



US007770093B2

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

(10) **Patent No.:** **US 7,770,093 B2**
(45) **Date of Patent:** **Aug. 3, 2010**

(54) **SERIAL TURBO TRELLIS CODED MODULATION USING A SERIALY CONCATENATED CODER**

(76) Inventors: **Dariush Divsalar**, 1159 Las Pulgas Pl., Pacific Palisades, CA (US) 90272-2440; **Samuel J. Dolinar**, 8859 Riderwood Dr., Sunland, CA (US) 91040-2624; **Fabrizio Pollara**, 181 Starlight Crest Dr., La Canada, CA (US) 91011-2836

6,202,189	B1 *	3/2001	Hinedi et al.	714/786
6,298,461	B1 *	10/2001	Tong et al.	714/755
6,473,878	B1	10/2002	Wei	
6,629,287	B1 *	9/2003	Brink	714/755
6,662,337	B1 *	12/2003	Brink	714/792
6,754,290	B1 *	6/2004	Halter	375/340
6,795,507	B1 *	9/2004	Xin et al.	375/265
7,089,477	B1	8/2006	Divsalar et al.	

(*) 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.: **11/514,295**

(22) Filed: **Aug. 31, 2006**

(65) **Prior Publication Data**

US 2007/0130494 A1 Jun. 7, 2007

Related U.S. Application Data

(63) Continuation of application No. 09/760,514, filed on Jan. 11, 2001, now Pat. No. 7,243,294.

(60) Provisional application No. 60/176,404, filed on Jan. 13, 2000.

(51) **Int. Cl.**
H03M 13/03 (2006.01)

(52) **U.S. Cl.** 714/794; 714/795

(58) **Field of Classification Search** 714/794, 714/795

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,941,154	A	7/1990	Wei	
5,583,889	A	12/1996	Citta et al.	
5,841,818	A *	11/1998	Lin et al.	375/341
6,023,783	A *	2/2000	Divsalar et al.	714/792
6,029,264	A	2/2000	Kobayashi et al.	

OTHER PUBLICATIONS

Stephen B. Wicker, Error Control Systems for Digital Communication and Storage, Prentice-Hall, 1995, pp. 356-373.*

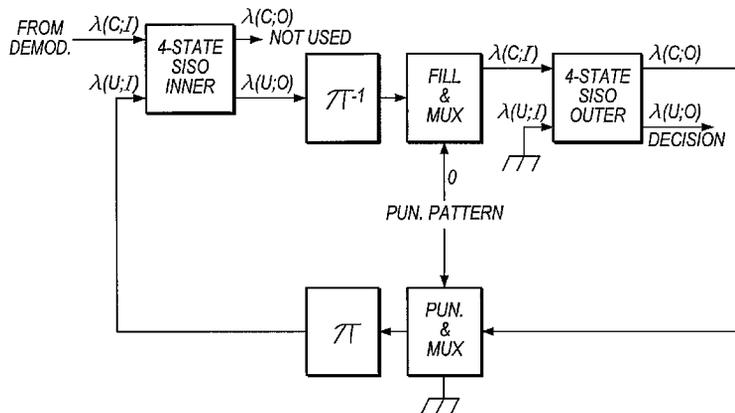
(Continued)

Primary Examiner—Joseph D Torres

(57) **ABSTRACT**

Serial concatenated trellis coded modulation (SCTCM) includes an outer coder, an interleaver, a recursive inner coder and a mapping element. The outer coder receives data to be coded and produces outer coded data. The interleaver permutes the outer coded data to produce interleaved data. The recursive inner coder codes the interleaved data to produce inner coded data. The mapping element maps the inner coded data to a symbol. The recursive inner coder has a structure which facilitates iterative decoding of the symbols at a decoder system. The recursive inner coder and the mapping element are selected to maximize the effective free Euclidean distance of a trellis coded modulator formed from the recursive inner coder and the mapping element. The decoder system includes a demodulation unit, an inner SISO (soft-input soft-output) decoder, a deinterleaver, an outer SISO decoder, and an interleaver.

18 Claims, 5 Drawing Sheets



OTHER PUBLICATIONS

- A.O. Berthet, R. Visod, B. Unal, P. Tortelier; A Comparison of Several Strategies for Iteratively Decoding Serially Concatenated Convolutional Codes in Multipath Rayleigh Fading Environment; IEEE, 2000, pp. 783-789.*
- S. Benedetto, D. Divsalar, G. Montorsi, F. Pollara; Serial Concatenated Trellis Coded Modulation with Iterative Decoding; IEEE 1997.*
- Benedetto, S.; Divsalar, D.; Montorsi, G.; Pollara, F.; "Serial concatenation of interleaved codes: performance analysis, design, and iterative decoding", IEEE Transactions on Information Theory, vol. 44, Issue 3, May 1998 pp. 909-926.*
- Benedetto S.; Divsalar D.; Garelo R.; Montorsi G.; Pollara F., Bit geometrically uniform encoders: a systematic approach to the design of serially concatenated TCM, Proceedings Information Theory Workshop 1998.*
- Benedetto, S.; Divsalar, D.; Montorsi, G.; Pollara, F.; "Parallel Concatenated Trellis Coded Modulation" IEEE International Conference on Communications; vol. 2, Jun. 23-27, 1996, pp. 974-978.
- Divsalar and R.J. McEliece: "Effective Free Distance of Turbo Codes" IEEE 1996, Jan. 3, 1996, Electronics Letters Online No. 19960321, Electronics Letters, p. 445, vol. 32, No. 5, Feb. 29, 1996.
- Sergio Benedetto, Dariush Divsalar, Guido Montorsi and Fabrizio Pollara: "Serial Concatenation of Interleaved Codes: Performance Analysis, Design, and Iterative Decoding" IEEE Transactions on Information Theory, p. 909, vol. 44, No. 3, May 1998.
- Divsalar, et al., Coding Theorems for "Turbo-Like" Codes, Proc. 1998 Allerton Conference, Sep. 23-25, 1998, pp. 210-210.
- Benedetto, et al., "Serial Concatenated Trellis Coded Modulation with Iterative Decoding: Design and Performance", IEEE Global Telecommunications Conference (CTMC), Nov. 1997 ("CTMC97").
- Benedetto, et al., "Serial Concatenated Trellis Coded Modulation with Iterative Decoding: Design and Performance", Nov. 4, 1997, JPL TRP 1992+, accessible from <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/22922/1/97-1466.pdf>.
- Ungerboeck, Gottfried, "Channel Coding with Multilevel/Phase Signals", IEEE Transactions on Information Theory, vol. IT-28, No. 1, Jan. 1982.
- Forney, G. David, "Concatenated Codes", NASA Technical Report 440, Dec. 1, 1965, available at <http://dspace.mit.edu/bitstream/handle/1721.1/4303/RLE-TR-440-04743368.pdf;jsessionid=D17E3F7616BCCD69D1374E06C6DF6947?sequence=1>
- Berrou, et al., "Near Shannon Limit Error-Correcting Coding: Turbo Codes," Proc. 1993 IEEE International Conf on Communications, Geneva, pp. 1064-1070, May 1993.
- Divsalar, et al., "On the Design of Turbo Codes," JPL TMO Progress Report 42-123, Nov. 15, 1995.
- Benedetto, et al., "Unveiling Turbo Codes: some results on parallel concatenated coding schemes," IEEE Trans on Inf. Theory, Mar. 1996.
- Legoff et al., "Turbo Codes and High Spectral Efficiency Modulation," Proceedings of IEEE ICC'94, May 1-5, 1994, New Orleans, LA.
- Benedetto, et al., A Soft-Input Soft Output Maximum A Posteriori (MAP) Module to Decode Parallel and Serial Concatenated Codes, TDA Progress Report, Nov. 15, 1996, accessible from <http://tmo.jpl.nasa.gov>.
- Divsalar, et al., "Hybrid Concatenated Codes and Iterative Decoding," TDA Progress Report 42-130, Aug. 15, 1997, accessible from <http://tmo.jpl.nasa.gov>.
- Benedetto et al., "Soft-Output Decoding Algorithms in Iterative Decoding of Turbo Codes," TDA Progress Report 42-124, Feb. 15, 1996, accessible from <http://tmo.jpl.nasa.gov>.
- Wachsmann, et al., Power and Bandwidth Efficient Digital Communication Using Turbo Codes in Multilevel Codes, European Transactions on Telecommunications, vol. 6, No. 5, Sep./Oct. 1995, pp. 557-567.
- "Signal Processing for Wireless Communications" by Joseph Bocuzzi, published by McGraw-Hill, 2008 ("Bocuzzi"): p. 242, lines 4-10; p. 232.
- "Satellite Communication Systems Design," edited by Sebastiano Tírró ("Tírró"), Springer 1993, p. 487.
- "Introduction to Convolutional Codes with Applications," A. Dholakia, Springer 1994 ("Dholakia"): p. 20, lines 2-5.
- "Systematic Code" at http://en.wikipedia.org/wiki/Systematic_code, Dec. 3, 2008.
- "A Comparison of Several Strategies for Iteratively Decoding Serially Concatenated Convolutional Codes in Multipath Rayleigh Fading Environment," Berthet et al., Global Telecommunications Conference, 2000 (GLOBECOM '00 IEEE), San Francisco, CA, vol. 2, pp. 783-789, Nov. 27, 2000-Dec. 1, 2000, accessible from http://ieeexplore.ieee.org/xpls/abs_all.jsp?tp=&arnumber=891246&isnumber=19260.
- "Serial Concatenated Trellis Coded Modulation with Rate-1 Inner Code", Divsalar et al., Sep. 7, 2000, downloaded from <http://trs-new.jpl.nasa.gov/dspace/handle/2014/16146>.
- S. Benedetto and G. Montorsi, "Iterative Decoding of Serially Concatenated Convolutional Codes", Electronics Letters, Jun. 20, 1996, pp. 1186-1188, vol. 32, No. 13.
- S. Benedetto and G. Montorsi, "Serial Concatenation of Block and Convolutional Codes", Electronics Letters, May 9, 1996, pp. 887-888, vol. 32, No. 10.
- S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Serial Concatenation of Interleaved Codes: Performance Analysis, Design, and Iterative Decoding", Jet Propulsion Laboratory, California Institute of Technology, TDA Progress Report 42-126, Aug. 15, 1996.

* cited by examiner

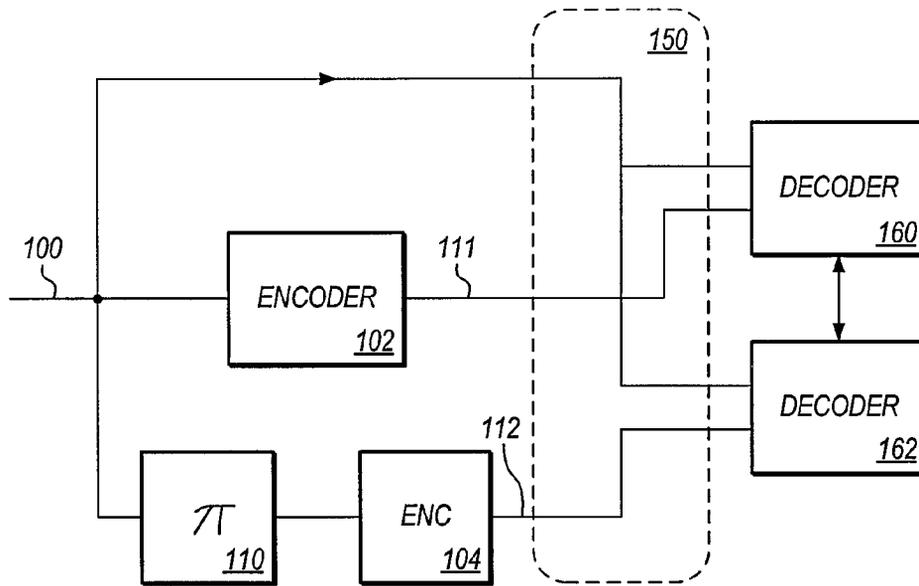


FIG. 1

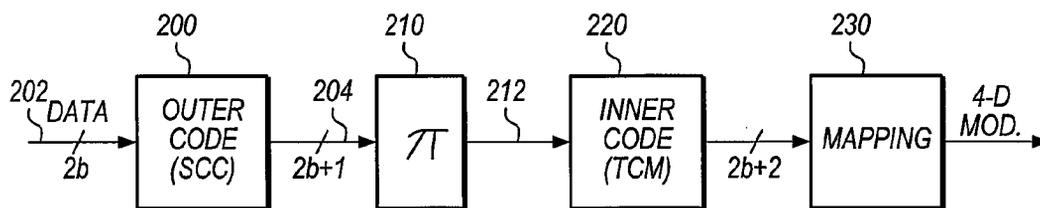


FIG. 2

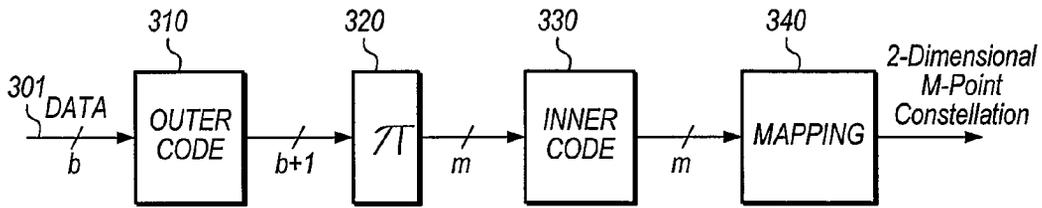


FIG. 3

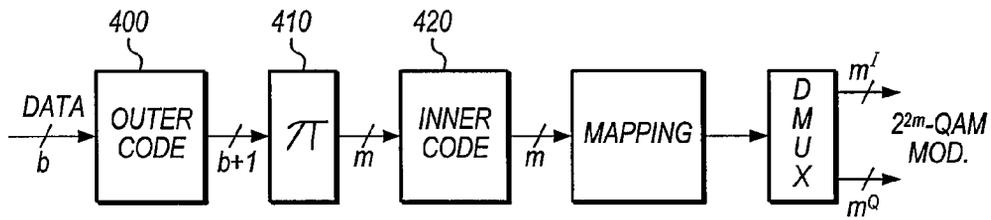


FIG. 4

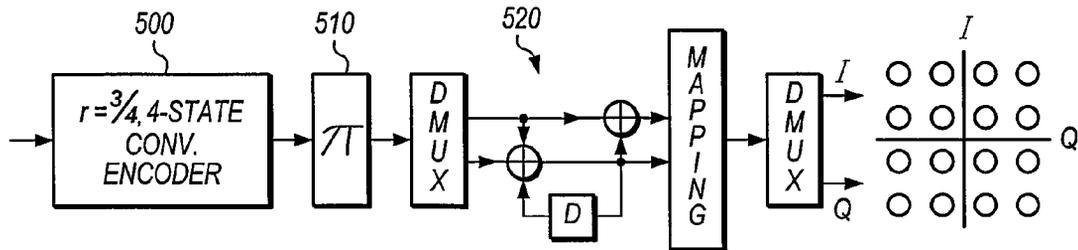


FIG. 5

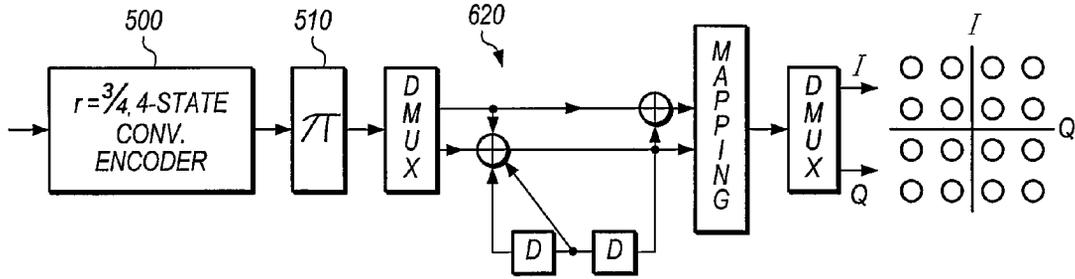


FIG. 6

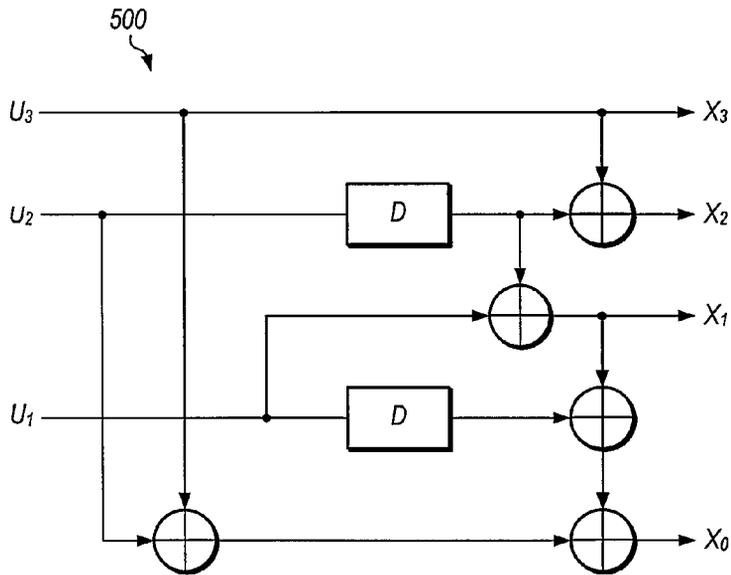


FIG. 7

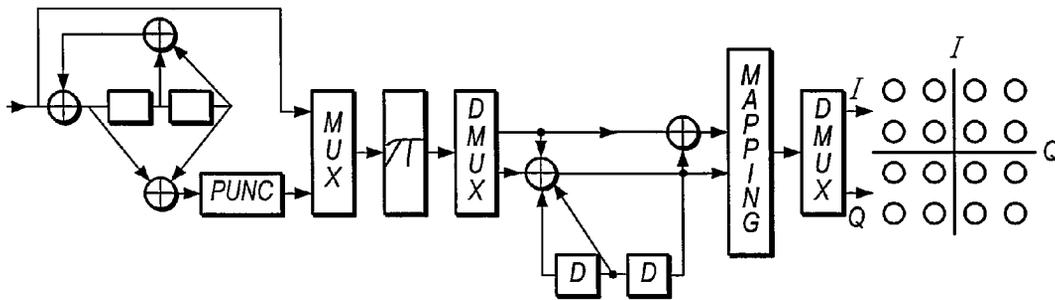


FIG. 8

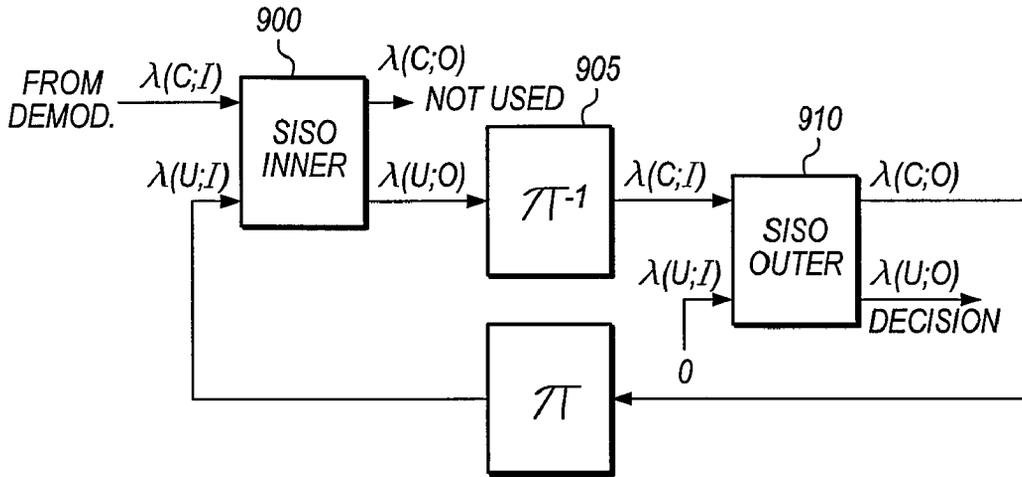


FIG. 9

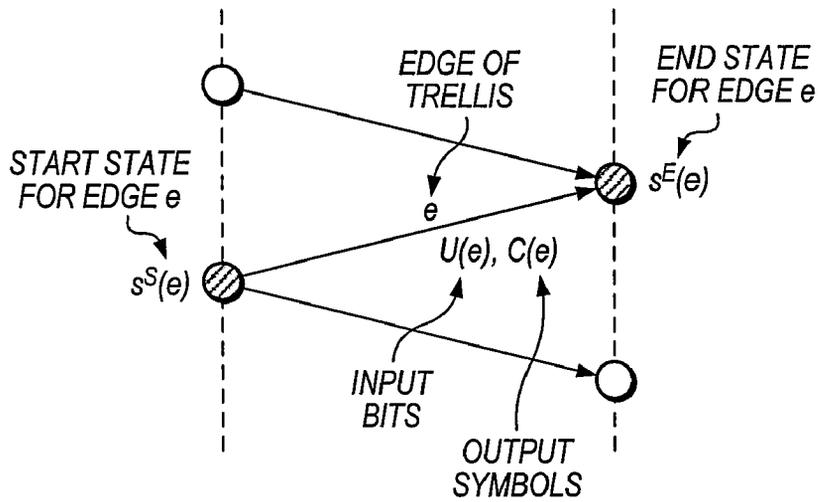


FIG. 10

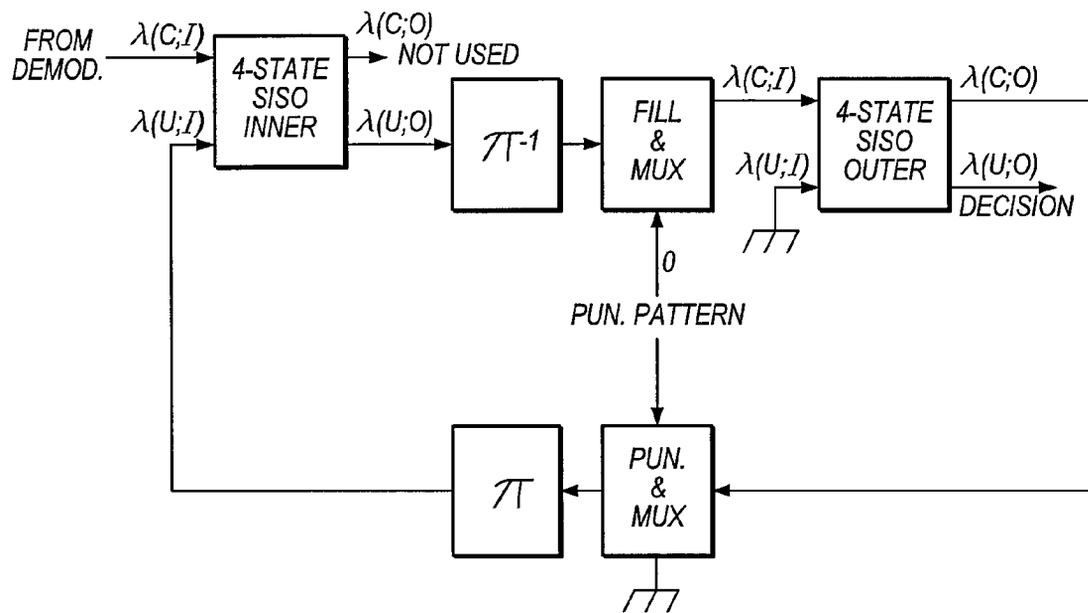


FIG. 11

1

SERIAL TURBO TRELLIS CODED MODULATION USING A SERIALLY CONCATENATED CODER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 9/760,514, entitled "Serial Turbo Trellis Coded Modulation Using A Serially Concatenated Coder", filed Jan. 11, 2001, (which is incorporated by reference herein in its entirety), which in turn claims the benefit of the U.S. Provisional Application No. 60/176,404, filed on Jan. 13, 2000.

STATEMENT AS TO FEDERALLY-SPONSORED RESEARCH

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provision of Public Law 96-517 (U.S.C. 202) in which the Contractor has elected to retain title.

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 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 is shown in FIG. 1. A block of k information bits **100** is input directly to a first encoder **102**. A k bit interleaver **110** also receives the k bits and interleaves them prior to applying them to a second encoder **104**. The second encoder produces an output that has more bits than its input, that is, it is a coder with rate that is less than 1. The encoders **102**, **104** are also typically recursive convolutional coders.

Three different items are sent over the channel **150**: the original k bits **100**, first encoded bits **111**, 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.

Turbo codes are effectively parallel concatenated codes with an encoder having two or more constituent coders joined through one or more interleavers. Input information bits feed the first encoder, are scrambled by the interleaver, and enter the second encoder. A code word is formed by a parallel concatenated code formed by the input bits to the first encoder followed by the parity check bits of both encoders.

Trellis coded modulation is described in "Channel Coding with Multilevel Phase Signaling", Ungerboeck, IEEE Trans

2

Inf.Th. Vol. IT-25, pp 55-67, January 1982. Trellis coded modulation can produce significant coding gains in certain circumstances.

In some situations it may be desirable to have a very low bit error rate, e.g. less than 10^{-9} .

SUMMARY

The present application combines a combination of trellis coded modulation with turbo codes, to obtain certain advantages of bandwidth and power efficiency from the trellis coded modulation, while also obtaining other advantages of the turbo codes. A specific embodiment combines serially concatenated coding for the inner coder with trellis codes on the outer coder.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects of the invention will be described in detail with reference to the accompanying drawings, wherein:

FIG. 1 shows a block diagram of a prior art turbo coder;

FIG. 2 shows a block diagram of inner coder for serially concatenated trellis coded modulation using a generic mapper;

FIG. 3 shows a block diagram of an inner coder using two-dimensional M point mapping;

FIG. 4 shows a coder using a mapping system that provides trellis coded modulation for QAM;

FIG. 5 shows a trellis coded modulator which has an inner coder formed of a two state device;

FIG. 6 shows a trellis coder with a four state trellis coded modulator;

FIG. 7 shows an outer coder for use in the FIGS. 5 and 6 embodiments;

FIG. 8 shows an alternative embodiment using bit puncturing;

FIG. 9 shows a block diagram of an iterative decoder;

FIG. 10 shows a trellis diagram for the decoder; and

FIG. 11 shows a turbo coder with lower complexity.

DETAILED DESCRIPTION

A disclosed embodiment uses serially concatenated codes with Trellis codes, to obtain low error floors and obtain the advantages of iterative coding as it is often used in a parallel concatenated code.

In a "classical" concatenated coding system, an interleaver is placed between inner and outer coders to separate bursts of errors produced by the inner encoder. In contrast, the serially concatenated coder described herein may optimize the inner and outer coders and the interleaver as a single entity thereby optimizing the whole serial structure. This has not been done in the past due to complexity and the difficulty of optimum coding.

The present application may use the technology of the uniform interleaver as described in "unveiling turbo codes: some results on parallel concatenated coding schemes", S. Benedetto, et al, IEEE TRANS of Inf Theory March 1996. The uniform interleaver allows setting criteria which optimize the component codes in order to construct more powerful serially concatenated codes with a relatively large block size.

The complexity of the coding is handled herewith using sub optimum iterative decoding methods. The concatenation of an outer convolutional code or a short block code with an

3

inner trellis coded modulation code is called a serially concatenated TCM code. This system enables a relatively very low bit error rate.

FIG. 2 shows the basic structure of the serially concatenated trellis coded modulation scheme. The outer coder, which is a serial concatenated coder **200**, receives input data **202** having $2b$ bits, and produces output data **204** having $2b+1$ bits. Hence, the outer coder **200** has a rate $2b/(2b+1)$. More generally, however, the coder should have a rate somewhat less than one. A short block code can alternatively be used as long as it has maximum free Hamming distance as the outer code.

An interleaver **210** permutes the output of the outer coder **200**. This produces interleaved data **212**. The interleaved data **212** enters an inner coding block **220** which is a recursive, convolutional inner coder having rate $(2b+1)/(2b+2)$. Mapper **230** then maps the $2b+2$ output bits of the inner coder **220** to two symbols. Each symbol belongs to a 2^{b+1} level modulation or four dimensional modulation. This system uses $2b$ information bits for each two modulation symbol intervals, thereby resulting in a b bit/second/Hz transmission when ideal Nyquist pulse shaping is used. In other words, this provides b bits per modulation symbol. The inner code and the mapping are jointly optimized based on maximum effective free Euclidean distance of the inner trellis coded modulation, as described above.

There are many different ways of configuring two-dimensional and multidimensional trellis coded modulators. Conventional trellis coded modulator designs may have drawbacks when used in this situation. Therefore, while the present application contemplates using conventional trellis coded modulators, it is noted that there are reasons why such conventional modulators may be less useful.

In a serial trellis coded modulator, the Euclidean distance of encoded sequences can be very large for input sequences having a Hamming distance equal to one. This may not be satisfied even if the encoder structure has feedback. Some of the input bits may remain uncoded in a conventional trellis coded modulator. These uncoded bits may select a point from among a set that has been chosen according to the encoded bits. The combination of coded and uncoded bits is then mapped to either two or higher dimensional modulation.

It has been considered by the present inventors to use conventional trellis coded modulation without parallel branches. This, however, may require that the number of states be greater than the number of transition per states. This in turn may prevent the use of simple codes with a small number of states.

Conventional trellis coded modulators also assign the input labels effectively arbitrarily. It has been thought by many that the assignment of input labels did not play an important role in coding. According to the present specified coding system, input labels are carefully selected.

Another aspect is the complexity of the code selection. The serially concatenated trellis coded modulation described with reference to FIG. 2 has a number of transitions per state of 2^{2b+1} . For specific case of interest, b may equal 3. Therefore, even if the number of states is low, the number of transitions may be high. For two states, there still may be 128 transitions per state, resulting in 256 edges in the trellis section. The complexity of the decoder may depend on the number of edges per trellis section. This complexity as described above may actually interfere with high-speed operation, since the complexity of operation takes time to complete.

Another serial concatenated trellis coded modulation scheme is shown in FIG. 3. This system uses a two-dimensional constellation with M points. For purposes of explanation,

4

we can define $m = \log_2 M$, where M is the number of phases. In this structure, the input data **300** is coupled to an outer coder **310** producing $b+1$ bits for the b input bits. Hence, the outer coder is a rate $b/b+1$ binary convolutional coder. An interleaver **320** permutes the output of the outer coder. The interleaved data enters a rate $m/m=1$ recursive convolutional inner coder. The m output bits are then mapped to one symbol along into a 2^m level modulation by a mapping element **340**. This system uses b information bits per $b+1/m$ modulation symbol interval. It effectively results in $bm/b+1$ bits per modulation symbol.

The inner coder **330** and mapping **340** are jointly optimized based on maximization of the effective free Euclidean distance of the inner trellis coded modulator.

For example consider 8PSK modulation, where $m=3$. Then, the throughput $r=3b/(b+1)$ is as follows: for $b=2$, $r=2$; for $b=3$, $r=2.25$; and for $b=4$, $r=2.4$. Accordingly, a $1/2$ convolutional code with puncturing can be used to obtain various throughput values, without changing the inner coder modulation.

For rectangular M^2 -QAM, where $m = \log_2 M$, the structure may become even simpler. In this case, to achieve throughput of $2mb/(b+1)$ bps/Hz a rate $b/(b+1)$ outer coder and a rate m/m inner coder may be used, where the m output bits are alternatively assigned to in-phase and quadrature components of the M^2 -QAM modulation.

The structure of the SCTCM encoder is shown in FIG. 4. An outer coder **400** is connected to an interleaver **410**, which drives a trellis code modulator inner coder **420**.

For example consider 16-QAM modulation, where $m=2$, then the throughput $r=4b/(b+1)$ is: for $b=1$, $r=2$; for $b=2$, $r=2.67$; for $b=3$, $r=3$; and for $b=4$, $r=3.2$.

For this embodiment, $b=r=3$. This causes the number of transitions per state of the inner TCM **420** to be reduced to 4. This results in a large reduction in complexity: 32 times lower than the previous case. Moreover, the outer coder also has a lower code rate; this code rate may be reduced from $6/7$ to $3/4$.

Other embodiments of this basic idea are also possible by changing the mapping. In the FIGS. 5 and 6 embodiments, the output of the inner coder is mapped to the I and Q components of 16QAM alternatively. The encoder structure of a SCTCM for 2-state inner TCM is shown in FIG. 5, which shows the rate $3/4$ four state coder **500** operating as the outer coder. An interleaver **510** drives the inner coder **520**.

The encoder structure of SCTCM for 4-state inner TCM is shown in FIG. 6. The inner coder **620** includes two delay elements as shown. The outer coder **500** has an optimum rate $3/4$, 4-state nonrecursive convolutional code with free Hamming distance of 3.

The detailed structure of the outer encoder **500** is shown in FIG. 7. This rate $3/4$, 4-state outer code has 32 edges per trellis section and produces 4 output bits. Thus the complexity per output bit is $32/4=8$. The complexity per input bit is $32/3$.

The complexity of the outer coder may be further reduced using a rate of $1/2$, 4-state systematic recursive convolutional code. This code can be punctured to rate $3/4$, by puncturing only the parity bits. The minimum distance of this punctured code is 3, the same as for the optimum code. Now the code has 8 edges per trellis section and produces 2 output bits. Thus the complexity per output bit is $8/2=4$. Since this code is systematic there is no complexity associated with the input. The encoder structure for this low complexity SCTCM is shown in FIG. 8.

Using this low complexity scheme with 5 iterations is roughly equal to the complexity of a standard Viterbi decoder. However, this obtains a 2 db advantage over the "Pragmatic" TCM system.

5

It can be shown that a dominant term in the transfer function bound on bit error probability of serially concatenated TCM, employing an outer code with free (or minimum) Hamming distance d_f^0 , averaged over all possible interleavers of N bits, is proportional for large N to

$$N^{3.1} [(d_f^0 + 1)/2] e^{-\delta^2 (E_s/4N_0)}$$

Where $[x]$ represents, the integer part of x , and

$$\delta^2 = \frac{d_f^0 d_{f,eff}^2}{2} \text{ for } d_f^0 \text{ even, and}$$

$$\delta^2 = \frac{(d_f^0 - 3)d_{f,eff}^2}{2} + (h_m^{(3)})^2, \text{ for } d_f^0 \text{ odd}$$

The parameter $d_{f,eff}$ the effective free Euclidean distance of the inner code, $h_m^{(3)}$ is the minimum Euclidean distance of inner code sequences generated by input sequences with Hamming distance 3, and E_s/N_0 is the M-ary symbol signal-to-noise-ratio.

The above results are valid for very large N . On the other hand, for large values of the signal-to-noise ratio E_s/N_0 , the performance of SCTCM is dominated by

$$N^{-(h_m(h_m-1))} e^{-h_m^2 (E_s/4N_0)}$$

where h_m is the minimum Euclidean distance of the SCTCM scheme, and $l_m(h_m) \cong d_f^0$.

Based on these results, the design criterion for serially concatenated TCM for larger interleavers and very low bit error rates is to maximize the free Hamming distance of the outer code (to achieve interleaving gain), and to maximize the effective free Euclidean distance of the inner TCM code.

Let z be the binary input sequence to the inner TCM code, and $x(z)$ be the corresponding inner TCM encoder output with M-ary symbols. The present application defines criteria for selecting the constituent inner TCM encoder:

1. The constituent inner TCM encoder may be configured for a given two or multidimensional modulation such that the minimum Euclidean distance $d(x(z), x(z'))$ over all z, z' pairs, $z \neq z'$ is maximized given that the Hamming distance $d_H(z, z')=2$. We call this minimum Euclidean distance the effective free Euclidean distance of the inner TCM code, $d_{f,eff}$.

2. If the free distance of outer code d_f^0 is odd, then, among the selected inner TCM encoders, choose those that have the maximum Euclidean distance $d(x(z), x(z'))$ over all z, z' pairs, $z \neq z'$, given that the Hamming distance $d_H(z, z')=3$. This value is the minimum Euclidean distance of the inner TCM code due to input Hamming distance 3, denoted by $h_m^{(3)}$.

3. Among the candidate encoders, select the one that has the largest minimum Euclidean distance in encoded sequences produced by input sequences with Hamming distance d_f^0 . This minimum Euclidean distance of the SCTCM is called h_m .

It has been found by the inventors that that sequences with Hamming distances of 2 or 3 at the input of the TCM encoder are still important, even if the free Hamming distance d_f^0 of the outer code is larger than 2 or even 3. This is because the interleaving gain at low signal to noise ratios may depend on the number of error events that a pair of input sequences generate in the trellis of the inner code. For a given input Hamming distance, a larger number of error events may create a smaller interleaving gain. For example, if the input Hamming distance between sequences to the inner TCM is 4, the largest number of error events that produce small output Euclidean distances is 2 (two events with an input Hamming distance of 2 each).

6

As described above, the present embodiments also use mapping of output labels for TCM. As soon as the input labels and output signals are assigned to the edges of a trellis, a complete description of the TCM code is obtained. The selection of the mapping (output labels) does not change the trellis code. However, it influences the encoder circuit required to implement the TCM scheme. A convenient mapping should be selected to simplify the encoder circuit and, if possible, to yield a linear circuit that can be implemented with exclusive Ors. The set partitioning of the constellation and the assignment of constellation points to trellis edges, and the successive assignments of input labels to the edges may be important. Ungerboeck proposed a mapping called "Mapping by set partitioning", leading to the "natural mapping". This mapping for two-dimensional modulation may be useful if one selects the TCM scheme by searching among all encoder circuits that maximize the minimum Euclidean distance.

The "inner" trellis code modulator can be configured as follows:

The well known set partitioning techniques for signal sets may be used.

The input label assignment is based on the codewords of the parity check code $(m, m-1, 2)$ and the set partitioning, to maximize the quantities described in the equations above. The minimum Hamming distance between input labels for parallel transitions will be equal to 2. The assignment of codewords of the parity check code as input labels to the two-dimensional signal points is not arbitrary.

A sufficient condition to have very large output Euclidean distances for input sequences with Hamming distance 1 is that all input labels to each state be distinct.

A pair of input labels and two-dimensional signal points are assigned to the edges of a trellis diagram based on the design criteria described above.

Let the eight phases of 8PSK be denoted by $\{0, 1, 2, 3, 4, 5, 6, 7\}$. Here $m=3$. Consider the 8PSK signal set $A=\{0, 2, 4, 6\}$, and set $B=\{1, 3, 5, 7\}$. For unit radius 8PSK constellation, the minimum intra-set square Euclidean distance for each set is 2. The minimum inter-set square Euclidean distances is 0.586.

Select the input label set L_0 as codewords of the $(3, 2, 2)$ parity check code, i.e. $L_0=[(000), (011), (101), (110)]$, next generate input label $L_1=L_0+(001)$, i.e., $L_1=[(001), (010), (100), (111)]$. Consider a 2-state trellis. Assign the input-output pair (L_0, A) to four edges from state 0 to state 0. Assign the input-output pair (L_1, B) to four edges from state 0 to state 1. Next assign the input-output pair (L_2, A) to four edges from the state 1 to state 0, and assign the input-output pair (L_3, B) to four edges from-state 1 to state 1. L_2 has the same elements as in L_1 but with different order, and L_3 has the same elements as in L_0 again with different order. In order to maximize the minimum Euclidean distance due to the input sequences with Hamming distance 2, we have to find the right permutation within each set. In this case it turns out that using the complement operation suffices. Therefore define input label L_2 as the complement of the elements of L_0 without changing the order, i.e., $L_2=[(111), (100), (010), (001)]$. Finally L_3 is generated in the same way, as the complement of elements in L_1 , i.e. $L_3=[(110), (101), (011), (000)]$.

Such assignment guarantees that the squared effective free Euclidean distance of trellis code is 2, where the minimum squared Euclidean distance of the code is 0.586.

Having determined the code by its input labels and two-dimensional output signals, the encoder structure can then be obtained by selecting any appropriate labels (output labels) for the two-dimensional output signals. The following output mapping may be used: $\{(000), (001), (010), (011), (110),$

(111), (100), (101)], mapped to phases [0, 1, 2, 3, 4, 5, 6, 7], which is called “reordered mapping”. For this 2-state inner code, $d_{f,eff}^2=2$, and $h_m^{(3)=\infty}$, and $h_m^2=0.586$. The outer code for this example can be selected as a 4-state, rate 2/3, convolutional code with $d_f^0=3$ (this is a recursive systematic rate 1/2 convolutional code where the parity bits are punctured). Since $h_m^{(3)=\infty}$ then d_f^0 is increased effectively to 4. This method of design was used to obtain the encoders in the previous examples for 16QAM.

A decoder is described herein. This decoder can be a Bit-by-Bit Iterative Decoder. The iterative decoder for serially concatenated trellis coded modulation uses a generalized Log-APP (a-posteriori probability) decoder module with four ports, called SISO APP module or simply SISO. The block diagram of the iterative decoder for serial concatenated TCM is shown in FIG. 9. The device has a SISO inner decoder 900 coupled to a deinterleaver 905, an outer decoder 910. Feedback is passed through an interleaver 920 back to the inner decoder.

The decoding techniques may be used for the inner TCM code and outer convolutional code, using the trellis section shown in FIG. 10. Consider an inner TCM code with p_1 input bits and q_1 nonbinary complex output symbols with normalized unit power, and an outer code with p_2 input bits and q_2 binary outputs {0,1}. Let $U_k(e)$ represent $u_{k,i}(e)$; $i=1,2,\dots,p_m$ the input bits on a trellis edge at time k ($m=1$ for the inner TCM, and $m=2$ for the outer code), and let $c_k(e)$ represents $c_{k,i}(e)$; $i=1,2,\dots,q_m$ the output symbols ($m=1$ for the inner TCM, with nonbinary complex symbols, and $m=2$ for the outer code with binary {0,1} symbols).

Define the reliability of a bit Z taking values {0,1} at time k as

$$\lambda_k[z; \dots] \triangleq \log \frac{P_k[Z=1;]}{P_k[Z=0;]}$$

The second argument in the brackets, shown as a dot, may represent I, the input, or O, the output, to the SISO. We use the following identity

$$a = \log \left[\sum_{i=1}^L e^{a_i} \right] = \max_i \{a_i\} + \delta(a_1, \dots, a_L) \triangleq \max_i \{a_i\}$$

where $\delta(a_1, \dots, a_L)$ is the correction term which can be computed using a look-up table.

The “max” operation is a maximization (compare/select) plus a correction term (lookup table). Small degradations occur if the “max” operation is replaced by “max”. The received complex samples $\{Y_{k,i}\}$ at the output of the receiver matched filter are normalized such that additive complex noise samples have unit variance per dimension.

SISO can be used for the Inner TCM.

The forward and the backward recursions are:

$$a_k(s) =$$

$$\max_{e: s^E(e)=s} * \left\{ a_{k-1}[s^E(e)] + \sum_{i=1}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] \right\} + h_{a_k}$$

-continued

$$\beta_k(s) = \max_{e: s^E(e)=s} * \left\{ \beta_{k+1}[s^E(e)] + \sum_{i=1}^{p_1} u_{k+1,i}(e) \lambda_{k+1}[U_{k+1,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_{k+1}[c_{k+1,i}(e); I] \right\} + h_{\beta_k}$$

for all states s , and $k=1, \dots, (n-1)$, where n represents the total number of trellis steps from the initial state to the final state.

The extrinsic bit information for $U_{k,j}$; $j=1,2,\dots,p_1$ can be obtained from:

$$\lambda_k(U_{k,j}; O) = \max_{e: u_{k,j}(e)=1} * \left\{ a_{k-1}[s^E(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\} - \max_{e: u_{k,j}(e)=0} * \left\{ a_{k-1}[s^E(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\}$$

where

$$\bar{\lambda}_k[c_{k,i}(e); I] = - \left| y_{k,i} - \sqrt{\left(\frac{2E_s}{N_o}\right)} c_{k,i}(e) \right|^2 / 2.$$

We assume the initial and the final states of the inner encoder (as well as the outer encoder) are the all zero state. Forward recursions start with initial values, $\alpha_0(s)=0$, if $s=0$ (initial zero state) and $\alpha_0(s)=-\infty$, if $s \neq 0$. Backward recursions start with $\beta_n(s)=0$, if $s=0$ (final zero state) and $\beta_n(s)=-\infty$, if $s \neq 0$. The $h_{a_0,k}$ and h_{β_k} are normalization constants which, in the hardware implementation of the SISO, are used to prevent buffer overflow. These operations are similar to the Viterbi algorithm used in the forward and backward directions, except for a correction term that is added when compare-select operations are performed. At the first iteration, all $\lambda_k[U_{k,i}; I]$ are zero. After the first iteration, the inner SISO accepts the extrinsics from the outer SISO, through the interleaver π , as reliabilities of input bits of TCM encoder, and the external observations from the channel. The inner SISO uses the input reliabilities and observations for the calculation of new extrinsics $\lambda_k(U_{k,j}; O)$ for the input bits. These are then provided to the outer SISO module, through the deinterleaver π^{-1} . The forward and the backward recursions for SISO are:

$$\alpha_k(s) = \max_{e: s^E(e)=s} * \left\{ a_{k-1}[s^S(e)] + \sum_{i=1}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] \right\} + h_{\alpha_k}$$

$$\beta_k(s) = \max_{e: s^E(e)=s} * \left\{ \beta_{k+1}[s^E(e)] + \sum_{i=1}^{p_1} u_{k+1,i}(e) \lambda_{k+1}[U_{k+1,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_{k+1}[c_{k+1,i}(e); I] \right\} + h_{\beta_k}$$

The extrinsic information for $C_{k,j}; j=1, 2, \dots, q_2$, can be obtained from:

$$\lambda_k(U_{k,j}; O) = \max_{e: u_{k,j}(e)=1} * \left\{ a_{k-1}[s^S(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\} - \max_{e: u_{k,j}(e)=0} * \left\{ a_{k-1}[s^S(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\}$$

with initial values, $\alpha_0(s)=0$, if $s=0$ and $\alpha_0(s)=-\infty$, if $s \neq 0$ and $\beta_n(s)=0$, if $s=0$ and $\beta_n(s)=-\infty$, if $s \neq 0$, where h_{α_k} and h_{β_k} are normalization constants which, in the hardware implementation of the SISO, are used to prevent the buffer overflow.

The final decision is obtained from the bit reliability computation of $U_{k,j}; j=1, 2, \dots, p_2$, passing through a hard limiter, as

$$\lambda_k(U_{k,j}; O) = \max_{e: u_{k,j}(e)=1} * \left\{ a_{k-1}[s^S(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\} - \max_{e: u_{k,j}(e)=0} * \left\{ a_{k-1}[s^S(e)] + \sum_{\substack{i=1 \\ i \neq j}}^{p_1} u_{k,i}(e) \lambda_k[U_{k,i}; I] + \sum_{i=1}^{q_1} \bar{\lambda}_k[c_{k,i}(e); I] + \beta_k[s^E(e)] \right\}$$

The outer SISO accepts the extrinsics from the inner SISO as input reliabilities of coded bits of the outer encoder. For the outer SISO there is no external observation from the channel. The outer SISO uses the input reliabilites for calculation of new extrinsics $\lambda_k(C_{k,j}; O)$ for coded bits. These are then provided to the inner SISO module.

The structure of iterative decoder for punctured outer code is shown in FIG. 11.

Other embodiments are within the disclosed invention.

What is claimed is:

1. A decoding apparatus configured to decode first symbols received from a channel, wherein the first symbols correspond to output symbols transmitted onto the channel by an encoder system, wherein the encoder system is configured to perform an outer encoding on source data in order to generate first data, and to perform an inner trellis coded modulation (TCM) on an interleaved version of the first data to generate the output symbols, the decoding apparatus comprising:

an inner soft-input soft-output (SISO) module configured to compute first feedforward information based on input information and on first feedback information, wherein the input information is derived from the first symbols received from the encoder system, wherein the inner SISO module is configured to compute the first feedforward information based on an inner trellis defined by said inner TCM of the encoder system;

a fill and multiplex (FAM) unit configured to generate augmented information by interleaving zero bits with bits of a deinterleaved version of the first feedforward information;

an outer SISO module configured to compute output information and second feedback information based on the augmented information, wherein the outer SISO module is configured to compute the output information and the second feedback information based on an outer trellis defined by the outer encoding of the encoding system; and

a puncture and demultiplex (PAD) unit configured to puncture the second feedback information according to a puncturing pattern, in order to generate punctured feedback information, wherein the first feedback information is an interleaved version of the punctured feedback information;

wherein the inner TCM of the encoder system includes an inner encoding and a mapping, wherein the inner encoding encodes the interleaved version of the first data to generate intermediate data according to a rate 1 recursive code, wherein the mapping generates the output symbols of the inner TCM from the intermediate data according to a first map, wherein the rate 1 recursive code and the first map maximize the effective free Euclidean distance of the inner TCM.

2. The decoding apparatus of claim 1, wherein the decoding apparatus is configured to generate an estimate of at least a portion of the source data from the output information.

3. The decoding apparatus of claim 1, wherein the decoding apparatus is configured to operate said inner SISO module and said outer SISO module in an iterative fashion.

4. The decoding apparatus of claim 1, wherein the output symbols are points in a quadrature amplitude modulation (QAM) constellation, wherein the number of points in said QAM constellation is equal to 2^{2m} , wherein m is an integer greater than one.

5. The decoding apparatus of claim 1, wherein the output symbols correspond to a phase-shift keying (PSK) modulation, wherein the PSK modulation has a constellation with 2^m points, wherein m is larger than one.

11

6. The apparatus of claim 1, wherein the outer encoding is configured to maximize free Hamming distance.

7. The apparatus of claim 6, wherein the free Hamming distance of the outer encoding is odd, wherein the rate 1 recursive code and the first map are also selected to maximize Euclidean distance $d(x(z), x(z'))$ over pairs z, z' given that the Hamming distance $d_H(z, z')$ is equal to three, wherein z and z' are possible input sequences to the rate 1 recursive code.

8. The apparatus of claim 1, wherein the inner trellis is a 4-state trellis.

9. The apparatus of claim 1, wherein the inner trellis is a 2-state trellis.

10. A decoding apparatus configured to decode first symbols received from a channel, wherein the first symbols correspond to output symbols transmitted onto the channel by an encoder system, wherein the encoder system is configured to perform an outer encoding on source data in order to generate first data, and to perform an inner trellis coded modulation (TCM) on an interleaved version of the first data to generate the output symbols, the decoding apparatus comprising:

a first means for computing first feedforward information based on input information and on first feedback information, wherein the input information is derived from the first symbols received from the encoder system, wherein said computing the first feedforward information is based on an inner trellis defined by said inner TCM of the encoder system;

a second means for generating augmented information by interleaving zero bits with bits of a deinterleaved version of the first feedforward information;

a third means for computing output information and second feedback information based on the augmented information, wherein said computing the output information and the second feedback information is based on an outer trellis defined by the outer encoding of the encoding system;

a fourth means for puncturing the second feedback information according to a puncturing pattern in order to generate punctured feedback information, wherein the

12

first feedback information is an interleaved version of the punctured feedback information; and

wherein the inner TCM of the encoder system includes an inner encoding and a mapping, wherein the inner encoding encodes the interleaved version of the first data to generate intermediate data according to a rate 1 recursive code, wherein the mapping generates the output symbols of the inner TCM from the intermediate data according to a first map, wherein the rate 1 recursive code and the first map maximize the effective free Euclidean distance of the inner TCM.

11. The decoding apparatus of claim 10, wherein the decoding apparatus is configured to generate an estimate of at least a portion of the source data from the output information.

12. The decoding apparatus of claim 10, wherein the decoding apparatus is configured to operate said first means, said second means, said third means and said fourth means in an iterative fashion.

13. The decoding apparatus of claim 10, wherein the output symbols are points in a quadrature amplitude modulation (QAM) constellation, wherein the number of points in said QAM constellation is equal to 2^{2m} , wherein m is an integer greater than one.

14. The decoding apparatus of claim 10, wherein the output symbols correspond to a phase-shift keying (PSK) modulation, wherein the PSK modulation has a constellation with 2^m points, wherein m is larger than one.

15. The apparatus of claim 10, wherein the outer encoding is configured to maximize free Hamming distance.

16. The apparatus of claim 15, wherein the free Hamming distance of the outer encoding is odd, wherein the rate 1 recursive code and the first map are also selected to maximize Euclidean distance $d(x(z), x(z'))$ over pairs z, z' given that the Hamming distance $d_H(z, z')$ is equal to three, wherein z and z' are possible input sequences to the rate 1 recursive code.

17. The apparatus of claim 10, wherein the inner trellis is a 4-state trellis.

18. The apparatus of claim 10, wherein the inner trellis is a 2-state trellis.

* * * * *