$ ,  $ML(3,23)$ , and  $ML(3,24)$  are connected to the middle switch  $MS(3,1)$  from middle switch  $MS(2,4)$  and also are connected to exactly d output switches in output stage 120 through 3xd links (for example the links  $ML(4,1)$ ,  $ML(4,$ 2), and ML(4,3) are connected to output switch OS1 from middle switch MS(3,1), and the links ML(4,4), ML(4,5), and ML(4,6) are connected to output switch OS2 from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected from exactly 3xd switches in middle stage 150 through 3xd links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and ML(4,3), and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,22)$ ,  $ML(4,$ 23), and ML(4,24)).

Finally the connection topology of the network 300C shown in FIG. 3C is hereinafter called nearest neighbor connection topology.

Similar to network 300A ofFIG. 3A, 300B ofFIG.3B, and 300C of FIG. 3C, referring to FIG. 3D, FIG. 3E, FIG. 3F, FIG. 3G,FIG. 3H, FIG. 3] and FIG. 3J with exemplary symmetrical multi-link multi-stage networks 300D, 300E, 300F, 300G, 300H, 300I, and 300J respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches 1S1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle  $5$ stage 130 consists of four, six by six switches MS(1,1)-MS (1,4), middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, six by six switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 15 3J), a fan-out of four is possible to satisfy a multicast connec-

The networks 300D, 300E, 300F, 300G, 300H, 300] and 300] ofFIG.3D, FIG. 3E, FIG.3F, FIG. 3G, FIG.3H,FIG.3], and FIG. 3J are also embodiments of symmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input 25 switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1- OL8, in a symmetrical network they are the same.

Just like networks of 300A, 300B and 300C, for all the networks 300D, 300E, 300F, 300G, 300H, 300I and 300J of 30 FIG. 3D, FIG. 3E, FIG. 3F, FIG. 3G, FIG. 3H, FIG.3], and FIG. 3J, each of the N/d input switches IS1-IS4 are connected to exactly  $3 \times d$  switches in middle stage 130 through  $3 \times d$ inks.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the 35 middle stage 130 are connected from exactly d input switches hrough 3xd links and also are connected to exactly d switches in middle stage 140 through 3xd links.

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ 4) in the middle stage 140 are connected from exactly d 40 switches in middle stage 130 through 3xd links and also are connected to exactly d switches in middle stage 150 through 3xd links.

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ 4) in the middle stage 150 are connected from exactly d  $45$ switches in middle stage 140 through 3xd links and also are connected to exactly d output switches in output stage 120 through 3xd links.

Each of the N/d output switches OS1-OS4 are connected from exactly 3xd switches in middle stage 150 through 3xd links.

In all the ten embodiments of FIG. 3A to FIG. 3J the connection topology is different. That is the way the links  $ML(1,1)-ML(1,24)$ ,  $ML(2,1)-ML(2,24)$ ,  $ML(3,1)-ML(3,$ 24), and  $ML(4,1)-ML(4,24)$  are connected between the 55 respective stages is different. Even though only ten embodiments are illustrated, in general, the network  $V_{mlink}(N, d, s)$ can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{mlink}(N, d, d)$ s) may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{mlink}(Nd, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N, d, s)$  can be built. The ten embodiments of FIG. 3A to FIG. 3J are only three examples of network  $V_{mlink}(N, d, s)$ . milli-stage network can be represented with the notion 2011 million of the mathemal of all inquiring the limit of the independent of all inquiring the first cannot counter the limit of the cannot of the inquiring the limi

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In all the ten embodiments of FIG. 3A to FIG.3J, each of the links ML(1,1)-ML(1,24), ML(2.1)-ML(2,24), ML(3,1)-  $ML(3,24)$  and  $ML(4,1)-ML(4,24)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1- OS4are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and  $MS(3,1)$ - $MS(3,4)$  are referred to as middle switches or middle ports.

In the example illustrated in FIG. 3A (or in FIG. 1B to FIG. tion request if input switch is [S2, but only two switches in middle stage <sup>130</sup> will be used. Similarly, althougha fan-out of three is possible for a multicast connection request ifthe input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection requestissatisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network 300A (or 300B to 300J), to be operated in strictly nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. asingle middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the strictly nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request.

Generalized Symmetric SNB Embodiments:

Network 300K of FIG. 3K is an example of general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  with  $(2 \times \log_d N)-1$  stages. The general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  can be operated in strictly nonblocking manner for multicast when  $s \ge 3$  according to the current invention (and in the example of FIG.  $3K$ ,  $s=3$ ). The general symmetrical multi-link multi-stage network  $V_{mlink}$  $(N, d, s)$  with  $(2 \times \log_d N) - 1$  stages has d inlet links for each of N/d input switches IS1-IS(N/d) (for example the links IL1-  $IL(d)$  to the input switch IS1) and  $3 \times d$  outgoing links for each of N/d input switches IS1-IS(N/d) (for example the links  $ML(1,1)-ML(1,3d)$  to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS(N/d) (for example the links OL1-OL(d) to the output switch OS1) and 3xd incoming links for each of N/d output switches OS1-OS (N/d) (for example  $ML(2 \times Log_d N-2,1)$ -ML $(2 \times Log_d N-2,3 \times$ d) to the output switch OS1).

Each of the N/d input switches IS1-IS(N/d) are connected to exactly d switches in middle stage 130 through 3xd links.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,N/d)$  in the middle stage 130 are connected from exactly d input switches through 3xd links and also are connected to exactly d switches in middle stage 140 through 3xd links.

 $\overline{\mathbf{S}}$ 

25

30

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Similarly each of the N/d middle switches

$$
MS(\text{Log}_d N - 1, 1) - MS(\text{Log}_d N - 1, \frac{N}{d})
$$

in the middle stage  $130+10*(\text{Log}_{d} N-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{N}-3)$ through 3xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d \text{N}-1)$  through 3xd links.

Similarly each of the N/d middle switches

$$
MS(2 \times \text{Log}_d N - 3, 1) - MS\left(2 \times \text{Log}_d N - 3, \frac{N}{d}\right)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub> 20)$ N-5) through 3xd links and also are connected to exactly d output switches in output stage  $120$  through  $3 \times d$  links.

Each of the N/d output switches OS1-OS(N/d) are connected from exactly d switches in middle stage 130+10\*  $(2*Log<sub>d</sub> N-4)$  through 3xd links.

As described before, again the connection topology of a general  $V_{mlink}(N, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{mlink}(N, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N, d, s)$  can be built. The embodiments of FIG. 3A to FIG. 3J are ten examples of network  $V_{mlink}(N, d, s)$ .

The general symmetrical multi-link multi-stage network  $V_{mlink}(N, d, s)$  can be operated in strictly nonblocking manner for multicast when  $s \ge 3$  according to the current invention.

Every switch in the multi-link multi-stage networks discussed herein has multicast capability. In a  $V_{mlink}(N, d, s)$ network, ifa networkinlet link is to be connected to more than one outlet link on the same output switch, then it is only necessary for the corresponding input switch to have one path o that output switch. This follows because that path can be multicast within the output switch to as many outlet links as necessary. Multicast assignments can therefore be described in terms of connections between input switches and output switches.An existing connection or a new connection from an input switch to r' output switches is said to have fan-out r'. If all multicast assignments ofa first type, wherein any inlet link of an input switch is to be connected in an output switch to at most one outlet link are realizable, then multicast assignments of a second type, wherein any inlet link of each input switch is to be connected to more than one outlet link in the same output switch, can also be realized. For this reason, the following discussion is limited to general multicast connecions of the first type Invoting 1 set into a state of the case connected to concert<br>
and the set of the state of the state of the state of the state of the first<br>
smilicity even in the first smiller than the state of the first smiller<br>
Smiller To characterize <sup>a</sup> multicast assignment, for eachinlet link

$$
i \in \Big\{1, 2, \ldots, \frac{N}{d}\Big\},\
$$

let  $I_i = O$ , where

$$
O \subset \Big\{1, 2, \ldots, \frac{N}{d}\Big\},\
$$

denote the subset of output switches to which inlet link i is to  $_{15}$  be connected in the multicast assignment. For example, the network of FIG. 3C shows an exemplary five-stage network, namely  $V_{mlink}(8,2,3)$ , with the following multicast assignment I<sub>1</sub> = {1,4} and all other I<sub>j</sub> =  $\phi$  for j = [2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,2)$  in middle stage 130, and fans out in middle switches  $MS(1,1)$  and  $MS(1,2)$  only once into middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and MS(2,3) only once into middle switches MS(3,1) and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,4)$  only once into output switches OS1 and OS4in output stage 120. Finally the connection  $I_1$  fans out once in the output stage switch OS1 into outlet link OL1 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

Asymmetric SNB  $(N_2>N_1)$  Embodiments:

Referring to FIG. 3A1, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 300A1 with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by six switches MS(1,1)-MS(1,4), middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists offour, four by eight switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

$$
\left(\text{with fan-out } r', 1 \le r' \le \frac{N}{d}\right)
$$

N  $\frac{v_1}{r},$ 

although the samediscussion is applicable to the secondtype. where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ .

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The number of middle switches in each middle stage is denoted by

 $\frac{N_1}{d}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and each output switch OS1- 10 OS4 can be denoted in general with the notation  $(2d+d<sub>2</sub>)<sup>*</sup>d<sub>2</sub>$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 3d\*3d. The size of each switch in the last middle stage can be denoted as 3d\*  $(2d+d<sub>2</sub>)$ . A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8), N represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input  $_{30}$ switch to the inlet links of each input switch,

Each of the

$$
\frac{N_1}{d}
$$

input switches [S1-IS4 are connected to exactly d switches in middle stage 130 through 3xdlinks (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $40$  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ). Each of the

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 3xd <sup>50</sup> links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links  $ML(1,13)$ ,  $ML(1,14)$ , and  $ML(1,15)$  are connected to the middle switch  $MS(1,1)$  from input switch IS3) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ ; and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ). each switch in the last middle stage can be denoted as 3 d\*<br>
card-4s). A switch as used hencin can be either a crossbar<br>
switch, or a new since the a transition and the stage state of twistelus each of widelic and the sma

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$ from middle switch  $MS(1,1)$ , and the links  $ML(2,13)$ ,  $ML(2,$ 14), and ML(2,15) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 1), and the links  $ML(3,4)$ ,  $ML(3,5)$  and  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 2)).

Similarly each of the

 $\frac{N_1}{d}$ 

<sup>20</sup> middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ from middle switch  $MS(2,1)$ , and the links  $ML(3,13)$ ,  $ML(3,$ 14), and ML(3,15) are connected to the middle switch MS(3, 1) from middle switch  $MS(2,3)$  and also are connected to exactly

 $2d + d_2$ 

output switches in output stage  $120$  through  $2d+d_1$  links (For example the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$  are connected to output switch OS1 fromMiddle switch MS(3,1); the links  $ML(4,4)$ ,  $ML(4,5)$ , and  $ML(4,6)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ; the links  $ML(4,7)$ ,  $ML(4,8)$ , and  $ML(4,9)$  are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; the links  $ML(4,10)$ ,  $ML(4.11)$ , and  $ML(4,12)$  are connected to output switch OS2 from middle switch  $MS(3,1)$ ).<br>Each of the

 $\frac{N_1}{d}$ 

output switches ON1-OS4are connected fromexactly

$$
\frac{2d+d_2}{3}
$$

switches in middle stage 150 through  $2d+d_2$  links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ ; output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,16)$ ,  $ML(4,17)$ , and  $ML(4,$ 18); output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,28)$ ,  $ML(4,29)$ , and  $ML(4,$ 30); and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,43)$ ,  $ML(4,44)$ , and ML(4,45)).

Finally the connection topology of the network **300A1** shown in FIG. **3A1** is known to be back to back inverse Benes connection topology.

Referring to FIG. 3B1, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 300B1 with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by six switches MS(1,1)-MS(1,4), middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, four by eight switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking 15 manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches [S1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable  $\frac{1}{25}$ 

### N  $\frac{V_1}{d}$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and each output switch OS1- OS4 can be denoted in general with the notation  $(2d+d<sub>2</sub>)<sup>*</sup>d<sub>2</sub>$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 3d\*3d. The size of each switch in the last middle stage can be denoted as 2d\*  $(2d+d<sub>2</sub>)$ . A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the  $60$ notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , 65 and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. area or an embedded in general with the activate stage section of this include that the input<br>
in the one embedded in this activate of the input stage 110 and of<br>
using 150. and output switches OS1-OS4 are crossbar<br>
ewitc

$$
\frac{N_1}{d}
$$

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input switches IS1-IS4 are connected to exactly 3xd switches in middle stage 130 through 3xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ).

Each of the

Each of the



middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 3xd links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links  $ML(1,13)$ ,  $ML(1,14)$ , and  $ML(1,15)$  are connected to the middle switch  $MS(1,1)$  from input switch IS3) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ ; and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the

30

40

## $\frac{N_1}{d}$

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$ from middle switch  $MS(1,1)$ , and the links  $ML(2,13)$ ,  $ML(2,$ 14), and ML(2,15) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 1), and the links  $ML(3,4)$ ,  $ML(3,5)$  and  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 2)).

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ from middle switch  $MS(2,1)$ , and the links  $ML(3,13)$ ,  $ML(3,$ 14), and  $ML(3,15)$  are connected to the middle switch  $MS(3, 15)$ 

 $\overline{5}$ 

25

30

1) from middle switch  $MS(2,3)$  and also are connected to exactly

$$
\frac{2d+d_2}{3}
$$

output switches in output stage  $120$  through  $2d+d_2$  links (For example the links ML(4,1), ML(4,2), and ML(4,3) are con- $_{10}$ nected to output switch OS1 from Middle switch MS(3,1); the links  $ML(4,4)$ ,  $ML(4,5)$ , and  $ML(4,6)$  are connected to output switch OS2 from middle switch MS(3,1); the links ML(4,7),  $ML(4,8)$ , and  $ML(4,9)$  are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; the links  $ML(4,10)$ ,  $ML(4.11)$ , 15 and  $ML(4,12)$  are connected to output switch OS2 from middle switch MS(3,1)).

Each of the

$$
\frac{N_1}{d}
$$

output switches OS1-OS4 are connected from exactly

$$
\frac{2d+d_2}{3}
$$

switches in middle stage 150 through 2d+d, links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ ; output switch OS1 is also connected from middle switch 35  $MS(3,2)$  through the links  $ML(4,16)$ ,  $ML(4,17)$ , and  $ML(4,$ 18); output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,28)$ ,  $ML(4,29)$ , and  $ML(4,$ 30); and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,43)$ ,  $ML(4,44)$ , and  $40$  $ML(4,45)$ ).

Finally the connection topology of the network 300B1 shown in FIG. 3B1 is known to be back to back Omega connection topology.

Referring to FIG. 3C1, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 300C1 with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches 1S1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by six switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists offour, four by eight switches MS(3,1)-MS(3,4).  $\frac{N_2}{4}$ <br>
cutput switches OS1-OS4 are connected from exactly<br>  $\frac{2d_1 + d_2}{3}$ <br>
switches in middle stage 150 through 2d+d<sub>4</sub> links (for<br>
example output switch OS1 is connected from middle switch<br>
MS(3,1) through the li

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size eight by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches [S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

$$
\frac{N_1}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
\frac{N_1}{d}
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*3d and cach output switch OS1- 20 OS4 can be denoted in general with the notation  $(2d+d_2)^*d_2$ , where

$$
d_2=N_2\times \frac{d}{N_1}=p\times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as 3d\*3d. The size of each switch in the last middle stage can be denoted as 2d\*  $(2d+d<sub>2</sub>)$ . A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links ofall output switches (for example the links OL1-OL24), <sup>d</sup> represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.<br>Each of the

 $\frac{N_1}{d}$ 

input switches IS1-IS4 are connected to exactly 3xd switches in middle stage 130 through 3xd links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; and also to middle switch  $MS(1,2)$  through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ).

Each of the

 $\frac{N_1}{d}$ 

60 middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 3xd links (for example the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ) are connected to the middle switch  $MS(1,1)$  from input switch IS1, and the links  $ML(1,22)$ ,  $ML(1,23)$ , and  $ML(1,24)$  are connected to the middle switch  $MS(1,1)$  from input switch IS4)) and also are connected to exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(2,1)$ ,

40

 $MI(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and ML(2,3) are connected to the middle switch MS(2,1)  $_{15}$ from middle switch  $MS(1,1)$ , and the links  $ML(2,22)$ ,  $ML(2,$ 23), and ML(2,24) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,4)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links ML(3,1), ML(3,2), and ML(3,3) are con- $_{20}$ nected from middle switch MS(2,1) to middle switch MS(3, 1), and the links  $ML(3,4)$ ,  $ML(3,5)$ , and  $ML(3,6)$  are connected from middle switch MS(2,1) to middle switch MS(3, 2)). middle switches MS(2,1)-MS(2,4) in the middle stage 140<br>non-anomology 167<br>mean and those and the stage and independent of the stage and the stage of the links of from each of the stage in the links Mf.(2,1) MJ (2,2) and M

Similarly each of the

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ from middle switch  $MS(2,1)$ , and the links  $ML(3,22)$ ,  $ML(3, 35)$ 23), and  $ML(3,24)$  are connected to the middle switch  $MS(3, 4)$ 1) from middle switch  $MS(2,4)$  and also are connected to exactly

$$
\frac{2d+d_2}{3}
$$

output switches in output stage 120 through 2d+d, links

(For example the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$  are connected to output switch OS1 from Middle switch MS(3, 1); the links  $ML(4,4)$ ,  $ML(4,5)$ , and  $ML(4,6)$  are connected to output switch  $OS2$  from middle switch  $MS(3,1)$ ; the links  $ML(4,7)$ ,  $ML(4,8)$ , and  $ML(4,9)$  are connected to output switch OS3 from Middle switch  $MS(3,1)$ ; the links  $ML(4,10)$ ,  $ML(4.11)$ , and  $ML(4.12)$  are connected to output switch OS2 from middle switch MS(3,1)). 50

Each of the

$$
\frac{N}{d}
$$

output switches OS1-OS4 are connected from exactly

 $\frac{2d + d_2}{4}$ 

switches in middle stage 150 through 2d+d, links (for example output switch OS1 is connected from middle switch  $MS(3,1)$  through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ ; output switch OS1 is also connected from middle switch  $MS(3,2)$  through the links  $ML(4,16)$ ,  $ML(4,17)$ , and  $ML(4,$ 18); output switch OS1 is connected from middle switch  $MS(3,3)$  through the links  $ML(4,28)$ ,  $ML(4,29)$ , and  $ML(4,$ 30); and output switch OS1 is also connected from middle switch  $MS(3,4)$  through the links  $ML(4,43)$ ,  $ML(4,44)$ , and ML(4,45)).

Finally the connection topology of the network 300C1 shown in FIG. 3C1 is hereinafter called nearest neighbor connection topology.

USI-OS4. And all the middle stages namely middle stage 130<br>  $^{25}$  consists of four, six by six switches MS(1,1)-MS(1,4), middle Similar to network 300A1 of FIG. 3A1. 300B1 of FIG. 3B1, and 300C1 of FIG. 3C1, referring to FIG. 3D1, FIG. 3E1, FIG. 3F1, FIG. 3G1, FIG. 3H1, FIG. 311 and FIG. 3J1 with exemplary asymmetrical multi-link multi-stage networks 300D1, 300E1, 300F1, 300G1, 300H1, 300J1, and 300J1 respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by six switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130

stage 140 consists of four, six by six switches MS(2,1)-MS  $(2,4)$ , and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by six, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

The networks 300D1, 300E1, 300F1, 300G1. 300H1, 30011 and 300J1 ofFIG. 3D1, FIG. 3E1, FIG. 3F1, FIG. 3G1, FIG. 3H1, FIG. 311, and FIG. 3J1 are also embodiments of asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links

from each input switch to the inlet links of each input switch. Just like networks of 300A1, 300B1 and 300C1, for all the networks 300D1, 300E1, 300F1, 300G1, 300H1, 30011 and 300J1 ofFIG. 3D1, FIG. 3E1, FIG. 3F1, FIG. 3G1, FIG. 3H1, FIG. 311, and FIG. 3J1, each of the

# $\frac{N_1}{N_2}$

input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through 3xd links. Each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through 3xd links and also are connected to exactly d switches in middle stage 140 through 3xd links.

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links and also are connected to exactly d <sup>1</sup> switches in middle stage 150 through 3xd links.

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links and also are connected to exactly

$$
\frac{2d+d_2}{3}
$$

output switches in output stage 120 through 2d+d links. Each of the

output switches OS1-OS4 are connected from exactly

$$
\frac{2d+d_2}{3}
$$

switches in middle stage 150 through 2d+d, links

In all the ten embodiments of FIG. 3A1 to FIG. 3J1 the connection topology is different. That is the way the links  $ML(1,1)-ML(1,24)$ ,  $ML(2,1)-ML(2,24)$ ,  $ML(3,1)-ML(3,$ **24**), and  $ML(4,1)-ML(4,48)$  are connected between the respective stages is different. Even though only ten embodiments are illustrated, in general, the network  $V_{mlink}(N_1,N_2,d,$ s) can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{mlink}$  $(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{mlink}(N_1,N_2,d,s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the 55 network  $V_{mlink}(N_1, N_2, d, s)$  can be built. The ten embodiments of FIG. 3A1 to FIG. 3J1 are only three examples of network  $V_{mlink}(N_1, N_2, d, s)$ . through 3xd links and size are connected to exactly  $29$ <br>  $\frac{2d + d_2}{3}$ <br>
coulput switches in output stage 120 through 2d+d links.<br>
Each of the<br>  $\frac{N_1}{d}$ <br>
coulput switches OS1-OS4 are connected from exactly<br>  $\frac{N_1}{d}$ 

In all the ten embodiments ofFIG. 3.A1 to FIG. 3J1, each of the links ML(1,1)-ML(1,24), ML(2,1)-ML(2,24), ML(3,1)- 60  $ML(3,24)$  and  $ML(4,1)-ML(4,48)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1- OS4 are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The

middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and MS(3,1)-MS(3,4) are referred to as middle switches or middle ports.

In the example illustrated in FIG. 3A1 (or in FIG. 3B1 to FIG. 3J1), a fan-out of four is possible to satisfy <sup>a</sup> multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting 15 the fan-out from input switch to no more than two middle switches permits the network 300A1 (or 300B1 to 300J1), to be operated in strictly nonblocking manner in accordance with the invention.

<sub>25</sub> satisfy the request. Moreover, although in the above-de- $_{30}$  nonblocking nature of operation of the network for multicast The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. asingle middle stage switch in middle stage 130 is used to scribed embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the strictly connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request.

### Generalized Asymmetric SNB  $(N_2>N_1)$  Embodiments:

40 Network 300K1 of FIG. 3K1 is an cxample of general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, ...)$ d, s) with  $(2 \times \log_d N_1) - 1$  stages where  $N_2 > N_1$  and  $N = p^*N_1$ where  $p>1$ . In network 300K1 of FIG. 3K1, N<sub>1</sub>=N and  $N_2=p*N$ . The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for multicast when 3 according to the current invention (and in the example of FIG.  $3K1$ ,  $s=3$ ). The general asymmetrical multi-link multi-stage network  $V_{mlink}$  $(N_1, N_2, d, s)$  with  $(2 \times \log_d N_1)$ –1 stages has d inlet links for each of

 $\frac{N_1}{d}$ 

input switches IS1-IS( $N_1/d$ ) (for example the links IL1-IL(d) to the input switch IS1) and  $3\times d$  outgoing links for each of

> $\frac{N_1}{N_1}$  $\overline{d}$

input switches IS1-IS( $N_1/d$ ) (for example the links ML(1,1)- $ML(1,3d)$  to the input switch IS1). There are  $d_2$ 

(where 
$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d
$$
)

 $\overline{\mathbf{S}}$ 

20

85

outlet links for each of

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example the links OL1- $OL(p * d)$  to the output switch OS1) and  $2d+d$ , (=2d+p×d) incoming links for each of

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$  $N_1-2,1$ )-ML $(2\times Log_d N_1-2,2d+d_2)$  to the output switch O81).

Each of the

$$
\frac{N_1}{d}
$$

input switches IS1-IS( $N_1/d$ ) are connected to exactly 3xd 25 switches in middle stage 130 through 3xd links.

Each of the

middle switches  $MS(1,1)$ - $MS(1,N_1/d)$  in the middle stage 130 are connected from exactly d input switches through 3xd links and also are connected to exactly d switches in middle  $35$ stage 140 through 3xd links.

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(\text{Log}_d N_1 - 1, 1) - MS(\text{Log}_d N_1 - 1, \frac{N_1}{d})
$$

in the middle stage  $130+10*(Log_a N_1-2)$  are connected from 50 exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through 3xd links and also are connected to exactly d switches in middle stage  $130{+}10^{\rm{*}}(\text{Log}_d\,\text{N}_1{-}1)$  through  $3{\times}d$ links. Encoming limits for each of<br>  $\frac{N_1}{d}$ <br>
cutiput switches OS1-OS[N<sub>1</sub>(d) (for example M1.(2x1 og, <sup>15</sup><br>
N-2.1)-ML(2x1 og, N<sub>1</sub>-2.2d+4.) to the output switch<br>
OS1).<br>
Each of the<br>  $\frac{N_1}{d}$ <br>
input switches IS1-IS[N<sub>1</sub>(d)

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(2 \times \text{Log}_d N_1 - 3, 1) - MS\left(2 \times \text{Log}_d N_1 - 3, \frac{N_1}{d}\right)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log_{d})$  $N<sub>1</sub>$ -5) through 3xd links and also are connected to exactly

$$
\frac{2d+d_2}{3}
$$

output switches in output stage 120 through 2d+d, links. Each of the

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  are connected from exactly

$$
\frac{2d+d_2}{3}
$$

switches in middle stage  $130+10*(2*Log_{d} N_{1}-4)$  through 2d+d, links.

30 networks, Delta Networks and many more combinations. The As described before, again the connection topology of a general  $V_{mlink}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{mlink}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$ can be built. The embodiments of FIG. 3A1 to FIG. 3J1 are ten examples of network  $V_{mlink}(N_1, N_2, d, s)$  for s=3 and  $N_{2} > N_{1}$ .

The general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for multicast when 3 according to the current invention.

For example, the network of FIG. 3C1 shows an exemplary five-stage network, namely  $V_{mink}(8,24,2,3)$ , with the follow-<br>ing multicast assignment  $I_1$ ={1,4} and all other I<sub>J</sub>= $\phi$  for j=[2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,2)$ in middle stage 130, and fans out in middle switches  $MS(1,1)$ and  $MS(1,2)$  only once into middle switches  $MS(2,1)$  and MS(2,3) respectively in middle stage 140.

6 2 input stage switch into at most two middle stage switches in The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and  $MS(2,3)$  only once into middle switches  $MS(3,1)$  and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,4)$  only 55 once into output switches OS1 and OS4 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage Finally the connection  $1<sub>1</sub>$  lans out once in the output stage<br>switch OS1 into outlet links OL2 and in the output stage switch<br>OS4 twice into the outlet links OL19 and OL21. In accor- $\text{OS4}$  twice into the outlet links  $\text{OL19}$  and  $\text{OL21}$ . In accordance with the invention, each connection can fan out in the middle stage 130.

Asymmetric SNB  $(N_1>N_2)$  Embodiments:

Referring to FIG. 3A2, in one embodiment, an exemplary asymmetrical multi-link multi-stage network 300A2 with five stages oftwenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an

input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four <sup>5</sup> switches MS(1,1)-MS(1,4), middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage  $110$  are of size six by eight, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network cach of the input switches [S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

where  $N_i$  is the total number of inlet links or and  $N_i$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in cach middle stage is denoted by

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1$ <sup>\*</sup>(2d+ $d_1$ ) and each output switch OS1-OS4 can be denoted in general with the notation 3d\*d, where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as 3d\*3d. The size of each switch in the first middle stage can be denoted as (2d+  $d_1$ <sup>\*</sup>3d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be 50 a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24), N<sub>2</sub> represents the total number of outlet links  $55$ of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch. Such a network can be operated in strictly non-blocking<br>
in manner for multicast connections, because the widebec in the<br>input singe 110 are of size six by two, and there are four switches in the<br>singe 170 or of size is s

Each of the

### 88

input switches IS1-IS4 are connected to exactly

$$
\frac{2d+d_1}{3}
$$

switches in middle stage 130 through 2d+d, links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; input switch IS1 is also connected to middle switch  $MS(1,2)$ through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,7)$ ,  $ML(1,8)$ , and  $ML(1,9)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$  through the links  $ML(1,10)$ ,  $ML(1,11)$ , and  $ML(1,12)$ ).

Each of the

 $\frac{N_2}{N_1}$ 

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

 $\frac{2d + d_1}{4}$ 

30 input switches through 2d+d, links (for example middle 40 the links ML(2,1), ML(2,2), and ML(2,3) are connected from switch  $MS(1,1)$  is connected from input switch IS1 through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; middle switch  $MS(1,1)$  is connected from input switch IS2 through the links  $ML(1,16)$ ,  $ML(1,17)$ , and  $ML(1,18)$ ; middle switch  $MS(1,1)$ is connected from input switch IS3 through the links  $ML(1,$ 28), ML $(1,29)$ , and ML $(1,30)$ ; and middle switch MS $(1,1)$  is connected from input switch IS4 through the links  $ML(1,43)$ ,  $ML(1,44)$ , and  $ML(1,45)$  and also are connected to exactly d switches in middle stage 140 through 3xd links (for example middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,3)$ ). Similarly each of the

 $\frac{N_2}{N_1}$ 

 $10^{60}$  3)). middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$ from middle switch  $MS(1,1)$ , and the links  $ML(2,16)$ ,  $ML(2,$ 17), and ML(2,18) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 1), and the links  $ML(3,4)$ ,  $ML(3,5)$ , and  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ from middle switch MS(2,1), and the links ML(3,16), ML(3,  $\frac{5}{3}$ 17), and  $ML(3,18)$  are connected to the middle switch  $MS(3, 18)$ 1) from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through 3xd links (for example the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ are connected to output switch OS1 from Middle switch  $MS(3,1)$ , and the links  $ML(4,10)$ ,  $ML(4,11)$ , and  $ML(4,12)$ are connected to output switch OS2 from middle switch MS(3,1)).

Each of the

 $\frac{N_2}{d}$ 

output switches OS1-OS4 are connected from exactly d switches in middle stage <sup>150</sup> through 3xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ , and output switch OS1 is also connected from middle switch  $MS(3,2)$  25 through the links  $ML(4,10)$ ,  $ML(4,11)$  and  $ML(4,12)$ .

Finally the connection topology of the network 300A2 shown in FIG. 3A2 is knownto be back to back inverse Benes connection topology.

Referring to FIG. 3B2, in one embodiment, an exemplary <sup>30</sup> asymmetrical multi-link multi-stage network 300B2 with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of 40 four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4). output switches OSI-OS4 are connected from exactly  $d^2$ <br>switches in middle stage 159 menople and thinks (for example<br>output switch OSI is connected from middle switch MS(3,1)<br>through the stage MS(4,4), MI(4,4), MI(4,4),

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output 45 stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar 50 switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

$$
\frac{N_2}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$  where  $p > 1$ . number of outlet links and  $N_1 > N_2$  and  $N_1 = p^2 N_2$  where  $p > 1$ .<br>The number of middle switches in each middle stage is <sup>60</sup> denoted by

$$
\frac{N_2}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1$ <sup>\*</sup>(2d+ $d_1$ ) and each output switch OS1-OS4 can be denoted in general with the notation 3d\*d, where

$$
d_1=N_1\times \frac{d}{N_2}=p\times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $3d*3d$ . The size of each switch in the first middle stage can be denoted as (2d+ d,)\*3d. A switch as used herein can be either a crossbar  $_{15}$  switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetnc multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch. Eachofthe

 $\frac{N_2}{d}$ 

input switches IS1-IS4 are connected to exactly

$$
\frac{2d + d_1}{3}
$$

switches in middle stage 130 through 2d+d, links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; input switch IS1 is also connected to middle switch  $MS(1,2)$ through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ; input switch IS1 is connected to middle switch  $MS(1,3)$  through the links  $ML(1,7)$ ,  $ML(1,8)$ , and  $ML(1,9)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$  through the links  $ML(1,10)$ ,  $ML(1,11)$ , and  $ML(1,12)$ ).<br>Each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

 $\frac{2d + d_1}{2}$ 

input switches through 2d+d, links (for example middle switch MS(1,1) is connected from input switch IS1 through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; middle switch  $MS(1,1)$  is connected from input switch IS2 through the links  $ML(1,16)$ ,  $ML(1,17)$ , and  $ML(1,18)$ ; middle switch  $MS(1,1)$ is connected from input switch IS3 through the links MI.(1, **28**), ML $(1,29)$ , and ML $(1,30)$ ; and middle switch MS $(1,1)$  is connected from input switch IS4 through the links  $ML(1,43)$ ,

 $ML(1,44)$ , and  $ML(1,45)$  and also are connected to exactly d switches in middle stage <sup>140</sup> through 2xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ ; and the links ML $(2,4)$ , ML $(2,5)$ , and ML $(2,6)$  are connected from 5 middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ).

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$ from middle switch  $MS(1,1)$ , and the links  $ML(2,13)$ ,  $ML(2,$ 14), and ML(2,15) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,3)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch MS(2,1) to middle switch MS(3, 1), and the links  $ML(3,4)$ ,  $ML(3,5)$  and  $ML(3,6)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 2)).  $\frac{36}{4}$ <br>
middle switches MS(2,1)-MS(2.4) in the middle stage 140<br>
are connected from exactly d switches in middle stage 130<br>
through 5.2d links (for example the links MI.(2,1), MI.(2,2), 15<br>
and MLC2,3) are only develo 25

Similarly each of the

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links ML(3,1), ML(3,2),  $_{35}$ and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ from middle switch  $MS(2,1)$ , and the links  $ML(3,13)$ ,  $ML(3,$ 14), and  $ML(3,15)$  are connected to the middle switch  $MS(3, 15)$ 1) from middle switch  $MS(2,3)$  and also are connected to exactly d output switches in output stage 120 through  $3 \times d_{40}$ links (for example the links ML(4,1), ML(4,2), and ML(4,3) are connected to output switch OSI from Middle switch  $MS(3,1)$ , and the links  $ML(4,4)$ ,  $ML(4.5)$ , and  $ML(4,6)$  are connected to output switch OS2 from middle switch MS(3, 1)).

Each of the

output switches OS1-OS4 are connected from exactly d switches in middle stage <sup>150</sup> through 3xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ , and output 55 switch OS1 is also connected from middle switch  $MS(3,3)$ through the links  $ML(4,13)$ ,  $ML(4,14)$ , and  $ML(4,15)$ ).

Finally the connection topology of the network 300B2 shown in FIG. 3B2 is known to be back to back Omega connection topology.

Referring to FIG. 3C2, in one embodiment, an exemplary asymmetrical multi-link multi-stage network  $300C2$  with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four,

six by eight switches IS1-IS4 and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, six by six switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, six by six switches MS(3,1)-MS(3,4).

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output 10 stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network cach of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable



where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

### $\frac{N_2}{d}$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1$ <sup>\*</sup>(2d+ $d_1$ ) and each output switch OS1-OS4 can be denoted in general with the notation 3d\*d, where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $3d*3d$ . The size of each switch in the first middle stage can be denoted as (2d+  $d_1$ <sup>\*</sup>3d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch.

Each of the

 $\mathbf{v}$ t

input switches IS1-IS4 are connected to exactly

$$
\frac{2d+d_1}{3}
$$

switches in middle stage  $130$  through  $2d+d_1$  links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; input switch IS1 is also connected to middle switch MS(1,2) through the links  $ML(1,4)$ ,  $ML(1,5)$ , and  $ML(1,6)$ ; input switch IS1 is connected to middle switch MS(1,3) through the links  $ML(1,7)$ ,  $ML(1,8)$ , and  $ML(1,9)$ ; and input switch IS1 is also connected to middle switch  $MS(1,4)$  through the links ML(1,10), ML(1,11), and ML(1,12)).

Each of the

$$
\frac{N}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

$$
\frac{2d+d_1}{3}
$$

input switches through 2d+d, links (for example middle switch MS(1,1) is connected from input switch IS1 through the links  $ML(1,1)$ ,  $ML(1,2)$ , and  $ML(1,3)$ ; middle switch  $MS(1,1)$  is connected from input switch IS2 through the links  $ML(1,16)$ ,  $ML(1,17)$ , and  $ML(1,18)$ ; middle switch  $MS(1,1)$ is connected from input switch IS3 through the links ML(1, 28), ML $(1,29)$ , and ML $(1,30)$ ; and middle switch MS $(1,1)$  is connected from input switch IS4 through the links ML(1,43),  $ML(1,44)$ , and  $ML(1,45)$  and also are connected to exactly d switches in middle stage <sup>140</sup> through 3xd links (for example the links  $ML(2,1)$ ,  $MI(2,2)$ , and  $ML(2,3)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$ , and the links  $ML(2,4)$ ,  $ML(2,5)$ , and  $ML(2,6)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,2)$ ). NH (1,10), with (1,11), and M1(1,12).<br>
Each of the <br>
Each of the SV(1,1)-NMS(1,4) in the middle stage 130<br>
Tach of the SV(1,1)-NMS(1,4) in the middle stage 130<br>
are connected from eachly<br>  $\frac{2x + a}{3}$ <br>
input switches thr 25 30

Similarly each of the

middle switches MS(2,1)-MS(2,4) in the middle stage 140  $_{45}$ are connected from exactly d switches in middle stage 130 through 3xd links (for example the links  $ML(2,1)$ ,  $ML(2,2)$ , and  $ML(2,3)$  are connected to the middle switch  $MS(2,1)$ from middle switch  $MS(1,1)$ , and the links  $ML(2,22)$ ,  $ML(2,$ 23), and ML(2,24) are connected to the middle switch MS(2, 1) from middle switch  $MS(1,4)$  and also are connected to exactly d switches in middle stage 150 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected from middle switch MS(2,1) to middle switch MS(3, 1), and the links ML(3,4), ML(3,5), and ML(3,6) are con- $_{55}$ nected from middle switch  $MS(2,1)$  to middle switch  $MS(3, 1)$ 2)).

Similarly each of the

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links (for example the links  $ML(3,1)$ ,  $ML(3,2)$ , and  $ML(3,3)$  are connected to the middle switch  $MS(3,1)$ 

from middle switch  $MS(2,1)$ , and the links  $ML(3,22)$ ,  $ML(3,$ 23), and ML(3,24) are connected to the middle switch MS(3, 1) from middle switch MS(2,4)) and also are connected to exactly d output switches in output stage 120 through 3xd links (for example the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ are connected to output switch OS1 from middle switch  $MS(3,1)$ , and the links  $ML(4,4)$ ,  $ML(4,5)$ , and  $ML(4,6)$  are connected to output switch  $OS2$  from middle switch  $MS(3, 1)$ 1)).

Each of the

 $\frac{N_2}{d}$ 

<sub>20</sub> output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 3xd links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$ ,  $ML(4,2)$ , and  $ML(4,3)$ , and output switch OS1 is also connected from middle switch MS(3,4) through the links  $ML(4,22)$ ,  $ML(4,23)$ , and  $ML(4,24)$ .

Finally the connection topology of the network 300C2 shown in FIG. 3C2 is hereinafter called nearest neighbor connection topology.

tage 120 via middle stages 130, 140, and 150 is shown where<br><sup>40</sup> input stage 110 consists of four, six by eight switches IS1-IS4 Similar to network 300A2 of FIG. 3A2. 300B2 of FIG. 3B2, and 300C2 of FIG. 3C2, referring to FIG. 3D2, FIG. 3E2, FIG. 3F2, FIG. 3G2, FIG. 3H2, FIG. 312 and FIG. 3J2 with exemplary asymmetrical multi-link multi-stage networks 300D2, 300E2, 300F2, 300G2, 300H2, 30012, and 300J2 respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where and output stage 120 consists of four, six by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, eight by four switches  $MS(1,1)$ - $MS(1,4)$ , middle stage  $140$  consists of four, six by six switches  $MS(2,$ 1)- $MS(2,4)$ , and middle stage 150 consists of four, six by six switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in strictly non-blocking manner for multicast connections, because the switches in the input stage  $110$  are of size six by eight, the switches in output stage 120 are of size six by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

The networks 300D2, 300E2, 300F2, 300G2. 300H2, 30012 and 30032 ofFIG. 3D2, FIG. 3E2,FIG. 3F2, FIG. 3G2, FIG. 3H2, FIG. 3I2, and FIG. 3J2 are also embodiments of asymmetric multi-link multi-stage network can be represented with the notation  $V_{mlink}(N_1, N_2, d, s)$ , where  $N_1$  rep- $_{60}$  resents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

Just like networks of 300A2, 300B2 and 300C2, for all the networks 3001D2, 300F2, 300F2. 300G2, 300H2, 30012 and

300J2 ofFIG. 3D2,FIG. 3E2, FIG. 3F2, FIG. 3G2, FIG. 3H2, FIG. 312, and FIG. 3J2, each of the

## $\frac{N_2}{N_1}$

input switches IS1-IS4 are connected to exactly

## $\frac{2d + d_1}{4}$

switches in middle stage 130 through 2d+d, links. Each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly

$$
\frac{2d+d_1}{3}
$$

input switches through  $2d+d<sub>2</sub>$  links and also are connected to exactly d switches in middle stage 140 through 3xd links. Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through 3xd links and also are connected to exactly d 40 switches in middle stage 150 through 3xd links.

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through 3xd links and also are connected to exactly d output switches in output stage  $120$  through  $3 \times d$  links. 50

Each of the

$$
\frac{N_2}{d}
$$

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through 3xd links.

In all the ten embodiments of FIG. 3A2 to FIG. 3J2 the connection topology is different. That is the way the links  $ML(1,1)-ML(1,48)$ ,  $ML(2,1)-ML(2,24)$ ,  $ML(3,1)-ML(3,$ 24), and  $ML(4,1)-ML(4,24)$  are connected between the respective stages is different. Even though only ten embodi- 65 ments are illustrated, in general, the network  $V_{mlink}(N_1, N_2, d,$ s) can comprise any arbitrary type of connection topology.  $\frac{2d+d_1}{3}$ switches in middle stage 130 through 24+d<sub>2</sub> links.<br>
16<br>
Fach of the<br>
Fach of the<br>
Factor of the<br>  $\frac{N_2}{2}$ <br>
middle switches MS(1,1)-MS(1,4) in the middle stage 130<br>
are connected from exactly<br>  $\frac{2d+d_1}{2$ 

For example the connection topology of the network  $V_{mlink}$  $(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental propertyof <sup>a</sup> valid connection topology of the  $V_{mlink}(N_1,N_2,d,s)$  network is, when no connections are setup from any input link all the output links should be reach-

able. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$  can be built. The ten embodiments of FIG. 3A2 to FIG. 3J2 are only three examples of network  $V_{mlink}(N_1, N_2, d, s)$ .

20 In all the ten embodiments ofFIG. 3.A2 to FIG.3J2, each of the links  $ML(1,1)$ - $ML(1,48)$ ,  $ML(2,1)$ - $ML(2,24)$ ,  $ML(3,1)$ - $ML(3,24)$  and  $ML(4,1)-ML(4,24)$  are either available for use by a new connection or not available if currently used by an <sup>15</sup> existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1- OS4are also referred to as the network output ports. The output stage 120 is often referred to as the last stage. The middle stage switches  $MS(1,1)$ - $MS(1,4)$ ,  $MS(2,1)$ - $MS(2,4)$ , and MS(3,1)-MS(3,4) are referred to as middle switches or middle ports.

 $25$  connection request if input switch is IS2, but only two 30 In the example illustrated in FIG. 3A2 (or in FIG. 3B2 to FIG.3J2), a fan-out of four is possible to satisfy a multicast switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage  $130$  when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network 300A2 (or 300B2 to 300J2), to <sup>35</sup> be operated in strictly nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the strictly nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-oul may be used within any of the middle stage switches and the output stage switches to satisfy the connection request.

Generalized Asymmetric SNB  $(N_2>N_1)$  Embodiments: Network 3001K2 of FIG. 3K2 is an example of general asymmetrical multi-link multi-stage network  $\mathbf{V}_{mlink}(\mathbf{N}_1, \, \mathbf{N}_2,$ d, s) with  $(2 \times \log_d N_2) - 1$  stages where  $N_1 > N_2$  and  $N_1 = p^*N_2$ <sup>55</sup> where p>1. In network 300K2 of FIG. 3K2, N<sub>2</sub>=N and  $N_1=p*N$ . The general asymmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for multicast when s=3 according to the current invention (and in the example of FIG.  $3K2$ ,  $s=3$ ). The general asymmetrical multi-link multi-stage network  $V_{mlink}$  $(N_1, N_2, d, s)$  with  $(2 \times \log_d N_2) - 1$  stages has  $d_1$  (where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

 $\overline{\mathbf{S}}$ 

97

inlet links for each of

 $\frac{N_2}{d}$ 

input switches IS1-IS( $N_2/d$ ) (for example the links IL1-IL  $(p * d)$  to the input switch IS1) and  $2d+d_1$  (=2d+p×d) outgoing links for each of

input switches IS1-IS(N<sub>2</sub>/d) (for example the links ML(1,1)- $ML(1,(d+p*d))$  to the input switch IS1). There are d outlet links for each of

output switches OS1-OS(N,/d) (for example the links OL1-  $OL(d)$  to the output switch OS1) and  $2 \times d$  incoming links for each of  $25$ 

output switches OS1-OS(N<sub>2</sub>/d) (for example  $ML(2\times Log_d)$  $N_2$ -2,1)-ML(2×Log<sub>d</sub>  $N_2$ -2,3×d) to the output switch OS1). Each of the

input switches IS1-IS( $N_2/d$ ) are connected to exactly

 $2d + d$ 3

switches in middle stage  $130$  through  $2d+d<sub>2</sub>$  links. Each of the

middle switches  $MS(1,1)-MS(1,N_2/d)$  in the middle stage 130 are connected from exactly d input switches through 3xd links and also are connected to exactly d switches in middle stage 140 through 3xd links. Imis for each of<br>  $\frac{N_2}{d}$ <br>
imput awitches (SL-IS(N<sub>p</sub>/d) (for example the links MI (1,1)<sup>1</sup><br>
MI (1.6(4-p<sup>n</sup>4)) to the times switch IS1). There are d outlet<br>
links for each of<br>  $\frac{N_2}{d}$ <br>
cutput switches (NH-AS(N<sub>p</sub>/

Similarly each of the

 $\frac{N_2}{d}$ 

$$
MS(\text{Log}_{d}N_{2}-2) - MS(\text{Log}_{d}N_{2}-1, \frac{N_{2}}{d})
$$

in the middle stage  $130+10*(\text{Log}_A N_2-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_2-3)$ through 3xd links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d \text{N}_2-1)$  through 3xd links.

Similarly each of the

 $\frac{N_2}{d}$ 

middle switches

middle switches

20

30

$$
MS(\text{Log}_d N_2 - 3, 1) - MS(2 \times \text{Log}_d N_2 - 3, \frac{N_2}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$  $N<sub>2</sub>$ -5) through 3xd links and also are connected to exactly d output switches in output stage 120 through 3xd links. Each of the

 $\frac{N_2}{N}$ 

output switches  $OS1-OS(N_2/d)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  through 2xd links.

40 general  $V_{mlink}(N_1, N_2, d, s)$  may be any one of the connection As described before, again the connection topology of a topologies. For example the connection topology of the network  $V_{mlink}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{mlink}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{mlink}(N_1, N_2, d, s)$ <br>can be built. The embodiments of FIG. 3A2 to FIG. 3J2 are ten examples of network  $V_{mlink}(N_1, N_2, d, s)$  for s=3 and

 $N_2 > N_1$ . The general symmetrical multi-link multi-stage network  $V_{mlink}(N_1, N_2, d, s)$  can be operated in strictly nonblocking 55 manner for multicast when  $s \ge 3$  according to the current invention.

ing multicast assignment  $I_1 = \{1,4\}$  and all other  $I_2 = \{60, 8\}$ . It should be noted that the connection  $I_1$  fans out in the first For example, the network of FIG. 3C2 shows an exemplary five-stage network, namely  $V_{mlink}(8,24,2,3)$ , with the following multicast assignment  $I_1 = \{1,4\}$  and all other  $I_7 = \phi$  for j=[2stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,4)$ in middle stage 130, and fans out in middle switches  $MS(1,1)$ and  $MS(1,4)$  only once into middle switches  $MS(2,1)$  and MS(2,4) respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and  $MS(2,4)$  only once into middle switches  $MS(3,1)$  and  $MS(3,4)$  respectively in middle stage 150. The connection  $I_1$ 

25

also fans out in middle switches  $MS(3,1)$  and  $MS(3,4)$  only once into output switches OS1 and OS4in output stage 120. Finally the connection  $I_1$  fans out once in the output stage switch OS1 into outlet link OL1 and in the output stage switch OS4 twice into the outlet links OL7 and OL8. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

Folded Strictly Nonblocking Multi-lmk Multi-stage Networks:

The folded multi-link multi-stage network  $V_{fold\text{-}mlink}(N_1,$  $N<sub>2</sub>$ , d, s), disclosed in the current invention, is topologically exactly the same as the multi-stage network  $V_{mlink}(N_1, N_2, d, d)$ s), disclosed in U.S. Provisional Patent Application Ser. No. 60/940,392 that is incorporated by reference above, excepting that in the illustrations folded network  $V_{fold\text{-}mlink}(N_1,N_2,d,s)$ is shown as it is folded at middle stage  $130+10*(\text{Log}_d \text{N}_2-2)$ .

The general symmetrical folded multi-link multi-stage network  $V_{fold-mlink}(N_1, N_2, d, s)$  can also be operated in strictly nonblocking manner for multicast when  $s \ge 3$  according to the current invention. Similarly the general asymmetrical folded multi-link multi-stage network  $V_{\text{fold-mink}}(N_1, N_2, d, s)$  can also be operated in strictly nonblocking manner for multicast when  $s \ge 3$  according to the current invention. Folded Multi-Stage Network Embodiments:

Symmetric Folded RNB Embodiments:

Referring to FIG. 4A, in one embodiment, an exemplary symmetrical folded multi-stage network 400A with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, two by two switches MS(1,1)-MS(1,8), middle stage 140 consists of eight, two by two switches  $MS(2,1)$ - $MS(2,8)$ , and middle stage 150 consists of eight, two by two switches  $MS(3,1)$ -MS  $_{40}$  $(3,8).$ roades where 1 coloring Wildhim in Wallin-Sigge Net-<br>
works. Solida multi-link multi-arge network  $V_{\text{max,real}}$ ,  $\theta$ ,  $\theta$ ,  $\theta$ ,  $\theta$ ,  $\theta$ ,  $\theta$  and  $\theta$  is  $\theta$ , disclosed in the current inversion,  $k_{\text{max,real}}$ ,  $\theta$ ,  $\$ 

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there  $_{50}$ are cight switches in cach of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network cach of the input switches [S1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by

$$
2 \times \frac{N}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in 65 general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation 2d\*d. Like-

wise, the size of each switch in any of the middle stages can be denoted as d\*d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn maybe <sup>a</sup> crossbar switch or <sup>a</sup> network of switches. <sup>A</sup> symmetric folded multi-stage network can be represented with the notation  $V_{fold}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio US 8.2.6 (49) M2<br>
since function  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since function  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since function  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since  $\frac{\sqrt{3}}{2}$  (49) M2<br>
since  $\$ of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links  $IL1$ -IL $8$  as there are outlet links OL1-OL8, in a symmetrical network they are the same.

Each of the N/d input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,2)$ ,  $MS(1,5)$  and  $MS(1,6)$  through the links  $ML(1,1), ML(1,2), ML(1,3)$  and  $ML(1,4)$  respectively). Each of the

$$
2 \times \frac{N}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,5)$  are connected to the middle switch MS(1,1) from input switch IS1 and IS2 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$  respectively).

Similarly each of the

$$
2 \times \frac{N}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch MS(3,1) and MS(3,3) respectively).

Similarly each of the

$$
2 \times \frac{N}{d}
$$

are connected to the middle switch  $MS(3,1)$  from middle middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ ) are connected to output switches OS1 and O82 respectively from middle switches  $MS(3,1)$ ).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switches  $MS(3,1)$ ,  $MS(3,2)$ ,  $MS(3,5)$  and  $MS(3,6)$ through the links  $ML(4,1)$ ,  $ML(4,3)$ ,  $ML(4,9)$  and  $ML(4,11)$ respectively).

Finally the connection topology of the network 400A  $\frac{5}{3}$ shown in FIG. 4A is known to be back to back inverse Benes connection topology.

Referring to FIG. 4A1, in another embodiment of network  $V_{fold}(N, d, s)$ , an exemplary symmetrical folded multi-stage network 400A1 with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shownwhere  $15$ input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-O84. And all the middle stages namely middle stage 130 consists of eight, two by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage  $140$  consists of eight, two by two switches  $_{20}$ MS(2,1)-MS(2,8), and middle stage 150 consists of eight, two by two switches  $MS(3,1)$ - $MS(3,8)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output  $_{25}$ stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar  $_{35}$ switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by

$$
2 \times \frac{N}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as d\*d. A switch as used herein can be either a 50 crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The symmetric folded multi-stage network of FIG. 4A1 is also the network of the type  $V_{fold}(N,d,s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links  $IL1-IL8$  as there are outlet links OL1-OL8, in a symmetrical network they are the same. middle stage 140 consists of eigith, two by two switches  $\sim 2 \times \frac{N}{d}$ .<br>MS(2,1)-MS(2,8) and middle stage 150 consists of eight,  $v_0$ <br>We by two switches MS(3,1)-MS(3,8). And S(1,0)-MS(3,8). And the operated in strictly

Each of the N/d input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,2)$ ,  $MS(1,5)$  and  $MS(1,6)$  through the links  $ML(1,1), ML(1,2), ML(1,3)$  and  $ML(1,4)$  respectively).

Each of the

$$
2 \times \frac{N}{d}
$$

102

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,9)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS3 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,2)$  respectively).

Similarly each of the

$$
2 \times \frac{N}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,5)$ ) are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $MS(3,1)$  and  $MS(3,2)$  respectively).

Similarly each of the

$$
2 \times \frac{N}{d}
$$

40 through d links (for example the links  $ML(3,1)$  and  $ML(3,5)$ ) middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ are connected to output switches OS1 and OS2 respectively from middle switches  $MS(3,1)$ ).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switches  $MS(3,1)$ ,  $MS(3,3)$ ,  $MS(3,5)$  and  $MS(3,7)$ through the links  $ML(4,1)$ ,  $ML(4,5)$ ,  $ML(4,9)$  and  $ML(4,13)$ respectively).

Finally the connection topology of the network 400A1 shown in FIG. 4A1 is known to be back to back Omega connection topology.

Referring to FIG. 4A2, in another embodiment of network  $V_{\text{fold}}(N, d, s)$ , an exemplary symmetrical folded multi-stage network 400A2 with five stages of thirty two switches for satisfying communication requests, such as setting up a telephonecall or

a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists offour, two by four switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, two by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage

140 consists of eight, two by two switches  $MS(2,1)$ - $MS(2,8)$ , and middle stage 150 consists of eight, two by two switches MS(3,1)-MS(3,8).

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150.

In one embodiment of this network cach of the input switches [S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable N/d, where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by

$$
2 \times \frac{N}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1-  $^{30}$ OS4 can be denoted in general with the notation 2d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as d\*d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The symmetric folded multi-stage network of FIG. 4A2 is also the network of the type  $V_{fold}(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the inks IL1-IL8), d represents the inlet links of each input  $_{40}$ switch or outlet links of each output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links  $IL1$ - $IL8$  as there are outlet links OL1-OL8, in a symmetrical network they are  $_{45}$ he same. stage 1580. Such a network can be operated in recruzgeably in<br>smalle stage 180. Such a network can be operated in recruzged<br>with the smalle stage of 18 or 6 18 size to be y four, the switchs in the switchs in the paper st

Each of the N/d input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,2)$ ,  $MS(1,5)$  and  $MS(1,6)$  through the links 50  $ML(1,1)$ ,  $ML(1,2)$ ,  $ML(1,3)$  and  $ML(1,4)$  respectively).

Each of the

$$
2 \times \frac{\Lambda}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly d input switches through d links  $\frac{60}{200}$ (for example the links  $ML(1,1)$  and  $ML(1,14)$  are connected to the middle switch MS(1,1) from input switch IS1 and IS4 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch 65  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,2)$  respectively).

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 $2 \times \frac{N}{4}$ 

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,8)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,4)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch

 $MS(3,1)$  and  $MS(3,2)$  respectively). Similarly each of the

Similarly each of the

$$
2 \times \frac{N}{d}
$$

25 through d links (for example the links  $ML(3,1)$  and  $ML(3,8)$ ) middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,4)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ ) are connected to output switches OS1 and OS2 respectively from middle switches  $MS(3,1)$ ).

Each of the N/d output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OS1 is connected from middle switches MS(3,1), MS(3,4), MS(3,5) and MS(3,8) through the links  $ML(4,1)$ ,  $ML(4,2)$ ,  $ML(4,3)$  and  $ML(4,4)$ respectively).

Finally the connection topology of the network 400A2 shown in FIG. 4A2 is hereinafter called nearest neighbor connection topology.

In the three embodiments of FIG. 4A, FIG. 4A1 and FIG. 4A2 the connection topology is different. That is the way the links ML(1,1)-ML(1,16), ML(2,1)-ML(2,16), ML(3,1)-ML  $(3,16)$ , and ML $(4,1)$ -ML $(4,16)$  are connected between the respective stages is different. Even though only three embodiments are illustrated, in general, the network  $V_{fold}(N,d,s)$  can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}(N,d,s)$ may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{fold}$ (N,d, s) network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N,$ 55 d, s) can be built. The embodiments of FIG. 4A, FIG. 4A1, and FIG. 4A2 are only three examples of network  $V_{fold}(N, d, d)$ s)

In the three embodiments of FIG. 4A, FIG. 4A1 and FIG. 4A2, each of the links  $ML(1,1)$ - $ML(1,16)$ ,  $ML(2,1)$ - $ML(2,$ 16), ML(3,1)-ML(3,16) and ML(4,1)-ML(4,16) are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4arealso referred to as the network output ports. The output stage 120 is often referred to as the last stage. The middle stage switches MS(1,1)-MS(1,8),  $MS(2,1)$ - $MS(2,8)$ , and  $MS(3,1)$ - $MS(3,8)$  are referred to as middle switches or middle ports.

In the example illustrated in FIG. 4A (or in FIG. 1A1, or in FIG. 4A2), a fan-out of four is possible to satisfy a multicast connection request if input switch is IS2, but only two  $\frac{1}{5}$ switches in middle stage  $130$  will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage  $130$  when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network 400A (or 400A1, or 400A2), to be operated in rearrangeably nonblocking manner in accor- $_{15}$ dance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle  $_{25}$ stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request. Generalized Symmetric Folded RNB Embodiments: 20 30 105 8.363.569 122<br>
the main state and 105 state are connected to exactly detective and the main state and the main state and the main state are connected to exactly detective and the main state and the main state and the

Network 400B of FIG. 4B is an example of general symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  with  $(2 \times \log_d N) - 1$  stages. The general symmetrical folded multistage network  $V_{fold}(N, d, s)$  can be operated in rearrangeably  $_{35}$ nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multistage network  $V_{fold}(N, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \geq 2$  according to the current invention. (And in the example of FIG. 4B, s=2). The general symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  with  $(2 \times \log_d N) - 1$  stages has d inlet links for each of N/d input switches IS1-IS(N/d) (for example the links IL1-IL(d) to the input switch IS1) and  $2 \times d$  outgoing links for each of N/d input switches IS1-IS( $N/d$ ) (for example the links  $ML(1,1)-ML(1,$ 2d) to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS(N/d) (for example the links OL1-OL(d) to the output switch OS1) and 2xd incoming links for each of N/d output switches OS1-OS(N/d) (for example  $ML(2 \times Log_d N-2,1)$ - $ML(2 \times Log_d N-2,2 \times d)$  to the  $\zeta_0$ output switch OS1). middle sings 130 when soleting a final case of the beam in the counter of the comparison in the counter of the count 40 doutput switches in output stage 120 through links.

Each of the N/d input switches  $IS1$ -IS(N/d) are connected to exactly  $2 \times d$  switches in middle stage 130 through  $2 \times d$  links (for example input switch IS1 is connected to middle switches  $MS(1,1)-MS(1,d)$  through the links  $ML(1,1)-ML(1,d)$  and to middle switches  $MS(1,N/d+1)$ - $MS(1,\{N/d\}+d)$  through the links  $ML(1, d+1)$ - $ML(1, 2d)$  respectively.

Each of the

$$
2 \times \frac{N}{d}
$$

middle switches MS(1,1)-MS(1,2N/d) in the middle stage 130 are connected from exactly d input switches through d 65 links and also are connected to exactly d switches in middle stage 140 through d links.

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$$
2 \times \frac{N}{4}
$$

middle switches

Similarly each of the

$$
MS(\text{Log}_d N - 1, 1) - MS(\text{Log}_d N - 1, 2 \times \frac{N}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{N}-3)$ middle stage  $130+10*(\text{Log}_d N-1)$  through d links.

Similarly each of the

$$
2 \times \frac{N}{d}
$$

middle switches

$$
MS(2 \times \text{Log}_d N - 3, 1) - MS\left(2 \times \text{Log}_d N - 3, 2 \times \frac{N}{d}\right)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$ N-5) through d links and also are connected to exactly d

Each of the N/d output switches OS1-OS(N/d) are connected from exactly 2xd switches in middle stage 130+10\*  $(2 * Log<sub>A</sub> N-4)$  through 2×d links.

As described before, again the connection topology of a general  $V_{fold}(N, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{fold}(N, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold}(\bar{N}, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N, d, s)$  can be built. The embodiments of FIG. 4A, FIG. 4A1, and FIG. 4A2 are three examples of network  $V_{fold}(N, d, s)$ .

The general symmetrical folded multi-stage network  $V_{fold}$ (N, d, s) can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention.

Every switch in the folded multi-stage networks discussed herein has multicast capability. In a  $V_{fold}(N, d, s)$  network, if a network inlet link is to be connected to more than one outlet link on the same output switch, then it is only necessary for the corresponding input switch to have one path to that output switch. This follows because that path can be multicast within the output switch to as many outlet links as necessary. Multicast assignments can therefore be described in terms of connections between input switches and output switches. An existing connection or <sup>a</sup> new connection froman input switch to r' output switches is said to have fan-out r'. If all multicast

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assignments of a first type, wherein any inlet link of an input switch is to be connected in an output switch to at most one outlet link are realizable, then multicast assignments of a second type, wherein any inlet link of each input switch is to be connected to more than one outlet link in the same output <sup>5</sup> switch, can also be realized. For this reason, the following discussion is limited to general multicast connections of the first type (with fan-out r',

$$
\left(\text{With fan-out }\boldsymbol{r}',\, 1\leq \boldsymbol{r}'\leq \frac{N}{d}\right)
$$

although the same discussion is applicable to the second type. 15 To characterize a multicast assignment, for each inlet link

$$
i \in \Big\{1, 2, \ldots, \frac{N}{d}\Big\},\
$$

let  $I<sub>i</sub>=O$ , where

$$
O\subset\Big\{1,\,2,\,\ldots\,\,,\,\frac{N}{d}\Big\},
$$

denote the subset of output switches to which inlet link i is to be connected in the multicast assignment. For example, the  $_{30}$ network of FIG. 4A shows an exemplary five-stage network, namely  $V_{\text{fold}}(8,2,2)$ , with the following multicast assignment  $I_1$ ={2,3} and all other  $I_j$ = $\phi$  for j=[2-8]. It should be noted that the connection I, fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,5)$  in middle stage 130, 35 and fans out in middle switches  $MS(1,1)$  and  $MS(1,5)$  only once into middle switches MS(2,1) and MS(2,5) respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and  $MS(2,5)$  only once into middle switches  $MS(3,1)$  and 40  $MS(3,7)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,7)$  only once into output switches OS2 and OS3 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage Finally the connection  $1_1$  lans out once in the output stage switch  $\overline{45}$  and in the output stage switch  $\overline{45}$ OS3 twice into the outlet links OL5 and OL6. In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches in middle stage 130.

Asymmetric Folded RNB  $(N_2>N_1)$  Embodiments:

Referring to FIG. 4C, in one embodiment, an exemplary asymmetrical folded multi-stage network 400C with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, two by two 60 switches MS(1,1)-MS(1,8), middle stage 140 consists of eight, two by two switches  $MS(2,1)$ - $MS(2,8)$ , and middle stage 150 consists of eight, two by four switches MS(3,1)- MS(3,8). **EVALUATION** (Was the east  $\epsilon$ , 1  $z \neq \frac{N}{a}$ ) to the second type. 15<br>
although the same discussion is applicable to the second type. 15<br>
To characterize a motivicast assignment, for each indet link<br>  $\{\epsilon\} \{1, 2, ..., \frac{$ 

Such a network can be operated in strictly non-blocking 65 manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output

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stage 120 are of size eight by six, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are eight switches of size two by two in each of middle stage 130 and middle stage 140, and eight switches of size two by four in middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_1}{d}$ ,

 $_{20}$  where  $\rm N_1$  is the total number of inlet links or and  $\rm N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

 $2 \times \frac{N_1}{I}$ .

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation  $(d+d<sub>2</sub>)$ <sup>\*</sup>d, where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as d\*d. The size of each switch in the last middle stage can be denoted as

$$
d*\frac{(d+d_2)}{2}.
$$

A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multistage network can be represented with the notation  $V_{fold}(N_1,$  $N_1$ , d, s), where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), drepresents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Eachofthe



input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,$
60

2),  $MS(1,5)$  and  $MS(1,6)$  through the links  $ML(1,1)$ ,  $ML(1,$ 2),  $ML(1,3)$  and  $ML(1,4)$  respectively).

Each of the

$$
2\times \frac{N_1}{d}
$$

middle switches  $MS(1.1)$ - $MS(1.8)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,5)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS2 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$  respectively).

Similarly each of the

$$
2 \times \frac{N_1}{d}
$$

middle switches MS(2,1)-MS(2,8) in the middle stage 140  $_{25}$ are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch MS(3,1) and MS(3,3) respectively). magne switches based, 1.1-pass(1, a) are magnet is well made switched based since the model since the model since the model of the 30

Similarly each of the

$$
2\times \frac{N_1}{d}
$$

middle switches MS(3,1)-MS(3,8) in the middle stage 150  $_{40}$ are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly

$$
\frac{d+d_2}{2}
$$

output switches in output stage 120 through

$$
\frac{d+d_2}{2}
$$

links (for example the links  $ML(4,1)$ ,  $ML(4,2)$ ,  $ML(4,3)$  and ML(4,4) are connected to output switches OS1, OS2, OS3, and OS4 respectively from middle switches  $MS(3,1)$ ).<br>Each of the

output switches OS1-OS4 are connected from exactly d+d, switches in middle stage 150 through  $d+d_2$  links (for example

output switch OS1 is connected from middle switches MS(3, 1), MS(3,2), MS(3,3), MS(3.4), MS(3,5), MS(3,6), MS(3,7), and  $MS(3,8)$  through the links  $ML(4,1)$ ,  $ML(4,5)$ ,  $ML(4,9)$ , ML(4,13), ML(4,17), ML(4,21), ML(4,25) and ML(4,29) 5 respectively).

Finally the connection topology of the network 400C shown in FIG. 4C is knownto be back to back inverse Benes connection topology.

Referring to FIG. 4C1, in another embodiment of network  $V_{\text{fold}}(N_1, N_2, d, s)$ , an exemplary asymmetrical folded multistage network 400C1 with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, two by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage 140 consists of eight, two by two switches MS(2,1)-MS(2,8), and middle stage 150 consists of cight, two by four switches  $MS(3,1)$ - $MS(3,8)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are eight switches of size two by two in each of middle stage 130 and middle stage  $140$ , and eight switches of size two by four in middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

$$
\frac{N_1}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
2 \times \frac{N_1}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1- OS4 can be denoted in general with the notation  $(d+d_2)^*d$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as d\*d. The size of each switch in the last middle stage can be denoted as

$$
d*\frac{(d+d_2)}{2}.
$$

<sup>A</sup> switch as used herein canbe either <sup>a</sup> crossbar switch, or <sup>a</sup> network of switches each of which in turn may be a crossbar switch or a network of switches. The asymmetric folded multi-stage network of FIG. 4C1 is also the network of the

40

type  $V_{fold}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N<sub>2</sub>$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2>N_1$ , and s 5 is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

Each of the

input switches [S1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,$ 2),  $MS(1,5)$  and  $MS(1,6)$  through the links  $ML(1,1)$ ,  $ML(1,$ 2),  $ML(1,3)$  and  $ML(1,4)$  respectively).

Each of the

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,9)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS3 respectively) and also are connected to exactly d switches in  $_{30}$ middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,2)$  respectively). <sup>86</sup>/<sub>2</sub><br>
input switches IS1-154 are connected to exactly 2xd awitches<br>
in middle stage 130 divrop). 2xd links (for example input 15<br>
switch IS1 is connected to middle switch. MSCL, MSCL, MSCL, SIC, 20, and MSCL of 100<br>
2  $25$ 

Similarly each of the

$$
2\times \frac{N_1}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,5)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are 45 connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $MS(3,1)$  and  $MS(3,2)$  respectively).

Similarly each of the

$$
\times \frac{N_1}{d}
$$

middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,5)$ ) are connected to the middle switch MS(3,1) from middle are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are  $60$ connected to exactly

$$
\frac{d+d_2}{2}
$$

112

output switches in output stage 120 through

$$
\frac{d+d_2}{2}
$$

links (for example the links  $ML(4,1)$ ,  $ML(4,2)$ ,  $ML(4,3)$  and ML(4,4) are connected to output switches OS1, OS2, OS3, and OS4 respectively from middle switches  $MS(3,1)$ ).

Each of the

 $\frac{N_1}{N_2}$ 

output switches OS1-OS4are connected from exactly d+d, switches in middle stage 150 through  $d+d<sub>2</sub>$  links (for example output switch OS1 is connected from middle switches MS(3, 1), MS(3,2), MS(3,3), MS(3,4), MS(3,5), MS(3,6), MS(3,7), and MS $(3,8)$  through the links ML $(4,1)$ , ML $(4,5)$ , ML $(4,9)$ , ML(4,13), ML(4,17), ML(4,21), ML(4,25) and ML(4,29) respectively).

Finally the connection topology of the network 400C1 shown in FIG. 4C1 is known to be back to back Omega connection topology.

Referring to FIG. 4C2, in another embodiment of network  $V_{\text{fold}}(N_1, N_2, d, s)$ , an exemplary asymmetrical folded multistage network 400C2 with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by four switches IS1-IS4 and output stage 120 consists of four, eight by six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, two by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage 140 consists of eight, two by two switches MS(2,1)-MS(2,8), and middle stage 150 consists of eight,

two by four switches  $MS(3,1)$ - $MS(3,8)$ . Such a network can be operated in strictly non-blocking

manner for unicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size two by four, the switches in output stage 120 are of size eight by six, and there are eight switches of size two by two in each of middle stage 130 and middle stage 140, and eight switches of size two by four in middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

> M  $\frac{v_1}{r}$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2>N_1$  and  $N_2=p*N_1$  where  $p>1$ . The number of middle switches in each middle stage is denoted by

 $2 \times \frac{N_1}{N_2}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*2d and each output switch OS1 $\overline{\mathbf{S}}$ 

OS4 can be denoted in general with the notation  $(d+d<sub>2</sub>)$ <sup>\*</sup>d, where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as d\*d. The size of each switch in the last middle stage can be denoted as

$$
d*\frac{(d+d_2)}{2}.
$$

A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The asymmetric folded multi-stage network of FIG. 4C2 is also the network of the 20 type  $V_{\text{fold}}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of each input switch where  $N_2 > N_1$ , and s 25 is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. the last models stage can be denoted as  $u^2L$ .<br>
with in the last model stage can be denoted as<br>
switch in the last model stage can be denoted as<br>
<br>
A rewich as tused heren a certain a crossbar restrict. For<br>
a review of

Each of the

input switches IS1-IS4 are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example input  $35$ switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,$ 2),  $MS(1,5)$  and  $MS(1,6)$  through the links  $ML(1,1)$ ,  $ML(1,$ 2),  $ML(1,3)$  and  $ML(1,4)$  respectively).

Each of the

$$
2 \times \frac{N_1}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,14)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS4 respectively) and also are connected to exactly d switches in  $\zeta_0$ middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,2)$  respectively).

Similarly each of the

$$
2 \times \frac{N_1}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,8)$ ) are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,4)$  respectively) and also are 65 connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are

connected from middle switch MS(2,1) to middle switch MS(3,1) and MS(3,2) respectively). Similarly each of the

 $2 \times \frac{N_1}{I}$ 

middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,8)$ are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,4)$  respectively) and also are <sub>15</sub> connected to exactly

 $\frac{d+d_2}{2}$ 

output switches in output stage 120 through

$$
\frac{d+d_2}{2}
$$

links (for example the links  $ML(4,1)$ ,  $ML(4,2)$ ,  $ML(4,3)$  and ML(4,4) are connected to output switches OS1, OS2, OS3, and OS4 respectively from middle switches  $MS(3,1)$ ).

Each of the

30

## $\frac{N_1}{d}$

40 1), MS(3,2), MS(3,3). MS(3,4), MS(3,5), MS(3,6), MS(3,7), output switches OS1-OS4 are connected from exactly d+d, switches in middle stage 150 through d+d, links (for example output switch OS1 is connected from middle switches MS(3,

and  $MS(3,8)$  through the links  $ML(4,1)$ ,  $ML(4,5)$ ,  $ML(4,9)$ , ML(4,13), ML(4,17), ML(4,21), ML(4,25) and ML(4,29) respectively).

Finally the connection topology of the network 400C2 shown in FIG. 4C2 is hereinafter called nearest neighbor connection topology.

In the three embodiments of FIG. 4C, FIG. 4C1 and FIG. 4C2 the connection topology is different. That is the way the links ML(1,1)-ML(1,16). ML(2,1)-ML(2,16), ML(3,1)-ML  $(3,16)$ , and ML $(4,1)$ -ML $(4,16)$  are connected between the respective stages is different. Even though only three embodiments are illustrated, in general, the network  $V_{fold}(N_1, N_2, d, d)$ s) can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}$ 55 ( $N_1$ ,  $N_2$ , d, s) may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental propertyof <sup>a</sup> valid connection topology of the  $V_{fold}(N_1, N_2, d, s)$  network is, when no connections are setup from anyinput link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N_1, N_2, d, s)$  can be built. The embodiments of FIG. 4C, FIG. 4C1, and FIG. 4C2 are only three examples of network  $V_{fold}(N_1, N_2, d, s)$ .

In the three embodiments of FIG. 4C, FIG. 4C1 and FIG. 4C2, each of the links  $ML(1,1)$ - $ML(1,32)$ ,  $ML(2,1)$ - $ML(2,$ 16), ML $(3,1)$ -ML $(3,16)$  and ML $(4,1)$ -ML $(4,16)$  are either available for use by a new connection or not available if currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4are also referred to as the network output ports. The output stage 120 is often referred to as the <sup>5</sup> last stage. The middle stage switches  $MS(1,1)-MS(1,8)$ ,  $MS(2,1)$ - $MS(2,8)$ , and  $MS(3,1)$ - $MS(3,8)$  are referred to as middle switches or middle ports.

In the example illustrated in FIG. 4C (or in FIG. 1C1, or in FIG. 4C2), a fan-out of four is possible to satisfy a multicast connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in middle stage 130 when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle  $_{20}$ switches permits the network  $400C$  (or  $400C1$ , or  $400C2$ ), to be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be include the connection request of the type described above can be  $\frac{1}{25}$  N<sub>1</sub>-2,1)-ML(2xLog<sub>d</sub>N<sub>1</sub>-2, d+d<sub>2</sub>) to the output switch OS1). a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, 1.e.a single middle stage switch in middle stage 130 is used to satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can be greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output stage switches to satisfy the connection request. Generalized Asymmetric Folded RNB  $(N_2>N_1)$  Embodiments: If the compare interaction at the set of the relation of the set of the set of the set of the complete the relation relation to the set of the s 30 40 US 8.345.649 B2<br>
Stadio and the stage of the stage o

Network 400D of FIG. 4D is an example of general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d N_1)$ –1 stages where N<sub>2</sub>>N<sub>1</sub> and N<sub>2</sub>=p<sup>\*</sup>N<sub>1</sub> where p>1. In network 400D of FIG. 4D,  $N_1$ =N and  $N_2$ =p\*N. The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  45 can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general asymmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention. (And in the example of FIG. 4D, s=2). The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d)$  $N_1$ )–1 stages has d inlet links for each of 50

 $\frac{N_1}{N_2}$ 

input switches IS1-IS(N<sub>1</sub>/d) (for example the links IL1-IL(d)  $_{60}$ to the input switch  $IS1$ ) and  $2 \times d$  outgoing links for each of

 $\frac{N_1}{N_2}$ 

input switches IS1-IS( $N_1/d$ ) (for example the links ML(1,1)- $ML(1,2d)$  to the input switch IS1). There are d<sub>2</sub> (where

(where 
$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d
$$
)

outlet links for each of

output switches  $OS1-OS(N_1/d)$  (for example the links OL1- $OL(p*d)$  to the output switch OS1) and d+d<sub>2</sub> (=d+pxd) incoming links for each of

$$
\frac{N_1}{d}
$$

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$ Each of the

input switches IS1-IS( $N_1/d$ ) are connected to exactly 2xd switches in middle stage 130 through 2xd links (for example in one embodiment the input switch IS1 is connected to middle switches  $MS(1,1)$ - $MS(1, d)$  through the links  $ML(1, d)$ 1)-ML(1, d) and to middle switches  $MS(1,N_1/d+1)$ -MS(1,  ${N_1/d}$ +d) through the links ML(1, d+1)-ML(1,2d) respectively.

Each of the

$$
2 \times \frac{N_1}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,2N/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the

$$
MS(\text{Log}_d N_1 - 1, 1) - MS(\text{Log}_d N_1 - 1, 2 \times \frac{N_1}{d})
$$

middle switches

 $2 \times \frac{N_1}{N_2}$ 

in the middle stage  $130+10*(\text{Log}_d N_1-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through d links and also are connected to exactly d switches in middle stage  $130+10*(Log_d N_1-1)$  through d links.

Similarly each of the

$$
2 \times \frac{N_1}{d}
$$

middle switches

$$
MS(2 \times Log_d N_1 - 3, 1) - MS\left(2 \times Log_d N_1 - 3, 2 \times \frac{N_1}{d}\right)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub>N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d-15</sub>)$  $N_1-5$ ) through d links and also are connected to exactly d output switches in output stage 120 through d links.

Each of the

$$
\frac{N_1}{d}
$$

output switches  $OS1-OS(N_1/d)$  are connected from exactly butput switches  $OS_1$ -OS( $N_1$ /d) are connected from exactly<br>d+d<sub>2</sub> switches in middle stage  $130+10*(2*Log_a)N_1-4$   $^{25}$ through  $d+d_1$  links.

As described before, again the connection topology of a general  $V_{fold}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{fold}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold}(N_1, N_2, d, s)$  network is,  $_{35}$ when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N_1, N_2, d, s)$  can be built. The embodiments of FIG. 4C, FIG. 4C1, and FIG. 4C2 are three examples of network  $V_{fold}(N_1, N_2, d, s)$  for s=2 40 and  $N_2 > N_1$ .  $\frac{k(0)}{2} \times 1 \times \frac{1}{2} \times 10^{-1}$ <br>
in the middle stage 130+10<sup>6</sup>/<sup>21</sup>-1 stag. N<sub>1</sub>-4) are connected<br>
from exactly d swidels is an initial stage 130+10<sup>6</sup>/<sup>24</sup>-1 stag.<br>
19 of 20<sup>2</sup>/<sup>2</sup> (e.g. 15<br>
N<sub>1</sub>-5 of the widels in outp

The general symmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multi-stage 45 network  $V_{fold}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention.

For example, the network of FIG. 4C shows an exemplary five-stage network, namely  $V_{fold}(8,24,2,2)$ , with the follow-<br>ing multicast assignment  $I_1 = \{2,3\}$  and all other  $I_j = \emptyset$  for j=[2-8]. It should be noted that the connection  $I_1$  fans out in the first stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,5)$ in middle stage 130, and fans out in middle switches  $MS(1,1)$ and  $MS(1,5)$  only once into middle switches  $MS(2,1)$  and 55 MS(2,5) respectively in middle stage 140.

The connection  $I_1$  also fans out in middle switches MS(2,1) and  $MS(2,5)$  only once into middle switches  $MS(3,1)$  and  $MS(3,7)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,7)$  only 60 once into output switches OS2 and OS3 in output stage 120. Finally the connection  $I_1$  fans out once in the output stage Finally the connection  $I_1$  lans out once in the output stage<br>switch OS2 into outlet link OL7 and in the output stage switch<br>OS3 twice into the outlet links OL13 and OL16. In accordance with the invention, each connection can fan out in the 65 A switch as used herein can be either a crossbar switch, or a input stage switch into at most two middle stage switches in middle stage 130.

Asymmetric Folded RNB  $(N_1 > N_2)$  Embodiments:

Referring to FIG. 4E, in one embodiment, an exemplary asymmetrical folded multi-stage network 400E with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four,

six by eight switches IS1-IS4 and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, four by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage 140 consists of eight, two by two switches  $MS(2,1)$ - $MS(2,8)$ , and middle stage 150 consists of eight, two by two switches MS(3,1)-MS (3,8).

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are eight switches ofsize fourby two in middle stage 130, and eight switches of size two by two in middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

$$
\frac{N_2}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

$$
2 \times \frac{N_2}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d^*(d+d_1)$  and each output switch OS1-OS4 can be denoted in general with the notation  $(2\times d*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as d\*d. The size of each switch in the first middle stage can be denoted as

$$
\frac{(d+d_1)}{2}*d.
$$

network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multi-

15

stage network can be represented with the notation  $V_{fold}(N_1, N_2)$  $N_2$ , d, s), where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch.

Each of the

 $\frac{N_2}{d}$ 

input switches IS1-IS4 are connected to exactly  $d+d_1$ switches in middle stage 130 through  $d+d_1$  links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,2)$ ,  $MS(1,3)$ ,  $MS(1,4)$ ,  $MS(1,5)$ ,  $MS(1,6)$ ,  $MS(1,7)$ , and  $MS(1,8)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ ,  $ML(1,3)$ ,  $ML(1,4)$ ,  $ML(1,5)$ ,  $ML(1,6)$ ,  $ML(1,7)$ , and  $ML(1,8)$  respectively). 20

Each of the

$$
2 \times \frac{N_2}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly

$$
\frac{(d+d_1)}{2}
$$

input switches through

$$
\frac{(d+d_1)}{2}
$$

links (for example the links  $ML(1,1)$ ,  $ML(1,9)$ ,  $ML(1,17)$  and 45  $ML(1,25)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1, IS2, IS3, and IS4 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $50$  $MS(2,1)$  and  $MS(2,3)$  respectively).

Similarly each of the

$$
2 \times \frac{N}{a}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage  $130\%$ through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are 65 connected from middle switch  $MS(2,1)$  to middle switch MS(3,1) and MS(3,3) respectively).  $\frac{(d+d_1)}{2}$ links (for example the links ML(1,1), ML(1,9), ML(1,17) and 45<br>
ML(1,25) are connected to the middle switch MS(1,1) from<br>
input switch IS1, IS2, IS3, and IS4 respectively) and lao are<br>
connected to exactly d

Similarly each of the

 $2 \times \frac{N_2}{4}$ 

120

middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ ) are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ ) are connected to output switches OS1 and O82 respectively

from middle switches  $MS(3,1)$ ).<br>Each of the



 $25$  output switch OS1 is connected from middle switches  $MS(3)$ , output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example 1), MS(3,2), MS(3,5), and MS(3,6) through the links ML(4,

1),  $ML(4,3)$ ,  $ML(4,9)$ , and  $ML(4,11)$  respectively).

Finally the connection topology of the network 400E<br>shown in FIG.4E is known to be back to back inverse Benes connection topology.

Referring to FIG. 4E1, in another embodiment of network  $V_{\epsilon_0\nu}$ (N<sub>1</sub>, N<sub>2</sub>, d, s), an exemplary asymmetrical folded multistage network 400E1 with five stages of thirty two switches for satisfying communication requests, such as setting up a  $_{35}$  telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4 and output stage 120 consists of four, four by two switches  $_{40}$  OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, four by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage 140 consists of eight, two by two switches MS(2,1)-MS(2,8), and middle stage 150 consists of eight, two by two switches  $MS(3,1)$ - $MS(3,8)$ .

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are eight switches of size four by two in middle stage 130, and  $55$  eight switches of size two by two in middle stage 140 and middle stage 150.

In one embodiment of this network each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_2}{N_1}$ 

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$  where  $p > 1$ .  $\overline{\mathbf{S}}$ 

The number of middle switches in each middle stage is denoted by

 $2 \times \frac{N_2}{4}$ 

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d^*(d+d_1)$  and each output switch  $_{10}$ OS1-OS4 can be denoted in general with the notation  $(2\times d* d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $d * d$ . The size of each switch in the first middle stage can be denoted as 20

$$
\frac{(d+d_1)}{2}*d.
$$

A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The asymmetric folded multi-stage network of FIG. 4F1 is also the network of the type  $V_{fold}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d repre- $_{35}$ sents the inlet links of each input switch where  $N_1 > N_2$ , and s is the ratio of number of incoming links to each output switch to the outlet links of each output switch. general with the notation de<sup>n</sup>(4-1) and each output switch in (2x1)<br>
OS1-OS4 cam be denoted in general with the notation<br>
(2x1\*d), where<br>  $dz = N_1 \times \frac{d}{N_2} = \rho \times d$ .<br>
The street can be denoted in general with the notation<br> 30

Each of the

$$
\frac{I}{\sqrt{2}}
$$

input switches IS1-IS4 are connected to exactly d+d, switches in middle stage 130 through  $d+d_1$  links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ ,  $MS(1,2)$ ,  $MS(1,3)$ ,  $MS(1,4)$ ,  $MS(1,5)$ ,  $MS(1,6)$ ,  $MS(1,7)$ , and  $\overline{\text{MS}}(1,8)$  through the links  $\text{ML}(1,1)$ ,  $\text{ML}(1,2)$ ,  $\text{ML}(1,3)$ , so  $ML(1,4), ML(1,5), ML(1,6), ML(1,7),$  and  $ML(1,8)$  respectively).

Each of the

$$
2 \times \frac{N}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130  $_{60}$ are connected from exactly

$$
\frac{(d+d_1)}{2}
$$

122

 $\frac{(d+d_1)}{2}$ 

links (for example the links  $ML(1,1)$ ,  $ML(1,9)$ ,  $ML(1,17)$  and  $ML(1,25)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1, 1S2, [S3, and IS4 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch MS(1,1) to middle switch  $MS(2,1)$  and  $MS(2,2)$  respectively).

Similarly each of the

input switches through

$$
2 \times \frac{N_2}{d}
$$

are connected to the findate switch  $MS(\lambda,1)$  from findate<br><sup>25</sup> switches MS(1,1) and MS(1,3) respectively) and also are middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,5)$ are connected to the middle switch MS(2,1) from middle connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $MS(3,1)$  and  $MS(3,2)$  respectively).

Similarly each of the

$$
2\times \frac{N_2}{d}
$$

 $_{40}$  are connected to the middle switch MS(3,1) from middle middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,5)$ ) switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ are connected to output switches OS1 and OS2 respectively from middle switches  $MS(3,1)$ ).<br>Each of the

 $\frac{N_2}{4}$ 

output switches OS1-OS4 are connected from exactly 2xd switches in middle stage 150 through 2xd links (for example output switch OSI is connected from middle switches MS(3, 55 1), MS(3,3), MS(3,5), and MS(3,7) through the links ML(4, 1),  $ML(4,5)$ ,  $ML(4,9)$ , and  $ML(4,13)$  respectively).

Finally the connection topology of the network 400E1 shown in FIG. 4E1 is known to be back to back Omega connection topology.

Referring to FIG. 4E2, in another embodiment of network  $V_{\text{fold}}(N_1, N_2, d, s)$ , an exemplary asymmetrical folded multistage network 400E2 with five stages of thirty two switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by eight switches IS1-IS4

and output stage 120 consists of four, four by two switches OS1-OS4. And all the middle stages namely middle stage 130 consists of eight, four by two switches  $MS(1,1)$ - $MS(1,8)$ , middle stage 140 consists of eight, two by two switches  $MS(2,1)$ - $MS(2,8)$ , and middle stage 150 consists of eight, <sup>5</sup> two by two switches MS(3,1)-MS(3,8).

Such a network can be operated in strictly non-blocking manner for unicast connections, because the switches in the input stage 110 are of size six by eight, the switches in output stage 120 are of size four by two, and there are eight switches in each of middle stage 130, middle stage 140 and middle stage 150. Such a network can be operated in rearrangeably non-blocking manner for multicast connections, because the switches in the input stage 110 are of size six by eight, the  $_{15}$ switches in output stage 120 are of size four by two, and there are eight switches ofsize four bytwo in middle stage 130, and eight switches of size two by two in middle stage 140 and middle stage 150.

In one embodiment of this network each of the input  $_{20}$ switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of outpul stage 120 can be denoted in general with the variable

$$
\frac{N_2}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p*N_2$  where  $p>1$ . The number of middle switches in each middle stage is denoted by 30

$$
2 \times \frac{N_2}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d^*(d+d_1)$  and each output switch  $40$ OS1-OS4 can be denoted in general with the notation  $(2\times d*d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as d\*d. The size of each  $\frac{1}{50}$ switch in the first middle stage can be denoted as

$$
\frac{(d+d_1)}{2}*d.
$$

A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. The asymmetric folded multi-stage network of FIG. 4E1 is also the network of the 60 type  $V_{\text{fold}}(N_1, N_2, d, s)$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N<sub>2</sub>$ , represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each input switch where  $N_1 > N_2$ , and s 65 is the ratio of number of incoming links to each output switch to the outlet links of each output switch. mpts sage 110 are of 200 stars by eignin are switches in equal time<br>sage 120 are of sizes for by two, and there are eight wistlens<br>in most be a more bundled and the sage of the anity and the sage of the anity and the mode Each of the

 $\frac{N_2}{d}$ 

124

input switches IS1-IS4 are connected to exactly  $d+d_1$ switches in middle stage  $130$  through d+d, links (for example input switch IS1 is connected to middle switches  $MS(1,1)$ , MS(1,2), MS(1,3), MS(1,4), MS(1,5), MS(1,6), MS(1,7), and  $MS(1,8)$  through the links  $ML(1,1)$ ,  $ML(1,2)$ ,  $ML(1,3)$ ,  $ML(1,4)$ ,  $ML(1,5)$ ,  $ML(1,6)$ ,  $ML(1,7)$ , and  $ML(1,8)$  respectively).

Each of the

$$
2\times \frac{N_2}{d}
$$

middle switches  $MS(1,1)$ - $MS(1,8)$  in the middle stage 130 are connected from exactly

$$
\frac{(d+d_1)}{2}
$$

input switches through

$$
\frac{(d+d_1)}{2}
$$

links (for example the links ML(1,1), ML(1,9), ML(1,17) and  $ML(1,25)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1, IS2, IS3, and IS4 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch MS(1,1) to middle switch MS(2,1) and MS(2,2) respectively).

Similarly each of the

$$
2 \times \frac{N_2}{d}
$$

middle switches  $MS(2,1)$ - $MS(2,8)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,8)$ ) are connected to the middle switch  $MS(2,1)$  from middle switches  $MS(1,1)$  and  $MS(1,4)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $MS(3,1)$  and  $MS(3,2)$  respectively).

Similarly each of the

$$
2 \times \frac{N_2}{d}
$$

middle switches  $MS(3,1)$ - $MS(3,8)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,8)$ ) are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,4)$  respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$ ) are connected to output switches OS1 and OS2 respectively from middle switches MS(3,1)).

Each of the

 $\frac{N_2}{d}$ 

output switches OS1-OS4 are connected from exactly 2xd switches in middle stage <sup>150</sup> through 2xd links (for example output switch OS1 is connected from middle switches MS(3, 1), MS(3,4), MS(3,5), and MS(3,8) through the links ML(4,  $_{15}$ 1), ML $(4,8)$ , ML $(4,9)$ , and ML $(4,16)$  respectively).

Finally the connection topology of the network 400E2 shown in FIG. 4E2 is hereinafter called nearest neighbor connection topology.

In the three embodiments of FIG. 4E, FIG. 4E1 and FIG. 20 4E2 the connection topology is different. That is the way the links ML(1,1)-ML(1,32), ML(2,1)-ML(2,16), ML(3,1)-ML  $(3,16)$ , and ML $(4,1)$ -ML $(4,16)$  are connected between the respective stages is different. Even though only three embodiments are illustrated, in general, the network  $V_{fold}(N_1, N_2, d, 25)$ s) can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}$  $(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology <sup>30</sup> of the  $V_{\text{fold}}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{\text{fold}}(N_1, N_2, d, s)$  can be built. The embodiments of FIG. 4E, FIG. 4E1, and FIG. 4E2 are only three examples of 35 network  $V_{fold}(N_1, N_2, d, s)$ . output switches OSI-OS4 are connected from excepty 2x<br>model magnetary 24<br>model magnetary institutes and statistic means that the example source and the same of the first connected from middle cosiders MS(3, 1), MS(4,4), M

In the three embodiments of FIG. 4E, FIG. 4E1 and FIG. 4E2, each of the links  $ML(1,1)$ - $ML(1,32)$ ,  $ML(2,1)$ - $ML(2,$ 16), ML(3.1)-ML(3,16) and ML(4,1)-ML(4,16) are either available for use by a new connection or not available if  $40$ currently used by an existing connection. The input switches IS1-IS4 are also referred to as the network input ports. The input stage 110 is often referred to as the first stage. The output switches OS1-OS4are also referred to as the network output ports. The output stage 120 is often referred to as the 45 last stage. The middle stage switches  $MS(1,1)$ - $MS(1,8)$ ,  $MS(2,1)$ - $MS(2,8)$ , and  $MS(3,1)$ - $MS(3,8)$  are referred to as middle switches or middle ports.

In the example illustrated in FIG. 4E (or in FIG. 1E1, or in FIG. 4E2), a fan-out of four is possible to satisfy a multicast 50 connection request if input switch is IS2, but only two switches in middle stage 130 will be used. Similarly, although a fan-out of three is possible for a multicast connection request if the input switch is IS1, again only a fan-out of two is used. The specific middle switches that are chosen in 55 middle stage  $130$  when selecting a fan-out of two is irrelevant so long as at most two middle switches are selected to ensure that the connection request is satisfied. In essence, limiting the fan-out from input switch to no more than two middle switches permits the network  $400E$  (or  $400E1$ , or  $400E2$ ), to  $60$ be operated in rearrangeably nonblocking manner in accordance with the invention.

The connection request of the type described above can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, a fan-out of one is used, i.e. a single middle stage switch in middle stage 130 is used to

satisfy the request. Moreover, although in the above-described embodiment a limit of two has been placed on the fan-out into the middle stage switches in middle stage 130, the limit can he greater depending on the number of middle stage switches in a network (while maintaining the rearrangeably nonblocking nature of operation of the network for multicast connections). However any arbitrary fan-out may be used within any of the middle stage switches and the output

Generalized Asymmetric Folded RNB  $(N_1>N_2)$  Embodiments:

stage switches to satisfy the connection request.

Network 400F of FIG. 4F is an example of general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d N_2)$ –1 stages where N<sub>1</sub>>N<sub>2</sub> and N<sub>1</sub>=p\*N<sub>2</sub> where p>1. In network 400D of FIG. 4F,  $N_2=N$  and  $N_1=p*N$ . The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$ can be operated in rearrangeably nonblocking manner for multicast when  $s \geq 2$  according to the current invention. Also the general asymmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $s \ge 2$  according to the current invention. (And in the example of FIG.  $4F$ ,  $s=2$ ). The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d)$  $N_2$ )–1 stages has  $d_1$  (where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

inlet links for each of

$$
\frac{N_2}{d}
$$

input switches  $IS1$ -IS(N<sub>2</sub>/d) (for example the links IL1-IL  $(p * d)$  to the input switch IS1) and  $d+d_1$  (=d+p×d) outgoing links for each of

 $\frac{N_2}{d}$ 

input switches IS1-IS( $N_2/d$ ) (for example the links ML(1,1)- $ML(1,(d+p*d))$  to the input switch IS1). There are d outlet links for each of

 $\frac{N_2}{d}$ 

output switches  $OS1-OS(N_2/d)$  (for example the links OL1-OL(d) to the output switch OS1) and 2xd incoming links for each of

 $\frac{N_2}{N}$ 

output switches  $OS1-OS(N_2/d)$  (for example  $ML(2\times Log_d)$  $N_2$ –2,1)-ML $(2 \times \text{Log}_d N_2$ –2,2xd) to the output switch OS1).

Each of the

 $\frac{N_2}{d}$ 

input switches IS1-IS( $N_2/d$ ) are connected to exactly d+ $d_1$ switches in middle stage  $130$  through d+d, links (for example in one embodiment the input switch IS1 is connected to middle switches  $MS(1,1)$ - $MS(1, (d+d_1)/2)$  through the links  $ML(1,1)-ML(1,(d+d_1)/2)$  and to middle switches  $MS(1,N_1/$ d+1)-MS(1, $\{N_1/d\}$ +(d+d<sub>1</sub>)/2) through the links ML(1, ((d+  $d_1$ )/2)+1)-ML(1, (d+d<sub>1</sub>)) respectively. in one embodine the input switch is 11 is connected to all (1)-NM(1, (ded y2) intothe in the index signal or middle switches MS(1,1)-MS(1, (ded y2) more in the index MS(1,1)-N(2, (ded y2) m/1, (ded y2) in (ded y2) in (ded

Each of the

middle switches  $MS(1,1)$ - $MS(1,2*N<sub>2</sub>/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the

$$
2\times \frac{N_2}{d}
$$

middle switches

$$
MS(\text{Log}_d N_2 - 1, 1) - MS(\text{Log}_d N_2 - 1, 2 \times \frac{N_2}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_2-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_{d} N_{2}-3)$ through d links and also are connected to exactly d switches in 40 middle stage  $130+10*(\text{Log}_d N_2-1)$  through d links.

Similarly each of the

$$
2 \times \frac{N_2}{d}
$$

middle switches

$$
MS(2 \times Log_d N_2 - 3, 1) - MS(2 \times Log_d N_2 - 3, 2 \times \frac{N_2}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  are connected  $55$ from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$  $N_2$ –5) through d links and also are connected to exactly doutput switches in output stage 120 through d links. output switches in output stage 120 through d links.<br>Each of the

output switches  $OS1-OS(N_2/d)$  are connected from exactly 65 2xd switches in middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$ through 2xd links.

## 128

As described before, again the connection topology of a general  $V_{fold}(N_1, N_2, d, s)$  may be any one of the connection topologies. For example the connection topology of the network  $V_{\text{fold}}(N_1, N_2, d, s)$  may be back to back inverse Benes networks, back to back Omega networks, back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the general  $V_{fold}(N_1, N_2, d, s)$  network is, when no connections are setup from any input link if any output link should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N_1, N_2, d, s)$  can be built. The embodiments of FIG. 4E, FIG. 4E1, and FIG. 4E2 are three examples of network  $V_{fold}(N_1, N_2, d, s)$  for s=2 and  $N_1 > N_2$ .

20 The general symmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 2$  according to the current invention. Also the general symmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  can be operated in strictly nonblocking manner for unicast if  $S \geq 2$  according to the current invention.

ing mutucast assignment  $i_1$ -{ $2,3$ } and an other  $i_j$ - $\phi$  for  $j$ - $[2s$  8]. It should be noted that the connection  $I_1$  fans out in the first For example, the network of FIG. 4E shows an exemplary five-stage network, namely  $V_{fold}(24,8,2,2)$ , with the follow-<br>ing multicast assignment  $I_1 = \{2,3\}$  and all other  $I_j = \emptyset$  for j=[2stage switch IS1 into middle switches  $MS(1,1)$  and  $MS(1,5)$ in middle stage 130, and fans out in middle switches MS(1,1) and MS(1,5) only once into middle switches MS(2,1) and

MS(2,5) respectively in middle stage 140. The connection  $I_1$  also fans out in middle switches  $MS(2,1)$ and MS(2,5) only once into middle switches MS(3,1) and  $MS(3,7)$  respectively in middle stage 150. The connection  $I_1$ also fans out in middle switches  $MS(3,1)$  and  $MS(3,7)$  only once into output switches OS2 and OS3 in output stage 120. 35 Finally the connection  $I_1$  fans out once in the output stage switch OS2 into outlet link OL3 and in the output stage switch OS3 twice into the outlet links OL5 and OL6.In accordance with the invention, each connection can fan out in the input stage switch into at most two middle stage switches inmiddle stage 130.

SNB Embodiments:

The folded multi-stage network  $V_{\text{fold}}(N_1, N_2, d, s)$  disclosed, in the current invention, is topologically exactly the same as the multi-stage network  $V_{fold}(N_1, N_2, d, s)$ , disclosed in USS. Provisional Patent Application Ser. No. 60/940,391 that is incorporated by reference above, excepting that in the that is incorporated by reference above, excepting that in the<br>illustrations folded network  $V_{fold}(N_1, N_2, d, s)$  is shown as it<br>is folded at middle stage  $130+10*(\log_d N_1-2)$ .

The general symmetrical folded multi-stage network  $V_{fold}$  $(0, d, s)$  can also be operated in strictly nonblocking manner for multicast when  $s \ge 3$  according to the current invention. Similarly the general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  can also be operated in strictly nonblocking manner for multicast when  $S \geq 3$  according to the current invention.

Symmetric Folded RNB Unicast Embodiments:

60 as setting up <sup>a</sup> telephonecall or <sup>a</sup> data call, or <sup>a</sup> connection Referring to FIG. 5A, an exemplary symmetrical folded multi-stage network 500A respectively with five stages of twenty switches for satisfying communication requests, such between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by two switches IS1-IS4 and output stage 120 consists offour, two by two switches OS1-OS4. And all the middle stages namely middle stage  $130$  consists of four, two by two switches  $MS(1, 1)$ 1)-MS(1,4), middle stage 140 consists of four, two by two switches MS(2,1)-MS(2,4), and middle stage 150 consists of four, two by two switches  $MS(3,1)$ - $MS(3,4)$ .

Such a network can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in the input stage 110 are of size two by two, the 5 switches in output stage 120 are of size two by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

The connection topology of the network **500**A shown in FIG. **5A** is known to be back to back inverse Benes connection topology. In other embodiments the connection topology is different. That is the way the links  $ML(1,1)-ML(1,8)$ , ML(2,1)-ML(2,8), ML(3,1)-ML(3,8), and ML(4,1)-ML(4,8) are connected between the respective stages is different.

Even though only one embodiment is illustrated, in gen- 15 eral, the network  $V_{fold}(N, d, s)$  can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}(N, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{fold}(N, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N, d, s)$  can be built. The embodiment of FIG.  $5A$  is only one example of 25 network  $V_{fold}(N, d, s)$ .

The network 500A of FIG. 5A is also rearrangeably nonblocking for unicast according to the current invention. In one embodiment of these networks each of the input switches 1S1-IS4 and output switches OS1-OS4are crossbar switches. <sup>30</sup> The number of switches of input stage  $110$  and of output stage 120 can be denoted in general with the variable N/d, where N is the Lotal number ofinlet links or outlet links. The numberof middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general 35 with the notation d\*d and each output switch OS1-OS4 can be denoted in general with the notation d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as  $d^*d$ . A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar 40 switch or a network of switches. A symmetric folded multistage network can be represented with the notation  $V_{fold}(N, d, d)$ s), where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input switch or outlet links of each 45 output switch, and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same. tions. The applicant notes that the fundamental property of a<br>sointer varial connection topology of the V<sub>GeM</sub>(N, d, s) netvock is,<br>when no connections are esting from any input link all the<br>output links about the reachab 63.8.46 (MW) 1026 3.46 (MW) 122<br>
63.8.46 (MW) 122<br>
63.8.46 (MW) 122<br>
64.8.6 (MW) 122<br>
64.8.8 (MW) 122<br>
65.8 (MW) 122 doutput switches in output stage 120 through links.

In network 500A of FIG. 5A, each of the N/d input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through d links (for example input switch IS1 is connected to middle switches  $MS(1,1)$  and  $MS(1,2)$ through the links  $ML(1,1)$  and  $ML(1,2)$  respectively).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,4)$ are connected to the middle switch MS(1,1) from input switch IS1 and IS2 respectively) and also are connected to exactly  $d_{0}$ switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$ respectively).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2, 65)$ 4) in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the

links  $ML(2,1)$  and  $ML(2,6)$  are connected to the middle switch  $MS(2,1)$  from middle switches  $MS(1,1)$  and  $MS(1,3)$ respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$  and  $MS(3,3)$  respectively).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$  are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,3)$ respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switches OS1and O82 respectively from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected (for example output switch OS1 is connected from middle switches  $MS(3,1)$  and  $MS(3,2)$  through the links  $ML(4,1)$  and  $ML(4,4)$  respectively).

Generalized Symmetric Folded RNB Unicast Embodiments: Network 500B of FIG. 5B is an example of general symmetrical folded multi-stage network  $V_{fold}(N, d, s)$  with  $(2 \times \log_d N)$ –1 stages. The general symmetrical folded multistage network  $V_{fold}(N, d, s)$  can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention (and in the example of FIG. 5B, s=1). The general symmetrical folded multi-stage network  $V_{fold}(N, d, s)$ with  $(2 \times \log_d N) - 1$  stages has d inlet links for each of N/d input switches IS1-IS(N/d) (for example the links IL1-IL(d) to the input switch IS1) and d outgoing links for each of  $N/d$ input switches IS1-IS(N/d) (for example the links ML(1,1)- ML(1, d) to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS(N/d) (for example OL1-OL(d) to the output switch OS1) and d incoming links for each of N/d output switches OSI-OS(N/d) (for example  $ML(2\times Log_d N-2,1)$ -ML $(2\times Log_d N-2,d)$  to the output switch OS1).

Each of the  $N/d$  input switches IS1-IS( $N/d$ ) are connected to exactly d switches in middle stage 130 through d links.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,N/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the N/d middle switches

$$
MS(\text{Log}_d N - 1, 1) - MS(\text{Log}_d N - 1, \frac{N}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}-3)$ through d links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d \text{N}-1)$  through d links.

Similarly each of the N/d middle switches

$$
MS(2 \times Log_d N - 3, 1) - MS(2 \times Log_d N - 3, \frac{N}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$ N-5) through d links and also are connected to exactly d

Each of the N/d output switches OS1-OS(N/d) are connected from exactly d switches in middle stage 130+10\*

The general symmetrical folded multi-stage network  $V_{fold}$ (N, d, s) can be operated in rearrangeably nonblocking, manner for multicast when s=1 according to the current invention. Asymmetric Folded RNB  $(N_2>N_1)$  Unicast Embodiments:

Referring to FIG. 5C, an exemplary symmetrical folded multi-stage network 500C respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by two switches IS1-IS4 and output stage 120 consists of four, six by six switches OS1-OS4. And all the middle stages namely middle stage  $130$  consists of four, two by two switches  $MS(1, 1)$ 1)- $MS(1,4)$ , middle stage 140 consists of four, two by two switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of  $_{20}$ four, two by six switches  $MS(3,1)$ - $MS(3,4)$ .

Such networks can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in the input stage 110 are of size two by two, the switches in output stage 120 are of size six by six, and there are four 25 switches in each of middle stage 130, middle stage 140 and middle stage 150.

The connection topology of the network 500C shown in FIG.5C is knownto be back to back inverse Benes connection topology. The connection topology of the networks 500C is <sup>30</sup> different in the other embodiments. That is the way the links  $ML(1,1)-ML(1,8), ML(2,1)-ML(2,8), ML(3,1)-ML(3,8),$ and ML(4,1)-ML(4,8) are connected between the respective stages is different.

Even though only one embodiment is illustrated, in gen- 35 eral, the network  $V_{fold}(N_1, N_2, d, s)$  can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}(N_1, N_2, d, s)$  may be back<br>to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{fold}(N_1, N_2, d, s)$ network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N_1, N_2, d, s)$ can be built. The embodiment of FIG.  $5C$  is only one example 45 of network  $V_{fold}(N_1, N_2, d, s)$ . switches MRS(2.1)-MS(2.4), and middle asge 150 onesists of 20<br>four, two by six switches MRS(1.)-MS(3.4).<br>Some four who by six switches MRS(1.)-MS(3.4).<br>Some four whole sympler and concerned in rearrangeably monibles.<br>The 40

The networks 500C of FIG. 5C is also rearrangeably nonblocking for unicast according to the current invention. In one embodiment of these networks each of the input switches 1S1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage  $110$  and of output stage 120 can be denoted in general with the variable

$$
\frac{N_1}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . number of outlet links and  $N_2 > N_1$  and  $N_2 = p^N N_1$  where  $p > 1$ .<br>The number of middle switches in each middle stage is <sup>60</sup> denoted by

$$
\frac{J_1}{d}.
$$

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*d and each output switch OS1- OS4 can be denoted in general with the notation  $d_2 * d_2$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

U.S. 8,363,649 B2<br>
LGS 8,363,649 B2<br>
LGS 8,363,649 B2<br>
The size of scalar constraints where<br>
respectively. The size of scalar input switch as the size of scalar input switch 31-54 can be denoted in<br>
respectively. The para The size of each switch in any of the middle stages excepting the last middle stage can be denoted as d\*d. The size of each switch in the last middle stage can be denoted as  $d * d<sub>2</sub>$ . A switch as used herein can be cither a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multistage network can be represented with the notation  $V_{fold}(N_1,$  $N_2, d, s$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), drepresents the inlet links of each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

In network 500C of FIG. 5C, each of the

 $\frac{N_1}{d}$ 

input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through d links (for example input switch IS1 is connected to middle switches  $MS(1,1)$  and  $MS(1,2)$ through the links  $ML(1,1)$  and  $ML(1,2)$  respectively).

Each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,4)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS2 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$  respectively).

 $\frac{N_1}{d}$ 

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130<br>through d links (for example the links ML(2,1) and ML(2,6) are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$  and  $MS(3,3)$  respectively).

 $\overline{\mathbf{S}}$ 

outlet links for each of

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ )  $10$ are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through d, links (for example the links  $ML(4,1)$  and  $ML(4,2)$ ) are connected to output switches OS1 from middle switch 15  $MS(3,1)$ ; the links  $ML(4,3)$  and  $ML(4,4)$  are connected to output switches OS2 from middle switch MS(3,1); the link ML(4,5) is connected to output switches OS3 from middle switch  $MS(3,1)$ ; and the link  $ML(4,6)$  is connected to output switches OS4 from middle switch  $MS(3,1)$ ). 20

Each of the



output switches OS1-OS4 are connected from exactly d switches in middle stage  $150$  through  $d<sub>2</sub>$  links (for example output switch OS1 is connected from middle switch  $MS(3,1)$ <br>through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is connected from middle switch  $MS(3,2)$  through the links  $ML(4,7)$  and  $ML(4,8)$ ; output switch OS1 is connected from middle switch  $MS(3,3)$  through the link  $ML(4,13)$ ; and output switch OS1 is connected from middle switch MS(3,4) through the links  $ML(4,19)$ ).

Generalized Asymmetric Folded RNB (N,>N,) Unicast Embodiments:

Network 500D of FIG. 5D is an example of general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages where  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ .<br>In network 500D of FIG. 5D, N<sub>1</sub>=N and N<sub>2</sub>=p\*N. The general symmetrical folded multi-stage network  $\widetilde{V}_{\text{fold}}(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention (and in the example of FIG. 5D, s=1). The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d s)$ N)-1 stages has d inlet links for each of through the links ML(4,1) and ML(4,2); output switch OS1 is connected from middle switch MS(3,2) through the links ML(4,7) and ML(4,8); output switch OS1 is connected from middle switch MS(3,4) through the links put switc 40  $\overline{a}$ 

 $\frac{N_1}{4}$ 

input switches IS1-IS( $N_1/d$ ) (for example the links IL1-IL(d) to the input switch IS1) and d outgoing links for each of

 $\frac{N_1}{N_2}$ 

input switches IS1-IS(N<sub>1</sub>/d) (for example the links ML(1,1)- consider switches  $ML(1, d)$  to the input switch IS1). There are  $d_2$  (where

$$
\left(\text{where } d_2 = N_2 \times \frac{d}{N_1} = p \times d\right)
$$

134

 $N_1$  $\overline{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example the links OL1- $OL(p * d)$  to the output switch OS1) and  $d_2$  (=pxd) incoming links for each of

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$  $N_1$ –2,1)-ML(2×Log<sub>d</sub> $N_1$ –2, d<sub>2</sub>) to the output switch OS1). Each of the

 $\frac{N_1}{d}$ 

25 input switches  $IS1-IS(N/4)$  are connected to exactly d switches in middle stage 130 through d links. Each of the

 $\frac{N_1}{d}$ 

middle switches  $MS(1,1)-MS(1,N_1/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the

 $\frac{N_1}{d}$ 

middle switches

$$
MS(\text{Log}_d N_1 - 1, 1) - MS(\text{Log}_d N_1 - 1, \frac{N_1}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_1-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through d links and also are connected to exactly d switches in middle stage  $130+10^*(\text{Log}_d N_1-1)$  through d links. Similarly each of the

 $\frac{N_1}{d}$ 

$$
MS(2 \times Log_d N_1 - 3, 1) - MS(2 \times Log_d N_1 - 3, \frac{N_1}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$   $\overline{\phantom{a}}$ 

40

 $N<sub>1</sub>$ -5) through d links and also are connected to exactly d output switches in output stage 120 through d, links.

Each of the

 $\frac{N_1}{d}$ 

output switches OS1-OS(N,/d) are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  through  $d<sub>2</sub>$ links.

The general symmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for multicast when  $s \ge 1$  according to the current  $_{15}$ invention.

Asymmetric Folded RNB  $(N_1 > N_2)$  Unicast Embodiments:

Referring to FIG. 5E, an exemplary symmetrical folded multi-stage network  $500E$  with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by six switches IS1-IS4 and output stage  $120$  consists of four, two by two switches  $25$ <br>and output stage  $120$  consists of four, two by two switches  $25$ OS1-OS4. And all the middle stages namely middle stage 130 consists of four, six by two switches  $MS(1,1)$ - $MS(1,4)$ , middle stage  $140$  consists of four, two by two switches MS $(2, 1)$ 1)-MS(2,4), and middle stage 150 consists offour, two by two switches  $MS(3,1)$ - $MS(3,4)$ . 30

Such a network can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in the input stage 110 are of size six by six, the switches in output stage 120 are of size two by two, and there are four switches in each of middle stage 130, middle stage <sup>35</sup> 140 and middle stage 150.

The connection topology of the network **500**E shown in FIG. **5**E is known to be back to back inverse Benes connection topology. The connection topology of the networks 500E is different in the other embodiments. That is the way the links  $ML(1,1)-ML(1,8), ML(2,1)-ML(2,8), ML(3,1)-ML(3,8),$ and  $ML(4,1)$ - $ML(4,8)$  are connected between the respective stages is different.

Even though only one embodiment is illustrated, in general, the network  $V_{fold}(N_1, N_2, d, s)$ , comprise any arbitrary type of connection topology. For example the connection topology of the network  $V_{fold}(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V_{fold}(N_1, N_2, d, s)$ network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V_{fold}(N_1,N_2,d,s)$ can be built. The embodiment of FIG. 5E is only one example of network  $V_{fold}(N_1, N_2, d, s)$ . for satisfying communication requests, such as setting to provide the packing of the selection end of a domestion between configuration is the big blocks, between an intui stage 120 or and output is stage 120 or anomic st

The network 500E is rearrangeably nonblocking for unicast according to the current invention. In one embodiment of these networks each of the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches  $OST-O54$  are crossbar switches. The number of switches of input stage  $110$  and of output stage  $120$  can be  $60$ denoted in general with the variable

$$
\frac{N_2}{d},
$$

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$ . The number of middle switches in each middle stage is denoted by

 $\frac{N_2}{d}$ 

The size of each input switch [S1-IS4 can be denoted in general with the notation  $d_1 * d_1$  and each output switch OS1-OS4 can be denoted in general with the notation  $(d * d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $d * d$ . The size of each switch in the first middle stage can be denoted as  $d_1$ <sup>\*</sup>d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric folded multistage network can be represented with the notation  $V_{fold}(N_1,$  $N_2, d, s$ , where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL24),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of each output switch where  $N_1 > N_2$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

In network 500E of FIG. 5E, each of the

 $\frac{N_2}{N_1}$ 

input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through d, links (for example input switch IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$  and  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$ 4); input switch IS1 is connected to middle switch MS(1,3) through the link  $ML(1,5)$ ; and input switch IS1 is connected to middle switch  $MS(1,4)$  through the links  $ML(1,6)$ ).<br>Each of the

# $\frac{N_2}{4}$

 $55$  middle switches MS(1,1)-MS(1,4) in the middle stage 130 are connected from exactly d, input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,7)$  and  $ML(1,8)$  are connected to the middle switch  $MS(1,1)$  from input switch IS2; the link  $ML(1,13)$  is connected to the middle switch  $MS(1,1)$  from input switch IS3; and the link  $ML(1,19)$  is connected to the middle switch MS(1,1) from input switch IS4), and also are connected to exactly d switches in middle stage 140 through d links (for 65 example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,1)$ 3) respectively).

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ ) are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $_{15}$  $MS(3,1)$  and  $MS(3,3)$  respectively).

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ ) are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through  $d_1$  links (for example the links ML(4,1) and ML(4,2) 25 are connected to output switches OS1 and OS2 respectively  $30$ from middle switch  $MS(3,1)$ ).

Each of the

$$
\frac{N_1}{d}
$$

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through  $d_2$  links (for example  $40$ output switch OS1 is connected from middle switches MS(3, 1) and  $MS(3,2)$  through the links  $ML(4,1)$  and  $ML(4,4)$ respectively).

Generalized Asymmetric Folded RNB  $(N_1 > N_2)$  Unicast Embodiments:

Network 500F of FIG. 5F is an example of general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages where N<sub>1</sub>>N<sub>2</sub> and N<sub>1</sub>=p\*N<sub>2</sub> where p>1. In network 500F of FIG. 5F,  $N_2 = N$  and  $N_1 = p^*N$ . The general symmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  50 can be operated in rearrangeably nonblocking manner for unicast when s=1 according to the current invention (and in the example of FIG.  $5F$ ,  $s=1$ ). The general asymmetrical folded multi-stage network  $V_{fold}(N_1, N_2, d, s)$  with  $(2 \times \log_d)$ N)-1 stages has  $d_1$  (where switches in middle stage 150 through d<sub>2</sub> links (for example 40<br>output switches OSI is connected from middle switchs MS(3, 1<br>1) and MS(3,2) through the links ML(4,1) and ML(4,4)<br>respectively).<br>Generalized Asymmetric Folde dmiddle stage 1304 (a)  $\frac{1}{2}$  the stage 1404 (a)  $\frac{1}{2}$  through links in the

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

inlet links for each of

input switches  $IS1$ -IS(N<sub>2</sub>/d) (for example the links IL1-IL  $(p * d)$  to the input switch IS1) and  $d_1$  (=pxd) outgoing links for each of

 $\frac{N_2}{d}$ 

<sup>10</sup> input switches IS1-IS(N<sub>2</sub>/d) (for example the links ML(1,1)- $ML(1,(d+p*d))$  to the input switch IS1). There are d outlet links for each of

 $\frac{N_2}{4}$ 

 $20$  OL(d) to the output switch OS1) and d incoming links for output switches  $OS1-OS(N_2/d)$  (for example the links OL1each of

 $\frac{N_2}{4}$ 

output switches  $OS1-OS(N_2/d)$  (for example  $ML(2\times Log_d)$  $N_2-2,1$ )-ML(2×Log<sub>d</sub> N<sub>2</sub>-2, d) to the output switch OS1). Each of the

 $\frac{N_2}{d}$ 

input switches  $IS1$ -IS( $N_2/d$ ) are connected to exactly d switches in middle stage  $130$  through  $d_1$  links.

Each of the

 $\frac{N_2}{d}$ 

middle switches  $MS(1,1)$ - $MS(1,N_2/d)$  in the middle stage 130 are connected from exactly d input switches through  $d_1$ links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the

 $N_2$ 

middle switches

60

$$
MS(\text{Log}_{d}N_{2}-1, 1) - MS(\text{Log}_{d}N_{2}-1, \frac{N_{2}}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_2-2)$  are connected from  $_{65}$  exactly d switches in middle stage 130+10\*(Log<sub>d</sub> N<sub>2</sub>-3) through d links and also are connected to exactly d switches in

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(2 \times Log_d N_2 - 3, 1) - MS\Big(2 \times Log_d N_2 - 3, \frac{N_2}{d}\Big)
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log_{d-15})$  $N<sub>2</sub>$ -5) through d links and also are connected to exactly d output switches in output stage 120 through d links.

Each of the

$$
\frac{N_2}{d}
$$

output switches  $OS1-OS(N_2/d)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub> N<sub>2</sub>-4)$  through d 25 links.

The general symmetrical folded multi-stage network  $V_{fold}$  $(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention.

Symmetric RNB Unicast Embodiments:

Referring to FIG. 6A, FIG. 6B, FIG.6C, FIG. 6D,FIG. 6E, FIG. 6F, FIG. 6G, FIG. 600H, FIG. 6001 and FIG. 6J with exemplary symmetrical multi-stage networks 600A, 600B, 600C, 600D, 600E, 600F, 600G, 600H, 600], and 600] respectively with five stages of twenty switches for satisfying communication requests, such as setting up <sup>a</sup> telephonecall or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 40 highlight stages 130, 140, and 150 is shown where input stage 110 consists of four, two by two switches IS1-IS4 and output stage 120 consists of four, two by two switches OS1-OS4. Andall the middle stages namely middle stage 130 consists of four, two by two switches  $MS(1,1)$ - $MS(1,4)$ , middle stage 140 consists of four, two by two switches  $MS(2,1)$ - $MS(2,4)$ , 45 and middle stage 150 consists of four, two by two switches  $MS(3,1)$ - $MS(3,4)$ .  $\frac{\text{MS2} \times 1 \times \text{log}_2 N_2 - \lambda_1 \cdot 3 - \text{MS}[\times 1 \times \text{log}_2 N_1 - \lambda_1 \cdot 3] \cdot 10^{-15}$ <br>
in the middle stage 130+10<sup>6</sup>(24<sup>T</sup>l.og, N<sub>1</sub>-4) are connected<br>
from exactly d switches in a middle stage 1304-10<sup>6</sup>(2<sup>T</sup>l.og, t<sub>2</sub><br>
N<sub>1</sub>-5) thro

Such networks can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in he input stage 110 are of size two by two, the switches in 50 4) in the middle stage 140 are connected from exactly d output stage 120 are of size two by two, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In all the ten embodiments of FIG. 6A to FIG. 6J the connection topology is different. That is the way the links 55  $ML(1,1)-ML(1,8), ML(2,1)-ML(2,8), ML(3,1)-ML(3,8),$ and  $ML(4,1)$ - $ML(4,8)$  are connected between the respective stages is different. For example, the connection topology of the network 600A shown in FIG. 6A is known to be back to back inverse Benes connection topology; the connection 60 topology of the network 600B shown in FIG. 6B is known to be back to back Omega connection topology; and the connecion topology of the network 600C shown in FIG. 6C is hereinafter called nearest neighbor connection topology.

Even though only ten embodiments are illustrated, in gen- 65 eral, the network  $V(N, d, s)$  can comprise any arbitrary type of connection topology. For example the connection topologyof

## 140

the network  $V(N, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a valid connection topology of the  $V(N, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V(N, d, s)$  can be built. The ten embodiments of FIG.  $6A$  to FIG.  $6J$  are only three examples of network  $V(N, 1)$ d, s).

20 The networks 600A-600J of FIG. 6A-FIG. 6J are also rearrangeably nonblocking for unicast according to the current invention. In one embodiment of these networks each of the input switches IS1-IS4 and output switches OS1-OS4are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable  $N/d$ , where N is the total number of inlet links or outlet links. The number of middle switches in each middle stage is denoted by N/d. The size of each input switch IS1-IS4 can be denoted in general with the notation d\*d and each output switch OS1-OS4 can be denoted in general with the notation d\*d. Likewise, the size of each switch in any of the middle stages can be denoted as d\*d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. A symmetric multi-stage network can be represented with the notation  $V(N, d, s)$ , where N represents the total number of inlet links of all input switches (for example the links IL1-IL8), d represents the inlet links of each input SS  $(8.866669922)$ <br>
S of number of outgoing links from each input switch to the inlet links of each input switch. Although it is not necessary that there be the same number of inlet links IL1-IL8 as there are outlet links OL1-OL8, in a symmetrical network they are the same.

In network 600A of FIG. 6A, each of the N/d input switches IS1-IS4 are connected to exactly d switches in middle stage 130 through d links (for example input switch IS1 is connected to middle switches  $MS(1,1)$  and  $MS(1,2)$ through the links  $ML(1,1)$  and  $ML(1,2)$  respectively).

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,4)$ are connected to the middle switch  $MS(1,1)$  from input switch IS1 and 1S2 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$ respectively).

Similarly each of the N/d middle switches  $MS(2,1)$ - $MS(2,$ switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$  are connected to the middle switch  $MS(2,1)$  from middle switches  $MS(1,1)$  and  $MS(1,3)$ respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch  $MS(2,1)$  to middle switch  $MS(3,1)$  and  $MS(3,3)$  respectively).

Similarly each of the N/d middle switches  $MS(3,1)$ - $MS(3,$ 4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$  are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,3)$ respectively) and also are connected to exactly d output switches in output stage 120 through d links (for example the links  $ML(4,1)$  and  $ML(4,2)$  are connected to output switches OS1 and OS2 respectively from middle switch MS(3,1)).

Each of the N/d output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through d links (for example output switch OS1 is connected from middle switches  $MS(3,1)$  and  $MS(3,2)$  through the links  $ML(4,1)$  and ML(4,4) respectively).

Generalized Symmetric RNB Unicast Embodiments:

Network 600K of FIG. 6K is an example of general symmetrical multi-stage network V(N, d, s) with  $(2 \times \log_a N)$ –1 stages. The general symmetrical multi-stage network V(N,d, s) can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention (and in the example of FIG. 6K, s=1). The general symmetrical multi-stage network  $V(N, d, s)$  with  $(2 \times \log_{a} N)-1$  stages has d inlet links for each of N/d input switches 1S1-IS(N/d) (for example the links IL1-IL(d) to the input switch IS1) and d outgoing links for each ofN/d input switches IS1-IS(N/d) (for example the links  $ML(1,1)$ - $ML(1, d)$  to the input switch IS1). There are d outlet links for each of N/d output switches OS1-OS(N/d) (for example OL1-OL(d) to the output switch OS1) and d incoming, links for each of N/d output switches OS1-OS(N/d) (for example ML $(2 \times Log_A N-2,1)$ -ML $(2 \times Log_A N)$ N-2,d) to the output switch OS1). dthrough links and also are connected to exactly d switches in signs. In general sympathemic muni-sign ensives vive a consistent with a particular sympathemic multi-sign enter the CM<sub>C</sub> signs. The general sympathemic multi-sign enter the CM<sub>C</sub> signs and the H multi-sign enter  $N$ . An 20

Each of the N/d input switches IS1-IS(N/d) are connected to exactly d switches in middle stage 130 through d links.

Each of the N/d middle switches  $MS(1,1)$ - $MS(1,N/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the N/d middle switches

$$
MS(\text{Log}_d N - 1, 1) - MS(\text{Log}_d N - 1, \frac{N}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}-3)$ middle stage  $130+10*(\text{Log}_d N-1)$  through d links.

Similarly each of the N/d middle switches

$$
MS(2 \times \text{Log}_d N - 3, 1) - MS(2 \times \text{Log}_d N - 3, \frac{N}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$ N-5) through d links and also are connected to exactly d output switches in output stage 120 through d links.

Each of the N/d output switches OS1-OS(N/d) are con-50 nected from exactly d switches in middle stage 130+10\*  $(2^*Log_d N-4)$  through d links.

The general symmetrical multi-stage network V(N, d, s) can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention. Asymmetric RNB  $(N_2>N_1)$  Unicast Embodiments:

Referring to FIG. 6A1, FIG. 6B1, FIG. 6C1, FIG. 6D1, FIG.6E1,FIG. 6F1, FIG. 6G1, FIG. 600H1, FIG. 600H1 and FIG. 6J1 with exemplary symmetrical multi-stage networks 600A1, 600B1, 600C1, 600D1, 600E1, 600F1, 600G1, 60 600H1, 60011, and 600J1 respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, two by two switches IS1-IS4 and output stage 120 consists of four, six by

six switches OS1-OS4. And all the middle stages namely middle stage 130 consists of four, two by two switches  $MS(1, 1)$ 1)-MS(1,4), middle stage 140 consists of four, two by two switches  $MS(2,1)$ - $MS(2,4)$ , and middle stage 150 consists of four, two by six switches MS(3,1)-MS(3,4).

Such networks can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in the input stage 110 are of size two by two, the switches in output stage 120 are of size six by six, and there are four switches in each of middle stage 130, middle stage 140 and middle stage 150.

In all the ten embodiments of FIG. 6A1 to FIG. 6J1 the connection topology is different. That is the way the links  $ML(1,1)-ML(1,8), ML(2,1)-ML(2,8), ML(3,1)-ML(3,8),$ and ML(4,1)-ML(4,8) are connected between the respective stages is different. For example, the connection topology of the network 600A1 shown in FIG. 6A1 is known to be back to back inverse Benes connection topology; the connection topology of the network 600B1 shown in FIG. 6B1 is known to be back to back Omega connection topology; and the connection topology of the network 600C1 shown in FIG. 6C1 is hereinafter called nearest neighbor connection topology.

25 valid connection topology of the  $V(N_1, N_2, d, s)$  network is, Fven though only ten embodiments are illustrated, in general, the network  $V(N_1, N_2, d, s)$  can comprise any arbitrary type of connection topology. For example the connection topology of the network  $V(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V(N_1, N_2, d, s)$  can be built. The ten embodiments of FIG. 6A1 to FIG. 6J1 are only three examples of network  $V(N_1, N_2, d, s)$ .

die input switches 151-154 and output switches OS1-OS4 are<br>40 crossbar switches. The number of switches of input stage 110 The networks 600A1-600J1 of FIG. 6A1-FIG. 6J1 are also rearrangeably nonblocking for unicast according to the cur-rent invention. In one embodimentofthese networks each of rent invention. In one embodiment of these networks each of the input switches IS1-IS4 and output switches OS1-OS4 are and of output stage 120 can be denoted in general with the variable

$$
\frac{N_1}{d},
$$

where N, is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

The size of each input switch IS1-IS4 can be denoted in general with the notation d\*d and each output switch OS1- OS4 can be denoted in general with the notation  $d_2 * d_2$ , where

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d.
$$

The size of each switch in any of the middle stages excepting the last middle stage can be denoted as d\*d. The size of each  $15<sup>°</sup>$ 

switch in the last middle stage can be denoted as  $d^*d_2$ . A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-stage network can be represented with the notation  $V(N_1, N_2, d, s)$ , -5 where  $N_1$  represents the total number of inlet links of all input switches (for example the links IL1-IL8),  $N_2$  represents the total number of outlet links of all output switches (for example the links OL1-OL24), d represents the inlet links of  $10\,$ each input switch where  $N_2 > N_1$ , and s is the ratio of number of outgoing links from each input switch to the inlet links of each input switch.

In network 600A1 of FIG. 6A1, each of the

 $\frac{N_1}{4}$ 

input switches IS1-IS4 are connected to exactly d switches in  $_{20}$ middle stage 130 through d links (for example input switch IS1 is connected to middle switches  $MS(1,1)$  and  $MS(1,2)$ through the links  $ML(1,1)$  and  $ML(1,2)$  respectively).

Each of the

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130  $_{30}$ are connected from exactly d input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,4)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1 and IS2 respectively) and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,3)$  respectively).

Similarly each of the

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are connected from middle switch MS(2,1) to middle switch  $MS(3,1)$  and  $MS(3,3)$  respectively).

Similarly each of the

middle switches  $MS(3,1)$ - $MS(3,4)$  in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ are connected to the middle switch MS(3,1) from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through  $d_2$  links (for example the links ML(4,1) and ML(4,2) 65 are connected to output switches OS1 from middle switch  $MS(3,1)$ ; the links  $ML(4,3)$  and  $ML(4,4)$  are connected to mmul switches ISI-154 are connected to exactly d switches in pay is the some particular sine of 2021 is connected to middle switches MS(1,1) and ME(1,2) respectively).<br>
1981 is connected to middle switches MS(1,1) and ME( 60

output switches  $OS2$  from middle switch  $MS(3,1)$ ; the link ML(4,5) is connected to output switches OS3 from middle switch  $MS(3,1)$ ; and the link  $ML(4,6)$  is connected to output switches OS4 from middle switch  $MS(3,1)$ .<br>Each of the

 $\frac{N_1}{d}$ 

output switches OS1-OS4 are connected from exactly d switches in middle stage 150 through d<sub>2</sub> links (for example output switch OS1 is connected from middle switch MS(3,1) through the links  $ML(4,1)$  and  $ML(4,2)$ ; output switch OS1 is connected from middle switch MS(3,2) through the links  $ML(4,7)$  and  $ML(4,8)$ ; output switch OS1 is connected from middle switch  $MS(3,3)$  through the link  $ML(4,13)$ ; and output switch OS1 is connected from middle switch  $MS(3,4)$ through the links  $ML(4,19)$ ).

Generalized Asymmetric RNB  $(N_{2} > N_{1})$  Unicast Embodiments:

25  $(2xlog_d N)-1$  stages where  $N_2>N_1$  and  $N_2=p^*N_1$  where  $p>1$ . Network 600K1 of FIG. 6K1 is an example of general asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  with In network 400K1 of FIG. 4K1,  $N_1=N$  and  $N_2=p*N$ . The general symmetrical multi-stage network  $V(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention (and in the example of FIG.  $6K1$ ,  $s=1$ ). The general asymmetrical multistage network  $V(N_1, N_2, d, s)$  with  $(2 \times \log_d N) - 1$  stages has d inlet links for each of

$$
\frac{N_1}{d}
$$

input switches IS1-IS( $N_1/d$ ) (for example the links IL1-IL(d) to the input switch IS1) and d outgoing links for each of

$$
\frac{N_1}{d}
$$

input switches IS1-IS( $N_1/d$ ) (for example the links ML(1,1)- $ML(1, d)$  to the input switch IS1). There are  $d<sub>2</sub>$  (where

$$
\left(\text{where } d_2 = N_2 \times \frac{d}{N_1} = p \times d\right)
$$

outlet links for each of

40

 $\frac{N_1}{d}$ 

output switches  $OS1-OS(N_1/d)$  (for example the links OL1- $OL(p * d)$  to the output switch OS1) and  $d_2$  (=pxd) incoming links for each of

> $\frac{N_1}{N_1}$  $\overline{d}$

60

output switches  $OS1-OS(N_1/d)$  (for example  $ML(2\times Log_d)$  $N_1-2,1$ )-ML $(2\times Log_d N_1-2, d_2)$  to the output switch OS1). Each of the

 $\frac{N_1}{d}$ 

input switches  $IS1-IS(N_1/d)$  are connected to exactly d switches in middle stage 130 through d links.

Each of the

middle switches  $MS(1,1)$ - $MS(1,N_1/d)$  in the middle stage 130 are connected from exactly d input switches through d links and also are connected to exactly d switches in middle 20 stage 140 through d links.

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(\text{Log}_d N_1 - 1, 1) - MS(\text{Log}_d N_1 - 1, \frac{N_1}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_1-2)$  are connected from  $_{35}$ exactly d switches in middle stage  $130+10*(\text{Log}_d \text{ N}_1-3)$ through d links and also are connected to exactly d switches in middle stage  $130+10*(\text{Log}_d N_1-1)$  through d links. mpt varieties B31-18(N/3) are connected to exactly d in<br>switches in middle stoge 130 through d links.<br>
Each of the <br>
Each of the connected form exactly d avitable stoge 130 through d links.<br>
Each of the connected from exa

Similarly each of the

$$
\frac{N_1}{d}
$$

middle switches

$$
MS(2 \times \text{Log}_d N_1 - 3, 1) - MS(2 \times \text{Log}_d N_1 - 3, \frac{N_1}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub>)$  $N_1-5$ ) through d links and also are connected to exactly d output switches in output stage  $120$  through  $d_1$  links.<br>Fach of the

$$
\frac{N_1}{d}
$$

output switches OS1-OS(N,/d) are connected from exactly d switches in middle stage  $130+10*(2*Log<sub>d</sub> N-4)$  through  $d<sub>2</sub>$ links.

The general symmetrical multi-stage network  $V(N_1, N_2, d, 65)$ s) can be operated in rearrangeably nonblocking manner for multicast when s=1 according to the current invention.

Asymmetric RNB  $(N_1>N_2)$  Unicast Embodiments:

Referring to FIG. 6A2, FIG. 6B2, FIG. 6C2, FIG. 6D2, FIG. 6E2, FIG. 6F2, FIG. 6G2, FIG. 600H2, FIG. 60012 and FIG. 6J2 with exemplary symmetrical multi-stage networks 600A2, 600B2, 600C2, 600D2, 600E2, 600F2, 600G2, 600H2, 60012, and 600J2 respectively with five stages of twenty switches for satisfying communication requests, such as setting up a telephone call or a data call, or a connection <sub>10</sub> between configurable logic blocks, between an input stage 110 and output stage 120 via middle stages 130, 140, and 150 is shown where input stage 110 consists of four, six by six switches IS1-IS4 and output stage 120 consists of four, two by two switches OS1-OS4. And all the middle stages namely 15 middle stage 130 consists of four, six by two switches  $MS(1,$ 1)-MS(1,4), middle stage 140 consists of four, two by two switches MS(2,1)-MS(2,4), and middle stage 150 consists of four, two by two switches  $MS(3,1)$ - $MS(3,4)$ .

 $25$  stage 150. Such networks can be operated in rearrangeably nonblocking manner for unicast connections, because the switches in the input stage  $110$  are of size six by six, the switches in output stage 120 are of size two by two, and there are four switches in each of middle stage 130, middle stage 140 and middle

In all the ten embodiments of FIG. 6A2 to FIG. 6J2 he connection topology is different. That is the way the links  $ML(1,1)-ML(1,8), ML(2,1)-ML(2,8), ML(3,1)-ML(3,8),$ and  $ML(4,1)-ML(4,8)$  are connected between the respective stages is different. For example, the connection topology of<br>the network  $600A2$  shown in FIG.  $6A2$  is known to be back to back inverse Benes connection topology; the connection topology of the network 600B2 shown in FIG. 6B2 is known to be back to back Omega connection topology; and the connection topology of the network 600C2 shown in FIG. 6C2 is hereinafter called nearest neighbor connection topolopy.

 $\frac{1}{40}$  eral, the network  $V(N_1, N_2, d, s)$  can comprise any arbitrary Even though only ten embodiments are illustrated, in gentype of connection topology. For example the connection topology of the network  $V(N_1, N_2, d, s)$  may be back to back Benes networks, Delta Networks and many more combinations. The applicant notes that the fundamental property of a <sup>45</sup> valid connection topology of the  $V(N_1, N_2, d, s)$  network is, when no connections are setup from any input link all the output links should be reachable. Based on this property numerous embodiments of the network  $V(N_1, N_2, d, s)$  can be built. The ten embodiments of FIG. 6A2 to FIG. 6J2 are only three examples of network  $V(N_1, N_2, d, s)$ .

The networks 600A2-600J2 of FIG. 6A2-FIG. 6J2 are also rearrangeably nonblocking for unicast according to the cur-rent invention. In one embodimentofthese networks each of 55 the input switches IS1-IS4 and output switches OS1-OS4 are crossbar switches. The number of switches of input stage 110 and of output stage 120 can be denoted in general with the variable

 $\frac{N_2}{d}$ 

where  $N_1$  is the total number of inlet links or and  $N_2$  is the total number of outlet links and  $N_1 > N_2$  and  $N_1 = p^*N_2$  where  $p > 1$ . The number of middle switches in each middle stage is denoted by

The size of each input switch IS1-IS4 can be denoted in general with the notation  $d_1 * d_1$  and each output switch OS1-  $_{10}$ OS4 can be denoted in general with the notation  $(d * d)$ , where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d.
$$

The size of each switch in any of the middle stages excepting the first middle stage can be denoted as  $d * d$ . The size of each switch in the first middle stage can be denoted as  $d_1$ <sup>\*</sup>d. A switch as used herein can be either a crossbar switch, or a network of switches each of which in turn may be a crossbar switch or a network of switches. An asymmetric multi-stage network can be represented with the notation  $V(N_1, N_2, d, s)$ , where N, represents the total number of inlet links of all input  $_{25}$ switches (for example the links IL1-IL24), N, represents the total number of outlet links of all output switches (for example the links OL1-OL8), d represents the inlet links of seach of the of outgoing links from each input switch to the inlet links of  $30$ each input switch.

In network 600A2 of FIG. 6A2, each of the

 $\frac{N_2}{N_1}$ 

input switches [S1-IS4 are connected to exactly d switches in mput switches is 1-154 are connected to exactly d switches in<br>middle stage 130 through  $d_1$  links (for example input switch  $40$ IS1 is connected to middle switch  $MS(1,1)$  through the links  $ML(1,1)$  and  $ML(1,2)$ ; input switch IS1 is connected to middle switch  $MS(1,2)$  through the links  $ML(1,3)$  and  $ML(1,$ 4); input switch IS1 is connected to middle switch MS(1,3) through the link  $ML(1,5)$ ; and input switch IS1 is connected to middle switch  $MS(1,4)$  through the links  $ML(1,6)$ ).

Each of the

middle switches  $MS(1,1)$ - $MS(1,4)$  in the middle stage 130 are connected from exactly d, input switches through d links (for example the links  $ML(1,1)$  and  $ML(1,2)$  are connected to the middle switch  $MS(1,1)$  from input switch IS1; the links  $ML(1,7)$  and  $ML(1,8)$  are connected to the middle switch  $MS(1,1)$  from input switch IS2; the link  $ML(1,13)$  is connected to the middle switch  $MS(1,1)$  from input switch IS3; and the link  $ML(1,19)$  is connected to the middle switch MS(1,1) from input switch IS4), and also are connected to exactly d switches in middle stage 140 through d links (for example the links  $ML(2,1)$  and  $ML(2,2)$  are connected from 65 middle switch  $MS(1,1)$  to middle switch  $MS(2,1)$  and  $MS(2,1)$ 3) respectively). switch in the first middle stage can be denoted as  $4 \times 4.4 \times 2.4$ <br>switch in the first middle stage can be denoted as the stage of the main basis of  $\alpha$  is newtork of switches and of which in turn may be a creassbar<br>swit

148

middle switches  $MS(2,1)$ - $MS(2,4)$  in the middle stage 140 are connected from exactly d switches in middle stage 130 through d links (for example the links  $ML(2,1)$  and  $ML(2,6)$ are connected to the middle switch MS(2,1) from middle switches  $MS(1,1)$  and  $MS(1,3)$  respectively) and also are connected to exactly d switches in middle stage 150 through d links (for example the links  $ML(3,1)$  and  $ML(3,2)$  are  $_{15}$  connected from middle switch MS(2,1) to middle switch

 $MS(3,1)$  and  $MS(3,3)$  respectively). Similarly each of the

Similarly each of the



middle switches MS(3,1)-MS(3.4) in the middle stage 150 are connected from exactly d switches in middle stage 140 through d links (for example the links  $ML(3,1)$  and  $ML(3,6)$ ) are connected to the middle switch  $MS(3,1)$  from middle switches  $MS(2,1)$  and  $MS(2,3)$  respectively) and also are connected to exactly d output switches in output stage 120 through  $d_1$  links (for example the links ML $(4,1)$  and ML $(4,2)$ ) are connected to output switches OS1 and OS2 respectively from middle switch MS(3,1)).

Each of the

output switches OS1-OS4 are connected from exactly d switches in middle stage  $150$  through  $d_2$  links (for example output switch OS1 is connected from middle switches MS(3, 1) and  $MS(3,2)$  through the links  $ML(4,1)$  and  $ML(4,4)$ respectively).

Generalized Asymmetric RNB  $(N_1 > N_2)$  Unicast Embodiments:

Network 600K2 of FIG. 6K2 is an example of general asymmetrical multi-stage network  $V(N_1, N_2, d, s)$  with  $(2 \times \log_d N)$ –1 stages where  $N_1 > N_2$  and  $N_1 = p*N_2$  where  $p>1$ . In network 400K2 of FIG.  $4K2$ , N<sub>2</sub>=N and N<sub>1</sub>=p\*N. The  $_{50}$  general symmetrical multi-stage network  $V(N_1, N_2, d, s)$  can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention (and in the example of FIG.  $6K2$ ,  $s=1$ ). The general asymmetrical multistage network  $V(N_1, N_2, d, s)$  with  $(2 \times \log_d N) - 1$  stages has  $d_1$ (where

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

inlet links for each of

 $\frac{N_2}{d}$ 

 $\overline{\phantom{a}}$ 

input switches  $IS1$ -IS(N<sub>2</sub>/d) (for example the links IL1-IL  $(p * d)$  to the input switch IS1) and d,  $(=\frac{p}{d})$  outgoing links for each of

 $\frac{N_2}{d}$ 

input switches IS1-IS( $N_2/d$ ) (for example the links ML(1,1)- 10  $ML(1,(d+p^*d))$  to the input switch IS1). There are d outlet links for each of

 $\frac{N_2}{d}$ 

output switches OS1-OS(N,/d) (for example the links OL1-  $OL(d)$  to the output switch OS1) and d incoming links for  $20$ each of

$$
\frac{N_2}{d}
$$

output switches  $OS1-OS(N_2/d)$  (for example  $ML(2\times Log_d)$  $N_2$ –2,1)-ML(2xLog<sub>d</sub> N<sub>2</sub>–2, d) to the output switch OS1). Each of the

$$
\frac{N_2}{d}
$$

input switches  $IS1-IS(N<sub>2</sub>/d)$  are connected to exactly d switches in middle stage  $130$  through  $d_1$  links.

Each of the

middle switches  $MS(1,1)$ - $MS(1,N_2/d)$  in the middle stage 130 are connected from exactly d input switches through  $d_1$ links and also are connected to exactly d switches in middle stage 140 through d links.

Similarly each of the

$$
\frac{N_2}{d}
$$

middle switches

$$
MS(\text{Log}_{d}N_{2}-1, 1) - MS(\text{Log}_{d}N_{2}-1, \frac{N_{2}}{d})
$$

in the middle stage  $130+10*(\text{Log}_d N_1-2)$  are connected from exactly d switches in middle stage  $130+10*(\text{Log}_d N_1-3)$  65 through d links and also are connected to exactly d switches in middle stage  $130+10*(Log<sub>d</sub> N<sub>1</sub>-1)$  through d links. orgin wwitchs OS1-000(1-502) (ye cample me *mats* orientally and d incoming links for 20<br>
OL(d) to the output switch OS1) and d incoming links for 20<br>
each of<br>  $\frac{m_1}{d}$ <br>
output switches OS1-OS(N<sub>2</sub>4) (for example ML(2

150 Similarly each of the

> $N_2$  $\overline{d}$

middle switches

$$
MS(2 \times Log_d N_2 - 3, 1) - MS(2 \times Log_d N_2 - 3, \frac{N_2}{d})
$$

in the middle stage  $130+10*(2*Log<sub>d</sub> N<sub>1</sub>-4)$  are connected  $_{15}$  from exactly d switches in middle stage 130+10\*(2\*Log<sub>d</sub>)  $N_1-5$ ) through d links and also are connected to exactly d output switches in output stage 120 through d links.<br>
Fach of the

$$
\frac{N_2}{d}
$$

 $25$  switches in middle stage  $130+10*(2*Log_a N_1-4)$  through d output switches  $OS1-OS(N_2/d)$  are connected from exactly d links.

30 Scheduling Method Embodiments: The general symmetrical multi-stage network  $V(N_1, N_2, d, d)$ s) can be operated in rearrangeably nonblocking manner for unicast when  $s \ge 1$  according to the current invention.

FIG. 7A shows a high-level flowchart of a scheduling method 1000, in one embodiment executed to setup multicast and unicast connections in network 100A ofFIG. 1A (or any

of the networks  $\mathbf{V}_{mlink}(\mathbf{N}_1, \mathbf{N}_2, \mathbf{d}, \mathbf{s})$  and the networks  $\mathbf{V}(\mathbf{N}_1, \mathbf{N}_2)$  $N_2$ , d, s) disclosed in this invention). According to this embodiment, a multicast connection request is received in act 1010. Then the control goes to act 1020.

40 able outgoing middle link ofthe input switch ofthe multicast In act 1020, based on the inlet link and input switch of the multicast connection received in act 1010, from each availconnection, by traveling forward from middle stage 130 to middle stage  $130+10*(\text{Log}_d \text{N}-2)$ , the lists of all reachable middle switches in each middle stage are derived recursively. That is, first, by following each available outgoing middle link of the input switch all the reachable middle switches in middle stage 130 are derived. Next, starting from the selected middle switches in middle stage 130 traveling through all of their available out going middle links to middle stage <sup>140</sup> all the available middle switches in middle stage 140 are derived. This process is repeated recursively until all the reachable middle switches, starting from the outgoing middle link of input switch, in middle stage  $130+10*(\text{Log}_d \text{ N}-2)$  are derived. This process is repeated for each available outgoing middle link from the input switch of the multicast connection 55 and separate reachable lists are derived in each middle stage from middle stage 130 to middle stage  $130+10*(\text{Log}_d \text{N}-2)$ for all the available outgoing middle links from the input switch. Then the control goes to act 1030.

60 connection received in act 1010, from the output switch of In act 1030, based on the destinations of the multicast each destination, by traveling backward from output stage 120 to middle stage  $130+10*(\text{Log}_d N-2)$ , the lists of all middle switches in each middle stage from which each destination output switch (and hence the destination outlet links) is reachable, are derived recursively. That is, first, by following each available incoming middle link of the output switch of each destination link of the multicast connection, all the middle switches in middle stage  $130+10*(2*Log<sub>d</sub>N-4)$  from which the output switch is reachable, are derived. Next, starting from the selected middle switches in middle stage 130+  $10^*(2^*Log_{d} N-4)$  traveling backward through all of their available incoming middle links from middle stage 130+10\*  $(2*Log<sub>a</sub> N-5)$  all the available middle switches in middle stage  $130+10*(2*Log_A N-5)$  from which the output switch is reachable, are derived. This process is repeated recursively until all the middle switches in middle stage  $130+10*(\text{Log}_d)$ N-2) from which the output switch is reachable, are derived. 10 This process is repeated for cach output switch of cach destination link of the multicast connection and separate lists in each middle stage from middle stage  $130+10*(2*Log<sub>d</sub>N-4)$ to middle stage  $130+10*(\text{Log}_d \text{N}-2)$  for all the output switches of each destination link of the connection are derived. Then the control goes to act 1040.

In act 1040, using the lists generated in acts 1020 and 1030, particularly list of middle switches derived in middle stage 130+10\*( $\text{Log}_d$ N-2) corresponding to each outgoing link of the input switch of the multicast connection, and the list of 20 middle switches derived in middle stage  $130+10*(\text{Log}_{d}N-2)$ corresponding to each output switch of the destination links, the list of all the reachable destination links from each outgoing link of the input switch are derived. Specifically if a middle switch in middle stage  $130+10^*$ (Log<sub>d</sub> N-2) is reach- 25 able from an outgoing link of the input switch, say "x", and also from the same middle switch in middle stage 130+10\*  $(\text{Log}_{d} N-2)$  if the output switch of a destination link, say "y", is reachable then using the outgoing link of the input switch x, destination link y is reachable. Accordingly, the list of all the 30 reachable destination links from each outgoing link of the input switch is derived. The control then goes to act 1050.

In act 1050, among all the outgoing links of the input switch, it is checked if all the destinations are reachable using only one outgoing link of the input switch. If one outgoing link is available through which all the destinations of the multicast connection are reachable (i.e., act 1050 results in "yes"), the control goes to act 1070. And in act 1070, the multicast connection is setup by traversing from the selected only one outgoing middle link of the input switch in act 1050, 40 to all the destinations. Then the control transfers to act 1090.

If act 1050 results "no", that is one outgoing link is not available through which all the destinations of the multicast connection are reachable, then the control goes to act 1060. In act 1060, it is checked if all destination links of the multicast 45 connection are reachable using two outgoing middle links from the input switch. According to the current invention, it is always possible to find at most two outgoing middle links from the input switch through which all the destinations of a multicast connection are reachable. So act 1060 always results in "yes", and then the control transfers to act 1080. In act 1080, the multicast connection is setup by traversing from the selected only two outgoing middle links of the input switch in act 1060, to all the destinations. Then the control transfers to act 1090. the input switch of the minitest connection. Task of 20<br>middle switches derived in middle stage 130+10<sup>+</sup>(Log<sub>t</sub> N-2)<br>corresponding to each comput switch of the destination links,<br>from each other destination links from ea

In act 1090, all the middle links between anytwo stages of the network used to setup the connection in either act 1070 or act 1080 are marked unavailable so that these middle links will be made unavailable to other multicast connections. The with be made unavariable to other intititiest connections. The control then returns to act 1010, so that acts 1010, 1020, 1030, 60 1040, 1050, 1060, 1070, 1080, and 1090 are executed in a loop, for each connection request until the connections are set up.

In the example illustrated in FIG. 1A, four outgoing middle links are available to satisfy a multicast connection request if  $65$ input switch is IS2, but only at most two outgoing middle links of the input switch will be used in accordance with this

method. Similarly, although three outgoing middle links is available for a multicast connection requestifthe input switch is IS1, again only at most two outgoing middle links is used. The specific outgoing middle links of the input switch that are chosen when selecting two outgoing middle links of the input switch is irrelevant to the method of FIG. 7A so long as at most two outgoing middle links of the input switch are selected to ensure that the connection request is satisfied, i.e. the destination switches identified by the connection request can be reached from the outgoing middle links of the input switch that are selected. In essence, limiting the outgoing middle links of the input switch to no more than two permits the network  $V_{mlink}(N_1, N_2, d, s)$  and the network  $V(N_1, N_2, d, s)$ s) to be operated in nonblocking manner in accordance with the invention.

According to the current invention, using the method 1040 of FIG. 7A, the network  $V_{mlink}(N_1, N_2, d, s)$  and the networks  $V(N_1, N_2, d, s)$  are operated in rearrangeably nonblocking for unicast connections when  $s \ge 1$ , are operated in strictly nonblocking for unicast connections when  $s \ge 2$ , and are operated in rearrangeably nonblocking formulticast connections when  $s \geq 2$ .

The connection request of the type described above in reference to method 1000 of FIG. 7A can be unicast connection request, a multicast connection request or a broadcast connection request, depending on the example. In case of a unicast connection request, only one outgoing middle link of the input switch is used to satisfy the request. Moreover, in method 1000 described above in reference to FIG. 7A any number of middle links may be used between any two stages excepting between the input stage and middle stage 130, and also any arbitrary fan-out may be used within each output stage switch, to satisfy the connection request.

As noted above method 1000 of FIG. 7A can be used to setup multicast connections, unicast connections, or broadcast connection of all the networks  $V_{mlink}(N, d, s)$ ,  $V_{mlink}(N_1, s)$  $N_2$ , d, s),  $V(N, d, s)$  and  $V(N_1, N_2, d, s)$  disclosed in this invention.

Applications Embodiments:

All the embodiments disclosed in the current invention are useful in many varieties of applications. FIG. 8A1 illustrates the diagram of 800A1 which is a typical two by two switch with two inlet links namely IL1 and IL2, and two outlet links namely OL1 and OL2. The two by two switch also implements four crosspoints namely  $CP(1,1)$ ,  $CP(1,2)$ ,  $CP(2,1)$  and CP(2,2) as illustrated in FIG. 8A1. For example the diagram of 800A1 may the implementation of middle switch  $MS(1,1)$ of the diagram 400A of FIG. 4A where inlet link IL1 of diagram 800A1 corresponds to middle link  $ML(1,1)$  of diagram 400A, inlet link IL2 of diagram 800A1 corresponds to middle link  $ML(1,5)$  of diagram 400A, outlet link OL1 of diagram 800A1 corresponds to middle link ML(2,1) of diagram 400A, outlet link OL2 of diagram 800A1 corresponds to middle link ML(2,2) of diagram 400A.

1) Programmable Integrated Circuit Embodiments:

All the embodiments disclosed in the current invention are useful in programmable integrated circuit applications. FIG. 8A2 illustrates the detailed diagram 800A2 for the implementation of the diagram 800A1 in programmable integrated circuit embodiments. Lach crosspoint is implemented by a transistor coupled between the corresponding inlet link and outlet link, and a programmable cell in programmable integrated circuit embodiments. Specifically crosspoint  $CP(1,1)$ is implemented by transistor  $C(1,1)$  coupled between inlet link IL1 and outlet link OL1, and programmable cell  $P(1,1)$ ; crosspoint  $CP(1,2)$  is implemented by transistor  $C(1,2)$ coupled between inlet link IL1 and outlet link OL2, and programmable cell  $P(1,2)$ ; crosspoint  $CP(2,1)$  is implemented by transistor  $C(2,1)$  coupled between inlet link IL2 and outlet link OL1, and programmable cell  $P(2,1)$ ; and crosspoint  $CP(2,2)$  is implemented by transistor  $C(2,2)$  coupled between inlet link IL2 and outlet link OL2, and program- 5 mable cell P(2,2).

If the programmable cell is programmed ON, the corresponding transistor couples the corresponding inlet link and outlet link. If the programmable cell is programmed OFF, the corresponding inlet link and outlet link are not connected. For 10 example if the programmable cell  $P(1,1)$  is programmed ON, the corresponding transistor  $C(1,1)$  couples the corresponding inlet link IL1 and outlet link OL1. If the programmable cell  $P(1,1)$  is programmed OFF, the corresponding inlet link IL1 and outlet link OL1 are not connected. In volatile programmable integrated circuit embodiments the programmable cell may be an SRAM (Static Random Address Memory) cell. In non-volatile programmable integrated circuit embodiments the programmable cell may be a Flash memory cell. Also the programmable integrated circuit 20 embodiments may implement field programmable logic arrays (FPGA) devices, or programmable Logic devices (PLD), or Application Specific Integrated Circuits (ASIC) embedded with programmable logic circuits or 3D-FPGAs. 2) One-time Programmable Integrated Circuit Embodiments: 25

All the embodiments disclosed in the current invention are useful in one-time programmable integrated circuit applications. FIG. 8A3 illustrates the detailed diagram 800A3 for the implementation of the diagram 800A1 in one-time programmable integrated circuit embodiments. Each crosspoint is <sup>30</sup> implemented by a via coupled between the corresponding inlet link and outlet link in one-time programmable integrated circuit embodiments. Specifically crosspoint  $CP(1,1)$  is implemented by via  $V(1,1)$  coupled between inlet link IL1 and outlet link OL1; crosspoint CP $(1,2)$  is implemented by 35 via  $V(1,2)$  coupled between inlet link IL1 and outlet link OL2; crosspoint  $CP(2,1)$  is implemented by via  $V(2,1)$  coupled between inlet link IL2 and outlet link OL1; and crosspoint  $CP(2,2)$  is implemented by via  $V(2,2)$  coupled between inlet link IL2 and outlet link OL2.

If the via is programmed ON, the corresponding inlet link and outlet link are permanently connected which is denoted by thick circle at the intersection of inlet link and outlet link. If the via is programmed OFF, the corresponding inlet link and outlet link are not connected which is denoted by the 45 absence of thick circle at the intersection of inlet link and outlet link. For example in the diagram  $800A3$  the via  $V(1,1)$ is programmed ON, and the corresponding inlet link IL1 and outlet link OL1 are connected as denoted bythick circle at the intersection of inlet link IL1 and outlet link OL1; the via 50  $V(2,2)$  is programmed ON, and the corresponding inlet link IL2 and outlet link OL2 are connected as denoted by thick circle at the intersection of inlet link IL2 and outlet link OL2; the via  $V(1,2)$  is programmed OFF, and the corresponding inlet link IL1 and outlet link OL2 are not connected as 55 denoted by the absence of thick circle at the intersection of inlet link IL1 and outlet link OL2; the via  $V(2,1)$  is programmed OFF, and the correspondinginlet link IL2 and outlet link OL1 are not connected as denoted by the absence of ret link OLT are not connected as denoted by the absence of<br>thick circle at the intersection of inlet link IL2 and outlet link 60 OL1. One-time programmable integrated circuit embodiments may be anti-fuse based programmable integrated circuit devices or mask programmable structuredASIC devices. 3) Integrated Circuit Placement and Route Embodiments: memory cell. Also the programmable integrated circuit 2011<br>memory implement that the programmable logic arrays inplement that pergunamable logic devices or programmable language devices (FLD), or Application Specific inte

All the embodiments disclosed in the current invention are 65 useful in Integrated Circuit Placement and Route applications, for example in ASIC backend Placement and Route

tools. FIG. 8A4 illustrates the detailed diagram 800A4 for the implementation of the diagram 800A1 in Integrated Circuit Placement and Route embodiments. In an integrated circuit since the connections are known a-priori, the switch and crosspoints are actually virtual. However the concept of virtual switch and virtal crosspoint using the embodiments disclosed inthe current invention reduces the numberofrequired wires, wire length needed to connect the inputs and outputs of difterent netlists and the time required by the tool for placement and route of netlists in the integrated circuit.

Each virtual crosspoint is used to either to hardwire or provide no connectivity between the corresponding inlet link and outlet link. Specifically crosspoint  $CP(1,1)$  is implemented by direct connect point DCP(1,1) to hardwire (i.e., to permanently connect) inlet link IL1 and outlet link OL1 which is denoted by the thick circle at the intersection of inlet link IL1 and outlet link OL1; crosspoint CP(2,2) is implemented by direct connect point  $DCP(2,2)$  to hardwire inlet link IL2 and outlet link OL2 which is denoted by the thick circle at the intersection of inlet link IL2 and outlet link OL2. The diagram 800A4 does not show direct connect point DCP  $(1,2)$  and direct connect point DCP $(1,3)$  since they are not needed and in the hardware implementation they are eliminated. Alternatively inlet link IL1 needs to be connected to outlet link OL1 and inlet link IL1 does not need to be connected to outlet link OL2. Also inlet link IL2 needs to be connected to outlet link OL2 andinlet link IL2 does not need to be connected to outlet link OL1. Furthermore in the example of the diagram 800A4, there is no need to drive the signal of inlet link IL1 horizontally beyond outlet link OL1 and hence the inlet link IL1 is not even extended horizontally until the outlet link OL2. Also the absence of direct connect point DCP(2,1) illustrates there is no need to connect inlet link IL2 and outlet link OL1.

In summary in integrated circuit placement and route tools, the concept of virtual switches and virtual cross points is used during the implementation of the placement  $&$  routing algorithmically in software, however during the hardware implementation cross points in the cross state are implemented as hardwired connections between the corresponding inlet link and outlet link, and in the bar state are implemented as no connection between inlet link and outlet link

3) More Application Embodiments:

40

All the embodiments disclosed in the current invention are also useful in the design of SoC interconnects, Field programmable interconnect chips, parallel computer systems and in time-space-time switches.

Numerous modifications and adaptations of the embodiments, implementations, and examples described herein will be apparent to the skilled artisan in view of the disclosure.

What is claimed is:

1. A network having a plurality of multicast connections, said network comprising:

 $N_1$  inlet links and  $N_2$  outlet links, where  $N_1>1$ ,  $N_2>1$  and when  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$  then  $N_1 = N$ ,  $d_1 = d$ , and

$$
d_2=N_2\times \frac{d}{N_1}=p\times d;
$$

where  $N>1$ ,  $d_1>1$ ,  $d_2>1$ ,  $d>1$  and

 $\overline{\mathbf{S}}$ 

20

40

55

65

an input stage comprising

 $\frac{N_1}{N_2}$ 

input switches, and said each input switch comprising d inlet links and each said input switch further comprising xxd outgoing links connecting to switches in a second stage where x>0; and

an output stage comprising

$$
f_{\rm{max}}
$$

output switches, and said each output switch comprising d, outlet links and each said output switch further comprising

 $\frac{N_1}{N_2}$ 

$$
x \times \frac{(d + d_2)}{2}
$$

incoming links connecting from switches in a penultimate stage; and

- mate stage; and<br>a plurality of y middle stages comprising N/d middle <sup>25</sup> switches in each of said y middle stages wherein said second stage and said penultimate stage are one of said middle stages where y>3, and
- said each middle switch in all said middle stages excepting said penultimate stage comprising xxd incoming links 30 (hereinafter "incoming middle links") connecting from switches in its immediate preceding stage, and said each middle switch further comprising xxd outgoing links (hereinafter "outgoing middle links") connecting to switches in its immediate succeeding stage; and sing where  $x > R$ , and<br>
an output single compitaing<br>
an output single compitaing<br>  $\frac{N_1}{l}$ <br>
output swisches, and said dechoulput switch further compound<br>
d., vinthe finisce compound in the same of the same of the small
	- said each middle switch in said penultimate stage comprising xxd incoming links connecting from switches in its said immediate preceding, stage, and said each middle switch further comprising

$$
x\!\times\!\frac{(d+d_2)}{2}
$$

outgoing links connecting to switches in its said immediate succeeding stage i.e., said output stage; or when  $N_1 > N_2$  and  $N_1=p*N_2$  where  $p>1$  then  $N_2=N$ ,  $d_2=d$  and

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d
$$

and

an input stage comprising

$$
\frac{N_2}{d}
$$

input switches, and said each input switch comprising d, inlet links and said each input switch further comprising  $\epsilon_{60}$ 

$$
x \times \frac{(d+d_1)}{2}
$$

outgoing links connecting to switches in a second stage where  $x>0$ ; and

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an output stage comprising

 $N_2$  $\overline{d}$ 

output switches, and said each output switch comprising d outlet links and said each output switch further comprising xxd incoming links connecting from switches in a penullimate stage; and

a plurality of y middle stages comprising N/d middle switches in each of said y middle stages wherein said second stage and said penultimate stage are one of said middle stages where y>3, and

said each middle switch in said second stage comprising

$$
x \!\times\! \frac{(d+d_1)}{2}
$$

incoming links connecting from switches in its immediate preceding stage i.e., said input stage, and said each middle switch further comprising xxd outgoing links connecting to switches in its immediate succeeding stage; and

- said each middle switch in all said middle stages excepting said second stage comprising xxd incoming links (hereinafter "incoming middle links") connecting from switches in its immediate preceding stage, and said each middle switch further comprising xxd outgoing links (hereinafter "outgoing middle links") connecting to switches in its said immediate succeeding stage; and
- wherein said each multicast connection from an inlet link passes through at most two outgoing links in said input switch, and said multicast connection further passes through a plurality of outgoing links in a plurality switches in each said middle stage and in said output stage.

2. The network of claim 1, wherein all said incoming middle links and outgoing middle links are connected in any arbitrary topology such that when no connections are setup in said network, a connection from any said inlet link to any said outlet link can be setup.

3. The network of claim 2, wherein  $y \geq (2 \times \log_a N) - 3$  when  $N_2>N_1$ , and  $y\geq (2\times \log_d N_2)-3$  when  $N_1>N_2$ .

4. The network of claim 3, wherein  $x \ge 1$ , wherein said each multicast connection comprises only one destination link, 50 and

- said each multicast connection from an inlet link passes through only one outgoing link in input switch, and said multicast connection further passes through only one outgoing link in one of the switches in each said middle stage and in said output stage, and
- further is always capable of setting up said multicast connection by changing the path, detined by passage of an existing multicast connection, thereby to change only one outgoing link of the input switch used by said existing multicast connection, and said network is hereinafter "rearrangeably nonblocking network for unicast'.

5. The network of claim 3, wherein  $x \ge 2$ , wherein said each multicast connection comprises only one destination link, and

said each multicast connection from an inlet link passes through only one outgoing link in input switch, and said multicast connection further passes through only one outgoing link in one of the switches in each said middle stage and in said output stage, and

further is always capable of setting up said multicast connection by never changing path of an existing multicast connection, wherein said each multicast connection 5 comprises only one destination link and the network is hereinafter "strictly nonblocking network for unicast'.

6. The network of claim 3, wherein  $x \ge 2$ ,

- further is always capable of setting up said multicast connection by changing the path, defined by passage of an existing multicast connection, thereby to change one or two outgoing links of the input switch used by said existing multicast connection, and said network is hereinafter "rearrangeably nonblocking network". dinput switches in the said of  $\theta$  and  $\theta$  and
	- 7. The network of claim 3, wherein  $x \ge 3$ ,
	- further is always capable of setting up said multicast connection by never changing path of an existing multicast connection, and the network is hereinafter "strictly nonblocking network"

8. The network of claim 1, further comprising a controller 20 coupled to each of said input, output and middle stages to set up said multicast connection.

9. The network of claim 1, wherein said  $N_1$  inlet links and  $N_2$  outlet links are the same number of links, i.e.,  $N_1=N_2=N$ , and  $d_1 = d_2 = d$ .<br>10. The network of claim 1, wherein said each input switch,  $25$ 

said each output switch and said each middle switch is either fully populated or partially populated.

11. The network of claim 1,

wherein each of said input switches, or each of said output  $30$ switches, or each of said middle switches further recursively comprise one or more networks.

12. A method for setting up one or more multicast connections in a network having  $N_1$  inlet links and  $N_2$  outlet links, where  $N_1$ >1,  $N_2$ >1 and

when  $N_2>N_1$  and  $N_2=p*N_1$  where p>1 then  $N_1=N$ ,  $d_1=d$ , and

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d; \tag{40}
$$

where N>1,  $d_1$ >1,  $d_2$ >1,  $d$ >1 and having an input stage having

 $\frac{N_1}{N_2}$ 

mput switches, and said each mput switch having d met<br>links and said each input switch further having xxd <sup>50</sup> outgoing links connected to switches in a second stage where  $x>0$ ; and 8 The newook of claim 1, further compission a controller 2<br>
coupled to each of staid imput, output and middle seages to set<br>
or coupled to each of staid imput, output and middle seages to set<br>
y so The network of claim 1,

an output stage having

$$
\frac{N_1}{d}
$$

output switches, and said each output switch having  $d_2$ outlet links and said each output switch further having  $\epsilon_0$ 

$$
x \times \frac{(d + d_2)}{2}
$$

incoming links connected from switches in a penultimate stage; and

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- a plurality of y middle stages having N/d middle switches in each ofsaid y middle stages wherein said second stage and said penultimate stage being one of said middle stages where y>3, and
- said each middle switch in all said middle stages excepting said penultimate stage having xxd incoming links connected from switches in its immediate preceding stage, and said eachmiddle switch further having xxd outgoing links connected to switches in its immediate succeeding stage; and
- said each middle switch in said penultimate stage having x×d incoming links connected from switches in its said immediate preceding stage, and said each middle switch further having

$$
x \times \frac{(d+d_2)}{2}
$$

outgoing links connected to switches in its said immediate succeeding stage; or

when  $N_1 > N_2$  and  $N_1 = p^*N_2$ , where  $p > 1$  then  $N_2 = N_1$ ,  $d_2 = d$ and

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d;
$$

and having an input stage having

input switches, and said each input switch having  $d_1$  inlet links and said each input switch further having

$$
x \times \frac{(d+d_1)}{2}
$$

outgoing links connected to switches in a second stage where  $x>0$ ; and

an output stage having output

switches, and said each output switch having d outlet links and said each output switch further having xxd incoming links connected from switches in a penultimate stage: and

a plurality of y middle stages having N/d middle switches in each ofsaid y middle stages wherein said second stage and said penultimate stage being one of said middle stages where y>3, and

said each middle switch in said second stage having

$$
x \times \frac{(d+d_1)}{2}
$$

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incoming links connected from switches in its immediate preceding stage, and said each middle switch further having xxd outgoing links connected to switches in its said immediate succeeding stage; and

said each middle switch in all said middle stages excepting 5 said second stage having xxd incoming links connected from switches in its immediate preceding stage, and said each middle switch further having xxd outgoing links connected to switches in its immediate succeeding stage; and said method comprising: 10 Let us a strongen method in the stron Hereatag, has conserved from exciting the hereaton in Figure 1.6 (and the same of 2014) and the same of 2016 (and the same of 2016

receiving a multicast connection at said input stage; fanning out said multicast connection through at most two outgoing links in said input switch and a plurality of outgoing links in a plurality of middle switches in each said middle stage to set up said multicast connection to <sup>15</sup> a plurality of output switches among said

$$
\frac{N_2}{d}
$$

 $\frac{N_2}{d}$ 

output switches, wherein said plurality of output switches are specified as destinations of said multicast connection, wherein said at most two outgoing links in input switch and said plurality of outgoing links in said  $_{25}$ plurality of middle switches in each said middle stage are available.

13. A method of claim 12 wherein said act of fanning out is performed without changing any existing connection to pass through another set of plurality of middle switches in each said middle stage.  $30^{\circ}$ 

14. A method of claim 12 wherein said act of fanning out is performed recursively.

15. A method of claim 12 wherein a connection exists switches in each said middle stage and said method further <sup>35</sup> comprises:

if necessary, changing said connection to pass through another set of plurality of middle switches in each said middle stage, act hereinafter "rearranging connection".

16. A method of claim 12 wherein said acts of fanning out  $40$ and rearranging are performed recursively.

17. A method for setting up one or more multicast connections in a network having  $N_1$  inlet links and  $N_2$  outlet links, where  $N_1$ >1,  $N_2$ >1 and

when  $N_2 > N_1$  and  $N_2 = p^*N_1$  where  $p > 1$  then  $N_1 = N$ ,  $d_1 = d$ ,  $d_2 = 1$ and

$$
d_2 = N_2 \times \frac{d}{N_1} = p \times d;
$$

where N>1,  $d_1$ >1,  $d_2$ >1,  $d$ >1 and having an input stage having

$$
\frac{N_1}{d} \tag{55}
$$

input switches, and said each input switch having d inlet links and said each input switch further having xxd outgoing links connected to switches in a second stage butgoing this connected to switches in a second stage  $60$ <br>where  $x>0$ ; and an output stage having

$$
\frac{N_1}{d} \tag{65}
$$

output switches, and said each output switch having  $d_2$ outlet links and said each output switch further having

$$
x \times \frac{(d + d_2)}{2}
$$

incoming links connected from switches in a penultimate stage; and

- a plurality of y middle stages having N/d middle switches in each ofsaid y middle stages wherein said second stage and said penultimate stage being one of said middle stages where y>3, and
- said each middle switch in all said middle stages excepting said penultimate stage having xxd incoming links connected from switches in its immediate preceding stage, and said each middle switch further having xxd outgoing links connected to switches in its immediate succeeding stage; and
- said each middle switch in said penultimate stage having xxd incoming links connected from switches in its said immediate preceding stage, and said each middle switch further having

$$
x \times \frac{(d+d_2)}{2}
$$

outgoing links connected to switches in its said immediate succeeding stage; or

when  $N_1 > N_2$  and  $N_1 = p*N_2$  where  $p>1$  then  $N_2 = N$ ,  $d_2 = d$ and

$$
d_1 = N_1 \times \frac{d}{N_2} = p \times d;
$$

and having

an input stage having

$$
\frac{N_2}{d}
$$

input switches, and said each input switch having  $d_1$  inlet links and said each input switch further having

$$
x\!\times\!\frac{(d+d_1)}{2}
$$

outgoing links connected to switches in a second stage where x>0: and

an output stage having

 $\frac{N_2}{N_2}$ 

output switches, and said each output switch having d outlet links and said each output switch further having xxd incoming links connected from switches in a penultimate stage; and

a plurality of y middle stages having N/d middle switches in each of said y middle stages wherein said second stage and said penultimate stage being one of said middle stages where y>3, and

said each middle switch in said second stage having

$$
x\!\times\!\frac{(d+d_1)}{2}
$$

incoming links connected from switches in its immediate preceding stage, and said each middle switch further having xxd outgoing links connected to switches in its immediate succeeding stage; and

- said each middle switch in all said middle stages excepting said second stage having xxd incoming links connected from switches in its immediate preceding stage, and said each middle switch further having xxd outgoing links connected to switches in its immediate succeeding stage; and said method comprising:
- plurality of outgoing links in plurality of middle switches in each said middle stage are available to at switches in each said middle stage are available to at least a first subset of destination output switches of said  $\frac{25}{25}$ multicast connection; and connection to switches in its immediate succeeding  $_{20}$  sugge; and suid method comprising:<br>
checking if a linear oughly his in plurality of middle polynchic in the state and in first the polynchic polynchic leads in the
	- checking if a second outgoing link in input switch and second plurality of outgoing links in plurality of middle switches in each said middle stage are available to a second subset of destination output switches of said  $_{30}$ multicast connection,
	- wherein each destination output switch of said multicast connection is one of said first subset of destination output switches and said second subset of destination output switches.

18. The method of claim 17 further comprising:

prior to said checkings, checking if all the destination output switches of said multicast connection are available through said first outgoing link in input switch and said first plurality of outgoing links in plurality of middle switches in each said middle stage.

19. The method of claim 17 further comprising:

- achecking if a first outgoing link in input switch and first repeating said checkings of available second outgoing link in input switch and second plurality of outgoing links in plurality of middle switches in each said middle stage to a second subset of destination output switches of said multicast connection to each outgoing link in input switch other than said first and said second outgoing links in input switch,
	- wherein each destination output switch of said multicast connection is one of said first subset of destination output switches and said second subset of destination output switches.

20. The method of claim 17 further comprising:

- repeating said checkings of available first outgoing link in input switch and first plurality of outgoing links in plurality of middle switches in each said middle stage to a first subset of destination output switches of said multicast connection to each outgoing link in input switch other thansaid first outgoing link in input switch.
- 21. The method of claim 17 further comprising:
- setting up each of said multicast connection fromits said input switch to its said output switches through not more than two outgoing links, selected by said checkings, by fanning out said multicast connection in its said input switch into not more than said two outgoing links.

22. The method of claim 17 wherein any of said acts of checking and setting up are performed recursively.