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(71) **Applicant and**
(72) **Inventor: KONDA, Venkat** [US/US], 6278, Grand Oak Way, San Jose, CA 95135 (US)

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(54) **Title:** FULLY CONNECTED GENERALIZED MULTI-STAGE NETWORKS

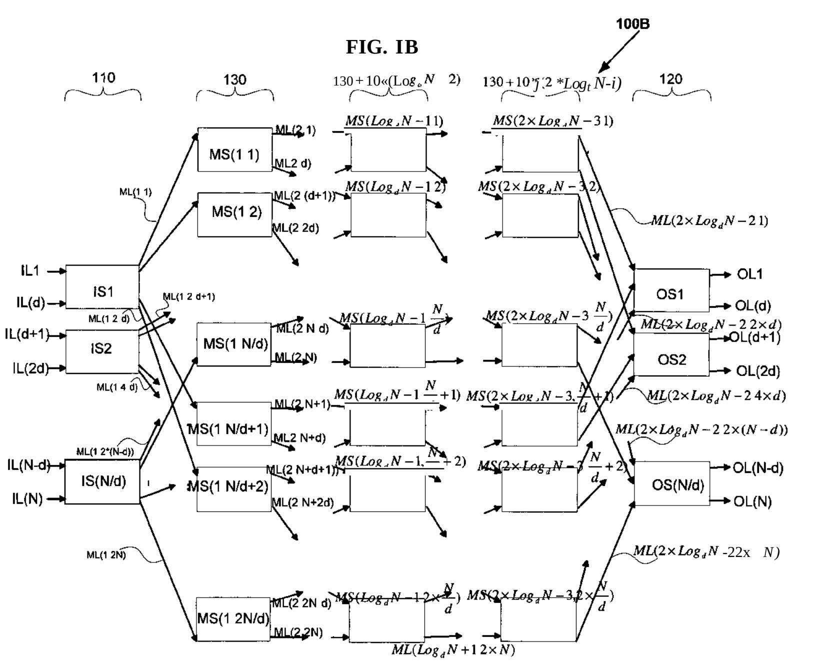

FIG. IB

(57) **Abstract:** A multi-stage network compπsing (2x $\log_d$ N) - I stages is operated in strictly nonblocking manner for unicast includes an input stage having N / *d* switches with each of them having d inlet links and 2x *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 *xd* incoming links connecting from switches in the penultimate stage The network also has (2x $\log_d$ N) - 3 middle stages with each middle stage having 2 x N / *d* switches, and each switch in the middle stage has *d* incoming links connecting from the switches in its immediate preceding stage, and *d* outgoing links connecting to the switches in its immediate succeeding stage Also the same 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 multi-stage network compπsing (2x $\log_d$ N) - I stages is operated in strictly nonblocking manner for multicast includes an input stage having N / *d* switches with each of them having^ inlet links and 3 x *d* outgoing links connecting to second stage switches, an output stage having N / *d* switches with each of them having *d* outlet links and *3 x d* incoming links connecting from switches in the penultimate stage The network also has (2x $\log_d$ N) - 3 middle stages with each middle stage having 3 x N / *d* switches, and each switch in the middle stage has *d* incoming links connecting from the switches in its immediate preceding stage, and *d* outgoing links connecting to the switches in its immediate succeeding stage

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FULLY CONNECTED GENERALIZED MULTI-STAGE NETWORKS

Venkat Konda

CROSS REFERENCE TO RELATED APPLICATIONS

This application is Continuation In Part PCT Application to and incorporates by reference in its entirety the U.S. Provisional Patent Application Serial 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 application, filed March 6, 2007.

This application is Continuation In Part PCT Application to and incorporates by reference in its entirety the U.S. Provisional Patent Application Serial No. 60/940, 383 entitled "FULLY CONNECTED GENERALIZED MULTI-STAGE 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 Serial No. 60/940, 387 entitled "FULLY CONNECTED GENERALIZED 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. Provisional Patent Application Serial No. 60/940, 389 entitled "FULLY CONNECTED GENERALIZED REARRANGEABLY NONBLOCKING MULTI-LINK MULTI-STAGE 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 Serial No. 60/940, 390 entitled "FULLY CONNECTED 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. Provisional Patent Application Serial 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 May 25, 2007.

This application is related to and incorporates by reference in its entirety the U.S. Provisional Patent Application Serial No. 60/940, 392 entitled "FULLY CONNECTED GENERALIZED STRICTLY NONBLOCKING MULTI-LINK MULTI-STAGE 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 Serial No. 60/940, 394 entitled "VLSI LAYOUTS OF FULLY CONNECTED GENERALIZED 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 Serial No. 60/984, 724 entitled "VLSI LAYOUTS OF FULLY CONNECTED NETWORKS WITH LOCALITY EXPLOITATION" by Venkat Konda assigned to the same assignee as the current application, filed November 2, 2007.

This application is related to and incorporates by reference in its entirety the U.S. Provisional Patent Application Serial No. 61/018, 494 entitled "VLSI LAYOUTS OF FULLY CONNECTED GENERALIZED AND PYRAMID NETWORKS" by Venkat Konda assigned to the same assignee as the current application, filed January 1, 2008.

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, 1965 that is incorporated by reference, as background). In a rearrangeably nonblocking network, a connection path is guaranteed as a result of the network's 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 if more 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 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. Patent 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" IEEE Transactions 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 $m \geq \min((« - l)(x + r^{llx}))$ where $1 \leq x \leq \min(« - 1, r)$, 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.

U.S. Patent 6,885,669 entitled "Rearrangeably Nonblocking Multicast Multi-stage Networks" by Konda showed that three-stage Clos network is rearrangeably nonblocking for arbitrary fan-out multicast connections when $m \geq 2xn$. And U.S. Patent 6,868,084 entitled "Strictly Nonblocking Multicast Multi-stage Networks" by Konda showed that three-stage Clos network is strictly nonblocking for arbitrary fan-out multicast connections when $m \geq 3 x n - 1$.

In general multi-stage networks for stages of more than three 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, Jan. 1953, No.l, pp. 406-424 showed a way of constructing large multi-stage networks by recursive substitution with a crosspoint complexity of $d^2 x N x (\log_d N)^{258}$ for strictly nonblocking unicast network. Similarly U.S. Patent 6,885,669 entitled "Rearrangeably Nonblocking 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 multi-stage networks with a crosspoint complexity of $d^2 x N x (\log_d N)^2$ for strictly nonblocking unicast, (by using $\log_d N$ number of Benes Networks for d = 2) and without counting the crosspoints in multiplexers and

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