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UNITED STATES DISTRICT COURT

CENTRAL DISTRICT OF CALIFORNIA

The CALIFORNIA INSTITUTE OF TECHNOLOGY, a California corporation,

Plaintiff,

vs.

HUGHES COMMUNICATIONS, INC., a Delaware corporation, HUGHES NETWORK SYSTEMS, LLC, a Delaware limited liability company, DISH NETWORK CORPORATION, a Nevada corporation, DISH NETWORK L.L.C., a Colorado limited liability company, and DISHNET SATELLITE BROADBAND L.L.C., a Colorado limited liability company,

Defendants.

CASE NO. CV13-07245-PA (JEMx)

COMPLAINT FOR PATENT INFRINGEMENT

JURY TRIAL DEMANDED

Plaintiff the California Institute of Technology ("Caltech" or "Plaintiff"), by and through its undersigned counsel, complains and alleges as follows against Hughes Communications, Inc., Hughes Network Systems, LLC, DISH Network Corporation, DISH Network L.L.C., and dishNET Satellite Broadband L.L.C. (collectively, "Defendants"):

NATURE OF THE ACTION

1. This is a civil action for patent infringement arising under the patent laws of the United States, 35 U.S.C. §§ 1 *et seq.*

2. Defendants have infringed and continue to infringe, contributed to and continue to contribute to the infringement of, and/or actively induced and continue to induce others to infringe Caltech's U.S. Patent No. 7,116,710, U.S. Patent No. 7,421,032, U.S. Patent No. 7,916,781, and U.S. Patent No. 8,284,833 (collectively, "the Asserted Patents"). Caltech is the legal owner by assignment of the Asserted Patents, which were duly and legally issued by the United States Patent and Trademark Office. Caltech seeks injunctive relief and monetary damages.

THE PARTIES

3. Caltech is a non-profit private university organized under the laws of the State of California, with its principal place of business at 1200 East California Boulevard, Pasadena, California 91125.

4. On information and belief, Hughes Communications, Inc. ("Hughes Communications") is a corporation organized under the laws of the State of Delaware, with its principal place of business located at 11717 Exploration Lane, Germantown, Maryland 20876. On information and belief, Hughes Communications is a wholly-owned subsidiary of Hughes Satellite Systems Corporation, which is a wholly-owned subsidiary of EchoStar Corporation ("EchoStar").

5. On information and belief, Hughes Network Systems, LLC ("Hughes Network") is a limited liability company organized under the laws of the State of

Delaware, with its principal place of business located at 11717 Exploration Lane, Germantown, Maryland 20876. On information and belief, Hughes Network is a wholly owned subsidiary of Hughes Communications. Hughes Communications and Hughes Network, collectively, are referred to as "Hughes Defendants."

6. On information and belief, DISH Network Corporation ("DISH Corp.") is a corporation organized under the laws of the State of Nevada with its principal place of business located at 9601 South Meridian Boulevard, Englewood, Colorado 80112.

7. On information and belief, DISH Network L.L.C. ("DISH L.L.C.") is a limited liability company organized under the laws of the State of Colorado with its principal place of business located at 9601 South Meridian Boulevard, Englewood, Colorado 80112. On information and belief, DISH L.L.C. is a wholly owned subsidiary of DISH Corp.

8. On information and belief, dishNET Satellite Broadband L.L.C. ("dishNET") is a limited liability company organized under the laws of the State of Colorado with its principal place of business located at 9601 South Meridian Boulevard, Englewood, Colorado 80112. On information and belief, dishNET is a wholly owned subsidiary of DISH Corp. On information and belief, dishNET and DISH L.L.C. are related entities. DISH Corp., DISH L.L.C., and dishNET, collectively, are referred to as "Dish Defendants."

9. On information and belief, Hughes Defendants' parent company, EchoStar, and Dish Defendants were previously one company. On information and belief, around January 2008, EchoStar and Dish Defendants became two separate companies (the "spin-off").

10. On information and belief, the business relationship among Dish Defendants, EchoStar and Hughes Defendants remains extremely integrated. The same individual serves as the Chairman of both Dish Defendants and EchoStar. Further, since the spin-off, a substantial majority of the voting power of the shares

of both Dish Defendants and EchoStar is owned beneficially by the Chairman, or by certain trusts established by the Chairman. Additionally, on information and belief, in addition to the Chairman, an individual responsible for the development and implementation of advanced technologies that are of potential utility and importance to both Dish Defendants and EchoStar serves on the board of both companies. On information and belief, in 2010, Dish Defendants accounted for 82.5% of EchoStar's total revenue and in 2012, Dish Defendants accounted for 49.5% of EchoStar's total revenue. Additionally, on information and belief, in October 2012, Dish Defendants and Hughes Defendants entered into a distribution agreement relating to Hughes Defendants' satellite internet service.

JURISDICTION AND VENUE

11. This Court has jurisdiction over the subject matter of this action under 28 U.S.C. §§ 1331 and 1338(a).

12. Hughes Defendants are subject to this Court's personal jurisdiction. On information and belief, Hughes Defendants regularly conduct business in the State of California, including in the Central District of California, and have committed acts of patent infringement and/or contributed to or induced acts of patent infringement by others in this District and elsewhere in California and the United States. As such, Hughes Defendants have purposefully availed themselves of the privilege of conducting business within this District; have established sufficient minimum contacts with this District such that they should reasonably and fairly anticipate being haled into court in this District; have purposefully directed activities at residents of this State; and at least a portion of the patent infringement claims alleged herein arise out of or are related to one or more of the foregoing activities.

13. Dish Defendants are subject to this Court's personal jurisdiction. On information and belief, Dish Defendants regularly conduct business in the State of California, including in the Central District of California, maintain employees in this District and elsewhere in California, and have committed acts of patent infringement

and/or contributed to or induced acts of patent infringement by others in this District and elsewhere in California and the United States. As such, Dish Defendants have purposefully availed themselves of the privilege of conducting business within this District; have established sufficient minimum contacts with this District such that they should reasonably and fairly anticipate being haled into court in this District; have purposefully directed activities at residents of this State; and at least a portion of the patent infringement claims alleged herein arise out of or are related to one or more of the foregoing activities.

14. Venue is proper in this judicial district pursuant to 28 U.S.C. §§ 1391 and 1400 because Defendants regularly conduct business in this District, and certain of the acts complained of herein occurred in this District.

CALTECH'S ASSERTED PATENTS

15. On October 3, 2006, the United States Patent Office issued U.S. Patent No. 7,116,710, titled "Serial Concatenation of Interleaved Convolutional Codes Forming Turbo-Like Codes" (the "'710 patent"). A true and correct copy of the '710 patent is attached hereto as Exhibit A.

16. On September 2, 2008, the United States Patent Office issued U.S. Patent No. 7,421,032, titled "Serial Concatenation of Interleaved Convolutional Codes Forming Turbo-Like Codes" (the "'032 patent"). A true and correct copy of the '032 patent is attached hereto as Exhibit B. The '032 patent is a continuation of the application that led to the '710 patent.

17. On March 29, 2011, the United States Patent Office issued U.S. Patent No. 7,916,781, titled "Serial Concatenation of Interleaved Convolutional Codes Forming Turbo-Like Codes" (the "'781 patent"). A true and correct copy of the '781 patent is attached hereto as Exhibit C. The '781 patent is a continuation of the application that led to the '032 patent, which is a continuation of the application that led to the '710 patent.

18. On October 9, 2012, the United States Patent Office issued U.S. Patent

No. 8,284,833, titled "Serial Concatenation of Interleaved Convolutional Codes Forming Turbo-Like Codes" (the "'833 patent"). A true and correct copy of the '833 patent is attached hereto as Exhibit D. The '833 patent is a continuation of the application that led to the '781 patent, which is a continuation of the application that led to the '032 patent, which is a continuation of the application that led to the '710 patent.

19. The Asserted Patents identify Hui Jin, Aamod Khandekar, and Robert J. McEliece as the inventors (the "Named Inventors").

20. Caltech is the owner of all right, title, and interest in and to each of the Asserted Patents with full and exclusive right to bring suit to enforce the Asserted Patents, including the right to recover for past damages and/or royalties.

21. The Asserted Patents are valid and enforceable.

BACKGROUND TO THIS ACTION

22. The Asserted Patents disclose a seminal improvement to coding systems and methods used for digital satellite transmission. The Asserted Patents disclose an ensemble of codes called irregular repeat-accumulate (IRA) codes, which are specific types of low-density parity check (LDPC) codes. The IRA codes disclosed in the Asserted Patents enable a transmission rate close to the theoretical limit, while also providing the advantage of a low encoding complexity.

23. In September 2000, the Named Inventors of the Asserted Patents published a paper regarding their invention, titled "Irregular Repeat-Accumulate Codes" for the Second International Conference on Turbo Codes. (Exhibit E.) This paper has been widely cited by experts in the industry.

24. Experts recognize the importance and usefulness of the IRA codes disclosed in the September 2000 paper by the Named Inventors of the Asserted Patents. For example, a paper praising these IRA codes was published in August 2004 by Aline Roumy, Souad Guemghar, Giuseppe Caire, and Sergio Verdú in the IEEE Transactions on Information Theory. This paper, titled "Design Methods for

Irregular Repeat-Accumulate Codes," states:

> IRA codes are, in fact, special subclasses of both irregular LDPCs and irregular turbo codes. . . . IRA codes are an appealing choice because the encoder is extremely simple, their performance is quite competitive with that of turbo codes and LDPCs, and they can be decoded with a very-low-complexity iterative decoding scheme.

(Exhibit F, at 1.) This paper also notes that, four years after the September 2000 paper, the Named Inventors were the only ones to propose a method to design IRA codes. (*Id.*)

25. The current standard for digital satellite transmissions embodies the invention of the Asserted Patents by using channel codes that are IRA codes. This digital satellite transmission standard is titled "Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications" (the "DVB-S2 standard").

26. Experts in the industry recognize that the DVB-S2 standard uses the IRA codes initially disclosed by the Named Inventors of the Asserted Patents. For example, a 2005 paper published by the highly regarded Institute of Electrical and Electronics Engineers (IEEE), titled "A Synthesizable IP Core for DVB-S2 LDPC Code Decoding," and authored by Frank Kienle, Torben Brack, and Norbert Wehn recognizes:

> The LDPC codes as defined in the DVB-S2 standard are IRA codes, thus the encoder realization is straight forward. Furthermore, the DVB-S2 code shows regularities which can be exploited for an efficient hardware realization.

(Exhibit G, at 1.)

27. Moreover, this paper provides credit to the September 2000 paper authored by the Named Inventors of the Asserted Patents for the origination of the IRA codes that are defined in the DVB-S2 standard. (*Id.* at 1 & n.8.)

28. Similarly, on information and belief, a 2007 paper titled "Factorizable Modulo *M* Parallel Architecture for DVB-S2 LDPC Decoding," and published in the Proceedings of the 6th Conference on Telecommunications, recognizes that the DVB-S2 standard uses the IRA codes initially disclosed by the Named Inventors of the Asserted Patents. This paper, authored by Marco Gomes, Gabriel Falcão, Vitor Silva, Vitor Ferreira, Alexandre Sengo, and Miguel Falcão, states:

> The new DVB-S2 [] standard adopted a special class of LDPC codes known by IRA codes [] as the main solution for the FEC system.

(Exhibit H, at 1.)

29. Moreover, this paper also credits the September 2000 paper authored by the Named Inventors of the Asserted Patents for the origination of the IRA codes that are defined in the DVB-S2 standard. (*Id.* at 1 & n.8.)

30. As even further support, on information and belief, a 2006 industry paper published in the Journal of Communications Software and Systems, titled "Design of LDPC Codes: A Survey and New Results" and authored by Gianluigi Liva, Shumei Song, Lan Lan, Yifei Zhang, Shu Lin, and William E. Ryan, confirms that the DVB-S2 standard uses the IRA codes, stating:

> The ETSI DVB S2 [] standard for digital video broadcast specifies two IRA code families with block lengths 64800 and 16200.

(Exhibit I, at 10-11.)

31. As such, products, methods, equipment, and/or services that implement the DVB-S2 standard practice one or more claims of each of the Asserted Patents because the DVB-S2 standard embodies the invention of the Asserted Patents by using IRA codes.

32. On information and belief, Hughes Defendants manufacture, use, import, offer for sale, or sell products, methods, equipment, and/or services that implement the DVB-S2 standard. For example, Hughes Defendants provide satellite

broadband internet access to consumers and broadband network services to the enterprise markets, among other activities, including through their HN System and HX System product lines. Hughes Defendants have extensively publicized that their flagship HN System and HX System satellite broadband internet product lines implement the DVB-S2 standard. On information and belief, Hughes Defendants market and sell, among other activities, certain broadband equipment and services that implements the DVB-S2 standard through the HughesNet brand. On information and belief, Hughes Defendants further sell or provide certain broadband equipment and services that implements the DVB-S2 standard to Dish Defendants. On information and belief, Hughes Defendants use their broadband equipment that implements the DVB-S2 standard for testing, consulting, and/or support services, among other activities.

33. On information and belief, Dish Defendants manufacture, use, import, offer for sale, or sell products, methods, equipment, and/or services that implement the DVB-S2 standard. For example, on information and belief, Dish Defendants market, offer for sale, sell, and distribute, among other activities, Hughes Defendants' satellite internet service, among other products and services, under the dishNET brand pursuant to a distribution agreement entered into with Hughes Defendants in October 2012. On information and belief, Dish Defendants purchase certain broadband equipment and services that implements the DVB-S2 standard from Hughes Defendants and offer for sale, sell, provide, and/or distribute this equipment and service to its customers. On information and belief, Dish Defendants use this broadband equipment and service that implements the DVB-S2 standard for testing, consulting and/or support services, among other activities. On information and belief, the dishNET services are primarily bundled with other services offered by Dish Defendants.

34. Hughes Defendants admit that their broadband satellite systems are compliant with "high-speed DVB-S2." (Exhibit J.) Additionally, Hughes

Defendants have touted that implementation of this DVB-S2 standard "provides for higher throughputs, better coding efficiency, and improved satellite resource utilization for the outbound channel." (Exhibit K.)

35. Further, Hughes Defendants' website advertises its HX System and provides a link to a brochure titled "High-Performance IP Satellite Broadband System." (Exhibit L.) This brochure similarly highlights Hughes Defendants' implementation of the DVB-S2 standard, stating that the core component of the HX System, the HX Gateway, "uses a DVB-S2 carrier . . . for the outbound channel received by all HX System remote terminals." (*Id.*)

36. Hughes Defendants' website also advertises its HN System and states that it is compliant with DVB-S2. (Exhibit M.)

COUNT I

Infringement of the '710 Patent

37. Plaintiff re-alleges and incorporates by reference the allegations of the preceding paragraphs of this Complaint as if fully set forth herein.

38. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are currently infringing, directly and/or through intermediaries, the '710 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services that practice one or more claims of the '710 patent. These products, methods, equipment, and/or services include products that implement the DVB-S2 standard, including without limitation products in the HN System and HX System product lines, satellite internet product lines distributed under the dishNET brand, network and network services that employ these products, and/or marketing, consulting, and/or support services provided for these products and services (collectively, the "Accused Services and Products"). For example, at least Paragraphs 32 and 33 illustrate a limited number of examples of Defendants' direct infringement of the '710 patent. Defendants have infringed and are currently infringing literally and/or

under the doctrine of equivalents.

39. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are continuing to infringe the '710 patent by contributing to and/or actively inducing the infringement by others of the '710 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services, including the Accused Services and Products, that practice one or more claims of the '710 patent.

40. Hughes Defendants have had actual knowledge of their infringement of the '710 patent before the filing date of this Complaint through letters alleging such infringement, or at least have had actual knowledge of their infringement of the '710 patent since no later than the filing date of this Complaint.

41. On information and belief, Dish Defendants have had actual knowledge of their infringement of the '710 patent before the filing date of this Complaint based on their marketing, sale, and distribution, among other activities, of Hughes Defendants' satellite internet service and their relationship with Hughes Defendants (*see* Paragraphs 9, 10, 33). Dish Defendants at least have had actual knowledge of their infringement of the '710 patent since no later than the filing date of this Complaint.

42. Notwithstanding Defendants' actual notice of infringement, Defendants have continued, directly and/or through intermediaries, to manufacture, use, import, offer for sale, or sell the Accused Services and Products with knowledge of or willful blindness to the fact that their actions will induce others, including but not limited to their customers, partners, and/or end users, to infringe the '710 patent. Defendants have induced and continue to induce others to infringe the '710 patent in violation of 35 U.S.C. § 271 by encouraging and facilitating others to perform actions that Defendants know to be acts of infringement of the '710 patent with intent that those performing the acts infringe the '710 patent. Upon information and belief, Defendants, directly and/or through intermediaries,

advertise and distribute the Accused Services and Products, publish instruction materials, specifications and/or promotional literature describing the operation of the Accused Services and Products, and/or offer training and/or consulting services regarding the Accused Services and Products to their customers, partners, and/or end users. At least consumers, partners, and/or end users of these Accused Services and Products then directly or jointly infringe the ’710 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

43. Upon information and belief, Defendants know that the Accused Services and Products are especially made or especially adapted for use in the infringement of the ’710 patent. The infringing components of these products are not staple articles or commodities of commerce suitable for substantial non-infringing use, and the infringing components of these products are a material part of the invention of the ’710 patent. Accordingly, in violation of 35 U.S.C. § 271, Defendants are also contributing, directly and/or through intermediaries, to the direct infringement of the ’710 patent by at least the customers, partners, and/or end users of these Accused Services and Products. The customers, partners, and/or end users of these Accused Services and Products directly infringe the ’710 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

44. As but one example of Hughes Defendants’ contributory and/or induced infringement, Hughes Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the ’710 patent by using the Accused Services and Products. As detailed in Paragraphs 34 through 36, Hughes Defendants’ website advertises its HN System and HX System, and provides information and brochures regarding these systems. (*See* Exhibits J, K, L, M.) These webpages and brochures highlight Hughes Defendants’ implementation of the DVB-S2 standard. On information and belief, through materials such as these, the

Hughes Defendants actively encourage their consumers, partners, and/or end users to infringe the '710 patent through at least use of the HN System and HX System product lines, knowing those acts to be infringement of the '710 patent with intent that those performing the acts infringe the '710 patent.

45. As but one example of Dish Defendants' contributory and/or induced infringement, Dish Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '710 patent by using the Accused Services and Products. According to Dish Defendants' 2012 Annual Report (10-K), Dish Defendants lease to dishNET satellite internet subscribers the customer premise equipment. On information and belief, this equipment implements the DVB-S2 standard. On information and belief, through providing this equipment, Dish Defendants actively encourage their consumers and end users to infringe the '710 patent through at least use of the equipment, knowing those acts to be infringement of the '710 patent with intent that those performing the acts infringe the '710 patent.

46. Defendants are not licensed or otherwise authorized to practice, contributorily practice and/or induce third parties to practice the claims of the '710 patent.

47. By reason of Defendants' infringing activities, Caltech has suffered, and will continue to suffer, substantial damages.

48. Caltech is entitled to recover from Defendants the damages sustained as a result of Defendants' wrongful acts in an amount subject to proof at trial.

49. Defendants' continuing acts of infringement are irreparably harming and causing damage to Caltech, for which Caltech has no adequate remedy at law, and will continue to suffer such irreparable injury unless Defendants' continuing acts of infringement are enjoined by the Court. The hardships that an injunction would impose are less than those faced by Caltech should an injunction not issue. The public interest would be served by issuance of an injunction. Thus, Caltech is entitled to a preliminary and a permanent injunction against further infringement.

50. Hughes Defendants' infringement of the '710 patent has been and continues to be willful and deliberate, justifying a trebling of damages under 35 U.S.C. § 284. Among other facts, Hughes Defendants have had knowledge of their infringement of the '710 patent before the filing date of this Complaint through letters alleging such infringement. Upon information and belief, Hughes Defendants' accused actions continued despite an objectively high likelihood that they constituted infringement of the '710 patent. Hughes Defendants either knew or should have known about their risk of infringing the '710 patent. Hughes Defendants' conduct despite this knowledge was made with both objective and subjective reckless disregard for the infringing nature of their activities as demonstrated by Hughes Defendants' knowledge regarding the claims of the '710 patent.

51. Defendants' infringement of the '710 patent is exceptional and entitles Caltech to attorneys' fees and costs incurred in prosecuting this action under 35 U.S.C. § 285.

COUNT II

Infringement of the '032 Patent

52. Plaintiff re-alleges and incorporates by reference the allegations of the preceding paragraphs of this Complaint as if fully set forth herein.

53. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are currently infringing, directly and/or through intermediaries, the '032 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services that practice one or more claims of the '032 patent. These products, methods, equipment, and/or services include products that implement the DVB-S2 standard, including without limitation products in the HN System and HX System product lines, satellite internet product lines distributed under the dishNET brand, network and network services that employ these products, and/or marketing, consulting,

and/or support services provided for these products and services (collectively, the "Accused Services and Products"). For example, at least Paragraphs 32 and 33 illustrate a limited number of examples of Defendants' direct infringement of the '032 patent. Defendants have infringed and are currently infringing literally and/or under the doctrine of equivalents.

54. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are continuing to infringe the '032 patent by contributing to and/or actively inducing the infringement by others of the '032 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services, including the Accused Services and Products, that practice one or more claims of the '032 patent.

55. Hughes Defendants have had actual knowledge of their infringement of the '032 patent before the filing date of this Complaint through letters alleging such infringement, or at least have had actual knowledge of their infringement of the '032 patent since no later than the filing date of this Complaint.

56. On information and belief, Dish Defendants have had actual knowledge of their infringement of the '032 patent before the filing date of this Complaint based on their marketing, sale, and distribution, among other activities, of Hughes Defendants' satellite internet service and their relationship with Hughes Defendants (*see* Paragraphs 9, 10, 33). Dish Defendants at least have had actual knowledge of their infringement of the '032 patent since no later than the filing date of this Complaint.

57. Notwithstanding Defendants' actual notice of infringement, Defendants have continued, directly and/or through intermediaries, to manufacture, use, import, offer for sale, or sell the Accused Services and Products with knowledge of or willful blindness to the fact that their actions will induce others, including but not limited to their customers, partners, and/or end users, to infringe the '032 patent. Defendants have induced and continue to induce others to infringe the '032 patent in

violation of 35 U.S.C. § 271 by encouraging and facilitating others to perform actions that Defendants know to be acts of infringement of the '032 patent with intent that those performing the acts infringe the '032 patent. Upon information and belief, Defendants, directly and/or through intermediaries, advertise and distribute the Accused Services and Products, publish instruction materials, specifications and/or promotional literature describing the operation of the Accused Services and Products, and/or offer training and/or consulting services regarding the Accused Services and Products to their customers, partners, and/or end users. At least consumers, partners, and/or end users of these Accused Services and Products then directly or jointly infringe the '032 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

58. Upon information and belief, Defendants know that the Accused Services and Products are especially made or especially adapted for use in the infringement of the '032 patent. The infringing components of these products are not staple articles or commodities of commerce suitable for substantial non-infringing use, and the infringing components of these products are a material part of the invention of the '032 patent. Accordingly, in violation of 35 U.S.C. § 271, Defendants are also contributing, directly and/or through intermediaries, to the direct infringement of the '032 patent by at least the customers, partners, and/or end users of these Accused Services and Products. The customers, partners, and/or end users of these Accused Services and Products directly infringe the '032 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

59. As but one example of Hughes Defendants' contributory and/or induced infringement, Hughes Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '032 patent by using the Accused Services and Products. As detailed in Paragraphs 34 through 36, Hughes

Defendants' website advertises its HN System and HX System, and provides information and brochures regarding these systems. (*See* Exhibits J, K, L, M.) These webpages and brochures highlight Hughes Defendants' implementation of the DVB-S2 standard. On information and belief, through materials such as these, the Hughes Defendants actively encourage their consumers, partners, and/or end users to infringe the '032 patent through at least use of the HN System and HX System product lines, knowing those acts to be infringement of the '032 patent with intent that those performing the acts infringe the '032 patent.

60. As but one example of Dish Defendants' contributory and/or induced infringement, Dish Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '032 patent by using the Accused Services and Products. According to Dish Defendants' 2012 Annual Report (10-K), Dish Defendants lease to dishNET satellite internet subscribers the customer premise equipment. On information and belief, this equipment implements the DVB-S2 standard. On information and belief, through providing this equipment, Dish Defendants actively encourage their consumers and end users to infringe the '032 patent through at least use of the equipment, knowing those acts to be infringement of the '032 patent with intent that those performing the acts infringe the '032 patent.

61. Defendants are not licensed or otherwise authorized to practice, contributorily practice and/or induce third parties to practice the claims of the '032 patent.

62. By reason of Defendants' infringing activities, Caltech has suffered, and will continue to suffer, substantial damages.

63. Caltech is entitled to recover from Defendants the damages sustained as a result of Defendants' wrongful acts in an amount subject to proof at trial.

64. Defendants' continuing acts of infringement are irreparably harming and causing damage to Caltech, for which Caltech has no adequate remedy at law, and will continue to suffer such irreparable injury unless Defendants' continuing

acts of infringement are enjoined by the Court. The hardships that an injunction would impose are less than those faced by Caltech should an injunction not issue. The public interest would be served by issuance of an injunction. Thus, Caltech is entitled to a preliminary and a permanent injunction against further infringement.

65. Hughes Defendants' infringement of the '032 patent has been and continues to be willful and deliberate, justifying a trebling of damages under 35 U.S.C. § 284. Among other facts, Hughes Defendants have had knowledge of their infringement of the '032 patent before the filing date of this Complaint through letters alleging such infringement. Upon information and belief, Hughes Defendants' accused actions continued despite an objectively high likelihood that they constituted infringement of the '032 patent. Hughes Defendants either knew or should have known about their risk of infringing the '032 patent. Hughes Defendants' conduct despite this knowledge was made with both objective and subjective reckless disregard for the infringing nature of their activities as demonstrated by Hughes Defendants' knowledge regarding the claims of the '032 patent.

66. Defendants' infringement of the '032 patent is exceptional and entitles Caltech to attorneys' fees and costs incurred in prosecuting this action under 35 U.S.C. § 285.

COUNT III

Infringement of the '781 Patent

67. Plaintiff re-alleges and incorporates by reference the allegations of the preceding paragraphs of this Complaint as if fully set forth herein.

68. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are currently infringing, directly and/or through intermediaries, the '781 patent by using, without authority, products, methods, equipment, and/or services that practice one or more claims of the '781 patent. These products, methods, equipment, and/or services include products that implement the DVB-S2

standard, including without limitation products in the HN System and HX System product lines, satellite internet product lines distributed under the dishNET brand, network and network services that employ these products, and/or marketing, consulting, and/or support services provided for these products and services (collectively, the "Accused Services and Products"). For example, at least Paragraphs 32 and 33 illustrate a limited number of examples of Defendants' direct infringement of the '781 patent. Defendants have infringed and are currently infringing literally and/or under the doctrine of equivalents.

69. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are continuing to infringe the '781 patent by contributing to and/or actively inducing the infringement by others of the '781 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services, including the Accused Services and Products, that practice one or more claims of the '781 patent.

70. On information and belief, Hughes Defendants have had actual knowledge of their infringement of the '781 patent, the subject matter of the '781 patent, and/or the invention of the '781 patent before the filing date of this Complaint. On information and belief, Hughes Defendants also had knowledge of the application that led to the '781 patent before the filing date of this Complaint. Hughes Defendants at least have had actual knowledge of their infringement of the '781 patent since no later than the filing date of this Complaint.

71. On information and belief, Dish Defendants have had actual knowledge of their infringement of the '781 patent before the filing date of this Complaint based on their marketing, sale, and distribution, among other activities, of Hughes Defendants' satellite internet service and their relationship with Hughes Defendants (*see* Paragraphs 9, 10, 33). Dish Defendants at least have had actual knowledge of their infringement of the '781 patent since no later than the filing date of this Complaint.

72. Notwithstanding Defendants' actual notice of infringement, Defendants have continued, directly and/or through intermediaries, to manufacture, use, import, offer for sale, or sell the Accused Services and Products with knowledge of or willful blindness to the fact that their actions will induce others, including but not limited to their customers, partners, and/or end users, to infringe the '781 patent. Defendants have induced and continue to induce others to infringe the '781 patent in violation of 35 U.S.C. § 271 by encouraging and facilitating others to perform actions that Defendants know to be acts of infringement of the '781 patent with intent that those performing the acts infringe the '781 patent. Upon information and belief, Defendants, directly and/or through intermediaries, advertise and distribute the Accused Services and Products, publish instruction materials, specifications and/or promotional literature describing the operation of the Accused Services and Products, and/or offer training and/or consulting services regarding the Accused Services and Products to their customers, partners, and/or end users. At least consumers, partners, and/or end users of these Accused Services and Products then directly or jointly infringe the '781 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

73. Upon information and belief, Defendants know that the Accused Services and Products are especially made or especially adapted for use in the infringement of the '781 patent. The infringing components of these products are not staple articles or commodities of commerce suitable for substantial non-infringing use, and the infringing components of these products are a material part of the invention of the '781 patent. Accordingly, in violation of 35 U.S.C. § 271, Defendants are also contributing, directly and/or through intermediaries, to the direct infringement of the '781 patent by at least the customers, partners, and/or end users of these Accused Services and Products. The customers, partners, and/or end users of these Accused Services and Products directly infringe the '781 patent by

making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

74. As but one example of Hughes Defendants' contributory and/or induced infringement, Hughes Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '781 patent by using the Accused Services and Products. As detailed in Paragraphs 34 through 36, Hughes Defendants' website advertises its HN System and HX System, and provides information and brochures regarding these systems. (*See* Exhibits J, K, L, M.) These webpages and brochures highlight Hughes Defendants' implementation of the DVB-S2 standard. On information and belief, through materials such as these, the Hughes Defendants actively encourage their consumers, partners, and/or end users to infringe the '781 patent through at least use of the HN System and HX System product lines, knowing those acts to be infringement of the '781 patent with intent that those performing the acts infringe the '781 patent.

75. As but one example of Dish Defendants' contributory and/or induced infringement, Dish Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '781 patent by using the Accused Services and Products. According to Dish Defendants' 2012 Annual Report (10-K), Dish Defendants lease to dishNET satellite internet subscribers the customer premise equipment. On information and belief, this equipment implements the DVB-S2 standard. On information and belief, through providing this equipment, Dish Defendants actively encourage their consumers and end users to infringe the '781 patent through at least use of the equipment, knowing those acts to be infringement of the '781 patent with intent that those performing the acts infringe the '781 patent.

76. Defendants are not licensed or otherwise authorized to practice, contributorily practice and/or induce third parties to practice the claims of the '781 patent.

77. By reason of Defendants' infringing activities, Caltech has suffered,

and will continue to suffer, substantial damages.

78. Caltech is entitled to recover from Defendants the damages sustained as a result of Defendants' wrongful acts in an amount subject to proof at trial.

79. Defendants' continuing acts of infringement are irreparably harming and causing damage to Caltech, for which Caltech has no adequate remedy at law, and will continue to suffer such irreparable injury unless Defendants' continuing acts of infringement are enjoined by the Court. The hardships that an injunction would impose are less than those faced by Caltech should an injunction not issue. The public interest would be served by issuance of an injunction. Thus, Caltech is entitled to a preliminary and a permanent injunction against further infringement.

80. Hughes Defendants' infringement of the '781 patent has been and continues to be willful and deliberate, justifying a trebling of damages under 35 U.S.C. § 284. Among other facts, on information and belief, Hughes Defendants have had knowledge of their infringement of the '781 patent, the subject matter of the '781 patent, and/or the invention of the '781 patent before the filing date of this Complaint. Upon information and belief, Hughes Defendants' accused actions continued despite an objectively high likelihood that they constituted infringement of the '781 patent. Hughes Defendants either knew or should have known about their risk of infringing the '781 patent. Hughes Defendants' conduct despite this knowledge was made with both objective and subjective reckless disregard for the infringing nature of their activities as demonstrated by Hughes Defendants' knowledge regarding the claims of the '781 patent.

81. Defendants' infringement of the '781 patent is exceptional and entitles Caltech to attorneys' fees and costs incurred in prosecuting this action under 35 U.S.C. § 285.

COUNT IV

Infringement of the '833 Patent

82. Plaintiff re-alleges and incorporates by reference the allegations of the

preceding paragraphs of this Complaint as if fully set forth herein.

83. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are currently infringing, directly and/or through intermediaries, the '833 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services that practice one or more claims of the '833 patent. These products, methods, equipment, and/or services include products that implement the DVB-S2 standard, including without limitation products in the HN System and HX System product lines, satellite internet product lines distributed under the dishNET brand, network and network services that employ these products, and/or marketing, consulting, and/or support services provided for these products and services (collectively, the "Accused Services and Products"). For example, at least Paragraphs 32 and 33 illustrate a limited number of examples of Defendants' direct infringement of the '833 patent. Defendants have infringed and are currently infringing literally and/or under the doctrine of equivalents.

84. On information and belief, in violation of 35 U.S.C. § 271, Defendants have infringed and are continuing to infringe the '833 patent by contributing to and/or actively inducing the infringement by others of the '833 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, products, methods, equipment, and/or services, including the Accused Services and Products, that practice one or more claims of the '833 patent.

85. On information and belief, Hughes Defendants have had actual knowledge of their infringement of the '833 patent, the subject matter of the '833 patent, and/or the invention of the '833 patent before the filing date of this Complaint. On information and belief, Hughes Defendants also had knowledge of the application that led to the '833 patent before the filing date of this Complaint. Hughes Defendants at least have had actual knowledge of their infringement of the '833 patent since no later than the filing date of this Complaint.

86. On information and belief, Dish Defendants have had actual knowledge of their infringement of the '833 patent before the filing date of this Complaint based on their marketing, sale, and distribution, among other activities, of Hughes Defendants' satellite internet service and their relationship with Hughes Defendants (*see* Paragraphs 9, 10, 33). Dish Defendants at least have had actual knowledge of their infringement of the '833 patent since no later than the filing date of this Complaint.

87. Notwithstanding Defendants' actual notice of infringement, Defendants have continued, directly and/or through intermediaries, to manufacture, use, import, offer for sale, or sell the Accused Services and Products with knowledge of or willful blindness to the fact that their actions will induce others, including but not limited to their customers, partners, and/or end users, to infringe the '833 patent. Defendants have induced and continue to induce others to infringe the '833 patent in violation of 35 U.S.C. § 271 by encouraging and facilitating others to perform actions that Defendants know to be acts of infringement of the '833 patent with intent that those performing the acts infringe the '833 patent. Upon information and belief, Defendants, directly and/or through intermediaries, advertise and distribute the Accused Services and Products, publish instruction materials, specifications and/or promotional literature describing the operation of the Accused Services and Products, and/or offer training and/or consulting services regarding the Accused Services and Products to their customers, partners, and/or end users. At least consumers, partners, and/or end users of these Accused Services and Products then directly or jointly infringe the '833 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

88. Upon information and belief, Defendants know that the Accused Services and Products are especially made or especially adapted for use in the infringement of the '833 patent. The infringing components of these products are

not staple articles or commodities of commerce suitable for substantial non-infringing use, and the infringing components of these products are a material part of the invention of the '833 patent. Accordingly, in violation of 35 U.S.C. § 271, Defendants are also contributing, directly and/or through intermediaries, to the direct infringement of the '833 patent by at least the customers, partners, and/or end users of these Accused Services and Products. The customers, partners, and/or end users of these Accused Services and Products directly infringe the '833 patent by making, using, selling, offering for sale, and/or importing into the United States, without authority, the Accused Services and Products.

89. As but one example of Hughes Defendants' contributory and/or induced infringement, Hughes Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '833 patent by using the Accused Services and Products. As detailed in Paragraphs 34 through 36, Hughes Defendants' website advertises its HN System and HX System, and provides information and brochures regarding these systems. (*See* Exhibits J, K, L, M.) These webpages and brochures highlight Hughes Defendants' implementation of the DVB-S2 standard. On information and belief, through materials such as these, the Hughes Defendants actively encourage their consumers, partners, and/or end users to infringe the '833 patent through at least use of the HN System and HX System product lines, knowing those acts to be infringement of the '833 patent with intent that those performing the acts infringe the '833 patent.

90. As but one example of Dish Defendants' contributory and/or induced infringement, Dish Defendants explicitly encourage their customers to practice the methods disclosed and claimed in the '833 patent by using the Accused Services and Products. According to Dish Defendants' 2012 Annual Report (10-K), Dish Defendants lease to dishNET satellite internet subscribers the customer premise equipment. On information and belief, this equipment implements the DVB-S2 standard. On information and belief, through providing this equipment, Dish

Defendants actively encourage their consumers and end users to infringe the '833 patent through at least use of the equipment, knowing those acts to be infringement of the '833 patent with intent that those performing the acts infringe the '833 patent.

91. Defendants are not licensed or otherwise authorized to practice, contributorily practice and/or induce third parties to practice the claims of the '833 patent.

92. By reason of Defendants' infringing activities, Caltech has suffered, and will continue to suffer, substantial damages.

93. Caltech is entitled to recover from Defendants the damages sustained as a result of Defendants' wrongful acts in an amount subject to proof at trial.

94. Defendants' continuing acts of infringement are irreparably harming and causing damage to Caltech, for which Caltech has no adequate remedy at law, and will continue to suffer such irreparable injury unless Defendants' continuing acts of infringement are enjoined by the Court. The hardships that an injunction would impose are less than those faced by Caltech should an injunction not issue. The public interest would be served by issuance of an injunction. Thus, Caltech is entitled to a preliminary and a permanent injunction against further infringement.

95. Hughes Defendants' infringement of the '833 patent has been and continues to be willful and deliberate, justifying a trebling of damages under 35 U.S.C. § 284. Among other facts, on information and belief, Hughes Defendants have had knowledge of their infringement of the '833 patent, the subject matter of the '833 patent, and/or the invention of the '833 patent before the filing date of this Complaint. Upon information and belief, Hughes Defendants' accused actions continued despite an objectively high likelihood that they constituted infringement of the '833 patent. Hughes Defendants either knew or should have known about their risk of infringing the '833 patent. Hughes Defendants' conduct despite this knowledge was made with both objective and subjective reckless disregard for the

infringing nature of their activities as demonstrated by Hughes Defendants' knowledge regarding the claims of the '833 patent.

96. Defendants' infringement of the '833 patent is exceptional and entitles Caltech to attorneys' fees and costs incurred in prosecuting this action under 35 U.S.C. § 285.

PRAYER FOR RELIEF

WHEREFORE, Plaintiff respectfully prays for the following relief:

(a) A judgment that Defendants have infringed each and every one of the Asserted Patents;

(b) A preliminary and permanent injunction against Defendants, its respective officers, agents, servants, employees, attorneys, parent and subsidiary corporations, assigns and successors in interest, and those persons in active concert or participation with them, enjoining them from infringement, inducement of infringement, and contributory infringement of each and every one of the Asserted Patents, including but not limited to an injunction against making, using, selling, and/or offering for sale within the United States, and/or importing into the United States, any products, methods, equipment and/or services that infringe the Asserted Patents;

(c) Damages adequate to compensate Caltech for Defendants' infringement of the Asserted Patents pursuant to 35 U.S.C. § 284;

(d) Prejudgment interest;

(e) Post-judgment interest;

(f) A judgment holding Hughes Defendants' infringement of the Asserted Patents to be willful, and a trebling of damages pursuant to 35 U.S.C. § 284;

(g) A declaration that this Action is exceptional pursuant to 35 U.S.C. § 285, and an award to Caltech of its attorneys' fees, costs and expenses incurred in connection with this Action; and

(h) Such other relief as the Court deems just and equitable.

DATED: October 1, 2013

Respectfully submitted,

QUINN EMANUEL URQUHART & SULLIVAN, LLP

By ______________________

James R. Asperger
Attorneys for Plaintiff California Institute of Technology

DEMAND FOR JURY TRIAL

Pursuant to Rule 38 of the Federal Rules of Civil Procedure and Local Rule 38-1 of this Court, Plaintiff hereby demands a trial by jury as to all issues so triable.

DATED: October 1, 2013

Respectfully submitted,

QUINN EMANUEL URQUHART & SULLIVAN, LLP

By ______________________

James R. Asperger

Attorneys for Plaintiff California Institute of Technology

US007116710B1

(12) **United States Patent**
Jin et al.

(10) **Patent No.: US 7,116,710 B1**
(45) **Date of Patent: Oct. 3, 2006**

(54) **SERIAL CONCATENATION OF INTERLEAVED CONVOLUTIONAL CODES FORMING TURBO-LIKE CODES**

(75) Inventors: **Hui Jin**, Glen Gardner, NJ (US); **Aamod Khandekar**, Pasadena, CA (US); **Robert J. McEliece**, Pasadena, CA (US)

(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 735 days.

(21) Appl. No.: **09/861,102**

(22) Filed: **May 18, 2001**

Related U.S. Application Data

(60) Provisional application No. 60/205,095, filed on May 18, 2000.

(51) **Int. Cl.**
H04B 1/66 (2006.01)

(52) **U.S. Cl.** **375/240**; 375/262; 375/265; 375/341; 341/51; 341/102; 714/752

(58) **Field of Classification Search** 375/259, 375/262, 265, 285, 296, 341, 346, 348; 714/746, 714/752, 755, 756, 786, 792, 794, 795, 796; 341/51, 52, 56, 102, 103
See application file for complete search history.

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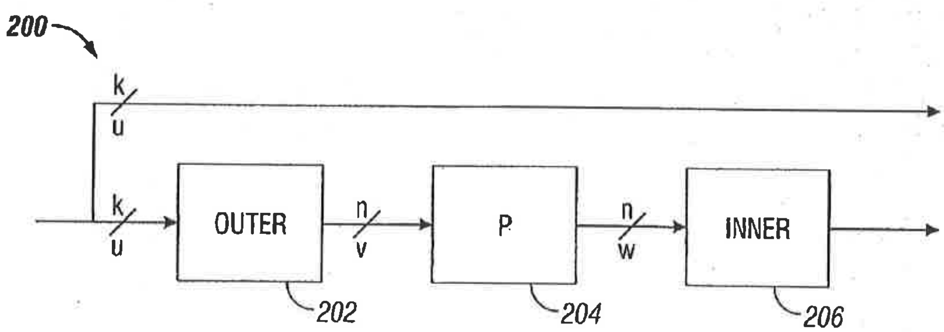
(Continued)

Primary Examiner—Dac V. Ha
(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

A serial concatenated coder includes an outer coder and an inner coder. The outer coder irregularly repeats bits in a data block according to a degree profile and scrambles the repeated bits. The scrambled and repeated bits are input to an inner coder, which has a rate substantially close to one.

33 Claims, 5 Drawing Sheets



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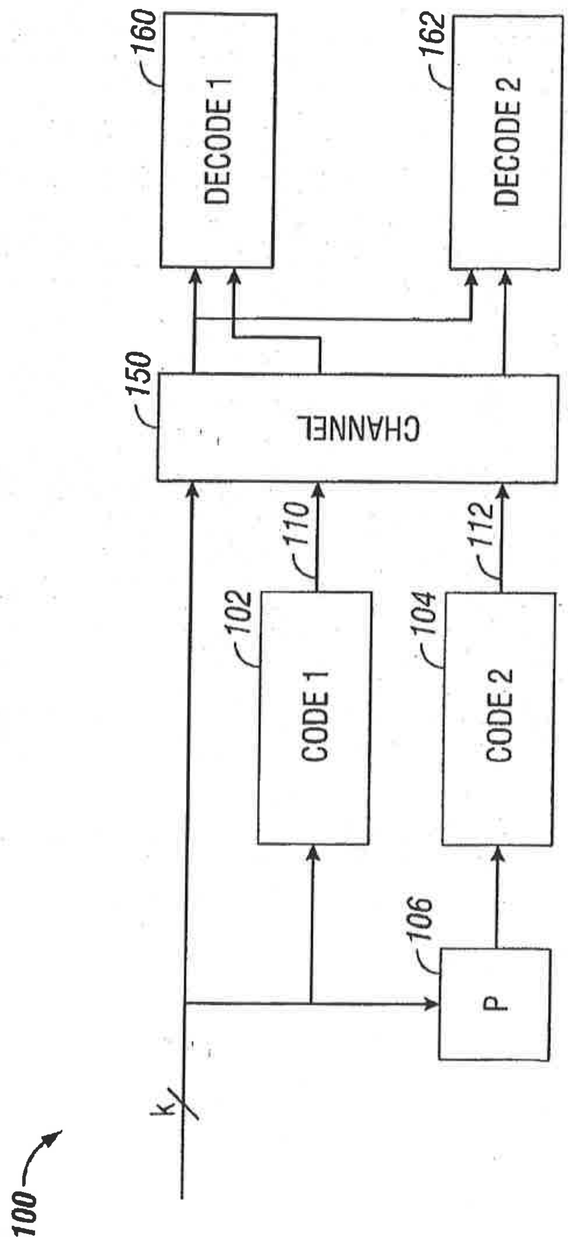

FIG. 1
(Prior Art)

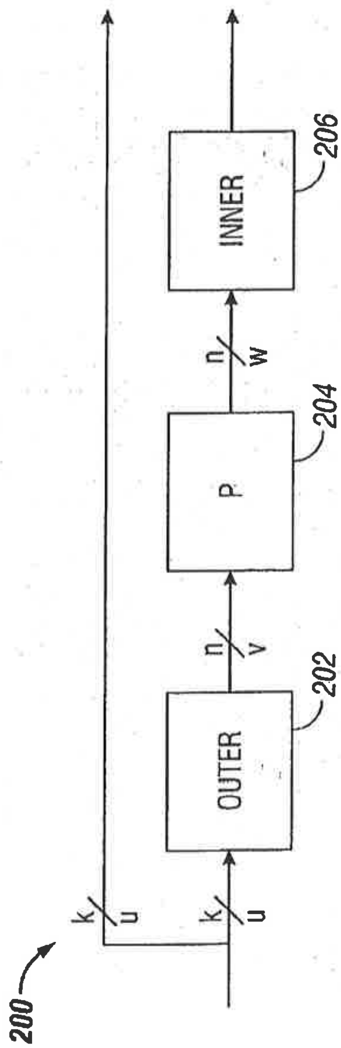

FIG. 2

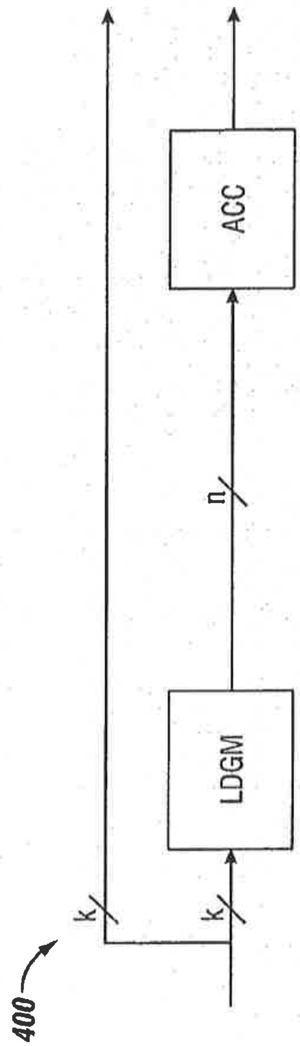

FIG. 4

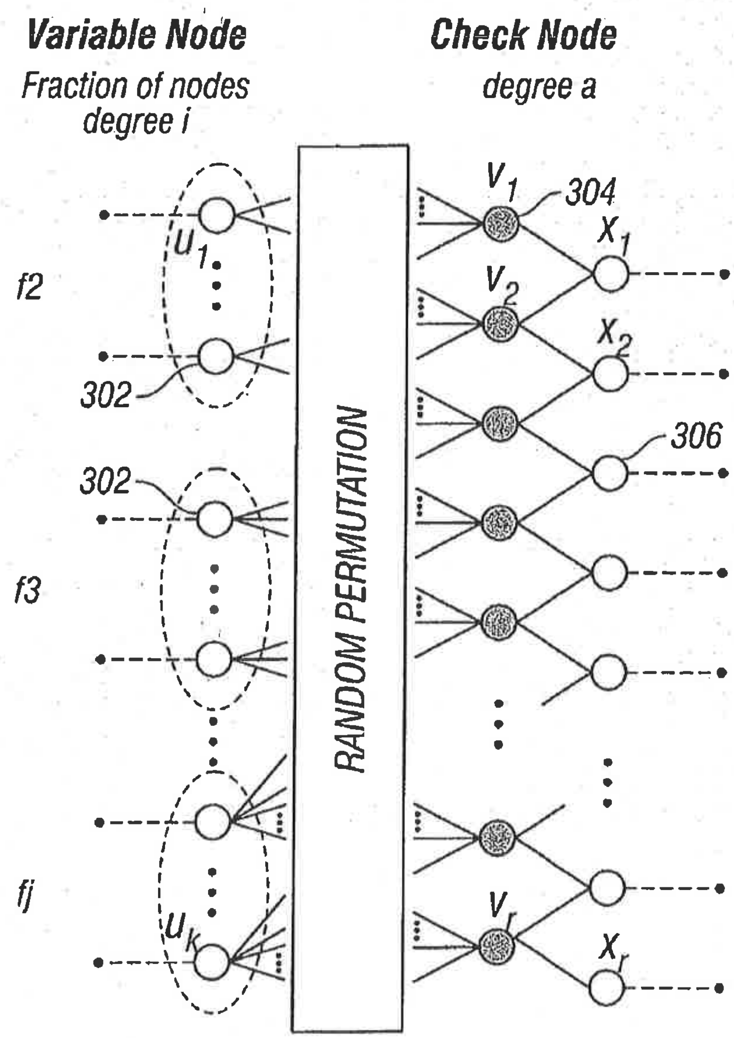
Variable Node
Fraction of nodes
degree i
Check Node
degree a
RANDOM PERMUTATION
f2
f3
fj
302
302
304
306
U1
Uk
V1
V2
Vr
X1
X2
Xr

FIG. 3

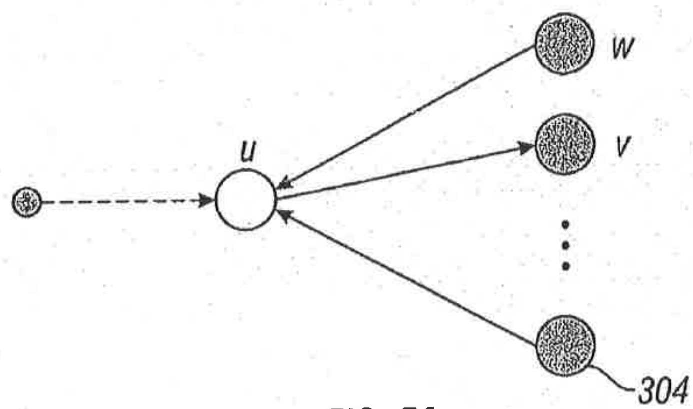

FIG. 5A

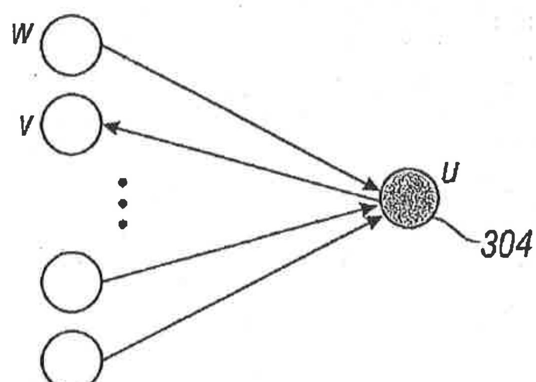

FIG. 5B

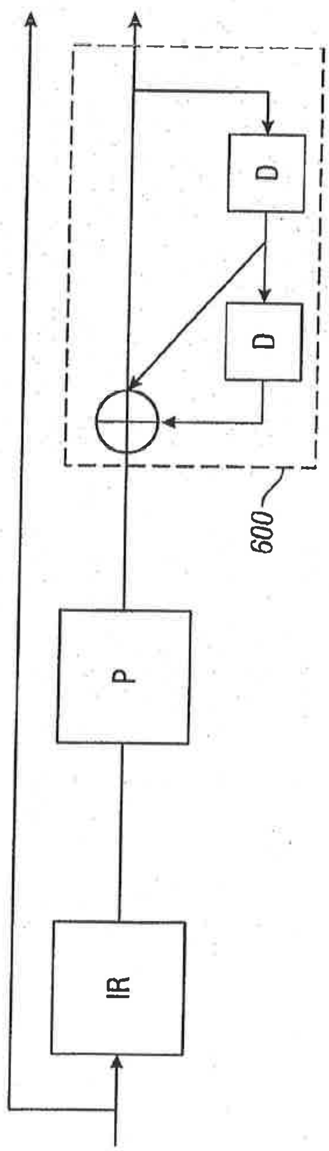

FIG. 6

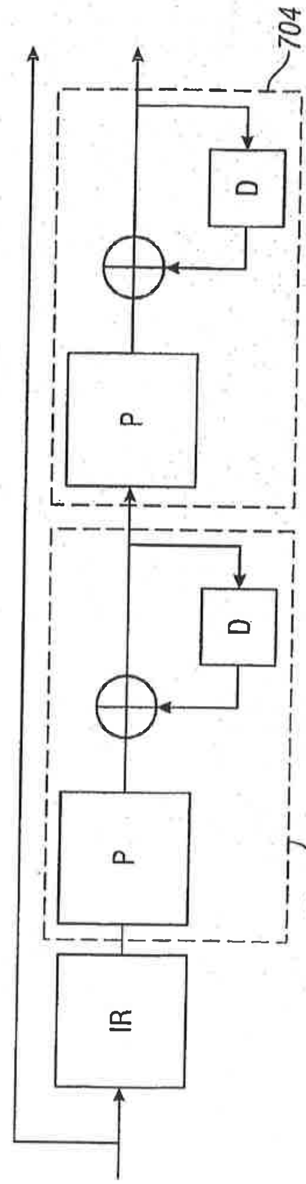

FIG. 7

SERIAL CONCATENATION OF INTERLEAVED CONVOLUTIONAL CODES FORMING TURBO-LIKE CODES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application Ser. No. 60/205,095, filed on May 18, 2000, and to U.S. application Ser. No. 09/922,852, filed on Aug. 18, 2000 and entitled Interleaved Serial Concatenation Forming Turbo-Like Codes.

GOVERNMENT LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Grant No. CCR-9804793 awarded by the National Science Foundation.

BACKGROUND

Properties of a channel affect the amount of data that can be handled by the channel. The so-called "Shannon limit" defines the theoretical limit of the amount of data that a channel can carry.

Different techniques have been used to increase the data rate that can be handled by a channel. "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo Codes," by Berrou et al. ICC, pp 1064–1070, (1993), described a new "turbo code" technique that has revolutionized the field of error correcting codes. Turbo codes have sufficient randomness to allow reliable communication over the channel at a high data rate near capacity. However, they still retain sufficient structure to allow practical encoding and decoding algorithms. Still, the technique for encoding and decoding turbo codes can be relatively complex.

A standard turbo coder **100** is shown in FIG. **1**. A block of k information bits is input directly to a first coder **102**. A k bit interleaver **106** also receives the k bits and interleaves them prior to applying them to a second coder **104**. The second coder produces an output that has more bits than its input, that is, it is a coder with rate that is less than **1**. The coders **102**, **104** are typically recursive convolutional coders.

Three different items are sent over the channel **150**: the original k bits, first encoded bits **110**, and second encoded bits **112**. At the decoding end, two decoders are used: a first constituent decoder **160** and a second constituent decoder **162**. Each receives both the original k bits, and one of the encoded portions **110**, **112**. Each decoder sends likelihood estimates of the decoded bits to the other decoders. The estimates are used to decode the uncoded information bits as corrupted by the noisy channel.

SUMMARY

A coding system according to an embodiment is configured to receive a portion of a signal to be encoded, for example, a data block including a fixed number of bits. The coding system includes an outer coder, which repeats and scrambles bits in the data block. The data block is apportioned into two or more sub-blocks, and bits in different sub-blocks are repeated a different number of times according to a selected degree profile. The outer coder may include a repeater with a variable rate and an interleaver. Alternatively, the outer coder may be a low-density generator matrix (LDGM) coder.

The repeated and scrambled bits are input to an inner coder that has a rate substantially close to one. The inner coder may include one or more accumulators that perform recursive modulo two addition operations on the input bit stream.

The encoded data output from the inner coder may be transmitted on a channel and decoded in linear time at a destination using iterative decoding techniques. The decoding techniques may be based on a Tanner graph representation of the code.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of a prior "turbo code" system.

FIG. **2** is a schematic diagram of a coder according to an embodiment.

FIG. **3** is a Tanner graph for an irregular repeat and accumulate (IRA) coder.

FIG. **4** is a schematic diagram of an IRA coder according to an embodiment.

FIG. **5A** illustrates a message from a variable node to a check node on the Tanner graph of FIG. **3**.

FIG. **5B** illustrates a message from a check node to a variable node on the Tanner graph of FIG. **3**.

FIG. **6** is a schematic diagram of a coder according to an alternate embodiment.

FIG. **7** is a schematic diagram of a coder according to another alternate embodiment.

DETAILED DESCRIPTION

FIG. **2** illustrates a coder **200** according to an embodiment. The coder **200** may include an outer coder **202**, an interleaver **204**, and inner coder **206**. The coder may be used to format blocks of data for transmission, introducing redundancy into the stream of data to protect the data from loss due to transmission errors. The encoded data may then be decoded at a destination in linear time at rates that may approach the channel capacity.

The outer coder **202** receives the uncoded data. The data may be partitioned into blocks of fixed size, say k bits. The outer coder may be an (n,k) binary linear block coder, where n>k. The coder accepts as input a block u of k data bits and produces an output block v of n data bits. The mathematical relationship between u and v is $v=T_0u$, where T_0 is an n×k matrix, and the rate of the coder is k/n.

The rate of the coder may be irregular, that is, the value of T_0 is not constant, and may differ for sub-blocks of bits in the data block. In an embodiment, the outer coder **202** is a repeater that repeats the k bits in a block a number of times q to produce a block with n bits, where n=qk. Since the repeater has an irregular output, different bits in the block may be repeated a different number of times. For example, a fraction of the bits in the block may be repeated two times, a fraction of bits may be repeated three times, and the remainder of bits may be repeated four times. These fractions define a degree sequence, or degree profile, of the code.

The inner coder **206** may be a linear rate-1 coder, which means that the n-bit output block x can be written as $x=T_iw$, where T_i is a nonsingular n×n matrix. The inner coder **210** can have a rate that is close to 1, e.g., within 50%, more preferably 10% and perhaps even more preferably within 1% of 1.

In an embodiment, the inner coder **206** is an accumulator, which produces outputs that are the modulo two (mod-2) partial sums of its inputs. The accumulator may be a truncated rate-1 recursive convolutional coder with the transfer function 1/(1+D). Such an accumulator may be considered a block coder whose input block $[x_1, \ldots, x_n]$ and output block $[y_1, \ldots, y_n]$ are related by the formula

$$y_1 = x_1$$

$$y_2 = x_1 \oplus x_2$$

$$y_3 = x_1 \oplus x_2 \oplus x_3$$

$$y_n = x_1 \oplus x_2 \oplus x_3 \oplus \ldots \oplus x_n.$$

where "⊕" denotes mod-2, or exclusive-OR (XOR), addition. An advantage of this system is that only mod-2 addition is necessary for the accumulator. The accumulator may be embodied using only XOR gates, which may simplify the design.

The bits output from the outer coder **202** are scrambled before they are input to the inner coder **206**. This scrambling may be performed by the interleaver **204**, which performs a pseudo-random permutation of an input block v, yielding an output block w having the same length as v.

The serial concatenation of the interleaved irregular repeat code and the accumulate code produces an irregular repeat and accumulate (IRA) code. An IRA code is a linear code, and as such, may be represented as a set of parity checks. The set of parity checks may be represented in a bipartite graph, called the Tanner graph, of the code. FIG. **3** shows a Tanner graph **300** of an IRA code with parameters $(f_1, \ldots, f_j; a)$, where $f_i \geqq 0$, $\Sigma_i f_i = 1$ and "a" is a positive integer. The Tanner graph includes two kinds of nodes: variable nodes (open circles) and check nodes (filled circles). There are k variable nodes **302** on the left, called information nodes. There are r variable nodes **306** on the right, called parity nodes. There are $r = (k\Sigma_i if_i)/a$ check nodes **304** connected between the information nodes and the parity nodes. Each information node **302** is connected to a number of check nodes **304**. The fraction of information nodes connected to exactly i check nodes is f_i. For example, in the Tanner graph **300**, each of the f_2 information nodes are connected to two check nodes, corresponding to a repeat of q=2, and each of the f_3 information nodes are connected to three check nodes, corresponding to q=3.

Each check node **304** is connected to exactly "a" information nodes **302**. In FIG. **3**, a=3. These connections can be made in many ways, as indicated by the arbitrary permutation of the ra edges joining information nodes **302** and check nodes **304** in permutation block **310**. These connections correspond to the scrambling performed by the interleaver **204**.

In an alternate embodiment, the outer coder **202** may be a low-density generator matrix (LDGM) coder that performs an irregular repeat of the k bits in the block, as shown in FIG. **4**. As the name implies, an LDGM code has a sparse (low-density) generator matrix. The IRA code produced by the coder **400** is a serial concatenation of the LDGM code and the accumulator code. The interleaver **204** in FIG. **2** may be excluded due to the randomness already present in the structure of the LDGM code.

If the permutation performed in permutation block **310** is fixed, the Tanner graph represents a binary linear block code with k information bits $(u_1, \ldots, u_k)$ and r parity bits $(x_1, \ldots, x_r)$, as follows. Each of the information bits is associated with one of the information nodes **302**, and each of the parity bits is associated with one of the parity nodes **306**. The value of a parity bit is determined uniquely by the condition that the mod-2 sum of the values of the variable nodes connected to each of the check nodes **304** is zero. To see this, set $x_0=0$. Then if the values of the bits on the ra edges coming out the permutation box are $(v_1, \ldots, v_{ra})$, then we have the recursive formula

$$x_j = x_{j-1} + \sum_{i=1}^{\lambda} v_{(j-1)\lambda+i}$$

for j=1, 2, . . . , r. This is in effect the encoding algorithm.

Two types of IRA codes are represented in FIG. **3**, a nonsystematic version and a systematic version. The nonsystematic version is an (r,k) code, in which the codeword corresponding to the information bits $(u_1, \ldots, u_k)$ is $(x_1, \ldots, x_r)$. The systematic version is a (k+r, k) code, in which the codeword is $(u_1, \ldots, u_k; x_1, \ldots, x_r)$.

The rate of the nonsystematic code is

$$R_{nsys} = \frac{a}{\sum_i if_i}$$

The rate of the systematic code is

$$R_{sys} = \frac{a}{a + \sum_i if_i}$$

For example, regular repeat and accumulate (RA) codes can be considered nonsystematic IRA codes with a=1 and exactly one f_i equal to 1, say $f_q=1$, and the rest zero, in which case R_{nsys} simplifies to R=1/q.

The IRA code may be represented using an alternate notation. Let λ_i be the fraction of edges between the information nodes **302** and the check nodes **304** that are adjacent to an information node of degree i, and let ρ_i be the fraction of such edges that are adjacent to a check node of degree i+2 (i.e., one that is adjacent to i information nodes). These edge fractions may be used to represent the IRA code rather than the corresponding node fractions. Define $\lambda(x)=\Sigma_i \lambda_i x^{i-1}$ and $\rho(x)=\Sigma_i \rho_i x^{i-1}$ to be the generating functions of these sequences. The pair (λ, ρ) is called a degree distribution. For $L(x)=\Sigma_i f_i x_i$,

$$f_i = \frac{\lambda_i / i}{\sum_j \lambda_j / j}$$

$$L(x) = \int_0^x \lambda(t)dt / \int_0^1 \lambda(t)dt$$

The rate of the systematic IRA code given by the degree distribution is given by

$$\text{Rate} = \left(1 + \frac{\sum_j \rho_j / j}{\sum_j \lambda_j / j}\right)^{-1}$$

"Belief propagation" on the Tanner Graph realization may be used to decode IRA codes. Roughly speaking, the belief propagation decoding technique allows the messages passed on an edge to represent posterior densities on the bit associated with the variable node. A probability density on a bit is a pair of non-negative real numbers p(0), p(1) satisfying p(0)+p(1)=1, where p(0) denotes the probability of the bit being 0, p(1) the probability of it being 1. Such a pair can be represented by its log likelihood ratio, m=log(p(0)/p(1)). The outgoing message from a variable node u to a check node v represents information about u, and a message from a check node u to a variable node v represents information about u, as shown in FIGS. 5A and 5B, respectively.

The outgoing message from a node u to a node v depends on the incoming messages from all neighbors w of u except v. If u is a variable message node, this outgoing message is

$$m(u \to v) = \sum_{w \neq v} m(w \to u) + m_0(u)$$

where $m_0(u)$ is the log-likelihood message associated with u. If u is a check node, the corresponding formula is

$$\tanh\frac{m(u \to v)}{2} = \prod_{w \neq v} \tanh\frac{m(w \to u)}{2}$$

Before decoding, the messages m(w→u) and m(u→v) are initialized to be zero, and $m_0(u)$ is initialized to be the log-likelihood ratio based on the channel received information. If the channel is memoryless, i.e., each channel output only relies on its input, and y is the output of the channel code bit u, then $m_0(i)=\log(p(u=0|y)/p(u=1|y))$. After this initialization, the decoding process may run in a fully parallel and local manner. In each iteration, every variable/check node receives messages from its neighbors, and sends back updated messages. Decoding is terminated after a fixed number of iterations or detecting that all the constraints are satisfied. Upon termination, the decoder outputs a decoded sequence based on the messages $m(u)=\Sigma w_m(w \to u)$.

Thus, on various channels, iterative decoding only differs in the initial messages $m_0(u)$. For example, consider three memoryless channel models: a binary erasure channel (BEC); a binary symmetric channel (BSC); and an additive white Gaussian noise (AGWN) channel.

In the BEC, there are two inputs and three outputs. When 0 is transmitted, the receiver can receive either 0 or an erasure E. An erasure E output means that the receiver does not know how to demodulate the output. Similarly, when 1 is transmitted, the receiver can receive either 1 or E. Thus, for the BEC, y∈{0, E, 1}, and

$$m_0(u) = \begin{cases} +\infty & \text{if } y = 0 \\ 0 & \text{if } y = E \\ -\infty & \text{if } y = 1 \end{cases}$$

In the BSC, there are two possible inputs (0,1) and two possible outputs (0, 1). The BSC is characterized by a set of conditional probabilities relating all possible outputs to possible inputs. Thus, for the BSC y∈{0, 1},

$$m_0(u) = \begin{cases} \log\frac{1-p}{p} & \text{if } y = 0 \\ -\log\frac{1-p}{p} & \text{if } y = 1 \end{cases}$$

and

In the AWGN, the discrete-time input symbols X take their values in a finite alphabet while channel output symbols Y can take any values along the real line. There is assumed to be no distortion or other effects other than the addition of white Gaussian noise. In an AWGN with a Binary Phase Shift Keying (BPSK) signaling which maps 0 to the symbol with amplitude $\sqrt{Es}$ and 1 to the symbol with amplitude $-\sqrt{Es}$, output y∈R, then

$$m_0(u)=4y\sqrt{E_s}/N_0$$

where $N_0/2$ is the noise power spectral density.

The selection of a degree profile for use in a particular transmission channel is a design parameter, which may be affected by various attributes of the channel. The criteria for selecting a particular degree profile may include, for example, the type of channel and the data rate on the channel. For example, Table 1 shows degree profiles that have been found to produce good results for an AWGN channel model.

TABLE 1

a	2	3	4
λ2	0.139025	0.078194	0.054485
λ3	0.2221555	0.128085	0.104315
λ5		0.160813	
λ6	0.638820	0.036178	0.126755
λ10			0.229816
λ11			0.016484
λ12		0.108828	
λ13		0.487902	
λ14			
λ16			
λ27			0.450302
λ28			0.017842
Rate	0.333364	0.333223	0.333218
σGA	1.1840	1.2415	1.2615
σ*	1.1981	1.2607	1.2780
(Eb/N0) * (dB)	0.190	−0.250	−0.371
S.L. (dB)	−0.4953	−0.4958	−0.4958

Table 1 shows degree profiles yielding codes of rate approximately ⅓ for the AWGN channel and with a=2, 3, 4. For each sequence, the Gaussian approximation noise threshold, the actual sum-product decoding threshold and the corresponding energy per bit (E_b)-noise power (N_0) ratio in dB are given. Also listed is the Shannon limit (S.L.).

As the parameter "a" is increased, the performance improves. For example, for a=4, the best code found has an iterative decoding threshold of $E_b/N_0=-0.371$ dB, which is only 0.12 dB above the Shannon limit.

The accumulator component of the coder may be replaced by a "double accumulator" 600 as shown in FIG. 6. The double accumulator can be viewed as a truncated rate 1 convolutional coder with transfer function $1/(1+D+D^2)$.

Alternatively, a pair of accumulators may be the added, as shown in FIG. 7. There are three component codes: the "outer" code 700, the "middle" code 702, and the "inner" code 704. The outer code is an irregular repetition code, and the middle and inner codes are both accumulators.

IRA codes may be implemented in a variety of channels, including memoryless channels, such as the BEC, BSC, and AWGN, as well as channels having non-binary input, non-symmetric and fading channels, and/or channels with memory.

A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

The invention claimed is:

1. A method of encoding a signal, comprising:
obtaining a block of data in the signal to be encoded;
partitioning said data block into a plurality of sub-blocks, each sub-block including a plurality of data elements;
first encoding the data block to from a first encoded data block, said first encoding including repeating the data elements in different sub-blocks a different number of times;
interleaving the repeated data elements in the first encoded data block; and
second encoding said first encoded data block using an encoder that has a rate close to one.

2. The method of claim 1, wherein said second encoding is via a rate 1 linear transformation.

3. The method of claim 1, wherein said first encoding is carried out by a first coder with a variable rate less than one, and said second encoding is carried out by a second coder with a rate substantially close to one.

4. The method of claim 3, wherein the second coder comprises an accumulator.

5. The method of claim 4, wherein the data elements comprises bits.

6. The method of claim 5, wherein the first coder comprises a repeater operable to repeat different sub-blocks a different number of times in response to a selected degree profile.

7. The method of claim 4, wherein the first coder comprises a low-density generator matrix coder and the second coder comprises an accumulator.

8. The method of claim 1, wherein the second encoding uses a transfer function of $1/(1+D)$.

9. The method of claim 1, wherein the second encoding uses a transfer function of $1/(1+D+D^2)$.

10. The method of claim 1, wherein said second encoding utilizes two accumulators.

11. A method of encoding a signal, comprising:
receiving a block of data in the signal to be encoded, the data block including a plurality of bits;
first encoding the data block such that each bit in the data block is repeated and two or more of said plurality of bits are repeated a different number of times in order to form a first encoded data block; and
second encoding the first encoded data block in such a way that bits in the first encoded data block are accumulated.

12. The method of claim 11, wherein the said second encoding is via a rate 1 linear transformation.

13. The method of claim 11, wherein the first encoding is via a low-density generator matrix transformation.

14. The method of claim 11, wherein the signal to be encoded comprises a plurality of data blocks of fixed size.

15. A coder comprising:
a first coder having an input configured to receive a stream of bits, said first coder operative to repeat said stream of bits irregularly and scramble the repeated bits; and
a second coder operative to further encode bits output from the first coder at a rate within 10% of one.

16. The coder of claim 15, wherein the stream of bits includes a data block, and wherein the first coder is operative to apportion said data block into a plurality of sub-blocks and to repeat bits in each sub-block a number of times, wherein bits in different sub-blocks are repeated a different number of times.

17. The coder of claim 16, wherein the second coder comprises a recursive convolutional encoder with a transfer function of $1/(1+D)$.

18. The coder of claim 16, wherein the second coder comprises a recursive convolutional encoder with a transfer function of $1/(1+D+D^2)$.

19. The coder of claim 15, wherein the first coder comprises a repeater having a variable rate and an interleaver.

20. The coder of claim 15, wherein the first coder comprises a low-density generator matrix coder.

21. The coder of claim 15, wherein the second coder comprises a rate 1 linear encoder.

22. The coder of claim 21, wherein the second coder comprises an accumulator.

23. The coder of claim 22, wherein the second coder further comprises a second accumulator.

24. The coder of claim 15, wherein the second coder comprises a coder operative to further encode bits output from the first coder at a rate within 1% of one.

25. A coding system comprising:
a first coder having an input configured to receive a stream of bits, said first coder operative to repeat said stream of bits irregularly and scramble the repeated bits;
a second coder operative to further encode bits output from the first coder at a rate within 10% of one in order to form an encoded data stream; and
a decoder operative to receive the encoded data stream and decode the encoded data stream using an iterative decoding technique.

26. The coding system of claim 25, wherein the first coder comprises a repeater operative to receive a data block including a plurality of bits from said stream of bits and to repeat bits in the data block a different number of times according to a selected degree profile.

27. The coding system of claim 26, wherein the first coder comprises an interleaver.

28. The coding system of claim 25, wherein the first coder comprises a low-density generator matrix coder.

29. The coding system of claim 25, wherein the second coder comprises a rate 1 accumulator.

30. The coding system of claim 25, wherein the decoder is operative to decode the encoded data stream using a posterior decoding techniques.

31. The coding system of claim 25, wherein the decoder is operative to decode the encoded data stream based on a Tanner graph representation.

32. The coding system of claim 25, wherein the decoder is operative to decode the encoded data stream in linear time.

33. The coding system of claim 25, wherein the second coder comprises a coder operative to further encode bits output from the first coder at a rate within 1% of one.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

Page 1 of 1

PATENT NO. : 7,116,710 B1
APPLICATION NO. : 09/861102
DATED : October 3, 2006
INVENTOR(S) : Hui Jin, Aamod Khandekar and Robert J. McEliece

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

At column **1**, line **8**, please amend the paragraph as follows:

This application claims the priority [[to]] of U.S. Provisional Application Ser. No. 60/205,095, filed on May 18, 2000, and [[to]] is a continuation-in-part of U.S. application Ser. No. 09/922,852, filed on Aug. 18, 2000 and entitled Interleaved Serial Concatenation Forming Turbo-Like Codes.

Signed and Sealed this

Twenty-second Day of July, 2008

JON W. DUDAS
Director of the United States Patent and Trademark Office

US007421032B2

(12) **United States Patent**
Jin et al.

(10) **Patent No.: US 7,421,032 B2**
(45) **Date of Patent: Sep. 2, 2008**

(54) **SERIAL CONCATENATION OF INTERLEAVED CONVOLUTIONAL CODES FORMING TURBO-LIKE CODES**

(75) Inventors: **Hui Jin**, Glen Gardner, NJ (US); **Aamod Khandekar**, Pasadena, CA (US); **Robert J. McEliece**, Pasadena, CA (US)

(73) Assignee: **California Institute of Technology**, Pasadena, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/542,950**

(22) Filed: **Oct. 3, 2006**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation of application No. 09/861,102, filed on May 18, 2001, now Pat. No. 7,116,710, and a continuation-in-part of application No. 09/922,852, filed on Aug. 18, 2000, now Pat. No. 7,089,477.

(60) Provisional application No. 60/205,095, filed on May 18, 2000.

(51) **Int. Cl.**
H04L 5/12 (2006.01)

(52) **U.S. Cl.** **375/262**; 375/265; 375/348; 714/755; 714/786; 714/792; 341/52; 341/102

(58) **Field of Classification Search** 375/259, 375/262, 265, 285, 296, 341, 346, 348; 714/746, 714/752, 755, 756, 786, 792, 794–796; 341/51, 341/52, 56, 102, 103
See application file for complete search history.

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(74) *Attorney, Agent, or Firm*—Fish & Richardson P.C.

(57) **ABSTRACT**

A serial concatenated coder includes an outer coder and an inner coder. The outer coder irregularly repeats bits in a data block according to a degree profile and scrambles the repeated bits. The scrambled and repeated bits are input to an inner coder, which has a rate substantially close to one.

23 Claims, 5 Drawing Sheets

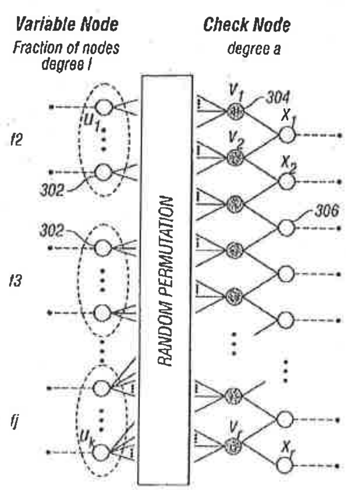

Exhibit B
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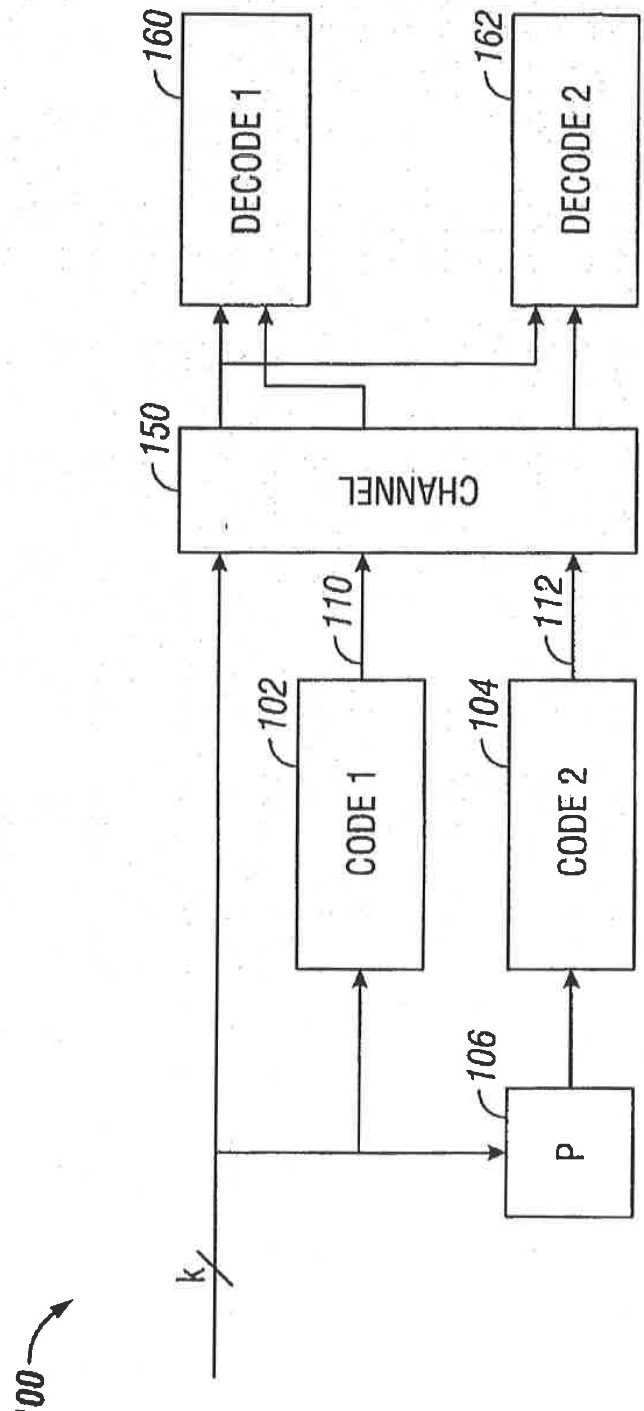


FIG. 1
(Prior Art)

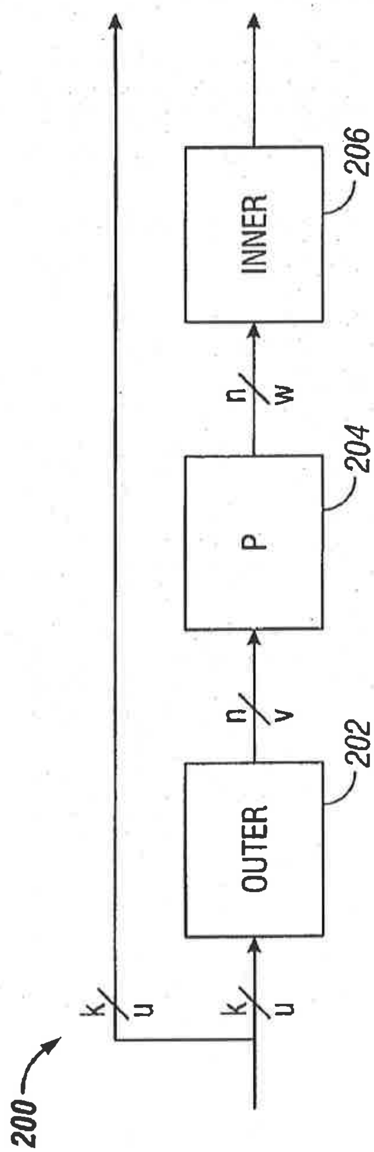


FIG. 2

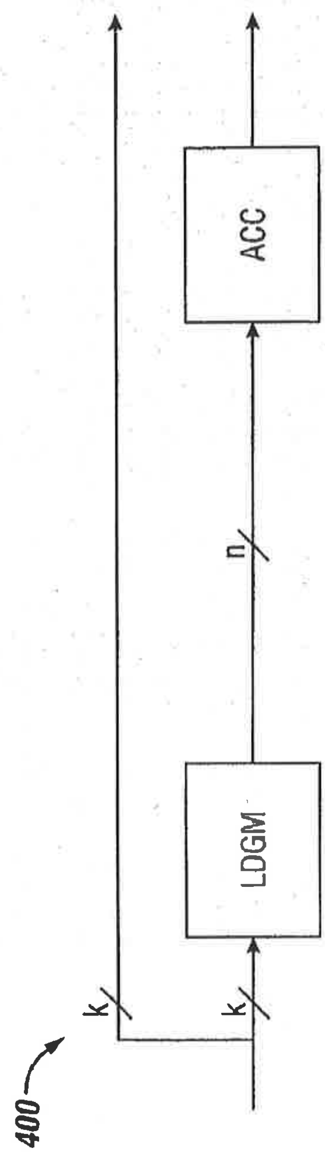


FIG. 4

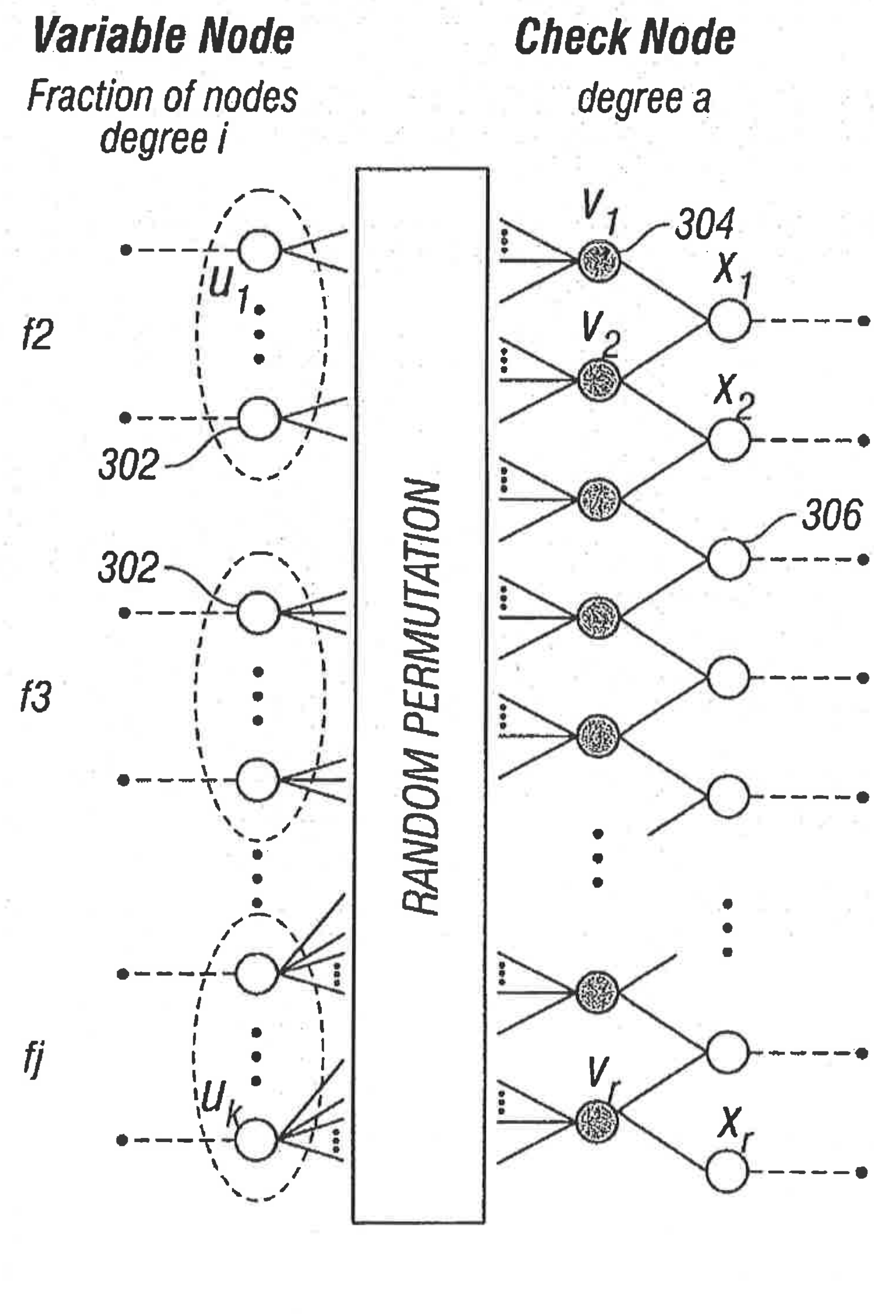


FIG. 3

Exhibit B
Page 46

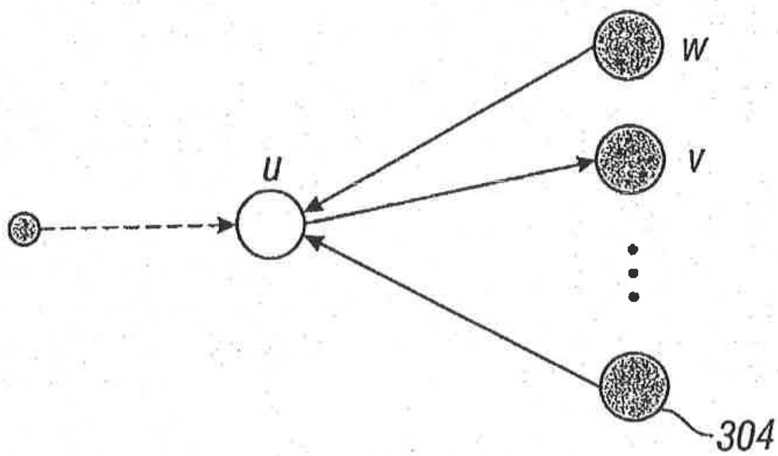


FIG. 5A

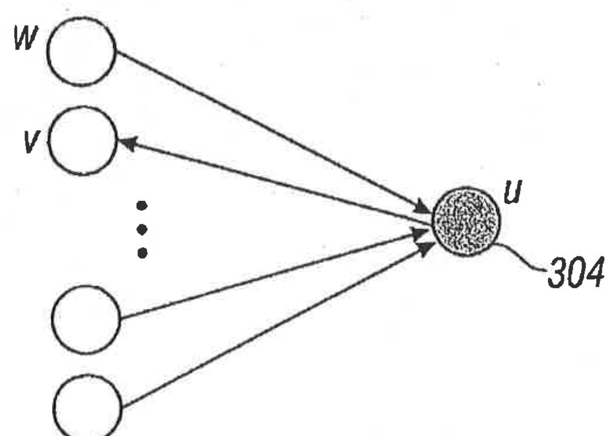


FIG. 5B

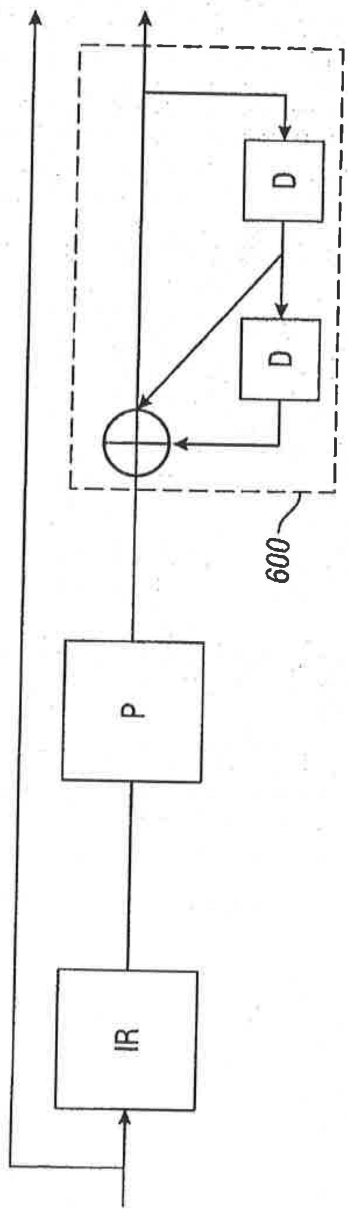


FIG. 6

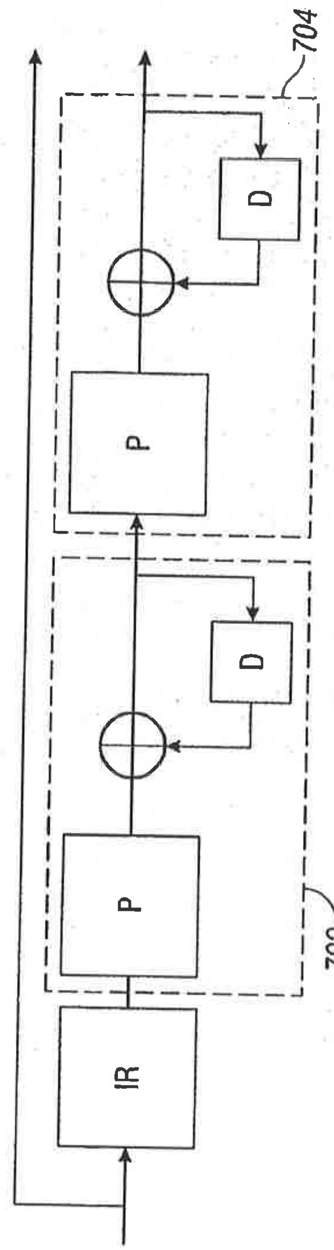


FIG. 7

SERIAL CONCATENATION OF INTERLEAVED CONVOLUTIONAL CODES FORMING TURBO-LIKE CODES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 09/861,102, filed May 18, 2001, now U.S. Pat. No. 7,116,710, which claims the priority of U.S. provisional application Ser. No. 60/205,095, filed May 18, 2000, and is a continuation-in-part of U.S. application Ser. No. 09/922,852, filed Aug. 18, 2000, now U.S. Pat. No. 7,089,477.

GOVERNMENT LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Grant No. CCR-9804793 awarded by the National Science Foundation.

BACKGROUND

Properties of a channel affect the amount of data that can be handled by the channel. The so-called "Shannon limit" defines the theoretical limit of the amount of data that a channel can carry.

Different techniques have been used to increase the data rate that can be handled by a channel. "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo Codes," by Berrou et al. ICC, pp 1064-1070, (1993), described a new "turbo code" technique that has revolutionized the field of error correcting codes. Turbo codes have sufficient randomness to allow reliable communication over the channel at a high data rate near capacity. However, they still retain sufficient structure to allow practical encoding and decoding algorithms. Still, the technique for encoding and decoding turbo codes can be relatively complex.

A standard turbo coder **100** is shown in FIG. **1**. A block of k information bits is input directly to a first coder **102**. A k bit interleaver **106** also receives the k bits and interleaves them prior to applying them to a second coder **104**. The second coder produces an output that has more bits than its input, that is, it is a coder with rate that is less than 1. The coders **102**, **104** are typically recursive convolutional coders.

Three different items are sent over the channel **150**: the original k bits, first encoded bits **110**, and second encoded bits **112**. At the decoding end, two decoders are used: a first constituent decoder **160** and a second constituent decoder **162**. Each receives both the original k bits, and one of the encoded portions **110**, **112**. Each decoder sends likelihood estimates of the decoded bits to the other decoders. The estimates are used to decode the uncoded information bits as corrupted by the noisy channel.

SUMMARY

A coding system according to an embodiment is configured to receive a portion of a signal to be encoded, for example, a data block including a fixed number of bits. The coding system includes an outer coder, which repeats and scrambles bits in the data block. The data block is apportioned into two or more sub-blocks, and bits in different sub-blocks are repeated a different number of times according to a selected degree profile. The outer coder may include a

repeater with a variable rate and an interleaver. Alternatively, the outer coder may be a low-density generator matrix (LDGM) coder.

The repeated and scrambled bits are input to an inner coder that has a rate substantially close to one. The inner coder may include one or more accumulators that perform recursive modulo two addition operations on the input bit stream.

The encoded data output from the inner coder may be transmitted on a channel and decoded in linear time at a destination using iterative decoding techniques. The decoding techniques may be based on a Tanner graph representation of the code.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of a prior "turbo code" system.

FIG. **2** is a schematic diagram of a coder according to an embodiment.

FIG. **3** is a Tanner graph for an irregular repeat and accumulate (IRA) coder.

FIG. **4** is a schematic diagram of an IRA coder according to an embodiment.

FIG. **5A** illustrates a message from a variable node to a check node on the Tanner graph of FIG. **3**.

FIG. **5B** illustrates a message from a check node to a variable node on the Tanner graph of FIG. **3**.

FIG. **6** is a schematic diagram of a coder according to an alternate embodiment.

FIG. **7** is a schematic diagram of a coder according to another alternate embodiment.

DETAILED DESCRIPTION

FIG. **2** illustrates a coder **200** according to an embodiment. The coder **200** may include an outer coder **202**, an interleaver **204**, and inner coder **206**. The coder may be used to format blocks of data for transmission, introducing redundancy into the stream of data to protect the data from loss due to transmission errors. The encoded data may then be decoded at a destination in linear time at rates that may approach the channel capacity.

The outer coder **202** receives the uncoded data. The data may be partitioned into blocks of fixed size, say k bits. The outer coder may be an (n,k) binary linear block coder, where n>k. The coder accepts as input a block u of k data bits and produces an output block v of n data bits. The mathematical relationship between u and v is $v=T_0u$, where T_0 is an n×k matrix, and the rate of the coder is k/n.

The rate of the coder may be irregular, that is, the value of T_0 is not constant, and may differ for sub-blocks of bits in the data block. In an embodiment, the outer coder **202** is a repeater that repeats the k bits in a block a number of times q to produce a block with n bits, where n=qk. Since the repeater has an irregular output, different bits in the block may be repeated a different number of times. For example, a fraction of the bits in the block may be repeated two times, a fraction of bits may be repeated three times, and the remainder of bits may be repeated four times. These fractions define a degree sequence, or degree profile, of the code.

The inner coder **206** may be a linear rate-1 coder, which means that the n-bit output block x can be written as $x=T_I w$, where T_I is a nonsingular n×n matrix. The inner coder **210** can have a rate that is close to 1, e.g., within 50%, more preferably 10% and perhaps even more preferably within 1% of 1.

In an embodiment, the inner coder **206** is an accumulator, which produces outputs that are the modulo two (mod-2) partial sums of its inputs. The accumulator may be a truncated rate-1 recursive convolutional coder with the transfer function 1/(1+D). Such an accumulator may be considered a block coder whose input block $[x_1, \ldots, x_n]$ and output block $[y_1, \ldots, y_n]$ are related by the formula

$$y_1 = x_1$$

$$y_2 = x_1 \oplus x_2$$

$$y_3 = x_1 \oplus x_2 \oplus x_3$$

$$\vdots$$

$$y_n = x_1 \oplus x_2 \oplus x_3 \oplus \ldots \oplus x_n.$$

where "⊕" denotes mod-2, or exclusive-OR (XOR), addition. An advantage of this system is that only mod-2 addition is necessary for the accumulator. The accumulator may be embodied using only XOR gates, which may simplify the design.

The bits output from the outer coder 202 are scrambled before they are input to the inner coder 206. This scrambling may be performed by the interleaver 204, which performs a pseudo-random permutation of an input block v, yielding an output block w having the same length as v.

The serial concatenation of the interleaved irregular repeat code and the accumulate code produces an irregular repeat and accumulate (IRA) code. An IRA code is a linear code, and as such, may be represented as a set of parity checks. The set of parity checks may be represented in a bipartite graph, called the Tanner graph, of the code. FIG. 3 shows a Tanner graph 300 of an IRA code with parameters $(f_1, \ldots, f_j; a)$, where $f_i \geqq 0$, $\Sigma_i f_i = 1$ and "a" is a positive integer. The Tanner graph includes two kinds of nodes: variable nodes (open circles) and check nodes (filled circles). There are k variable nodes 302 on the left, called information nodes. There are r variable nodes 306 on the right, called parity nodes. There are $r = (k\Sigma_i if_i)/a$ check nodes 304 connected between the information nodes and the parity nodes. Each information node 302 is connected to a number of check nodes 304. The fraction of information nodes connected to exactly i check nodes is f_i. For example, in the Tanner graph 300, each of the f_2 information nodes are connected to two check nodes, corresponding to a repeat of q=2, and each of the f_3 information nodes are connected to three check nodes, corresponding to q=3.

Each check node 304 is connected to exactly "a" information nodes 302. In FIG. 3, a=3. These connections can be made in many ways, as indicated by the arbitrary permutation of the ra edges joining information nodes 302 and check nodes 304 in permutation block 310. These connections correspond to the scrambling performed by the interleaver 204.

In an alternate embodiment, the outer coder 202 may be a low-density generator matrix (LDGM) coder that performs an irregular repeat of the k bits in the block, as shown in FIG. 4. As the name implies, an LDGM code has a sparse (low-density) generator matrix. The IRA code produced by the coder 400 is a serial concatenation of the LDGM code and the accumulator code. The interleaver 204 in FIG. 2 may be excluded due to the randomness already present in the structure of the LDGM code.

If the permutation performed in permutation block 310 is fixed, the Tanner graph represents a binary linear block code with k information bits $(u_1, \ldots, u_k)$ and r parity bits

$(x_1, \ldots, x_r)$, as follows. Each of the information bits is associated with one of the information nodes 302, and each of the parity bits is associated with one of the parity nodes 306. The value of a parity bit is determined uniquely by the condition that the mod-2 sum of the values of the variable nodes connected to each of the check nodes 304 is zero. To see this, set $x_0=0$. Then if the values of the bits on the ra edges coming out the permutation box are $(v_1, \ldots, v_{ra})$, then we have the recursive formula

$$x_j = x_{j-1} + \sum_{i=1}^{\lambda} v_{(j-1)\lambda+i}$$

for j=1, 2, . . . , r. This is in effect the encoding algorithm.

Two types of IRA codes are represented in FIG. 3, a nonsystematic version and a systematic version. The nonsystematic version is an (r,k) code, in which the codeword corresponding to the information bits $(u_1, \ldots, u_k)$ is $(x_1, \ldots, x_r)$. The systematic version is a (k+r, k) code, in which the codeword is $(u_1, \ldots, u_k; x_1, \ldots, x_r)$.

The rate of the nonsystematic code is

$$R_{nsys} = \frac{a}{\sum_i if_i}$$

The rate of the systematic code is

$$R_{sys} = \frac{a}{a + \sum_i if_i}$$

For example, regular repeat and accumulate (RA) codes can be considered nonsystematic IRA codes with a=1 and exactly one f_i equal to 1, say $f_q=1$, and the rest zero, in which case R_{nsys} simplifies to R=1/q.

The IRA code may be represented using an alternate notation. Let λ_i be the fraction of edges between the information nodes 302 and the check nodes 304 that are adjacent to an information node of degree i, and let ρ_i be the fraction of such edges that are adjacent to a check node of degree i+2 (i.e., one that is adjacent to i information nodes). These edge fractions may be used to represent the IRA code rather than the corresponding node fractions. Define $\lambda(x)=\Sigma_i\lambda_i x^{i-1}$ and $\rho(x)=\Sigma_i\rho_i x^{i-1}$ to be the generating functions of these sequences. The pair (λ, ρ) is called a degree distribution. For $L(x)=\Sigma_i f_i x_i$,

$$f_i = \frac{\lambda_i / i}{\sum_j \lambda_j / j}$$

$$L(x) = \int_0^x \lambda(t)\,dt \Big/ \int_0^1 \lambda(t)\,dt$$

The rate of the systematic IRA code given by the degree distribution is given by

$$\text{Rate} = \left(1 + \frac{\sum_j \rho_j / j}{\sum_j \lambda_j / j}\right)^{-1}$$

"Belief propagation" on the Tanner Graph realization may be used to decode IRA codes. Roughly speaking, the belief propagation decoding technique allows the messages passed on an edge to represent posterior densities on the bit associated with the variable node. A probability density on a bit is a pair of non-negative real numbers p(0), p(1) satisfying p(0)+p(1)=1, where p(0) denotes the probability of the bit being 0, p(1) the probability of it being 1. Such a pair can be represented by its log likelihood ratio, m=log(p(0)/p(1)). The outgoing message from a variable node u to a check node v represents information about u, and a message from a check node u to a variable node v represents information about u, as shown in FIGS. 5A and 5B, respectively.

The outgoing message from a node u to a node v depends on the incoming messages from all neighbors w of u except v. If u is a variable message node, this outgoing message is

$$m(u \to v) = \sum_{w \neq v} m(w \to u) + m_0(u)$$

where $m_0(u)$ is the log-likelihood message associated with u. If u is a check node, the corresponding formula is

$$\tanh\frac{m(u \to v)}{2} = \prod_{w \neq v} \tanh\frac{m(w \to u)}{2}$$

Before decoding, the messages m(w→u) and m(u→v) are initialized to be zero, and $m_0(u)$ is initialized to be the log-likelihood ratio based on the channel received information. If the channel is memoryless, i.e., each channel output only

relies on its input, and y is the output of the channel code bit u, then $m_0(u)=\log(p(u=0|y)/p(u=1|y))$. After this initialization, the decoding process may run in a fully parallel and local manner. In each iteration, every variable/check node receives messages from its neighbors, and sends back updated messages. Decoding is terminated after a fixed number of iterations or detecting that all the constraints are satisfied. Upon termination, the decoder outputs a decoded sequence based on the messages $m(u)=\Sigma w_m(w \to u)$.

Thus, on various channels, iterative decoding only differs in the initial messages $m_0(u)$. For example, consider three memoryless channel models: a binary erasure channel (BEC); a binary symmetric channel (BSC); and an additive white Gaussian noise (AGWN) channel.

In the BEC, there are two inputs and three outputs. When 0 is transmitted, the receiver can receive either 0 or an erasure E. An erasure E output means that the receiver does not know how to demodulate the output. Similarly, when 1 is transmitted, the receiver can receive either 1 or E. Thus, for the BEC, $y \in \{0, E, 1\}$, and

$$m_0(u) = \begin{cases} +\infty & \text{if } y = 0 \\ 0 & \text{if } y = E \\ -\infty & \text{if } y = 1 \end{cases}$$

In the BSC, there are two possible inputs (0,1) and two possible outputs (0, 1). The BSC is characterized by a set of conditional probabilities relating all possible outputs to possible inputs. Thus, for the BSC $y \in \{0, 1\}$,

$$m_0(u) = \begin{cases} \log\frac{1-p}{p} & \text{if } y = 0 \\ -\log\frac{1-p}{p} & \text{if } y = 1 \end{cases}$$

and

In the AWGN, the discrete-time input symbols X take their values in a finite alphabet while channel output symbols Y can take any values along the real line. There is assumed to be no distortion or other effects other than the addition of white Gaussian noise. In an AWGN with a Binary Phase Shift Keying (BPSK) signaling which maps 0 to the symbol with amplitude $\sqrt{Es}$ and 1 to the symbol with amplitude $-\sqrt{Es}$, output $y \in R$, then

$$m_0(u) = 4y\sqrt{E_s}/N_0$$

where $N_0/2$ is the noise power spectral density.

The selection of a degree profile for use in a particular transmission channel is a design parameter, which may be affected by various attributes of the channel. The criteria for selecting a particular degree profile may include, for example, the type of channel and the data rate on the channel. For example, Table 1 shows degree profiles that have been found to produce good results for an AWGN channel model.

TABLE 1

a	2	3	4
λ2	0.139025	0.078194	0.054485
λ3	0.2221555	0.128085	0.104315
λ5		0.160813	
λ6	0.638820	0.036178	0.126755
λ10			0.229816
λ11			0.016484
λ12		0.108828	
λ13		0.487902	
λ14			
λ16			
λ27			0.450302
λ28			0.017842
Rate	0.333364	0.333223	0.333218
σGA	1.1840	1.2415	1.2615
σ*	1.1981	1.2607	1.2780
(Eb/N0) * (dB)	0.190	−0.250	−0.371
S.L. (dB)	−0.4953	−0.4958	−0.4958

Table 1 shows degree profiles yielding codes of rate approximately ⅓ for the AWGN channel and with a=2, 3, 4. For each sequence, the Gaussian approximation noise threshold, the actual sum-product decoding threshold and the corresponding energy per bit (E_b)-noise power (N_0) ratio in dB are given. Also listed is the Shannon limit (S.L.).

As the parameter "a" is increased, the performance improves. For example, for a=4, the best code found has an iterative decoding threshold of $E_b/N_0=-0.371$ dB, which is only 0.12 dB above the Shannon limit.

The accumulator component of the coder may be replaced by a "double accumulator" **600** as shown in FIG. **6**. The double accumulator can be viewed as a truncated rate 1 convolutional coder with transfer function $1/(1+D+D^2)$.

Alternatively, a pair of accumulators may be the added, as shown in FIG. **7**. There are three component codes: the "outer" code **700**, the "middle" code **702**, and the "inner" code **704**. The outer code is an irregular repetition code, and the middle and inner codes are both accumulators.

IRA codes may be implemented in a variety of channels, including memoryless channels, such as the BEC, BSC, and AWGN, as well as channels having non-binary input, non-symmetric and fading channels, and/or channels with memory.

A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

The invention claimed is:

1. A method comprising:

receiving a collection of message bits having a first sequence in a source data stream;

generating a sequence of parity bits, wherein each parity bit "x_j" in the sequence is in accordance with the formula

$$x_j = x_{j-1} + \sum_{i=1}^{\lambda} v_{(j-1)\lambda+i},$$

where

"x_{j-1}" is the value of a parity bit "j−1," and

$$\text{"}\sum_{i=1}^{a} v_{(j-1)a+1}\text{"}$$

is the value of a sum of "a" randomly chosen irregular repeats of the message bits; and

making the sequence of parity bits available for transmission in a transmission data stream.

2. The method of claim **1**, wherein the sequence of parity bits is generated is in accordance with "a" being constant.

3. The method of claim **1**, wherein the sequence of parity bits is generated is in accordance with "a" varying for different parity bits.

4. The method of claim **1**, wherein generating the sequence of parity bits comprises performing recursive modulo two addition operations on the random sequence of bits.

5. The method of claim **1**, wherein generating the sequence of parity bits comprises:

generating a random sequence of bits that repeats each of the message bits one or more times with the repeats of the message bits being distributed in a random sequence, wherein different fractions of the message bits are each repeated a different number of times and the number of repeats for each message bit is irregular; and

XOR summing in linear sequential fashion a predecessor parity bit and "a" bits of the random sequence of bits.

6. The method of claim **5**, wherein generating the random sequence of bits comprises coding the collection of message bits using a low-density generator matrix (LDGM) coder.

7. The method of claim **5**, wherein generating the random sequence of bits comprises:

producing a block of data bits, wherein different message bits are each repeated a different number of times in a sequence that matches the first sequence; and

randomly permuting the different bits to generate the random sequence.

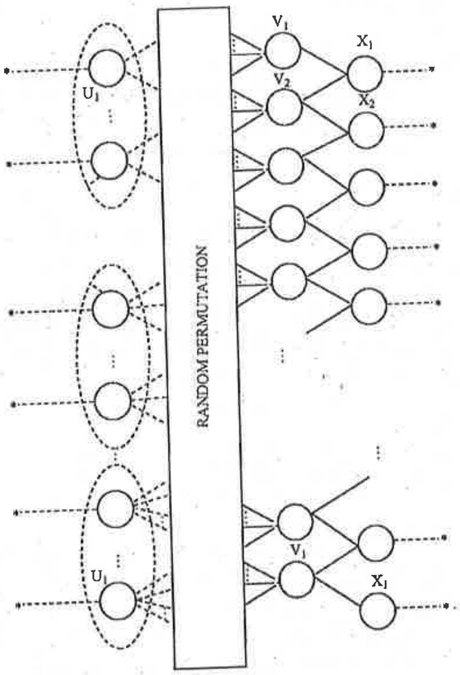
8. The method of claim **1**, further comprising transmitting the sequence of parity bits.

9. The method of claim **8**, wherein transmitting the sequence of parity bits comprises transmitting the sequence of parity bits as part of a nonsystematic code.

10. The method of claim **8**, wherein transmitting the sequence of parity bits comprises transmitting the sequence of parity bits as part of a systematic code.

11. A device comprising:

an encoder configured to receive a collection of message bits and encode the message bits to generate a collection of parity bits in accordance with the following Tanner graph:



12. The device of claim 11, wherein the encoder is configured to generate the collection of parity bits as if a number of inputs into nodes v_i was not constant.

13. The device of claim 11, wherein the encoder comprises:

a low-density generator matrix (LDGM) coder configured to perform an irregular repeat on message bits having a first sequence in a source data stream to output a random sequence of repeats of the message bits; and

an accumulator configured to XOR sum in linear sequential fashion a predecessor parity bit and "a" bits of the random sequence of repeats of the message bits.

14. The device of claim 12, wherein the accumulator comprises a recursive convolutional coder.

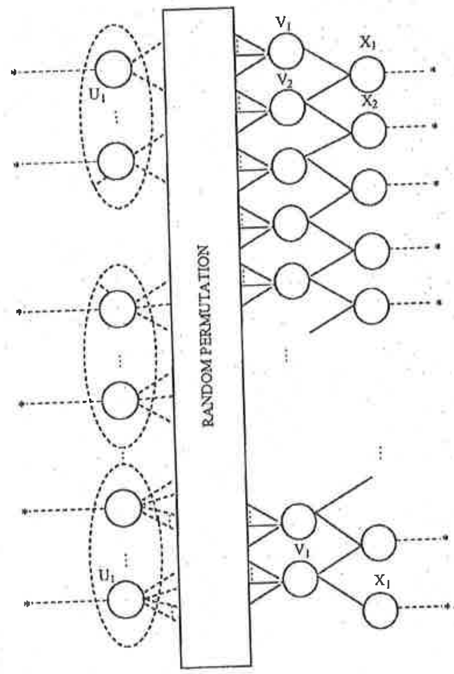
15. The device of claim 14, wherein the recursive convolutional coder comprises a truncated rate-1 recursive convolutional coder.

16. The device of claim 14, wherein the recursive convolutional coder has a transfer function of 1/(1+D).

17. The device of claim 12, further comprising a second accumulator configured to determine a second sequence of parity bits that defines a second condition that constrains the random sequence of repeats of the message bits.

18. A device comprising:

a message passing decoder configured to decode a received data stream that includes a collection of parity bits, the message passing decoder comprising two or more check/variable nodes operating in parallel to receive messages from neighboring check/variable nodes and send updated messages to the neighboring variable/check nodes, wherein the message passing decoder is configured to decode the received data stream that has been encoded in accordance with the following Tanner graph:



19. The device of claim 18, wherein the message passing decoder is configured to decode the received data stream that includes the message bits.

20. The device of claim 18, wherein the message passing decoder is configured to decode the received data stream as if a number of inputs into nodes v_i was not constant.

21. The device of claim 18, wherein the message passing decoder is configured to decode in linear time at rates that approach a capacity of a channel.

22. The device of claim 18, wherein the message passing decoder comprises a belief propagation decoder.

23. The device of claim 18, wherein the message passing decoder is configured to decode the received data stream without the message bits.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,421,032 B2
APPLICATION NO. : 11/542950
DATED : September 2, 2008
INVENTOR(S) : Hui Jin, Aamod Khandekar and Robert J. McEliece

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page, item [73] (Assignee), line 1, please delete "Callifornia" and insert --California--, therefor.

Claim 11, Column 9, line 28, delete "V_1" and insert --V_r--, therefor.

Claim 11, Column 9, line 29, delete "U_1" and insert --U_k--, therefor.

Claim 11, Column 9, line 29, delete "X_1" and insert --X_r--, therefor.

Claim 18, Column 10, line 35, delete "V_1" and insert --V_r--, therefor.

Claim 18, Column 10, line 36, delete "U_1" and insert --U_k--, therefor.

Claim 18, Column 10, line 37, delete "X_1" and insert --X_r--, therefor.

Signed and Sealed this

Seventeenth Day of February, 2009

John Doll

JOHN DOLL
Acting Director of the United States Patent and Trademark Office

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,421,032 B2

Page 1 of 1

APPLICATION NO. : 11/542950

DATED : September 2, 2008

INVENTOR(S) : Hui Jin, Aamod Khandekar and Robert J. McEliece

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

At column 4, line 14, please delete " $x_j = x_{j-1} + \sum_{i=1}^{\lambda} v_{(j-1)\lambda+i}$ " and insert

-- $x_j = x_{j-1} + \sum_{i=1}^{a} v_{(j-1)a+i}$ --.

In claim 1, column 8, line 4, please delete " $x_j = x_{j-1} + \sum_{i=1}^{\lambda} v_{(j-1)\lambda+i}$, " and insert

-- $x_j = x_{j-1} + \sum_{i=1}^{a} v_{(j-1)a+i}$, --.

In claim 1, column 8, line 13, please delete " $\sum_{i=1}^{a} v_{(j-1)a+1}$ " and insert

-- $\sum_{i-1}^{a} v_{(j-1)a+i}$ --.

Signed and Sealed this

Twenty-seventh Day of July, 2010

David J. Kappos

David J. Kappos
Director of the United States Patent and Trademark Office

Exhibit B
Page 55