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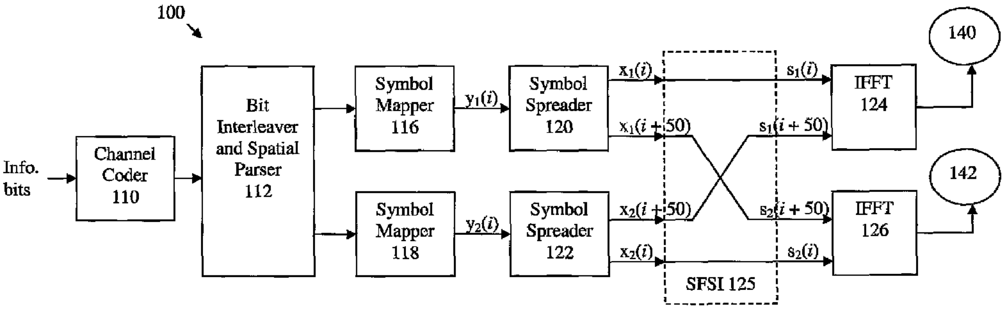

FIG. 1

(57) Abstract: A communication system transmits data through multiple transmitters (140/142, 540/542). The system includes a symbol mapper (116/118, 516/518), a symbol spreader (120/122, 520/522) and a symbol interleaver (125, 525). The symbol mapper (116/118, 516/518) receives one bit stream of the data and maps at least one set of bits of the one bit stream to a corresponding set of symbols of a symbol stream. The set of symbols includes at least two symbols. The symbol spreader (120/122, 520/522) receives the set of symbols from the symbol mapper (116/118, 516/518) and spreads the set of symbols so that each of the spread symbols contain all the information of the set of symbols from the symbol mapper (116/118, 516/518). The symbol interleaver (125, 525) receives the spread symbols from symbol spreaders (120/122, 520/522) of all the symbol streams, distributes the spread symbols to non-adjacent subcarriers of the transmitters (140/142, 540/542) so that the spread symbols from the same symbol spreader are distributed to different subcarriers of different transmitters.

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SYSTEM AND METHOD OF TRANSMITTING AND RECEIVING MIMO-OFDM SIGNALS

This patent application claims the benefit of U.S. Provisional Application No. 60/952,314 filed on July 27, 2007.

This invention pertains to the field of data communications, and more particularly to a system and method of transmitting and receiving an orthogonal frequency division multiplexing (OFDM) signal using a spatial multiplexing multiple-input-multiple-output (MIMO) system.

Orthogonal frequency division multiplexing (OFDM) is an effective transmission method for high data rate wireless communication applications due to its robustness against frequency-selective fading, high bandwidth efficiency, and relatively easy implementation. Particularly, OFDM can remove inter-symbol interference caused by multi-path fading effectively. Therefore, it has been widely adopted for use in wideband and ultra-wideband wireless communication systems. For example, the Worldwide Interoperability for Microwave Access (WiMAX) standards and the WiMedia® Alliance Ultra-Wideband (UWB) Common Radio Platform employ OFDM.

In addition, multiple antennas have been incorporated into OFDM systems to provide spatial diversity and/or multiplexing gain, further enhancing efficiency and reliability. One multiple antenna technique is typically referred to as the multiple-input-multiple-output (MIMO) technique. Multiple antennas can be used to simultaneously transmit multiple data streams to increase data rates and/or to improve system robustness against fading. Combining MIMO and OFDM techniques is useful in wideband high-rate communication systems, and has been adopted for use in the IEEE 802.11n wireless local area networks (WLAN), 3G high-speed downlink packet access (HSDPA) networks and WiMAX networks.

The current WiMedia UWB specification is based on a multi-band OFDM (MB-OFDM) technique for use over single antenna systems (hereinafter, "WiMedia MB-OFDM Standard"). The WiMedia MB-OFDM Standard includes, in part, dual carrier modulation (DCM), according to which four information data bits are mapped to two separate symbols from two different constellation diagrams, similar to 16QAM mapping. The two symbols are modulated onto two separate subcarriers (of 100 available data-bearing subcarriers), where the two subcarriers are spaced apart by 50 (i.e., 100/2) data subcarriers. Separating the subcarriers in this way reduces the probability that all four bits will be negatively impacted by multi-path fading, thereby increasing the chance that any lost bits can be recovered by the error correction code. The highest physical layer data rate of a system operating in accordance with the WiMedia MB-OFDM Standard is 480Mbps, which does not meet the demands of future wideband wireless applications, such as HDTV wireless connectivity. In fact, the next generation WiMedia UWB systems target more than 1Gbps physical layer data rates.

International Patent Application No. PCT/IB2006/054613 describes a MIMO-OFDM scheme by which all symbols output from a symbol spreader are transmitted through the same transmitter. Generally, the scheme is based on the assumption that the transmission channels through which the different subcarriers of the same transmitter pass are completely uncorrelated. However, the transmission channels for different subcarriers of the same transmitter may not be completely uncorrelated in practical applications, for example, in actual UWB working scenarios such as strong line-of-sight (LOS) channels, in which the frequency-domain channels are correlated which may decrease the diversity gain achieved by the symbol-spreading block. Therefore, there may be a performance loss whenever there is significant correlation between the different subcarriers to which the original four data bits are mapped.

The use of multiple antennas may achieve a spatial multiplexing gain (high data rates), as well as a spatial diversity gain (system robustness). However, there is a trade-off between these two gains, as discussed, for example, in D. Tse et al., "*Fundamentals of Wireless Communication,*" Cambridge University Press (2005). In spatial multiplexing MIMO schemes, a high spatial multiplexing gain may be obtained at the cost of a low diversity gain, while in the space-time coding MIMO schemes, a high diversity gain may be obtained at the cost of a low spatial multiplexing gain. In the next generation wideband wireless communications systems, spatial multiplexing MIMO schemes are needed to achieve high data rates, which means there is little to no transmitter diversity. However, high diversity is important in wideband communications systems due to the use of frequency-selective transmission channels.

In one aspect of the invention, a system is provided for transmitting data through a plurality of transmitters. The system comprises a symbol mapper configured to receive one bit stream corresponding to a portion of the data and to map at least one set of sequential bits of the one bit stream to a corresponding set of symbols of a symbol stream, the set of symbols comprising at least a first symbol and a second symbol; a symbol spreader configured to receive the set of symbols from the symbol mapper and to generate the set of spread symbols by precoding the set of symbols from the symbol mapper; and a symbol interleaver configured to receive the first and second spread symbols from the symbol spreader, to distribute the first spread symbol to a first transmitter for transmission over a first subcarrier of the non-adjacent subcarriers, and to distribute the second spread symbol to a second transmitter for transmission over a second subcarrier of the non-adjacent subcarriers.

In another aspect of the invention, a method is provided for transmitting an input bit stream. The method comprises parsing the input bit stream into a plurality of bit streams; mapping the plurality of bit streams to a corresponding plurality of symbol streams, each symbol stream comprising at least one set of symbols representing a group of sequential bits in the corresponding bit stream; precoding the symbols to the spread symbols, associating each of the symbols in the at least one set of spread symbols with different, non-adjacent subcarriers, respectively; and distributing the symbols of the at least one set of spread symbols to different transmitters, respectively, for transmission on the associated non-adjacent subcarriers of different transmitters.

In yet another aspect of the invention, a system for transmitting input information bits comprises a first symbol mapper for receiving a first parsed bitstream of the information bits and mapping the first parsed bitstream to a first symbol stream, the first symbol stream comprising a first pair of symbols corresponding to a first set of bits of the first parsed bitstream; a second symbol mapper for receiving a second parsed bitstream of the information bits and mapping the second parsed bitstream to a second symbol stream, the second symbol stream comprising a second pair of symbols corresponding to a second set of bits of the second parsed bitstream; a first symbol spreader for spreading the first pair of symbols to a first pair of spread symbols, which are associated with non-adjacent subcarriers; a second symbol spreader for spreading the second pair to a second pair of spread symbols, which are associated with non-adjacent subcarriers; and a symbol interleaver for distributing the first symbol of the first pair of spread symbols and the second symbol of the second pair of spread symbols to a first transmitter for transmission on the associated subcarriers, and for distributing the second symbols of the first pair of spread symbols and the first symbol of the second pair of spread symbols to a second transmitter for transmission on the associated subcarriers.

FIG. 1 is a functional block diagram of one embodiment of a multiple input multiple output (MIMO) orthogonal frequency division multiplex (OFDM) transmission system.

FIG. 2 is a functional block diagram of one embodiment of an MIMO-OFDM receiving system.

FIG. 3 plots frame error rate and noise of the MIMO-OFDM system according to one embodiment as compared to a conventional system.

FIG. 4 plots frame error rate and noise of the MIMO-OFDM system according to one embodiment as compared to a conventional system.

FIG. 5 is a functional block diagram of another embodiment of an MIMO-OFDM transmission system.

FIG. 6 is a function block diagram of another embodiment of an MIMO-OFDM receiving system.

FIG. 7 shows a four-subcarrier precoded interleaving pattern according to one embodiment of an MIMO-OFDM system.

In the following detailed description, for purposes of explanation and not limitation, example embodiments disclosing specific details are set forth in order to provide a thorough understanding of an embodiment according to the present teachings. However, it will be apparent to one having ordinary skill in the art having had the benefit of the present disclosure that other embodiments according to the present teachings that depart from the specific details disclosed herein remain within the scope of the appended claims. Moreover, descriptions of well-known devices and methods may be omitted so as to not obscure the description of the example embodiments. Such methods and devices are clearly within the scope of the present teachings.

In the various embodiments, a precoding MIMO-OFDM scheme for next generation wideband wireless communications systems, such as WiMedia UWB systems, distributes precoded symbols to different subcarriers of different transmitters. The symbols are therefore transmitted through uncorrelated channels. Since the transmission channels for two subcarriers of the different transmitters are less correlated than for two subcarriers of the same transmitter, the disclosed embodiments are expected to achieve better performance in actual wideband wireless communications systems.

FIG. 1 is a functional block diagram of one embodiment of an MIMO-OFDM transmission system 100. As will be appreciated by those skilled in the art, the various functions shown in FIG. 1 may be physically implemented using a software-controlled microprocessor, hard-wired logic circuits, or a combination thereof. Also, while the functional blocks are illustrated as being segregated in FIG. 1 for explanation purposes, they may be combined in any physical implementation.

MIMO-OFDM transmission system 100 includes a channel coder 110, a bit interleaver and spatial parser 112, first and second symbol mappers 116 and 118, first and second symbol spreaders 120 and 122, and a spatial-frequency symbol interleaver (SFSI) 125. The transmission system 100 also includes first and second time-domain transformers, such as first and second inverse fast Fourier transformers (IFFTs) 124 and 126, although other implementations of inverse time-domain transformers may be employed. The outputs of the IFFTs 124, 126 are sent to first and second transmitters 140 and 142, including corresponding antenna systems (not shown). In an embodiment, MIMO-OFDM transmission system 100 may be a WiMedia UWB system.

As shown in FIG. 1, information bits are input through channel coder 110, which may be a convolutional encoder, for example. The encoded bits are interleaved and parsed into first and second bit streams by bit interleaver and spatial parser 112. In alternative embodiments, the channel coder 110 and the interleaving process of bit interleaver and spatial parser 112 may be omitted, or different types of coders and/or data processing may be incorporated into MIMO-OFDM transmission system 100.

The first and second bit streams are mapped by first and second symbol mappers 116, 118 to first and second symbol streams, respectively. For example, symbol vectors may be obtained using quadrature phase shift keying (QPSK), or 4QAM, the QPSK symbol streams having output symbols $y_m(i)$, where m is the stream index. In FIG. 1, first symbol mapper 116 outputs symbols $y_1(i)$ of the first symbol stream and second symbol mapper 118 outputs symbols $y_2(i)$ of the second symbol stream. For example, in an embodiment compliant with the WiMedia MB-OFDM Standard, first symbol mapper 116 may map four information bits from the first bit stream to two separate sets of I/Q points. Thus, for each set of four information bits, first symbol mapper 116 provides a pair of symbols.

The symbols output from first and second symbol mappers 116, 118 are input to first and second symbol spreaders 120, 122, respectively, to spread the symbols, so that each spread symbol contains all the information of the four information bits. In one embodiment, the symbols may be precoded by modulating the symbol pairs according to dual carrier modulation (DCM), discussed above, so that the symbol pairs are effectively mapped to multiple different constellation points. For example, sets of four information bits may be mapped to two separate sets of I/Q points from two separate constellation diagrams, and each constellation is modulated onto two separate subcarriers, *i* and *i* + 50, as discussed below. In other words, each pair of symbols (representing the same four data bits) is mapped for modulation onto two different subcarriers. The DCM linear precoding matrix, according to the illustrative embodiment, is as follows:

$$R = \frac{1}{\sqrt{5}} \begin{bmatrix} 2 & 1 \\ 1 & -2 \end{bmatrix}$$

More particularly, in one embodiment, the mapped symbols are divided into 100 symbol long blocks, and grouped into 50 pairs ($x_m(i)$, $x_m(i + 50)$) spread over corresponding subcarriers, where *i* is the subcarrier index. For example, the first symbol spreader 120 outputs precoded symbols $x_1(i)$ and $x_1(i + 50)$ and the second symbol spreader 122 outputs precoded symbols $x_2(i)$ and $x_2(i + 50)$.

The spread symbols are input into spatial-frequency symbol interleaver 125. Spatial-frequency symbol interleaver 125 distributes the spread symbols, such that the spread symbols $x_m(i)$ having the same *m* parameter are transmitted on different subcarriers of different transmitters, as follows:

$$\begin{bmatrix} s_1(i) \\ s_2(i+50)) \end{bmatrix} = R * \begin{bmatrix} x_1(i) \\ x_1(i+50)) \end{bmatrix} = \frac{1}{\sqrt{5}} \begin{bmatrix} 2 & 1 \\ 1 & -2 \end{bmatrix} * \begin{bmatrix} x_1(i) \\ x_1(i+50)) \end{bmatrix},$$

$$\begin{bmatrix} s_2(i) \\ s_1(i+50)) \end{bmatrix} = R * \begin{bmatrix} x_2(i) \\ x_2(i+50)) \end{bmatrix} = \frac{1}{\sqrt{5}} \begin{bmatrix} 2 & 1 \\ 1 & -2 \end{bmatrix} * \begin{bmatrix} x_2(i) \\ x_2(i+50)) \end{bmatrix}$$

For example, according to the depicted embodiment, spatial-frequency symbol interleaver 125 generates $s_1(i)$ and $s_1(i + 50)$, which are to be sent to first transmitter 140, from the spread symbols $x_1(i)$ received from first symbol spreader 120 and $x_2(i + 50)$ received from second symbol spread 122, respectively. Likewise, spatial-frequency symbol interleaver 125 generates $s_2(i)$ and $s_2(i + 50)$, which are to be sent to second transmitter 142, from spread symbols $x_2(i)$ received from second symbol spreader 122 and $x_1(i + 50)$ received from the first symbol spreader 120, respectively. The symbols are thus distributed onto carriers and transmitted to have a reduced correlation and thereby to improve the diversity gain.

The symbols output from the spatial frequency symbol interleaver 125 are fed into first and second IFFTs 124, 126, which generate the time-domain signals for first and second transmitters 140, 142, respectively. For example, $s_1(i)$ and $s_1(i + 50)$ are fed into first IFFT 124, while $s_2(i)$ and $s_2(i + 50)$ are fed into second IFFT 126.

As a result, two related symbols originating from the same (parsed) bitstream are distributed to two different subcarriers of two different transmitters. For example, the first output symbol of first symbol spreader 120 is transmitted on the i-th subcarrier through the first transmitter 140, while the second output symbol of first symbol spreader 120 is transmitted on the $(i + 50)$-th subcarrier through the second transmitter 142. Likewise, the first output symbol of second symbol spreader122 is transmitted on the i-th subcarrier through second transmitter 142, while the second output symbol of second symbol spreader 122 is on the $(i + 50)$-th subcarrier transmitted through the first transmitter 140. By distributing the spread symbols to different subcarriers of different transmitters, it is more likely that the spread symbols will be transmitted through transmission channels having reduced correlation, thus improving diversity gain.

FIG. 2 is a functional block diagram of one embodiment of an MIMO-OFDM receiving system 200, which complements MIMO-OFDM transmission system 100. As will be appreciated by those skilled in the art, the various functions shown in FIG. 2 may be physically implemented using a software-controlled microprocessor, hard-wired logic circuits, or a combination thereof. Also, while the functional blocks are illustrated as being segregated in FIG. 2 for explanation purposes, they may be combined in any physical implementation.

Receiving system 200 includes a channel decoder 210, a bit deinterleaver 212, a symbol spreading demodulator 220, and first and second time-domain transformers 224 and 226. Although the time-domain transformers 224 and 226 are indicated as fast Fourier transformers, other implementations may be employed. Receiving system 200 further includes first and second receivers 240 and 242, corresponding to time-domain transformers 224 and 226. Each of the receivers 240 and 242 may include corresponding antenna systems (not shown). In an embodiment, receiving system 200 may be a WiMedia UWB system, for example.

Receivers 240, 242 receive the signals including the precoded symbols from transmitters 140, 142 of FIG. 1, which are transformed from the time-domain to the frequency-domain by FFTs 224, 226, respectively. The frequency-domain symbols are indicated as $r_1(i)$, $r_1(i+50)$, $r_2(i)$ and $r_2(i+50)$. More particularly, the received frequency-domain signals can be written as follows:

$$\begin{bmatrix} r_1(i) \\ r_2(i) \\ r_1(i+50) \\ r_2(i+50) \end{bmatrix} = \begin{bmatrix} h_{11}(i) & h_{12}(i) & 0 & 0 \\ h_{21}(i) & h_{22}(i) & 0 & 0 \\ 0 & 0 & h_{11}(i+50) & h_{12}(i+50) \\ 0 & 0 & h_{21}(i+50) & h_{22}(i+50) \end{bmatrix} \begin{bmatrix} s_1(i) \\ s_2(i) \\ s_1(i+50) \\ s_2(i+50) \end{bmatrix} + \vec{n}$$

$$= \begin{bmatrix} h_{11}(i) & 0 & h_{12}(i) & 0 \\ h_{21}(i) & 0 & h_{22}(i) & 0 \\ 0 & h_{12}(i+50) & 0 & h_{11}(i+50) \\ 0 & h_{22}(i+50) & 0 & h_{21}(i+50) \end{bmatrix} \begin{bmatrix} 2 & 1 & 0 & 0 \\ 1 & -2 & 0 & 0 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & -2 \end{bmatrix} \begin{bmatrix} x_1(i) \\ x_1(i+50) \\ x_2(i) \\ x_2(i+50) \end{bmatrix} + \vec{n}$$

In the above equation, $h_{mn}(i)$, where $i = 1, 2, \ldots, 100$, and $m,n = 1, 2$, denotes the transmission channel transfer function parameter of subcarrier i between the *m-th* transmit antenna and the *n-th* receive antenna. The vector $\vec{n}$ denotes noise.

The transformed symbols are demodulated by symbol spreading demodulator 220, which outputs an interleaved, encoded bit sequence. Also, soft bit decision information, indicating reliability measures of the received data, may be generated by symbol spreading demodulator 220. For example, the optimal maximum-likelihood (ML) estimator, or sub-optimal minimum mean square error (MMSE) or zero-forcing (ZF) linear estimators, can be used to calculate the soft-information for each bit. The bit soft information may include log-likelihood-ratios (LLR).

Bit deinterleaver 212 deinterleaves the interleaved, encoded bit sequence and soft bit decision information and outputs an encoded bit sequence and its corresponding soft bit decision information. Channel decoder 210 decodes the encoded bit sequence and outputs an output data sequence corresponding to the input information bits of FIG. 1.

FIGS. 3 and 4 depict simulation results comparing frame error rate performances of MIMO-OFDM systems according to embodiments of the present invention (indicated by plotted lines with x's) with a conventional system, for example, as described in International Patent Application No. PCT/IB2006/054613 (indicated by plotted lines with o's). The frame error rates are graphed with respect to the signal to noise ratio E_B/N_0 in dB, as measured at the receiving system (e.g., the receiving system 200).

The simulations used typical UWB channel models, such as IEEE standard UWB channel models. In particular, the simulation of FIG. 3 used an IEEE CM1 channel model from the IEEE 802.15.3a working group, which is a short range (i.e., less than four meters) line-of-sight communication, and the simulation of FIG. 4 used an IEEE CM2 channel model, which is a short range non-line-of-sight communication. Also, it was assumed that there was no spatial correlation. For each simulation, 10000 channel realizations were used, the packet size was 2048 bytes, and the channel code was a convolutional code of rate $R = 3/4$, from the WiMedia MB-OFDM Standard. FIGS. 3 and 4 show that the depicted embodiments have approximately 1 dB improvement over the conventional system for any given frame error rate.

FIGS. 5 and 6 are functional block diagrams of a more generalized embodiment of an MIMO-OFDM data communication system, in which there are two or more transmitters and corresponding transmit antennas. As shown, the MIMO-OFDM transmission system 500 of FIG. 5 includes M transmit antennas and the MIMO-OFDM receiving system 600 of FIG. 6 includes N receive antennas.

MIMO-OFDM transmission system 500 includes a channel coder 510, a bit interleaver and spatial parser 512, symbol mappers 516 through 518, symbol spreaders 520 through 522, and a spatial-frequency symbol interleaver (SFSI) 525. MIMO-OFDM transmission system 500 also includes time-domain transformers, such as inverse fast Fourier transformers (IFFTs) 524 through 526, although other implementations of inverse time-domain transformers may be employed. The outputs of IFFTs 524, 526 are sent to first and second transmitters 540 and 542, including corresponding antenna systems (not shown).

An information bit stream is input into channel coder 510. The coded bits are parsed into M bit streams by bit interleaver and spatial parser 512, as discussed above with respect to the bit interleaver and spatial parser 112. Each of the parsed bit streams are mapped to symbol streams by multiple symbol mappers, indicated by representative symbol mappers 516 through 518, where the output symbols may be from PSK or QAM constellations, for example. Then, k symbols of the m-th stream ($m = 0, \ldots, M$) are spread and/or precoded together at multiple symbol spreaders corresponding to the symbol mappers, indicated by representative symbol spreaders 520 through 522. The precoding may be linear or nonlinear. For example, a linear precoder disclosed in International Patent Application No. PCT/IB2006/054720 can be used for QAM symbol mappings.

An example of a linear precoder may be represented by the following equation, in which T denotes the matrix transpose operation and R is a k by k linear rotation matrix:

$$[x_m(i_1), x_m(i_2), \ldots, x_m(i_k)]^T = R * [y_m(i_1), y_m(i_2), \ldots, y_m(i_k)]^T$$

Alternatively, an example of a nonlinear precoder may be represented by the following equation, in which where f is a mapping function:

$$(x_m(i_1), x_m(i_2), \ldots, x_m(i_k)) = f\,(y_m(i_1), y_m(i_2), \ldots, y_m(i_k))$$

After spreading/precoding, all Mk output symbols $x_m(i)$, where $i = i_1, i_2, \ldots, i_k$ and $m = 1, 2, \ldots, M$, output from symbol spreaders 520 through 522 are grouped together and distributed to k subcarriers (the subcarrier indices are $i_1, i_2, \ldots, i_k$) of M transmitters by spatial-frequency symbol interleaver 525. Spatial-frequency symbol interleaver 525 assures that symbols $x_m(i)$ having the same m parameter are transmitted on different subcarriers of as many as possible different transmitters, e.g., transmitters 540 through 542, so that the channels on which they are transmitted have reduced correlation, thereby achieving an improved diversity gain. The precoded symbols are transformed to the time-domain by multiple time-domain transformers, indicted by representative IFFTs 524 through 526, for transmission by M transmitters through corresponding antenna systems.

For example, when $M = k$, the interleaving process of spatial-frequency symbol interleaver 525 can be performed according to the following equation:

$$s_m(i_\alpha) = x_{\mathrm{mod}(m+\alpha-2,\, M)\,+\,1}(i_\alpha)$$

FIG. 7 shows a representative interleaving pattern, according to the above equation, when $M = k = 4$. Accordingly, FIG. 7 shows a four-subcarrier precoding interleaving pattern, based on four (M) transmitters 1 through 4 and four (k) subcarriers i_1 through i_4. Each transmitter 1 through 4 thus transmits only one symbol from any particular bitstream m, enhancing diversity gain. For example, transmitter 1 sends $x_1(i_1)$, $x_4(i_2)$, $x_3(i_3)$ and $x_2(i_4)$, each of which are from different bitstreams. Further, each symbol is transmitted on a different subcarrier.

Referring to FIG. 6, receiving system 600 receives the time-domain symbols through multiple (N) receivers each having a corresponding antenna system (not shown), indicated by representative receivers 640 through 642. The received symbols are transformed to the frequency-domain by multiple domain transformers corresponding to the receivers, indicated by representative FFTs 624 through 626, providing frequency-domain symbols $r_n(i)$, where $i = i_1, i_2, \ldots, i_k$ and $n = 1, 2, \ldots, N$. At the symbol spreading demodulator 620, all of the frequency-domain symbols $r_n(i)$ are grouped together and bit soft decision information is calculated, through an ML estimator or other suboptimal estimator, as discussed above. The channel decoder 610 decodes the deinterleaved soft bit information to obtain decoded bits, thus recovering the information bits input to the transmission system 500.

Various embodiments may include MIMO-OFDM data communication systems in which multiple antennas are used to achieve high data rates, such as IEEE802.11n WLAN, 3G WCDMA HSDPA, WiMax and MB-OFDM based WiMedia UWB systems. Further, a current WiMedia UWB system may be upgraded to a MIMO UWB system, according to various embodiments, since many of the baseband components of the WiMedia UWB system may be incorporated. Accordingly, data rates increase significantly while a reasonable robustness is maintained, even when a weak channel code is used. It is understood that this scheme can be naturally extended to systems with other channel codes and space-time coded schemes, such as turbo codes, space-time trellis codes, and the like.

While preferred embodiments are disclosed herein, many variations are possible which remain within the concept and scope of the invention. Such variations would become clear to one of ordinary skill in the art after inspection of the specification, drawings and claims herein. The invention therefore is not to be restricted except within the spirit and scope of the appended claims.

CLAIMS

What is claimed is:

1. A system for transmitting data through a plurality of transmitters, the system comprising:

a symbol mapper (116/118, 516/518) configured to receive one bit stream corresponding to a portion of the data and to map at least one set of sequential bits of the one bit stream to a corresponding set of symbols of a symbol stream, the set of symbols comprising at least a first symbol and a second symbol;

a symbol spreader (120/122, 520/522) configured to receive the set of symbols from the symbol mapper and to precode the set of symbols to a set of spread symbols; and

a symbol interleaver (125, 525) configured to receive the first and second spread symbols from the symbol spreader, to distribute the first spread symbol to a first transmitter for transmission over a first subcarrier and to distribute the second spread symbol to a second transmitter for transmission over a second subcarrier, the first subcarrier and the second subcarrier being non-adjacent subcarriers.

2. The system of claim 1, further comprising:

a parser (112, 512) configured to parse a stream of coded data corresponding to the data into a plurality of bit streams, including the one bit stream.

3. The system of claim 2, further comprising:

a plurality of time-domain transformers (124/126, 524/526) configured to transform the first and second distributed symbols from a frequency-domain to a time-domain.

4. The system of claim 3, wherein each of the time-domain transformers (124/126, 524/526) comprises an inverse fast Fourier transformer (IFFT).

5. The system of claim 1, wherein the symbol spreader (120/122, 520/522) includes a dual carrier modulation (DCM) modulator.

6. The system of claim 1, wherein the symbol spreader (120/122, 520/522) includes one of a linear precoder or a non-linear precoder.

7. The system of claim 1, wherein the symbol stream comprises one of a PSK and a QAM constellation.

8. A receiving system for receiving the plurality of data streams transmitted by the transmitting system of claim 1, the receiving system comprising:

a plurality of receivers (240/242, 640/642) configured to receive the first distributed symbol on the first subcarrier from the first transmitter and the second symbol on the second distributed subcarrier from the second transmitter; and

a symbol spreading demodulator (220, 620) configured to demodulate the first and second received symbols to obtain at least one set of bits.

9. The system of claim 8, further comprising:

a plurality of frequency-domain transformers (224/226, 624/626) corresponding to the plurality of receivers (240/242, 624/626), the plurality of frequency-domain transformers being configured to transform the first and second received symbols from a time-domain to a frequency-domain.

10. A method of transmitting an input bit stream, comprising:

parsing the input bit stream into a plurality of bit streams;

mapping the plurality of bit streams to a corresponding plurality of symbol streams, each symbol stream comprising at least one set of symbols representing a group of sequential bits in the corresponding bit stream;

associating each of the symbols in the at least one set of symbols with different, non-adjacent subcarriers, respectively; and

distributing the symbols of the at least one set of symbols to different transmitters, respectively, for transmission on the associated non-adjacent subcarriers.

11. The method of claim 10, wherein the plurality of symbol streams comprise a plurality of PSK or QAM symbol streams.

12. The method of claim 11, further comprising:

transforming the symbols of the at least one set of symbols from a frequency-domain to a time-domain before the transmission.

13. The method of claim 12, wherein transforming the distributed symbols of the at least one set of symbols from the frequency-domain to the time-domain comprises an inverse fast Fourier transformation.

14. The method of claim 10, wherein associating the symbols of the at least one set of symbols with different, non-adjacent subcarriers comprises one of linear precoding or non-linear precoding.

15. The method of claim 10, wherein associating the symbols of the at least one set of symbols with different, non-adjacent subcarriers comprises dual carrier modulation (DCM).

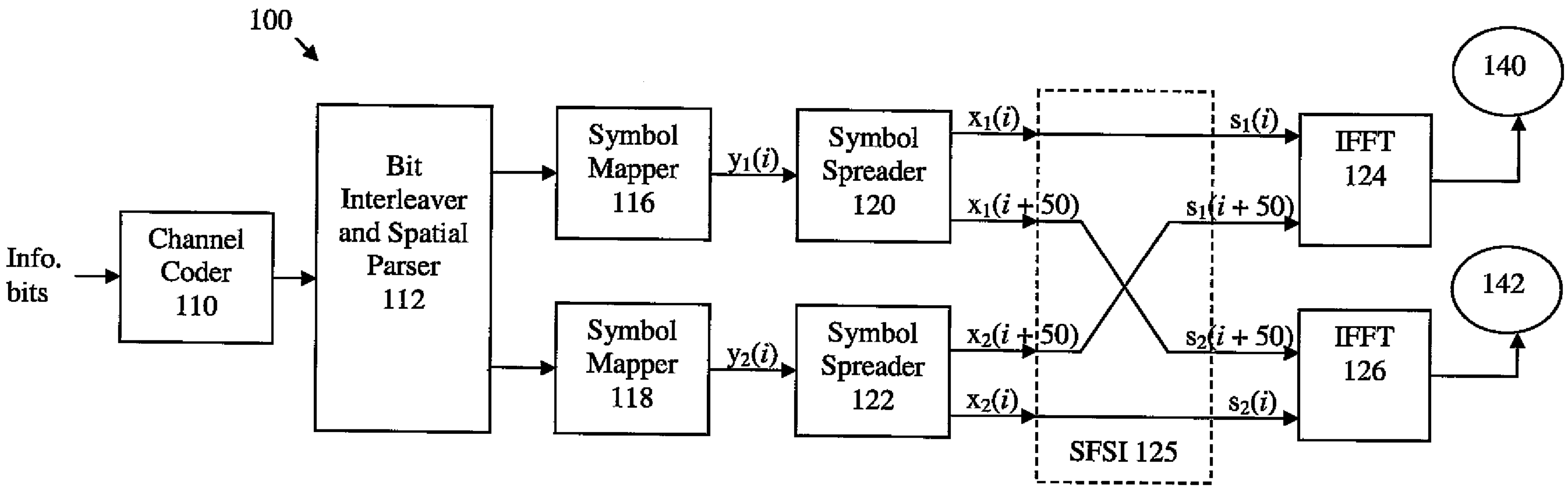
100
Info. bits
Channel Coder 110
Bit Interleaver and Spatial Parser 112
Symbol Mapper 116
Symbol Mapper 118
$y_1(i)$
$y_2(i)$
Symbol Spreader 120
Symbol Spreader 122
$x_1(i)$
$x_1(i+50)$
$x_2(i+50)$
$x_2(i)$
SFSI 125
$s_1(i)$
$s_1(i+50)$
$s_2(i+50)$
$s_2(i)$
IFFT 124
IFFT 126
140
142

FIG. 1

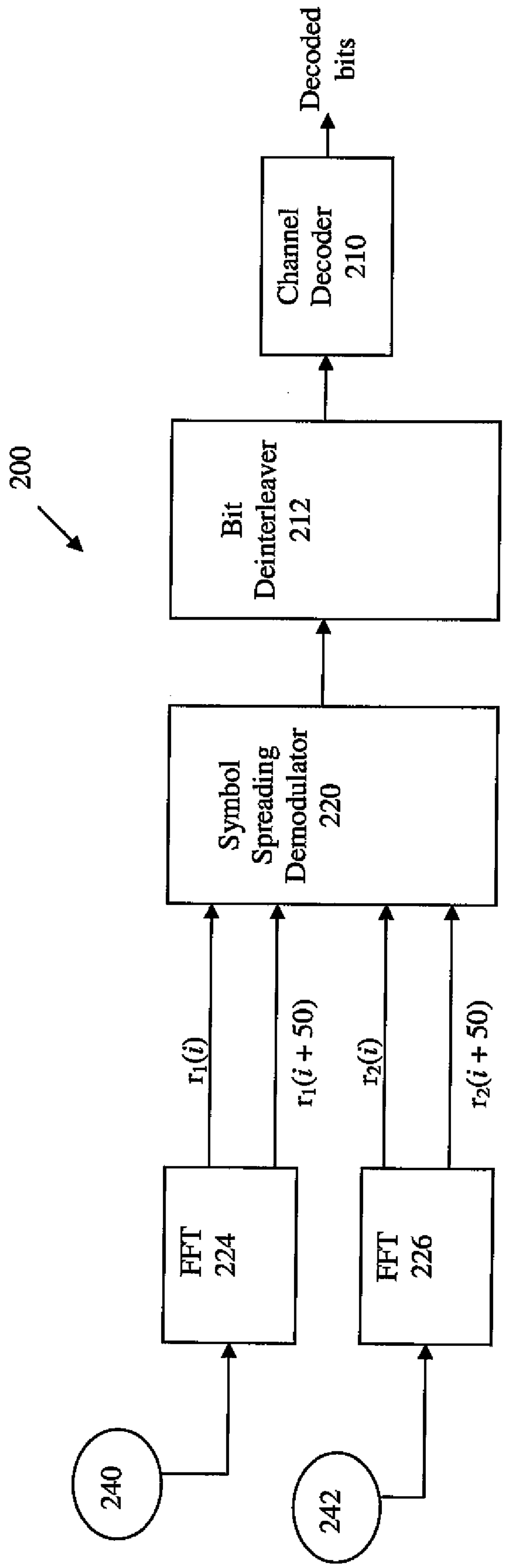
200
240
242
FFT 224
FFT 226
$r_1(i)$
$r_1(i+50)$
$r_2(i)$
$r_2(i+50)$
Symbol Spreading Demodulator 220
Bit Deinterleaver 212
Channel Decoder 210
Decoded bits

FIG. 2

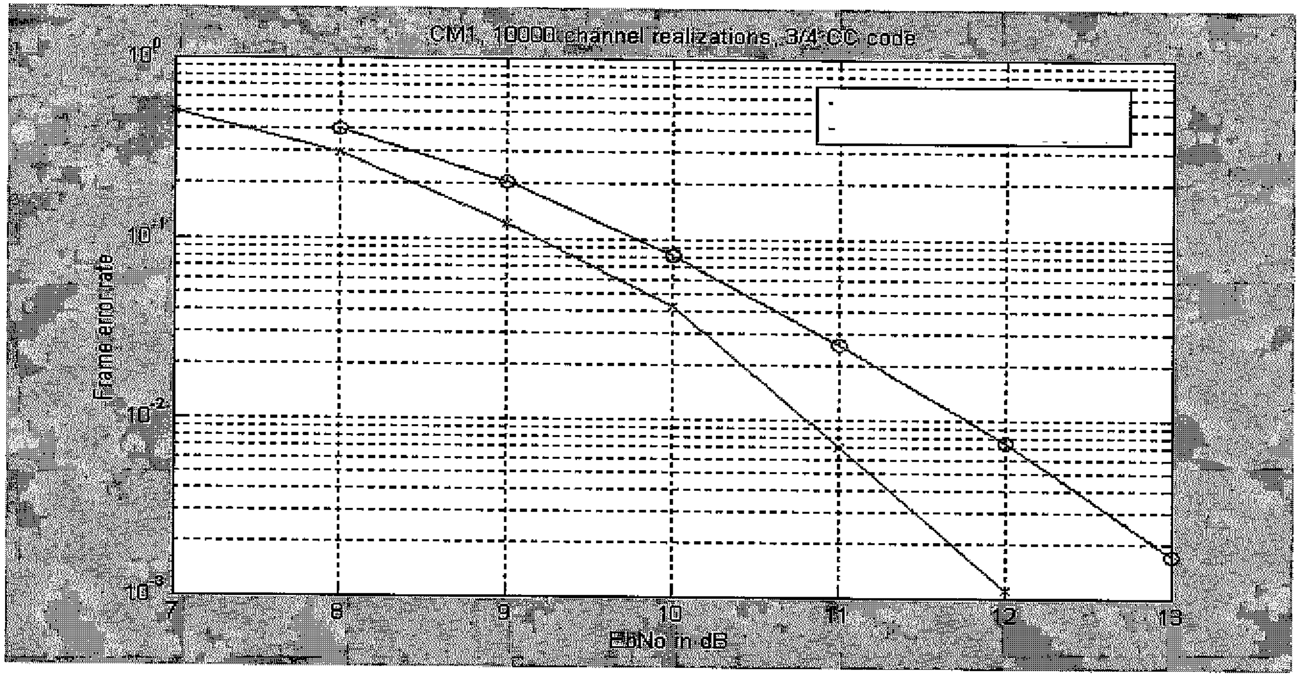
CM1, 10000 channel realizations, 3/4 CC code
Frame error rate
10^0
10^{-1}
10^{-2}
10^{-3}
7
8
9
10
11
12
13
EbNo in dB

FIG. 3

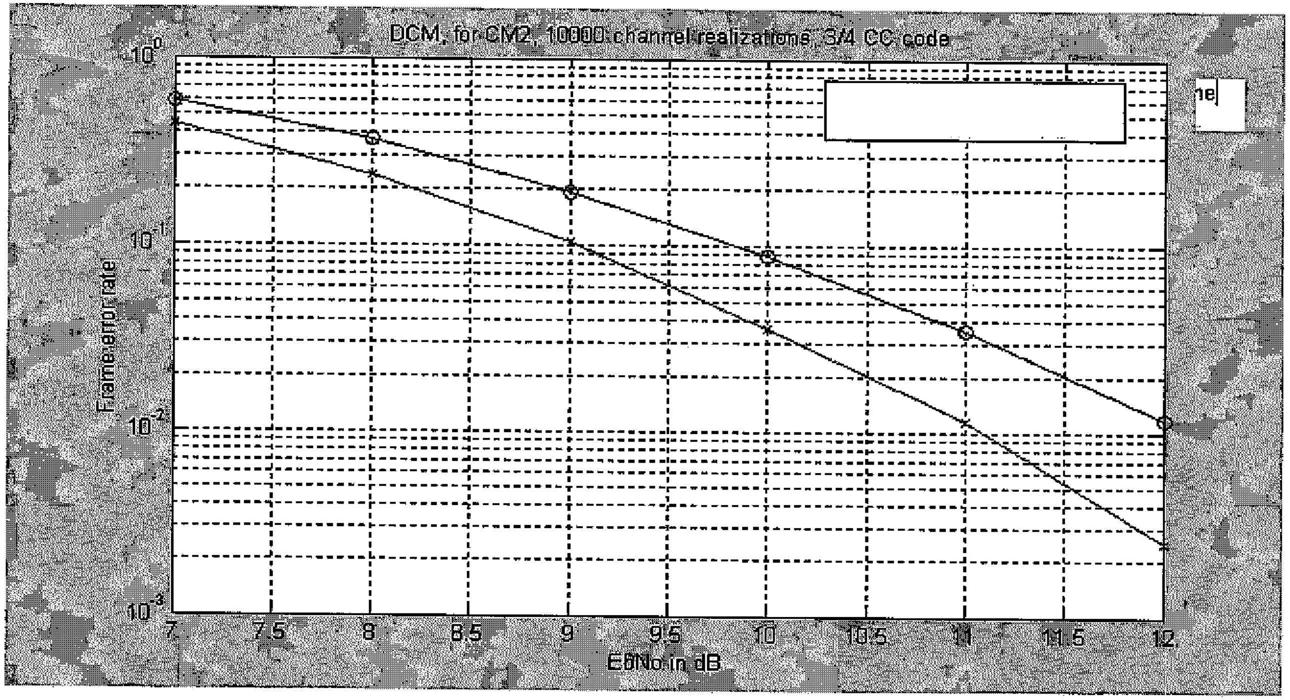
DCM, for CM2, 10000 channel realizations, 3/4 CC code
10^0
10^{-1}
10^{-2}
10^{-3}
Frame error rate
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
EbNo in dB
ne

FIG. 4

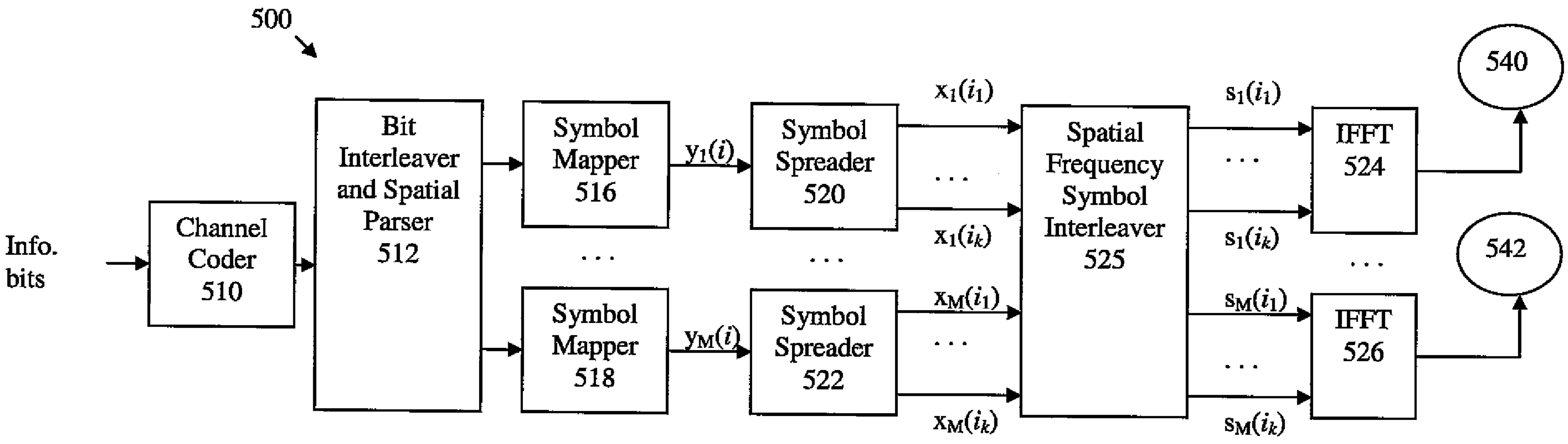
500
Info. bits
Channel Coder 510
Bit Interleaver and Spatial Parser 512
Symbol Mapper 516
Symbol Mapper 518
$y_1(i)$
$y_M(i)$
Symbol Spreader 520
Symbol Spreader 522
$x_1(i_1)$
$x_1(i_k)$
$x_M(i_1)$
$x_M(i_k)$
Spatial Frequency Symbol Interleaver 525
$s_1(i_1)$
$s_1(i_k)$
$s_M(i_1)$
$s_M(i_k)$
IFFT 524
IFFT 526
540
542

FIG. 5

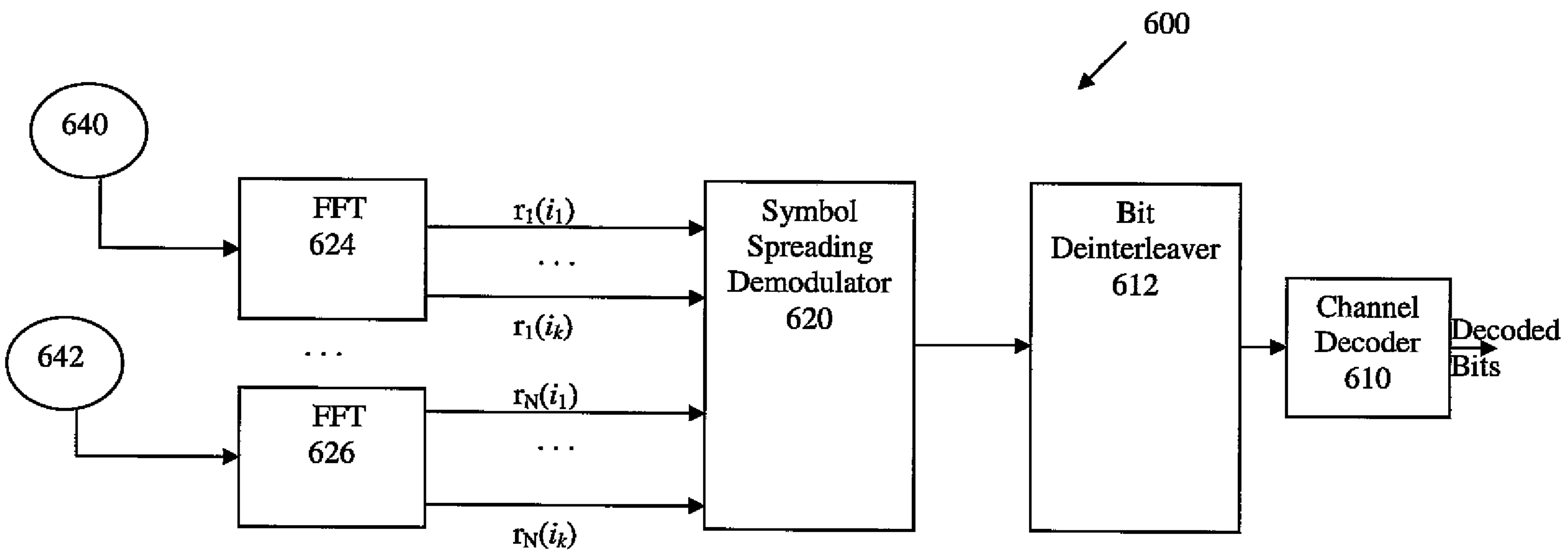
600
640
642
FFT
624
FFT
626
$r_1(i_1)$
. . .
$r_1(i_k)$
$r_N(i_1)$
. . .
$r_N(i_k)$
. . .
Symbol
Spreading
Demodulator
620
Bit
Deinterleaver
612
Channel
Decoder
610
Decoded
Bits

FIG. 6

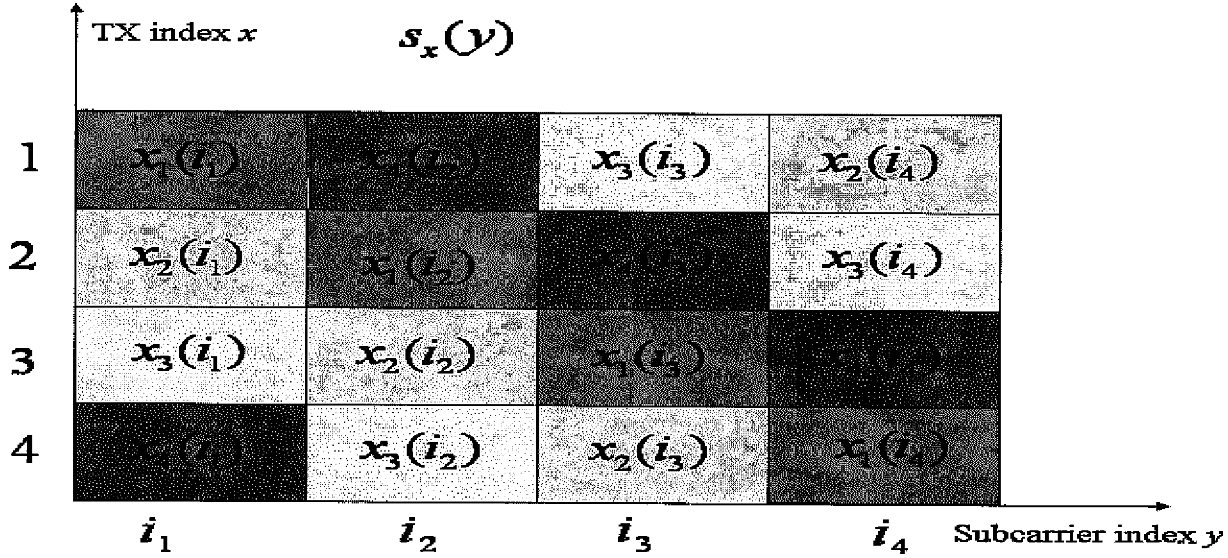
TX index x
$s_x(y)$
1
2
3
4
$x_1(i_1)$
$x_3(i_3)$
$x_2(i_4)$
$x_2(i_1)$
$x_1(i_2)$
$x_3(i_4)$
$x_3(i_1)$
$x_2(i_2)$
$x_1(i_3)$
$x_3(i_2)$
$x_2(i_3)$
$x_1(i_4)$
i_1
i_2
i_3
i_4
Subcarrier index y

FIG. 7