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**Wolf**

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(54) **DECODING METHOD AND APPARATUS**

(75) Inventor: **Jack K. Wolf**, La Jolla, CA (US)

(73) Assignee: **QUALCOMM Incorporated**, San Diego, CA (US)

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**Related U.S. Application Data**

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(51) **Int. Cl.**<sup>7</sup> ..... **H04L 23/02**; H04L 5/12; H04J 3/16

(52) **U.S. Cl.** ..... **375/265**; 375/262; 375/341; 370/468; 370/480; 714/794

(58) **Field of Search** ..... 375/262, 265, 375/326, 327, 130, 150, 332, 259, 340, 341; 370/335, 441, 468, 480; 714/786, 791, 755, 751, 792

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*Primary Examiner*—Khair Tran

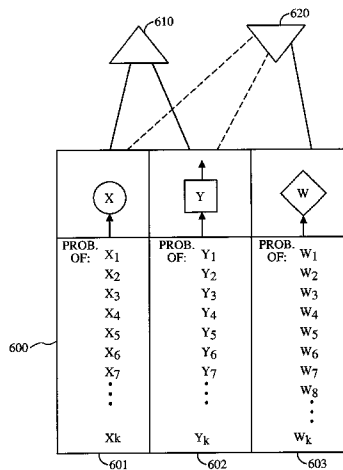
*Assistant Examiner*—Qutbuddin Ghulamali

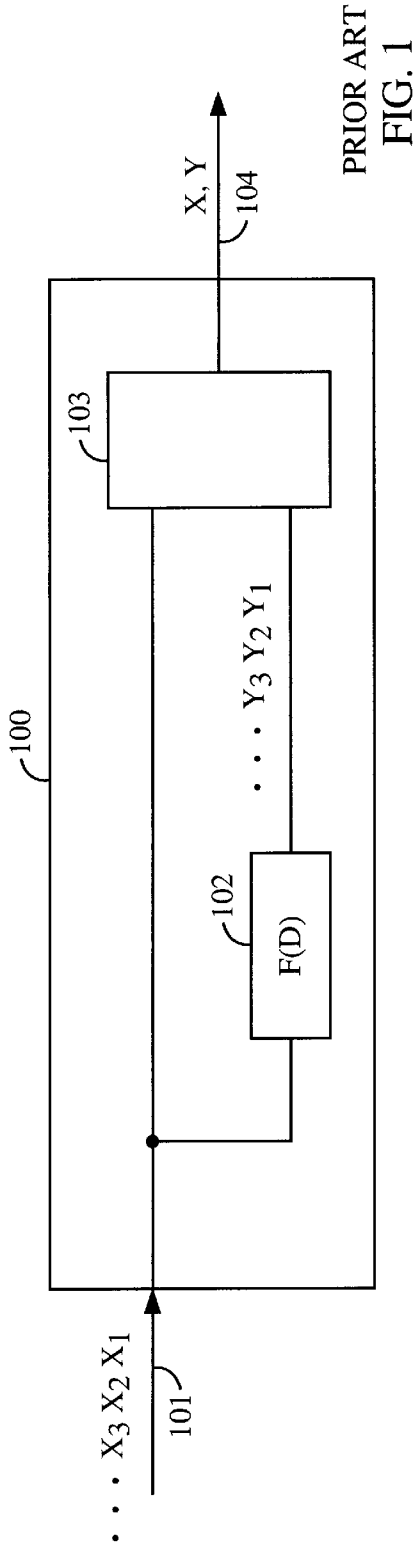
(74) *Attorney, Agent, or Firm*—Philip Wadsworth; Sandra L. Godsey; S. Hossain Boladi

(57) **ABSTRACT**

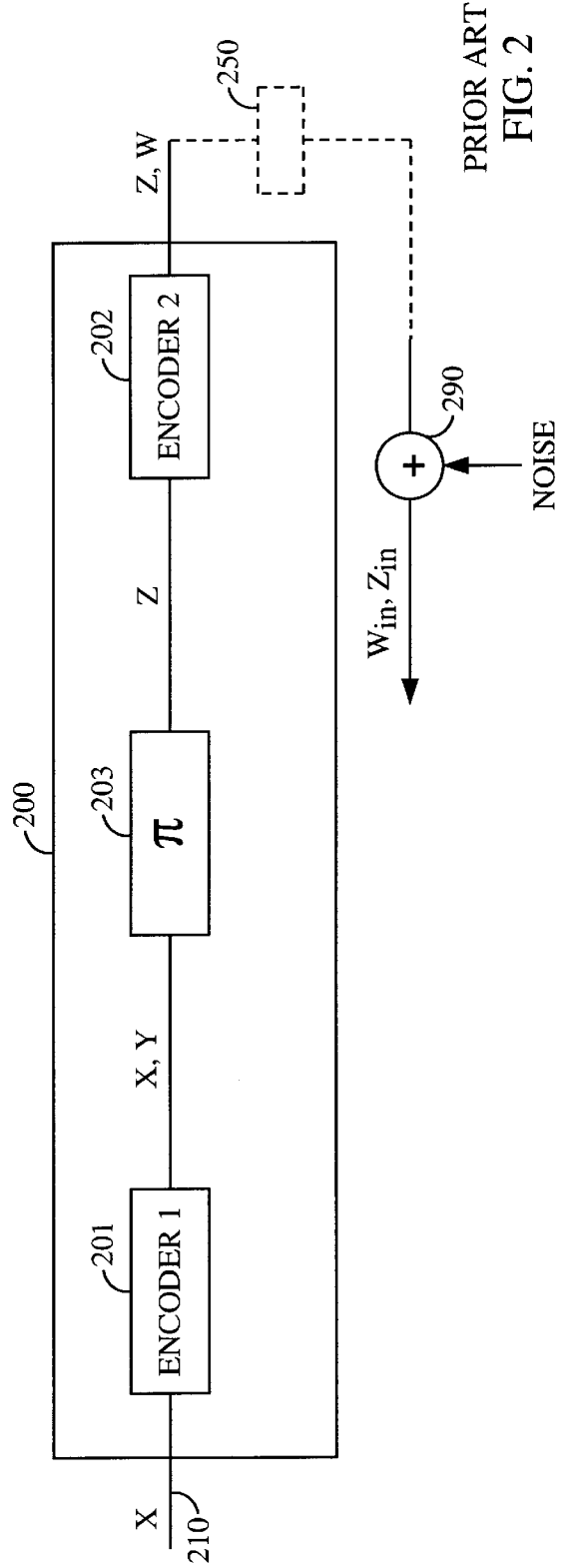
A decoding method and apparatus include providing capability for decoding data symbols that were encoded in a transmitter by either a serial-concatenated code or turbo code in a parallel processing fashion. The receiver upon knowing the encoding method may reconfigure the selection of data symbols from a table to accommodate the appropriate decoding process. Initially a data symbol estimate for a number of data symbols of a plurality of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  are determined. The estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  passing to a first and second decision nodes include estimates for the variables in one or more encoding equations. A new estimate for the data symbol  $X_i$  is determined based on the estimate determined at the initial step and the new estimate for each occurrence of the data symbol  $X_i$  at the first and second decision nodes. After normalizing estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$ , a new estimate for data symbol  $X_i$  may be determined which holds more confidently a true value for the data symbol  $X_i$  than a previously determined estimate.

**8 Claims, 7 Drawing Sheets**

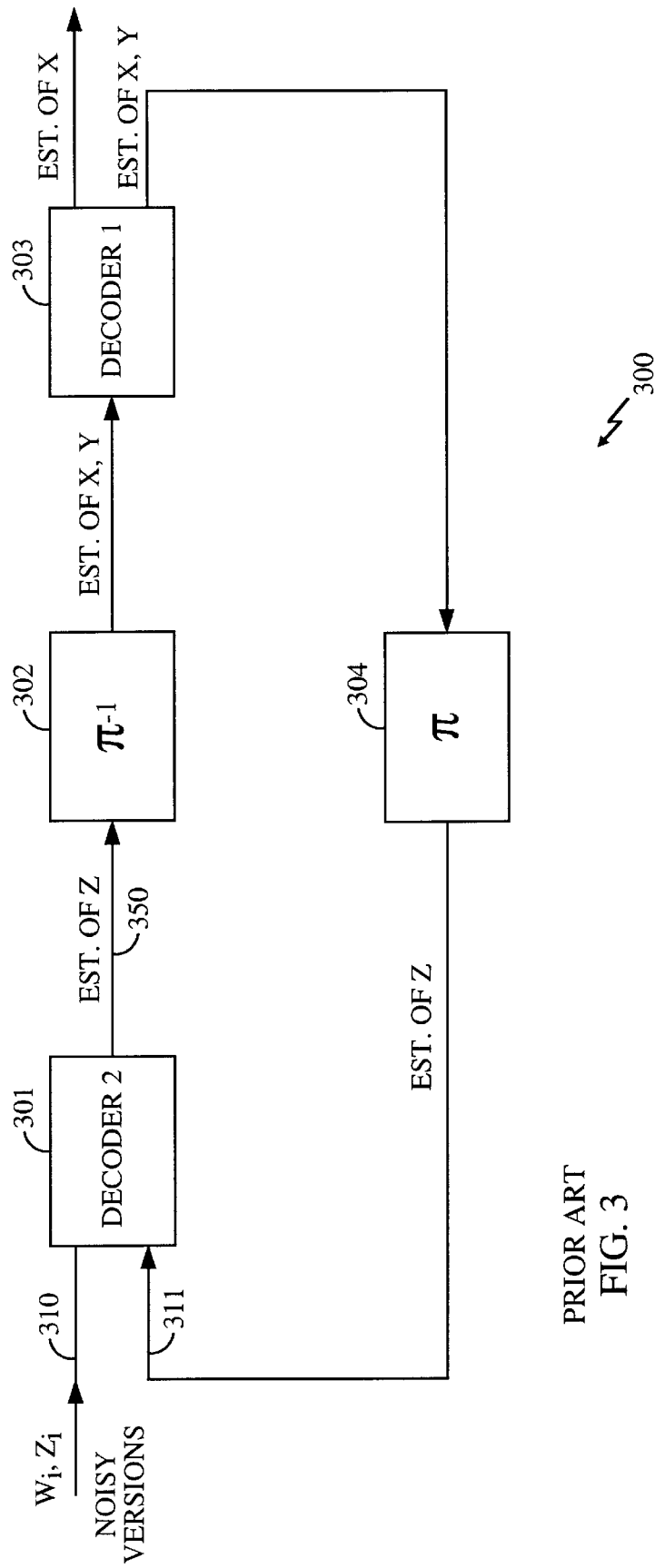




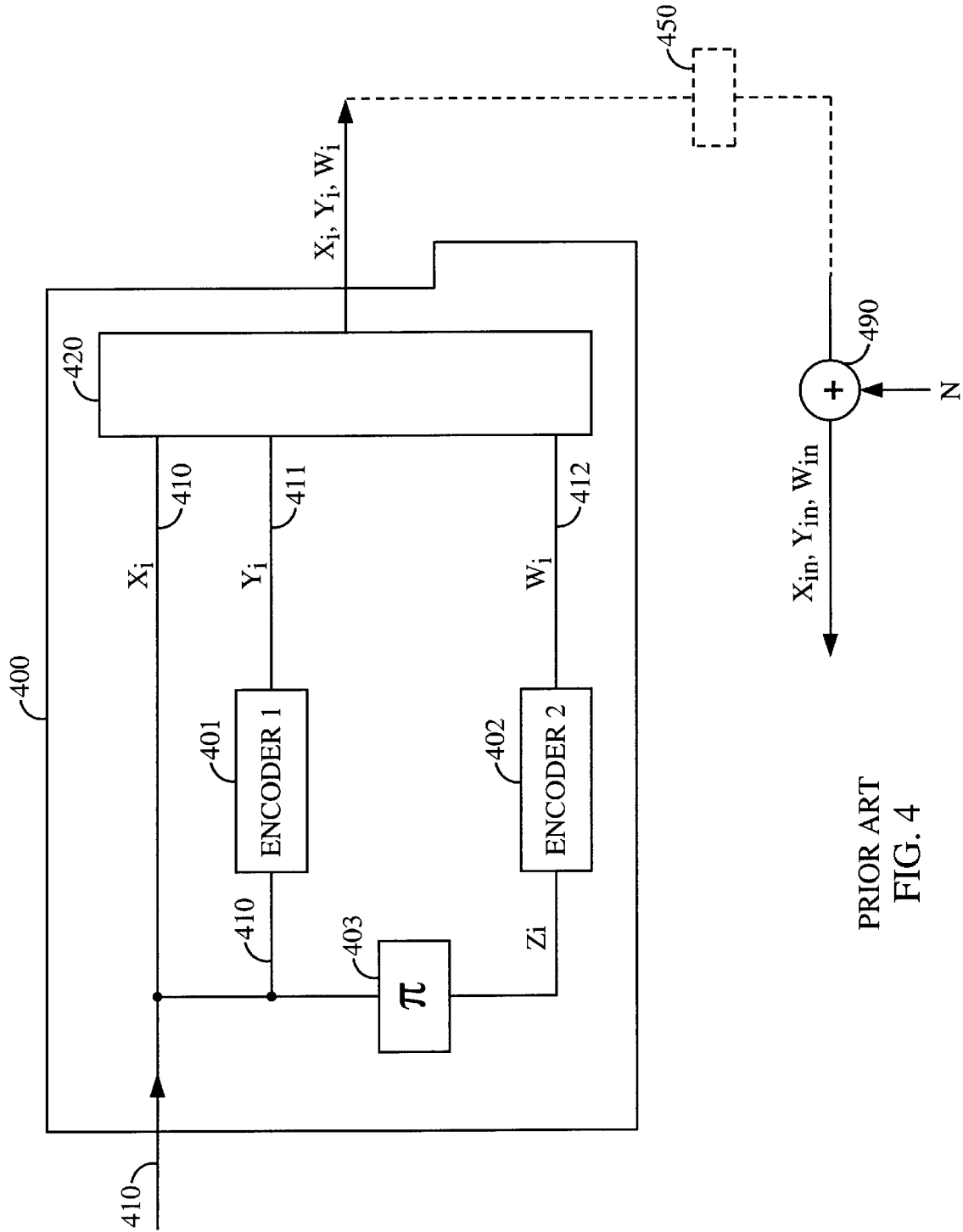
PRIOR ART  
FIG. 1



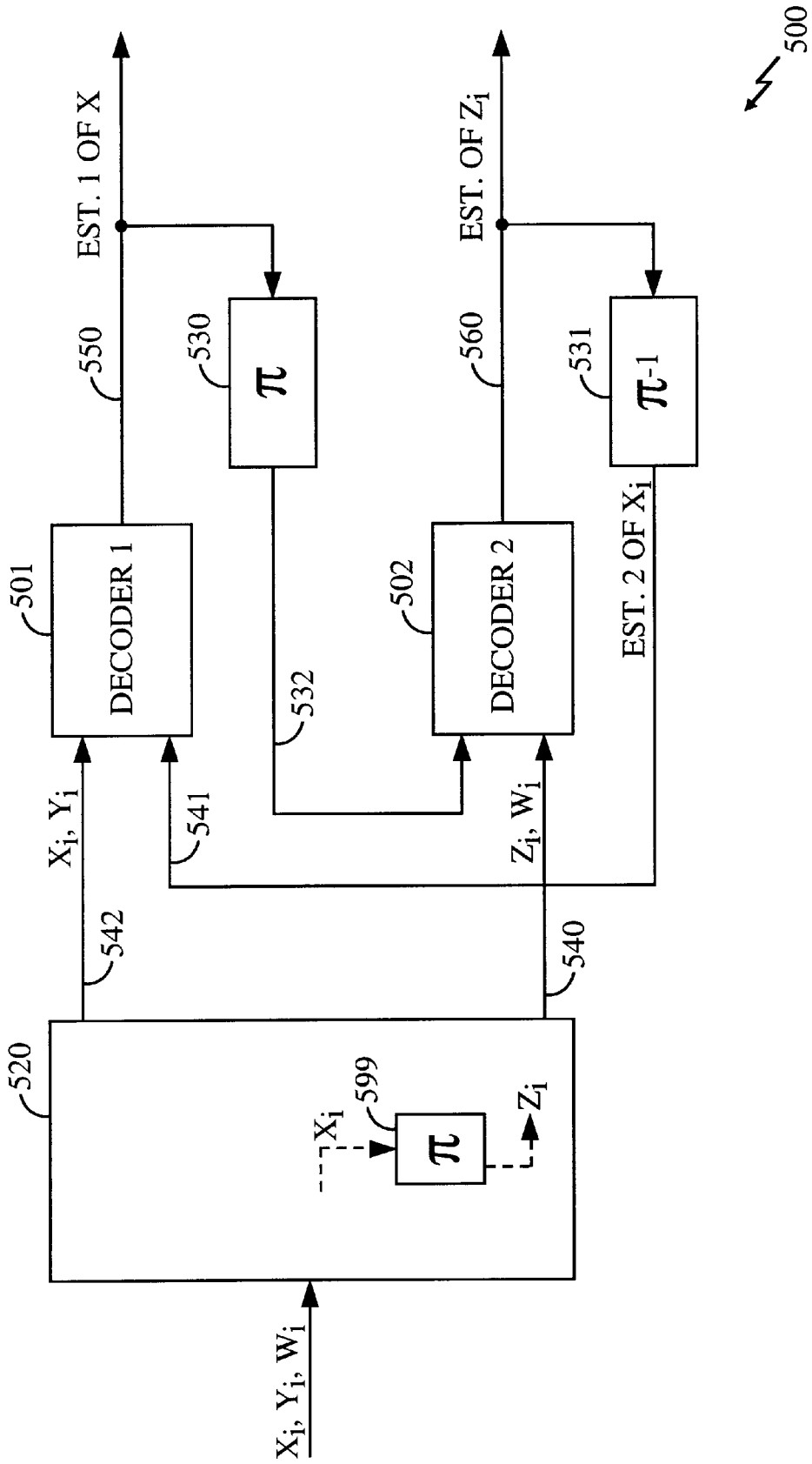
PRIOR ART  
FIG. 2



PRIOR ART  
FIG. 3



PRIOR ART  
FIG. 4



PRIOR ART  
FIG. 5

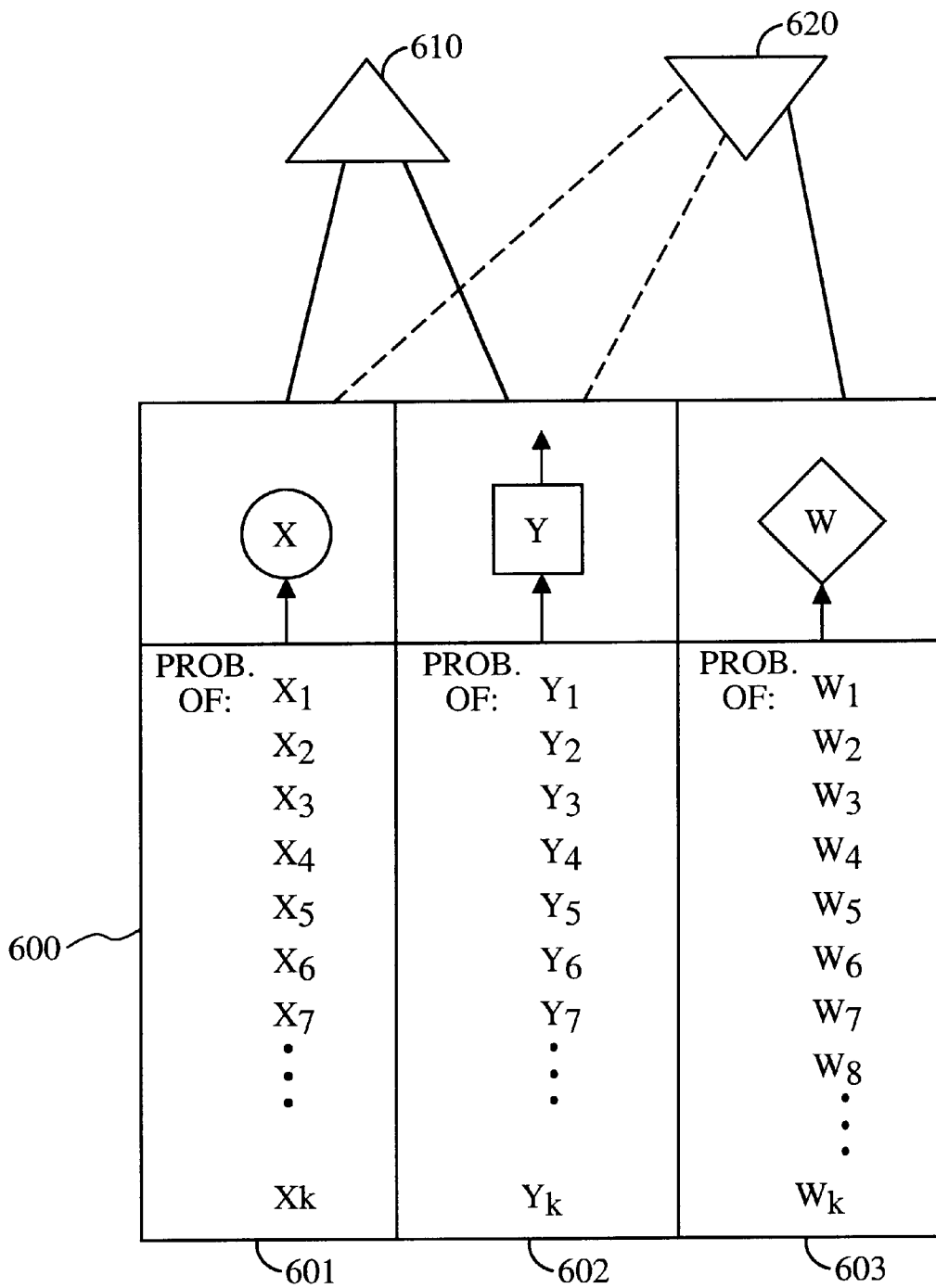


FIG. 6

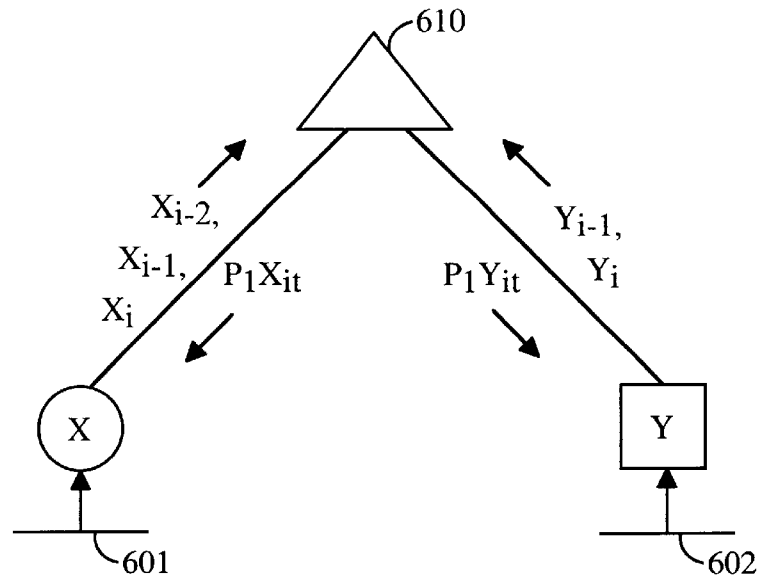


FIG. 7

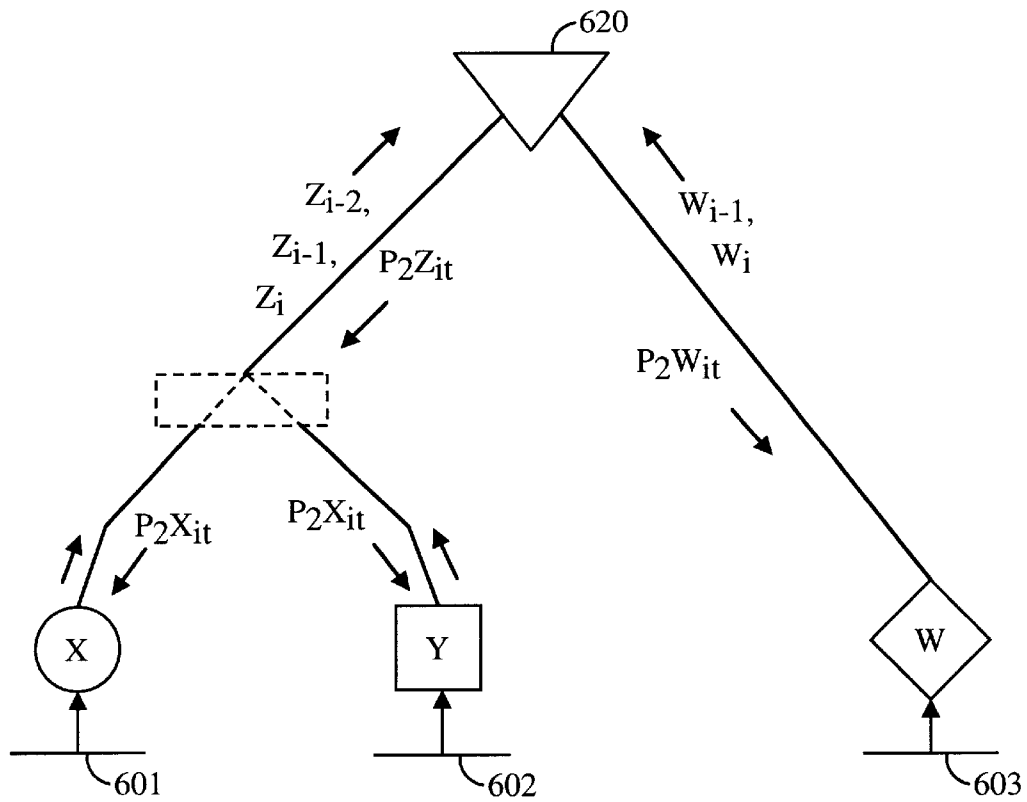


FIG. 8

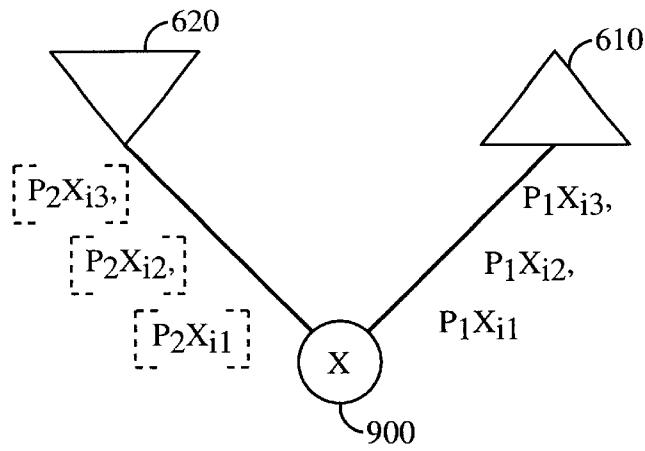


FIG. 9

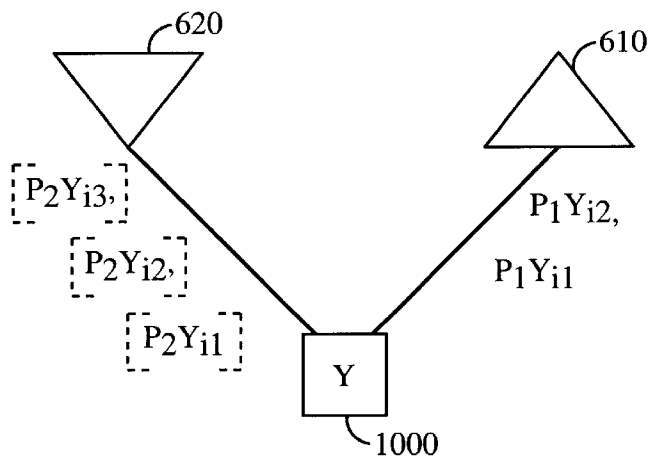


FIG. 10

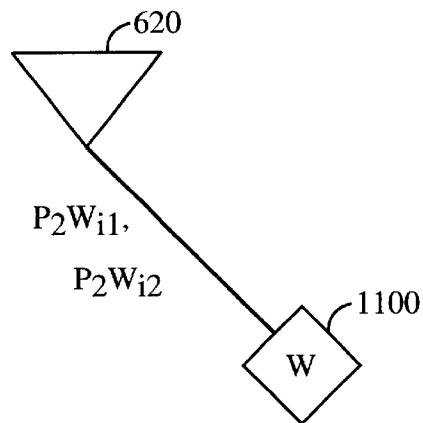


FIG. 11



**DECODING METHOD AND APPARATUS**

This is a continuation of application Ser. No. 09/571,066, filed May 15, 2000, now U.S. Pat. No. 6,542,559.

**BACKGROUND OF THE INVENTION**

The present invention generally relates to communication systems, and more particularly, a code division multiple access (CDMA) communication system. The invention provides an efficient method and apparatus for decoding data symbols in a receiver portion of a CDMA communication system.

Communications in a CDMA system involve coding and decoding data symbols at different stages. Data symbols, for transmission to a destination user, are encoded in a transmitter portion of the CDMA system before being transmitted over a communication link, such as a wireless link. Upon receiving the transmitted signal, the destination user decodes the data symbols to retrieve the information. A convolutional code is a very popular code used for the encoding operation. To achieve an effective communication between users, in addition to coding, data symbols are interleaved. A destination user in the process of receiving the information decodes and de-interleaves the received data symbols to retrieve the information. The combination of interleaving and convolutional coding provides a more effective way of dealing with channel disturbances, for example, due to noise, fading or interference from other users in a communication system, such as a CDMA system.

A combination of coding and interleaving commonly known as a turbo code performed in a transmitter of a CDMA communication system has shown to provide superior results in ways of dealing with channel disturbances. A combination of coding and interleaving commonly known as a Serial-Concatenated Code (SCC) has shown also to provide superior results. As such, a CDMA system may use either a turbo code or an SCC.

Generally speaking, a turbo code and a serial-concatenated code each include at least two encoding blocks. As such, a receiver attempting to decode the received data symbols may have to deal with two decoding operations. Multiple decoding operations in a receiver takes time and adds complexity and cost to the receiver portion of the CDMA systems.

Several differences exist between turbo and serial-concatenated codes. A turbo code uses parallel encoding, in contrast to a serial encoding used in serial-concatenated code. Such a difference presents a difficulty for a receiver attempting to provide decoding functionality for both turbo and serial-concatenated codes.

Therefore, there is a need for a method and apparatus with minimal complexity for fast and efficient decoding of encoded data symbols in a receiver.

**SUMMARY OF THE INVENTION**

According to various embodiments of the invention, a method and apparatus for decoding a data symbol  $X_i$  of a plurality of data symbols  $X_i$ , with subscript (i) having a value from (1) to (k), (k) being a finite number, includes determining initially a data symbol estimate for a number of data symbols of the plurality of data symbols  $X_i$ . A data symbol estimate is determined for a number of data symbols of a plurality of data symbols  $Y_i$ . The plurality of data symbols  $Y_i$  are produced in a transmitter in the communication system by encoding the plurality of data symbols  $X_i$

according to a first convolutional code. A data symbol estimate is determined for a number of data symbols of a plurality of data symbols  $W_i$ . The plurality of data symbols  $W_i$  are produced in the transmitter by interleaving, in case of serial-concatenated code, the plurality of data symbols  $Y_i$  and  $X_i$ , and in case of turbo code, the plurality of data symbols  $X_i$ , to produce a plurality of data symbols  $Z_i$ . The plurality of data symbols  $Z_i$  are encoded according to a second convolutional code to produce the plurality of data symbols  $W_i$ . The estimates of data symbols  $X_i$  and  $Y_i$  pass to a first decision node. The estimates of data symbols  $X_i$  and  $Y_i$  passing to the first decision node include the estimates for the variables in an equation  $F1(X_i, Y_i)$ . The variables  $X_i$  and  $Y_i$  in the equation  $F1$  are determined according to the first convolutional code. The estimates of data symbols  $W_i$  and  $Z_i$  pass to a second decision node. The estimates of data symbols  $W_i$  and  $Z_i$  passing to the second decision node include the estimates for the variables in an equation  $F2(W_i, Z_i)$ . The variables  $W_i$  and  $Z_i$  in the equation  $F2$  are determined according to the second convolutional code. The estimates for the variables  $Z_i$  include the estimates of data symbols  $X_i$ , or  $Y_i$ , or  $X_i$  and  $Y_i$  determined according to the interleaving. While equating the equations  $F1$  and  $F2$  to zero at respectively the first and second decision nodes, a new estimate is determined for each occurrence of the data symbol  $X_i$  at the first and second decision nodes. A new estimate for the data symbol  $X_i$  is determined based on the estimate determined at the initial step and the new estimate for each occurrence of the data symbol  $X_i$  at the first and second decision nodes.

The new estimate for the data symbol  $X_i$  may confidently hold a true value for the data symbol  $X_i$ . The process may be repeated many times until the new estimate for the data symbol  $X_i$  confidently holds a true value for the data symbol  $X_i$ . When more than one iteration is necessary to build the confidence level, an embodiment of the invention includes determining a normalized estimate of data symbol  $X_i$  based on the estimate determined at the initial step and at least one of the new estimates for each occurrence of the data symbol  $X_i$  at the first and second decision nodes. The steps of passing estimates of data symbols to the first and second nodes are repeated while substituting the normalized estimate of data symbol  $X_i$  for at least one of the estimates of data symbols  $X_i$ . As such, an embodiment of the invention provides a method and apparatus for determining at the same time in a parallel fashion estimates of the plurality of data symbols  $X_i$  with minimal delay and complexity.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 depicts a general block diagram of a conventional encoder.

FIG. 2 depicts a general block diagram of a conventional encoder encoding data symbols according to an (SCC).

FIG. 3 depicts a block diagram of a conventional decoder for decoding data symbols encoded according to a serial-concatenated code.

FIG. 4 depicts a general block diagram of a conventional encoder encoding data symbols according to a turbo code.

FIG. 5 depicts a block diagram of a conventional decoder for decoding data symbols encoded according to a turbo code.

FIG. 6 depicts a decoding process according to various embodiments of the invention for decoding operations on a block of data having a length of "k" data symbols, "k" being a finite number.

FIG. 7 depicts passing estimates of data symbols  $X_i$  and  $Y_i$  to a first decision node as a part of the decoding process according to various embodiments of the invention.

FIG. 8 depicts passing the estimates of data symbols  $W_i$  and  $Z_i$  to a second decision node as a part of the decoding process according to various embodiments of the invention.

FIG. 9 depicts an example of passing three estimates of data symbols  $X_i$  involved in three occurrences at a decision node for determining a normalized value and a new estimate for data symbol  $X_i$ .

FIGS. 10 and 11 depict the processes of determining a new estimate and a normalized value for data symbols  $Y_i$  and  $W_i$  which are similar to the process for determining a new estimate and a normalized value for data symbols  $X_i$ .

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Various embodiments of the invention may be more apparent by making references to the following diagrams.

Referring to FIG. 1, a general block diagram of a conventional encoder **100** is shown. Encoder **100** at an input **101** inputs data symbols  $X_i$  for encoding. An encoding block **102** encodes the input data symbols according to a convolutional code defined by a transfer function  $F(D)$ . The transfer function  $F(D)$  may be according to any convolutional code transfer function. A commonly used function may be defined by a relationship:  $F(D)=(1+D+D^2)/(1+D)$ , where  $D$  denotes a delay step and the plus sign (+) denotes an exclusive OR operation. Implementation of such a function is well known by one of ordinary skill in a relevant art. Encoding block **102** outputs data symbols  $Y_i$ . Data symbols  $X_i$  and  $Y_i$  pass to a data symbol selector block **103**. Data selector block **103** may include data symbol multiplexing and puncturing functions (not shown). Data selector block **103** outputs two data symbols for every input data symbol  $X_i$  for a coding rate of  $1/2$ . Other possible coding rates are also possible. As a result, encoder **100** outputs at an output **104** encoded data symbols consisting of data symbols  $X_i$  and  $Y_i$ .

Referring to FIG. 2, a general block diagram of a conventional serial-concatenated code (SCC) **200** is shown. SCC **200** includes first and second encoder blocks **201**, **202**. An interleaver block **203** is inserted between encoders **201** and **202**. SCC **200** inputs data symbols  $X_i$  at an input **210** of encoder **201**. Encoder **201** after encoding produces data symbols  $X_i$  and  $Y_i$  according to an operation shown and explained for encoder **100** of FIG. 1. Interleaver **203** inputs data symbols  $X_i$  and  $Y_i$  for an interleaving operation. The interleaving operation in interleaver **203** may be according to any of the known interleaver operations. An interleaving operation may include reading the input data symbols and outputting them as data symbols  $Z_i$  according to a mapping scheme. Such a mapping scheme may be based on a random process. Data symbols  $Z_i$  consist of data symbols  $X_i$  and  $Y_i$  re-arranged in an order according to the mapping function. Such interleaving operations are well known to one of ordinary skill in the art. It is possible that data symbols  $Z_i$  include only data symbols  $X_i$  or data symbols  $Y_i$  for several consecutive data symbols  $Z_i$  depending on the mapping function. Encoder **202** encodes data symbols  $Z_i$  and outputs data symbols  $W_i$  according to an encoding function used in encoder **202**. SCC **200** outputs Data symbols  $Z_i$  and  $W_i$ . Encoding functions used in encoders **201** and **202** may be the same or different.

Data symbols  $W_i$  and  $Z_i$  are transmitted from a transmitter in a communication system to a destination user. Transmission of data symbols  $Z_i$  and  $W_i$  may include signal processing, up-conversion to an appropriate frequency, and signal amplification. Such a transmitter is well known to one of ordinary skill in the art. The entire process of

transmission, propagation, and reception by the destination user may be collectively modeled as a channel **250**. The propagation of the transmitted signal in the channel and reception mainly includes adding noise and interference to data symbols  $W_i$  and  $Z_i$ , shown as  $W_{in}$  and  $Z_{in}$  for the noisy versions of  $W_i$  and  $Z_i$ . The process of adding noise is collectively shown at a summing block **290**. A decoder in the receiver then receives data symbols  $W_{in}$  and  $Z_{in}$ . To decode the data symbols, the received signal may go through signal processing, frequency conversion and signal conditioning. Such functions are well known to one of ordinary skill in the art. The subscript (n) for the noisy versions of data symbols in the receiver is eliminated in the subsequent description in order to simplify the explanation of various related embodiments of the invention. One of ordinary skill in the art recognizes that data symbols processed in the receiver are the noisy versions without carrying the subscript (n).

Referring to FIG. 3, a block diagram of a conventional decoder **300** for decoding data symbols  $W_i$  and  $Z_i$  to produce estimates of data symbols  $X_i$  is shown. The decoding process is the reverse of the encoding process used in SCC **200**. Decoder **300** includes a decoder **301** for decoding, data symbols  $W_i$  and  $Z_i$  according to a coding function used in the second encoder block **202** in the transmitter portion. Decoder **301** produces estimates of data symbols  $Z_i$  at an output **350**. Estimates of data symbols  $Z_i$  at output **350** pass through a de-interleaver **302** to produce estimates of data symbols  $X_i$  and  $Y_i$ . De-interleaver **302** operates according to a reverse interleaving function used in interleaver **203**. Estimates of data symbols  $X_i$  and  $Y_i$  pass to a decoder **303** to produce estimates of data symbols  $X_i$ . Decoder **303** operates according to a coding function used in the first encoder block **201**.

To increase confidence level for accuracy of the estimates of data symbols  $X_i$ , decoder **303** also produces estimates of data symbols  $Y_i$  and passes estimates of data symbols  $X_i$  and  $Y_i$  to an interleaver **304** to produce estimates of  $Z_i$ . Interleaver **304** operates according to the operations of interleaver **203** in the transmitter portion. Estimates of data symbols  $Z_i$ , produced by interleaver **304**, input decoder **301** at an input **311**. Estimates of data symbols  $Z_i$  are used with data symbols  $W_i$  and  $Z_i$  in decoder **301** to produce estimates of data symbols  $Z_i$  at output **350**. A new estimate for each data symbol  $Z_i$  at output **350** is produced after each iteration. The new estimates of data symbols  $Z_i$  pass to de-interleaver **302** to produce new estimates of data symbols  $X_i$  and  $Y_i$ . The process in decoder **303** is repeated with the new estimates of data symbols  $X_i$  and  $Y_i$  to produce a new estimate for the data symbol  $X_i$ . After each iteration, the new estimate of data symbol  $X_i$  has a higher confidence level to hold a true value than the previous estimate. The process may be repeated until the confidence level of an estimate of data symbol  $X_i$  reaches an acceptable level. The estimate with the highest confidence level is selected to hold a true value of the data symbol  $X_i$ .

Decoding process accordingly may take a long time. The estimates of data symbols  $X_i$  may not be produced unless each data symbol has been processed at least through two decoding steps, namely decoders **301** and **303**. Moreover, the process of decoding data symbols  $X_i$  includes serial processing of data symbols. Therefore, decoding data symbols  $X_i$  according to a conventional method is inefficient for an application that requires fast decoding process. Such an application includes wireless communication of voice and data in a CDMA communication system. Such a system has been described in the communication standard commonly known as TIA/EIA/IS-95 and its subsequent advancements

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in TIA/EIA/IS-2000. Publications describing IS-95 and IS-2000 systems entitled: Mobile Base-station Compatibility Standard, are publicly available, and incorporated by reference herein.

Similar problems and difficulties exist if the transmitted data symbols are encoded using a turbo code. Referring to FIG. 4, a general block diagram of a conventional turbo code **400** is shown. Turbo code **400** includes a first and second encoder blocks **401** and **402** and an interleaver block **403**. Data symbols  $X_i$  input turbo code **400** at an input **410** of encoder **401**. Encoder **401**, after encoding, produces data symbols  $Y_i$  according to an operation shown and explained for encoder **102**. Data symbols  $X_i$  input interleaver **403** for an interleaving operation to produce data symbols  $Z_i$ . The interleaving operation in interleaver **403** may be according to any of the known interleaver operations. Data symbols  $Z_i$  consist of data symbols  $X_i$  re-arranged in an order according to a mapping function. Encoder **402** encodes data symbols  $Z_i$  and outputs data symbols  $W_i$  according to an encoding function used in encoder **402**. Encoding functions used in encoders **401** and **402** may be the same or different. Data symbols  $X_i$ ,  $Y_i$  and  $W_i$  pass to a puncturing block **420**. Puncturing block **420** receives data symbols  $X_i$  at input **410**, data symbols  $Y_i$  produced by encoder **401** at an input **411**, and data symbols  $W_i$  produced by encoder **402** at an input **412**. Puncturing block **420** according to a puncturing pattern selects data symbols from data symbols  $X_i$ ,  $Y_i$  and  $W_i$ . The selected data symbols pass to a transmitter portion for transmission to a remote receiver. As such, the transmitted data symbols consist mainly of data symbols  $X_i$ ,  $Y_i$  and  $W_i$ .

Transmission of data symbols  $X_i$ ,  $Y_i$  and  $W_i$  may include signal processing, up-conversion to an appropriate frequency and signal amplification. Such a transmitter is well known by one of ordinary skill in the art. The entire process of transmission, propagation and reception by the destination user may be collectively modeled as a channel **450**. The process mainly includes adding noise and interference to data symbols  $X_i$ ,  $Y_i$  and  $W_i$ , shown as data symbols  $X_{in}$ ,  $Y_{in}$  and  $W_{in}$  for the noisy versions of respectively data symbols  $X_i$ ,  $Y_i$  and  $W_i$ . The process of adding noise is collectively shown at a summing block **490**. A decoder in the receiver then receives data symbols  $X_{in}$ ,  $Y_{in}$  and  $W_{in}$ . To decode the data symbols, the received signal may go through signal processing, frequency conversion and signal conditioning. Such functions are well known to one of ordinary skill in the art. The subscript (n) for the noisy versions of data symbols in the receiver is eliminated in order to simplify the explanation of the various related embodiments of the invention. One of ordinary skill in the art recognizes that data symbols processed in a receiver are the noisy versions without carrying the subscript (n).

Referring to FIG. 5, a block diagram of a conventional decoder **500** is shown for decoding data symbols  $X_i$ ,  $Y_i$  and  $W_i$  to produce estimates of data symbols  $X_i$ . The decoding process is reverse of the encoding process used in encoder **400**. Data symbols  $X_i$ ,  $Y_i$  and  $W_i$  pass through a data symbol selector block **520** which operates to select data symbols  $X_i$  and  $Y_i$  for routing to a decoder block **501** at an input **542**. Data symbols  $X_i$  internally pass through an interleaver **599** to reproduce data symbols  $Z_i$ . Data symbols  $Z_i$  and  $W_i$  pass to a decoder block **502** at an input **540**. Decoder **501** decodes data symbols  $X_i$  and  $Y_i$  according to a coding function used in encoder block **401**. Decoder **501** produces estimates of data symbols  $X_i$  at an output **550**. Decoder **502** decodes data symbols  $Z_i$  and  $W_i$  according to a coding function used in encoder block **402**. Decoder **502** produces estimates of data symbols  $Z_i$  at an output **560**.

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To increase confidence for estimates to hold true value of the data symbols  $X_i$ , estimates of data symbols  $X_i$  at output **550** pass through an interleaver **530** to produce estimates of data symbols  $Z_i$  at an input **532** of decoder **502**. Decoder **502** uses the estimates of data symbols  $Z_i$  at input **532** with estimates of data symbols at input **540** to produce new estimates of data symbols  $Z_i$  at output **560**. Estimates of data symbols  $Z_i$  at output **560** pass through a de-interleaver **531** to reverse the process of interleaving function of interleaver **430** in the turbo code **400**, and to produce estimates of data symbols  $X_i$  at an input **541**. Estimates of data symbols  $X_i$  at input **541** are used with estimates of data symbols at input **542** to produce estimates of data symbols  $X_i$  at output **550**. The process may be repeated until confidence for estimates of data symbols  $X_i$  reaches an acceptable level.

Decoding process for a turbo encoded signal accordingly may take a long time. The estimates of data symbols  $X_i$  with high confidence may not be produced unless data symbols have been processed at least through two decoding steps, namely decoders **501** and **502**. Moreover, the process includes serial processing of data symbols. Therefore, decoding data symbols  $X_i$  according to a conventional method is inefficient for an application that requires fast decoding process. Such an application includes wireless communication of voice and data in a CDMA communication system. Such a system has been described in the communication standard commonly known as TIA/EIA/IS-95 and its subsequent advancements in TIA/EIA/IS-2000. Publications describing IS-95 and IS-2000 systems entitled: Mobile Base-station Compatibility Standard, are publicly available.

A receiver incorporating an embodiment of the invention greatly benefits from various aspects of the invention. An embodiment of the invention provides a fast decoding operation for determining accurate estimates of data symbols  $X_i$  with high confidence. The advantages of an embodiment of the invention include providing decoding operations in an embodiment for data symbols that have been encoded according to either serial-concatenated code or turbo code.

According to an embodiment of the invention, the decoding process is limited to operations over data symbols  $X_i$ ,  $Y_i$  and  $W_i$ . In case the data symbols have been encoded according to SCC **200**, data symbols  $X_i$ , data symbols  $Y_i$  at output of encoder **201** and data symbols  $W_i$  at the output of encoder **202** are used in the decoding operations. In case the data symbols have been encoded according to turbo code **400**, data symbols  $X_i$ , data symbols  $Y_i$  at output **411** of encoder **401** and data symbols  $W_i$  at output **412** of encoder **402** are used in the decoding operations. As such, while using the same data symbol references in SCC **200** and turbo code **400**, various embodiments of the invention may be explained.

Referring to FIG. 6, the decoding process according to various embodiments of the invention includes operations on a block of data having a length of "k" data symbols, "k" being a finite number. Initially, a data symbol estimate for a number of data symbols of the plurality of data symbols  $X_i$  is determined. The value for each estimate of data symbols  $X_i$  is shown in column **601**. A data symbol estimate is determined for a number of data symbols of a plurality of data symbols  $Y_i$ . The value for each estimate of data symbols  $Y_i$  is shown in column **602**. The plurality of data symbols  $Y_i$  are produced in a transmitter in the communication system by encoding the plurality of data symbols  $X_i$  according to a first convolutional code. The first convolutional code, in case of SCC **200**, is used in encoder **201**, and in case of turbo code **400**, in encoder **401**. A data symbol

estimate is determined for a number of data symbols of a plurality of data symbols  $W_i$ . The value for each estimate of data symbols  $W_i$  is shown in column **603**. In case of SCC **200**, the plurality of data symbols  $Y_i$  and  $X_i$ , and in case of turbo code **400**, the plurality of data symbols  $X_i$ , are interleaved to produce a plurality of data symbols  $Z_i$ . The plurality of data symbols  $Z_i$  are encoded according to a second convolutional code to produce the plurality of data symbols  $W_i$ . The second convolutional code is used in encoder **202** in case of SCC **200**, and in case of turbo code **400**, encoder **402**.

For a case of Gaussian noise, the estimate for each data symbol may be determined by a Gaussian probability process. For example, to determine an estimate of data symbol  $X_i$ , the process determines the probability of data symbol  $X_i$  having a value equal to "1" given the value of its noisy version metric. Estimating the value of a data symbol based on a probability process is well known by one of ordinary skill in the art. As such, an initial estimate of data symbols  $X_i$ ,  $Y_i$  and  $W_i$  may be determined and stored in a table **600** having columns **601**, **602** and **603** for respectively data symbols  $X_i$ ,  $Y_i$  and  $W_i$ . The information contained in table **600** may be stored in a memory device.

FIGS. **6** and **7** show the estimates of data symbols  $X_i$  and  $Y_i$  passing to a first decision node **610**. The estimates of data symbols  $X_i$  and  $Y_i$  passing to the first decision node **610** include estimates for the variables in an equation  $F1(X_i, Y_i)$ . The variables  $X_i$  and  $Y_i$  in the equation  $F1$  are determined according to the first convolutional code. For example, if the first convolutional code is governed by a relationship defined by:  $F1(D)=(1+D+D^{*2})/(1+D)$ , then  $F1(X_i, Y_i)$  is equal to:  $Y_i+Y(i-1)+X_i+X(i-1)+X(i-2)$ . For example, if "i" is equal to seven, then  $F1$  is equal to:  $Y7+Y6+X7+X6+X5$ . The estimates for data symbols  $Y7$ ,  $Y6$ ,  $X7$ ,  $X6$  and  $X5$  may be retrieved from columns **601** and **602**.

Referring to FIGS. **6** and **8**, the estimates of data symbols  $W_i$  and  $Z_i$  are shown to pass to a second decision node **620**. The estimates of data symbols  $W_i$  and  $Z_i$  passing to the second decision node **620** include estimates for the variables in an equation  $F2(W_i, Z_i)$ . The variables  $W_i$  and  $Z_i$  in the equation  $F2$  are determined according to the second convolutional code. The first and the second convolutional codes may be the same. The estimates for the variables  $Z_i$  include the estimates of data symbols  $X_i$ , or  $Y_i$ , or  $X_i$  and  $Y_i$ , determined according to the interleaving function used, in case of SCC **200**, in interleaver **203**, and in case of turbo code **400**, interleaver **403**. The variables selected for equation  $F2$  include the variables taken from columns **601**, **602** and **603**, or columns **601** and **603**, or columns **602** and **603**.

For an illustration purpose, for example if  $F2(D)=(1+D+D^{*2})/(1+D)$ , then  $F2(Z_i, W_i)=W_i+W(i-1)+Z_i+Z(i-1)+Z(i-2)$ . In case of SCC **200**, the variables  $Z_i$  may include  $X_i$ , or  $Y_i$ , or  $X_i$  and  $Y_i$  since input to the interleaver **203** include both data symbols  $X_i$  and  $Y_i$ . Depending on the interleaving function, the output of the interleaver for several consecutive data symbols may include exclusively data symbols  $X_i$  or data symbols  $Y_i$ . At other times, the output may include both data symbols  $X_i$  and  $Y_i$  for several consecutive data symbols. As such, the estimates for the variables  $Z_i$  include the estimates of data symbols  $X_i$ , or  $Y_i$ , or  $X_i$  and  $Y_i$  taken from columns **601** and **602**. The estimates for the variables  $W_i$  and  $W(i+1)$  are taken from column **603**.

In case of turbo code **400**, the variables selected for equation  $F2$  include the variables taken from columns **601** and **603** since the input to the interleaver **403** includes only data symbols  $X_i$ . As such, the variables selected for equation

$F2$ , in the case of turbo code **400**, include the variables  $X_i$  and  $W_i$  taken from respectively columns **601** and **603**.

To provide capability for decoding data symbols in either an SCC or a turbo code mode, the decoding process according to an embodiment of the invention allows selecting the variables from columns **601**, **602** and **603**. As such, the decoding process allows decoding data symbols that were encoded in a transmitter according to either an SCC or a turbo code.

While equating the equations  $F1$  and  $F2$  to zero at respectively the first and second decision nodes **610** and **620**, a new estimate is determined for each occurrence of the data symbol  $X_i$  at the first and second decision nodes **610** and **620**. By way of an example at node **610** for equation  $F1$ , for "i=7," the probability of the estimated values for  $Y7$ ,  $Y6$ ,  $X7$ ,  $X6$  and  $X5$  may be respectively:  $P(Y7)=0.8$ ,  $P(Y6)=0.7$ ,  $P(X7)=0.5$ ,  $P(X6)=0.2$  and  $P(X5)=0.6$ . A new estimate for  $X7$  is computed based on estimated values of a set of data symbols including data symbols:  $Y7$ ,  $Y6$ ,  $X6$  and  $X5$ . Accordingly, a new estimate for  $P(X(i=7))$  equal to "1," in case of equating equation  $F1$  to zero, may be equal to the probability of having an odd number of "1s" in the set of data symbols  $Y7$ ,  $Y6$ ,  $X6$  and  $X5$ . Since there are four data symbols, in this case, there is a possibility of having one or three data symbols having a value equal to "1." Therefore, the probability of data symbol  $X7$  may be determined as follows:

$$\begin{aligned}
 P(X7)= & P(Y7)*(1-P(Y6))*(1-P(X6))*(1-P \\
 & (X5))+(1-P(Y7))*P(Y6)*P(X6)*P(X5)+ \\
 & P(Y6)*(1-P(Y7))*(1-P(X6))*(1-P(X5))+ \\
 & (1-P(Y6))*P(Y7)*P(X6)*P(X5)+ \\
 & P(X6)*(1-P(Y7))*(1-P(Y6))*(1-P(X5))+ \\
 & (1-P(X6))*P(Y7)*P(Y6)*P(X5)+ \\
 & P(X5)*(1-P(Y7))*(1-P(Y6))*(1-P(X6))+ \\
 & (1-P(X5))*P(Y7)*P(Y6)*P(X6).
 \end{aligned}$$

Note that, probability of, for example,  $P(1-X6)$  is probability of  $X6$  having a value of zero when estimates of  $X_i$  in column **601** represent values of the estimates of  $X_i$  having a value of "1."

The number of occurrences of  $X7$  in equation  $F2$  depends on the interleaving function used in the respective encoder interleaver, interleaver **403** or **203**. As indicated, for a given value of "i,"  $F2$  may not include any variables related to data symbols  $X_i$ . As such, there may or may not be an occurrence of  $X_i$  in equation  $F2$  for a given value of "i." If there is an occurrence of  $X7$ , in this example, in equation  $F2$ , a new estimate for the occurring data symbol  $X_i$  is determined like the example shown for the equation  $F1$ .

Moreover, since values in column **601**, **602** and **603** may pass to nodes **610** and **620** at the same time while operating on different values of "i," more than one  $P(X_i)$  value may pass to nodes **610** and **620**. This may be clear by noting that, while relating to equation  $F1$ , for a given "i" value, values for the variables:  $Y_i+Y(i-1)+X_i+X(i-1)+X(i-2)$ , for "i+1," values for the variables:  $Y(i+1)+Y(i)+X(i+1)+X(i)+X(i-1)$ , and for "i+2," values for the variables:  $Y(i+2)+Y(i+1)+X(i+2)+X(i+1)+X(i)$  pass to node **610**. As such, since an embodiment of the invention includes parallel processing of data symbols, in this example, three occurrences of estimates of  $X_i$  may appear at node **610**. Note that, the values of  $X_i$  involving in three consecutive "i" values is due to

using an encoding function defined by the relationship:  $(1+D+D^{*2})/(1+D)$ . If a different encoding function is used, the number of occurrences of Xi for a given "i" value may be different.

A new estimate for the data symbol Xi is determined based on the estimate determined at the initial step and the new estimate for each occurrence of the data symbol Xi at the first and second decision nodes 601 and 602. Referring to FIG. 9, for example, three estimates of data symbols Xi involved in three occurrences at node 610 pass to a node 900 for determining a new estimate for data symbol Xi. Moreover, depending on the interleaver function used in the encoding process, estimates of data symbol Xi may also have passed to node 620 as a part of data symbols Zi involved in the encoding function. As such, there is a possibility of having an estimate of data symbol Xi pass from node 620 to node 900 for determining a new estimate for Xi at node 900. The new estimate for data symbol Xi may be a normalized product of the initial estimate and all estimates of data symbol Xi pass from nodes 610 and 620. For example, if there has been a total of "L" occurrences of Xi, node 900 receives "L" number of estimates of data symbol Xi. The new estimate for Xi may then be equal to:  $(P(0)P(1)P(2)P(3) \dots P(L-1)P(L))/[P(0)P(1)P(2)P(3) \dots P(L-1)P(L)+(1-P(0))(1-P(1))(1-P(2))(1-P(3)) \dots (1-P(L-1))(1-P(L))]$ , where P denotes an estimate value of Xi for each occurrence passed to node 900. Note that P(0) is the initial estimate, and others are the new estimate for each occurrence of the data symbol Xi at the first and second decision nodes.

The new estimate determined at node 900 for the data symbol Xi may confidently hold a true value for the data symbol Xi. The process may be repeated many times until the new estimate for the data symbol Xi confidently holds a true value for the data symbol Xi. When more than one iteration is necessary to build the confidence level, an embodiment of the invention includes determining a normalized estimate of data symbol Xi based on the estimate determined at the initial step and at least one of the new estimates for each occurrence of the data symbol Xi at the first and second decision nodes 610 and 620. The steps of passing data symbols to the first and second nodes 610 and 620 are then repeated while substituting the normalized estimate of data symbol Xi for at least one of the estimates of data symbols Xi passing to the first and second nodes 610 and 620. Preferably, all estimates of data symbols Xi passing to nodes 610 and 620 after the first iteration are the normalized versions.

To determine an estimate for a normalized version of data symbol Xi, each estimate of data symbols Xi determined for each occurrence of data symbol Xi at nodes 610 and 620 and the initial estimate of Xi are used. For illustration purposes, assume three occurrences of data symbol Xi took place, for example, at node 610, and none at node 620. The estimates determined for occurrences of data symbol Xi maybe labeled Xi1, Xi2 and Xi3. The reason for having three occurrences is due to having Xi involved in three F1 equations, in this example. The number following the subscript "i" identifies the F1 equation that used the Xi value. The initial value may be labeled Xi0. A normalized value for data symbol Xi to be used in the first F1 equation may be equal to:  $(P(Xi0)*P(Xi2)*P(Xi3))/[(P(Xi1)*P(Xi2)*P(Xi3)+(1-P(Xi0))*(1-P(Xi2))*(1-P(Xi3)))]$ . A normalized value for data symbol Xi to be used in the second F1 equation, for example at node 610, may then be equal to:  $(P(Xi0)*P(Xi1)*P(Xi3))/[(P(Xi1)*P(Xi2)*P(Xi3)+(1-P(Xi0))*(1-P(Xi1))*(1-P(Xi3)))]$ . The normalized value for

data symbols Xi to be used in the third F1 equations are also determined in a similar fashion. The normalized value of data symbol Xi to be used for the third F1 equation may be equal to:  $(P(Xi0)*P(Xi1)*P(Xi2))/[(P(Xi1)*P(Xi2)*P(Xi3)+(1-P(Xi0))*(1-P(Xi1))*(1-P(Xi2)))]$ .

FIGS. 10 and 11 show the processes of determining a new estimate and a normalized value for data symbols Yi and Wi which are similar to the process explained for determining a new estimate and a normalized value for data symbols Xi. When equations F1 and F2 are set to zero to determine a new estimate for data symbol Xi, a new estimate for each occurrence of the data symbol Yi at the first and second decision nodes are also determined when the process takes more than one iteration. Consequently, for a subsequent determination of estimates while equating equations F1 and F2 to zero, a normalized estimate of data symbol Yi is also determined. The normalized estimate of data symbol Yi is based on the initial estimate and at least one of the new estimates for each occurrence of the data symbol Yi at the first and second decision nodes 610 and 620. The steps of passing estimates of data symbols to the first and second decision nodes 610 and 620 are repeated while substituting the normalized estimate of data symbol Yi for at least one of the estimates of data symbols Yi passing from a node 1000 to nodes 610 and 620. Preferably, the estimates of data symbols Yi passing from node 1000 to nodes 610 and 620 all include the normalized version after the first iteration.

Similarly for data symbol Wi, when equations F1 and F2 are set to zero to determine a new estimate for data symbol Xi, a new estimate for each occurrence of the data symbol Wi at the first and second decision nodes are also determined when the process takes more than one iteration. Consequently, for a subsequent determination of estimates while equating equations F1 and F2 to zero, a normalized estimate of data symbol Wi is also determined. The normalized estimate of data symbol Wi is based on the initial estimate and at least one of the new estimates for each occurrence of the data symbol Wi at the second decision node 620. Note that, data symbols Wi may occur only at node 620. The steps of passing estimates of data symbols to the first and second nodes 610 and 620 are repeated while substituting the normalized estimate of data symbol Wi for at least one of the estimates of data symbols Wi from a node 1100 to node 620. Preferably, the estimates of data symbols Wi passing from node 1100 to nodes 610 and 620 all include the normalized version after the first iteration.

The process of decoding by determining a new estimate of data symbols Xi may be repeated as many times as necessary until the confidence level for the estimate holding a true value for data symbol Xi rises to an acceptable level.

Various embodiments of the invention may be implemented in a specific application signal processing hardware commonly known to one of ordinary skill in the art. Alternatively, or in combination, various embodiments of the invention may be implemented in a microprocessor environment, commonly known to one of ordinary skill in the art.

Advantages of an embodiment of the invention include providing capability for decoding data symbols encoded in a transmitter by either an SCC or turbo code. The receiver upon knowing the encoding method may reconfigure the selection of data symbols from table 600 to accommodate the appropriate decoding process. Moreover, since the decoding process takes place while allowing operations on multiple data symbols, many data symbols Xi may be decoded simultaneously. The process and operation over the respective data symbols are very similar. As a result, a

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software routine written to execute various steps may be reused with minimal reconfiguration for either SCC and turbo codes. Most common microprocessors and digital signal processors allow parallel processing operation to take place without sacrificing processing speed. As such, an embodiment of the invention allows fast and efficient decoding of a block of data symbols.

I Claim:

1. An apparatus for decoding a data symbol  $X_i$  of a plurality of data symbols  $X_i$  with subscript (i) having a value from (1) to (k) and (k) being a finite number, comprising:

means for determining a data symbol initial estimate for all data symbols of said plurality of data symbols  $X_i$  for "i" being equal from 1 to k, all data symbols of a plurality of data symbols  $Y_i$  for "i" being equal from 1 to k, and all data symbols of a plurality of data symbols  $W_i$  for "i" being equal from 1 to k, wherein all data symbols of said plurality of data symbols  $Y_i$  for "i" being equal from 1 to k are produced in a transmitter in said communication system by a first convolutional encoding of all data symbols of said plurality of data symbols  $X_i$  for different values of "i" between 1 and "k", wherein all data symbols of said plurality of data symbols  $W_i$  for "i" being equal from 1 to k are produced in said transmitter by interleaving all data symbols of said plurality of data symbols  $X_i$ , or  $X_i$  and  $Y_i$  for different values of "i" between 1 and "k" to produce all data symbols of a plurality of data symbols  $Z_i$  for "i" being equal from 1 to k, and a second convolutional encoding of all data symbols of said plurality of data symbols  $Z_i$  for different values of "j" between 1 and "k" to produce all data symbols of said plurality of data symbols  $W_i$  for "i" being equal from 1 to k;

means for passing said estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  for different values of "i" between 1 and "k" to a decision node, wherein said estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  for different values of "i" between 1 and "k" passing to said decision node are determined according to said first and second convolutional encodings, wherein said estimates of data symbols  $Y_i$  and  $W_i$  are in terms of estimates of data symbols  $X_i$  for different values of "i" between 1 and "k" based on said first and second convolutional encodings, thereby producing more than one occurrences of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node;

means for determining a new estimate for said data symbol  $X_i$  for different values of "i" between 1 and "k" based on said initial estimate and each occurrence of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node based on said passing.

2. The apparatus as recited in claim 1 further comprising:

means for determining a normalized estimate of data symbol  $X_i$  for different values of "i" between 1 and "k" based on said initial estimate of data symbol  $X_i$  and at least one occurrence of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node based on said passing;

means for repeating said passing of estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  for different values of "i" between 1 and "k" while substituting said normalized estimate of data symbol  $X_i$  for different values of "i" between 1 and "k" for at least one of said estimate of data symbols  $X_i$  for different values of "i" between 1 and "k" in said passing;

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means for repeating determining a new estimate for said data symbol  $X_i$  for different values of "i" between 1 and "k" based on said initial estimate and each occurrence of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node based on said repeated passing.

3. The apparatus as recited in claim 1 further comprising: means for determining a new estimate for each occurrence of said data symbol  $Y_i$  for different values of "i" between 1 and "k" at said decision node, based on said new estimates of  $X_i$  for different values of "i" between 1 and "k" at said decision node and in accordance with said first convolutional encoding;

means for determining a normalized estimate of data symbol  $Y_i$  based on said initial estimate of data symbol  $Y_i$  for different values of "i" between 1 and "k" and said new estimate of data symbol  $Y_i$  for different values of "i" between 1 and "k" for at least one occurrence of said data symbol  $Y_i$  for different values of "i" between 1 and "k" at said decision node;

means for repeating said passing of estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  for different values of "i" between 1 and "k" while substituting said normalized estimate of data symbol  $Y_i$  for different values of "i" between 1 and "k" for at least one of said estimate of data symbols  $Y_i$  for different values of "i" between 1 and "k" in said passing

means for repeating determining a new estimate for said data symbol  $X_i$  for different values of "i" between 1 and "k" based on said initial estimate and each occurrence of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node based on said repeated passing.

4. The apparatus as recited in claim 1 further comprising: means for determining a new estimate for each occurrence of said data symbol  $W_i$  for different values of "i" between 1 and "k" at said decision node, based on said new estimates of  $X_i$  for different values of "i" between 1 and "k" at said decision node and in accordance with said second convolutional encoding;

means for determining a normalized estimate of data symbol  $W_i$  for different values of "i" between 1 and "k" based on said initial estimate of data symbol  $W_i$  for different values of "i" between 1 and "k" and said new estimate of data symbol  $W_i$  for different values of "i" between 1 and "k" for at least one occurrence of said data symbol  $W_i$  for different values of "i" between 1 and "k" at said decision node;

means for repeating said passing of estimates of data symbols  $X_i$ ,  $Y_i$ , and  $W_i$  for different values of "i" between 1 and "k" while substituting said normalized estimate of data symbol  $W_i$  for different values of "i" between 1 and "k" for at least one of said estimates of data symbols  $W_i$  for different values of "i" between 1 and "k" in said passing

means for repeating determining a new estimate for said data symbol  $X_i$  for different values of "i" between 1 and "k" based on said initial estimate and each occurrence of estimate of said data symbol  $X_i$  for different values of "i" between 1 and "k" at said decision node based on said repeated passing.

5. An apparatus for decoding a data symbol  $X_i$  of a plurality of data symbols  $X_i$  with subscript (i) having a value from (1) to (k) and (k) being a finite number, comprising:

(a) means for determining a data symbol estimate for all data symbols of said plurality of data symbols  $X_i$  for different values of "i" between 1 and "k";

- (b) means for determining a data symbol estimate for all data symbols of a plurality of data symbols  $Y_i$  for different values of “i” between 1 and “k”, wherein said plurality of data symbols  $Y_i$  for different values of “i” between 1 and “k” are produced in a transmitter in said communication system by a first convolutional encoding of said plurality of data symbols  $X_i$  for different values of “i” between 1 and “k”;
- (c) means for determining a data symbol estimate for all data symbols of a plurality of data symbols  $W_i$  for different values of “i” between 1 and “k”, wherein said plurality of data symbols  $W_i$  for different values of “i” between 1 and “k” are produced in said transmitter by interleaving said plurality of data symbols  $X_i$ , or  $Y_i$  and  $X_i$  for different values of “i” between 1 and “k” to produce a plurality of data symbols  $Z_i$  for different values of “i” between 1 and “k”, and a second convolutional encoding of said plurality of data symbols  $Z_i$  for different values of “i” between 1 and “k” to produce said plurality of data symbols  $W_i$  for different values of “i” between 1 and “k”;
- (d) means for passing said estimates of data symbols  $X_i$  and  $Y_i$  for different values of “j” between 1 and “k” to a first decision node, wherein said estimates of data symbols  $X_i$  and  $Y_i$  for different values of “i” between 1 and “k” passing to said first decision node include estimates for the variables  $X_i$  and  $Y_i$  for different values of “i” between 1 and “k” in an equation  $F_1$  determined according to said first convolutional encoding, wherein said estimates of data symbols  $Y_i$  are in terms of estimates of data symbols  $X_i$  for different values of “i” between 1 and “k” based on said first convolutional encodings, thereby producing more than one occurrences of estimate of said data symbol  $X_i$  for different values of “i” between 1 and “k” at said first decision node;
- (e) means for passing said estimates of data symbols  $W_i$  and  $Z_i$  for different values of “i” between 1 and “k” to a second decision node, wherein said estimates of data symbols  $W_i$  and  $Z_i$  for different values of “i” between 1 and “k” passing to said second decision node include estimates for the variables  $W_i$  and  $Z_i$  for different values of “i” between 1 and “k” in an equation  $F_2$  determined according to said second convolutional encoding, wherein estimates for said variables  $Z_i$  for different values of “i” between 1 and “k” include said estimates of data symbols  $X_i$ , or  $Y_i$ , or  $X_i$  and  $Y_i$  for different values of “i” between 1 and “k” determined according to said interleaving, wherein said estimates of data symbols  $W_i$  and  $Z_i$  are in terms of estimates of data symbols  $X_i$  for different values of “i” between 1 and “k” based on said second convolutional encodings, thereby producing more than one occurrences of estimate of said data symbol  $X_i$  for different values of “i” between 1 and “k” at said second decision node;
- (f) means for determining, while equating said equations  $F_1$  and  $F_2$  to zero at respectively said first and second decision nodes, a new estimate for each occurrence of estimates of said data symbol  $X_i$  for different values of “i” between 1 and “k” at said first and second decision nodes;
- (g) means for determining a new estimate for said data symbol  $X_i$  for different values of “i” between 1 and “k”

- based on said estimate determined at said step (a) and said new estimate determined for each occurrence of estimates of said data symbol  $X_i$  for different values of “i” between 1 and “k” at said first and second decision nodes.
- 6. The apparatus as recited in claim 5 further comprising:
  - (h) means for determining a normalized estimate of data symbol  $X_i$  for different values of “i” between 1 and “k” based on said estimate determined by process of said means (a) and at least one of said new estimates determined for each occurrence of estimates of said data symbol  $X_i$  for different values of “i” between 1 and “k” at said first and second decision nodes;
  - (i) means for repeating process of said means (d) and (e) while substituting said normalized estimate of data symbol  $X_i$  for different values of “i” between 1 and “k” for at least one of said estimates of data symbols  $X_i$  for different values of “i” between 1 and “k” in said passing.
- 7. The apparatus as recited in claim 5 further comprising:
  - (j) means for determining, while equating said equations  $F_1$  and  $F_2$  to zero at respectively said first and second decision nodes, a new estimate for each occurrence of estimates of said data symbol  $Y_i$  for different values of “i” between 1 and “k” at said first and second decision nodes;
  - (k) means for determining a normalized estimate of data symbol  $Y_i$  for different values of “i” between 1 and “k” based on said estimate determined at said means (b) and at least one of said new estimates for each occurrence of estimates of said data symbol  $Y_i$  for different values of “i” between 1 and “k” at said first and second decision nodes;
  - (l) means for repeating process of said steps (d) and (e) while substituting said normalized estimate of data symbol  $Y_i$  for different values of “i” between 1 and “k” for at least one of said estimates of data symbols  $Y_i$  for different values of “i” between 1 and “k” in said passing.
- 8. The apparatus as recited in claim 5 further comprising:
  - (m) means for determining, while equating said equation  $F_2$  to zero at said second decision nodes, a new estimate for each occurrence of estimates of said data symbol  $W_i$  for different values of “i” between 1 and “k” at said second decision node;
  - (n) means for determining a normalized estimate of data symbol  $W_i$  for different values of “i” between 1 and “k” based on said estimate determined by process of said means (c) and at least one of said new estimates for each occurrence of estimates of said data symbol  $W_i$  for different values of “i” between 1 and “k” at said second decision node;
  - (o) means for repeating process of said means (d) and (e) while substituting said normalized estimate of data symbol  $W_i$  for different values of “i” between 1 and “k” for at least one of said estimates of data symbols  $W_i$  for different values of “i” between 1 and “k” in said passing.

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 6,836,516 B2  
DATED : December 28, 2004  
INVENTOR(S) : Jack K. Wolf

Page 1 of 1

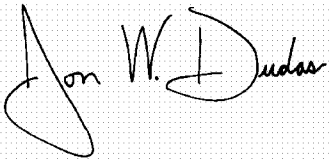
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,

Item [74], *Attorney, Agent, or Firm*, please correct "S. Hossain Boladi" to read  
-- S. Hossain Beladi --.

Signed and Sealed this

Sixth Day of September, 2005

A handwritten signature in black ink on a light gray dotted background. The signature reads "Jon W. Dudas" in a cursive style. The "J" is large and loops around the "on". The "W" and "D" are also prominent.

JON W. DUDAS

*Director of the United States Patent and Trademark Office*