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(71) Applicant *(for all designated States except US)*: **NTT DOCOMO, INC.** [JP/JP]; Sanno Park Tower, 11-1, Nagata-cho, 2-chome, Chiyoda-ku (JP).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **PAPADOPOULOS, Haralabos** [GR/US]; 390 South Cypress Avenue, San Jose, CA 95117 (US). **CHEN, Ming-yang** [—/US]; 344 Olmsted Road, Stanford, CA 94305 (US). **RAMPRASHAD, Sean, A.** [GB/US]; 960 Terrace Drive, Los Angeles, CA 94024 (US).

(74) Agents: **VINCENT, Lester J.** et al.; Blakely, Sokoloff, Taylor & Zafman Llp, 1279 Oakmead Parkway, Sunnyvale, CA 94085-4040 (US).

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(54) Title: A METHOD AND APPARATUS FOR ITERATIVE RECEIVER STRUCTURES FOR OF DM/MIMO SYSTEMS WITH BIT INTERLEAVED CODED MODULATION

(57) Abstract: The techniques and components described herein may improve the performance for a class of reduced-complexity receiver designs for coded OFDM MIMO systems with bit interleaved coded modulation. The receiver structures described are soft-input soft-output inner/outer decoder receiver structures that include one or more of the following: 1) an inner decoder that includes a linear front-end followed by a limited tree-search based on a soft-output M-algorithm; 2) a conventional near-optimal or optimal decoder for the outer binary code; and 3) iterative decoding (ID), whereby decoding (output) information is passed from one decoder module as input to the other and used to refine and improve the inner/outer decoding module outputs.

A METHOD AND APPARATUS FOR ITERATIVE RECEIVER STRUCTURES FOR OFDM/MIMO SYSTEMS WITH BIT INTERLEAVED CODED MODULATION

PRIORITY

[0001] The present patent application claims priority to and incorporates by reference the corresponding provisional patent application serial no. 61/097,148, titled, "A Method and Apparatus for Iterative Receiver Structures for OFDM/MIMO Systems with Bit Interleaved Coded Modulation," filed on September 15, 2008.

FIELD

[0002] Embodiments of the present invention relates to the field of wireless transmission in a wireless environment. More particularly, embodiments of the present invention relate to components and techniques receiving Orthogonal Frequency Division Multiplexing (OFDM) signals in multiple-input/multiple-output (MIMO) systems.

BACKGROUND

[0003] A broadly deployed class of open-loop single-user multiple-input/multiple-output (MIMO) systems includes coded orthogonal frequency division multiplexing (OFDM) MIMO systems with bit-interleaved coded modulation (BICM). These MIMO systems have the potential to produce very large transmission rates, by providing very high spectral efficiencies (i.e., very large throughputs per unit bandwidth), and optimized diversity-transmission rate trade offs. However, the computational complexity of near-optimal receiver structures for these systems grows exponentially fast with increased spectral efficiencies. Designing receivers for coded OFDM/MIMO systems with BICM that have good performance-complexity trade-offs is thus a very important challenge in deploying reliable systems that can be operated with practical receivers and can achieve high-spectral efficiencies.

[0004] Figure 1 illustrates a block diagram of a system for encoding of information-bearing signals for a single-user MIMO system. The signal is first encoded with an outer binary code, for example a convolutional code, which may be accomplished by convolutional coder 110. The coded signal is interleaved by interleaver 120 and mapped to vector parallel streams by serial-to-parallel converter 130. The parallel streams are modulated by mapper modems 140 and transmitted.

[0005] These coded OFDM/BICM/MIMO systems encode the information bearing signal with an outer binary code (e.g., convolutional code, turbo code, low-density parity check (LDPC) code) followed by a bit interleaver, a mapper of bits to symbols (e.g., quadrature amplitude modulation (QAM) symbols), followed by round robin transmission of these symbols over all transmit antennas via OFDM. The typical receivers for these systems have an inner-outer decoder structure, with soft-output decoder modules. The complexity of these receiver structures resides in the inner decoder, referred to as the inner joint demapper. Indeed, the complexity of these inner demappers grows exponentially fast with the number of bits transmitted per channel use, and as a result, exponentially fast with the system spectral efficiency (throughput per unit bandwidth).

[0006] A number of reduced complexity receiver structures have been proposed for these systems with various performance complexity trade-offs. One class of these techniques is based on inner demapper structures that make use of what is known as the soft-output M-Algorithm (SOMA) and its variants. The front-end operations that are performed prior to performing soft- SOMA inner decoding can have a significant impact in the performance of these schemes in iterative decoding structures. These designs perform jointly optimized front-end filtering and SOMA tree search and can be shown to significantly improve performance over other existing designs in iterative decoding.

[0007] For future wireless systems, it is desirable to have efficient utilization of the radio frequency spectrum in order to increase the data rate achievable within a given transmission bandwidth. This can be accomplished by employing multiple transmit and receive antennas combined with signal processing. A number of recently developed techniques and emerging standards are based on employing multiple antennas at a base station to improve the reliability of data communication over wireless media without compromising the effective data rate of the wireless systems. Specifically, recent advances in wireless communications have demonstrated that by jointly encoding symbols over time and transmit antennas at a base station one can obtain reliability (diversity) benefits as well as increases in the effective data rate from the base station to each cellular user.

[0008] These multiplexing (throughput) gains and diversity benefits depend on the space-time coding techniques employed at the base station. The multiplexing gains and diversity benefits are also inherently dependent on the number of transmit and receive antennas in the system being deployed. Specifically, these trade offs between multiplexing gains and diversity are fundamentally limited by the number of transmit and the number of receive antennas in the system.

[0009] For high data rates and wideband transmission the use of OFDM makes the equalizer unnecessary. With multilevel modems, coded modulation systems can be designed by means of an outer binary code, for example, a convolutional code and an interleaver in a bit-interleaved coded modulation (BICM) system.

[0010] Existing receiver structures for the transmission systems, for example, for coded MIMO/OFDM/BICM/ID systems, include an inner-outer decoder structure, whereby the outer decoder is optimally selected. The designs generally include the following features. Iterative decoding receivers using a MAP-based inner decoder and a MAP-based outer decoder yield the optimum bit-error-rate performance among all inner/outer decoder structures. However, the MAP-based inner decoder becomes computationally intractable as N (number of transmit antennas/number of QAM symbols that need to be jointly resolved) and B (number of bits represented by each QAM symbol) increase.

[0011] ID systems with a maxlogMAP-based inner decoder have less complexity than the MAP-based system and are asymptotically (high SNR) optimal in that they have near optimum bit-error-rate performance at high SNR. However, the maxlogMAP-based inner decoder also becomes computationally intractable as N and B increase.

[0012] Receivers using QRD/M-Algorithm based inner decoder also use a variant of the M-algorithm to produce hard bit estimates along with reliability information. As a result they can yield drastic reductions in complexity by proper choice of the M parameter, at a cost in bit-error-rate performance. These methods directly employ the "hard-output" M-algorithm, to generate hard-output estimates, and then employ the resulting M candidates to obtain soft information. However, to generate soft information for any bit location, both values of the bit must be available in the pool of the remaining M candidates. As a result, these methods resort to heuristic (and inferior) techniques to generate soft output for each bit. In addition these structures do not typically exploit iterative decoding.

[0013] MMSE-based inner decoders consisting of a linear MMSE-front end followed by QAM symbol/by QAM symbol soft-output generation methods have lower complexity, but suffer in bit-error-rate performance, especially at higher outer-code rates. At such rates higher-complexity inner decoders, which use QR-decomposition linear front-ends with channel-adaptive tree-search symbol-reordering, in order to perform tree searches that are based on a forward pass only or a forward-backward pass SOMA algorithm, have higher performance. However, these schemes are inferior to the proposed schemes in iterative decoding settings.

SUMMARY

[0014] Methods and apparatuses are disclosed herein for iterative decoding based on signals that are received from a transmitter that transmitted the signals using orthogonal frequency devision multiplexing (OFDM) and bit interleaved coded modulation. In all embodiments, the disclosed decoders comprise iterative inner/outer decoder structures with soft-output M-algorithm (SOMA) based inner decoders and whereby extrinsic information is exchanged between the outer and the inner decoder at each iteration.

[0015] One or more filtered signal estimates are generated based on the extrinsic information. A SOMA-based multiple-input/multiple-output (MIMO) detection process is performed over each tone of the signals by searching a detection tree for each tone, where tree search parameters are selected based on the one or more filtered signal estimates and at least in part on the extrinsic information.

[0016] In one embodiment, a receiver for use in an orthogonal frequency division multiplexing (OFDM) wireless communication system to receive signals from a transmitter that transmits the signals using OFDM and bit interleaved coded modulation includes an inner decoder structure and an outer decoder.

[0017] The inner decoder structure includes an adaptive front end and is coupled to receive extrinsic information from the outer decoder. The adaptive front end utilizes the extrinsic information from prior outer decoder iterations and channel information corresponding to a portion of the received signals to generate filtered signal estimates. The inner decoder comprises a soft output M-algorithm (SOMA) based multiple-in multiple-out (MIMO) demapper that utilizes the filtered signal estimates to perform inner demapping over each tone.

[0018] The outer decoder is coupled with the inner decoder to perform iterative decoding and to provide extrinsic information related to the iterative decoding to the adaptive front end.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The present invention will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the invention, which, however, should not be taken to limit the invention to the specific embodiments, but are for explanation and understanding only.

[0020] **Figure 1** illustrates a block diagram of a system for encoding of information-bearing signals for a single-user MIMO system.

[0021] **Figure 2** illustrates a block diagram of one embodiment of a decoding structure having an inner decoder and an outer decoder.

[0022] **Figure 3** illustrates a block diagram of one embodiment of joint demapper units of the receiver in a single user MIMO system based on OFDM.

[0023] **Figure 4** is a flow diagram of one embodiment of a MIMO demapper operation.

[0024] **Figure 5** is a block diagram of one embodiment of a front end.

[0025] **Figure 6** illustrates details of a MIMO demapper for a subchannel n illustrated in Figure 3 and expands on details in Figure 5.

[0026] **Figure 7** is a block diagram of one embodiment of an electronic system that may include a MIMO decoder as described herein.

DETAILED DESCRIPTION

[0027] The following description discloses techniques for receiver complexity reduction for MIMO/OFDM/BICM/ID systems of the form depicted in Figure 2, and is particularly attractive for high-rate schemes of this kind. The design ideas are related to the use of soft-output inner-decoding algorithms that rely on an M-algorithm-based reduced-size tree search. In one embodiment, this involves use of a channel-adaptive linear front end together with a selection of a symbol order that may be used in the tree-search by the soft-output M-algorithm. In one embodiment, both the linear front end, the process by means of which the detection tree is constructed (in terms of the decomposition of codeword metrics into a sum of branch metrics on a tree), the detection tree itself, and the symbol order in the tree-search may be adapted and optimized with iterations in the inner/outer decoding algorithms.

[0028] There are also described techniques for operating improved reduced-complexity high-performance receivers for wireless Multiple-Input Multiple-Output (MIMO) systems. MIMO systems transmit multiple streams from multiple transmit antennas in such a way that they can increase the overall system spectral efficiency (throughput per unit bandwidth) and thus the overall throughout. As the numbers of transmit and receive antennas employed are increased, higher overall spectral efficiencies (rate per unit bandwidth) can be attained. These higher rates however come at a cost in terms of increased complexity of the optimal receiver. Described herein are techniques that may reduce the computational complexity of the optimal receiver in these designs.

[0029] The techniques and components described herein may improve the performance for a class of reduced-complexity receiver designs for coded OFDM MIMO systems with bit interleaved coded modulation. In one embodiment, the receiver structures described are soft-input soft-output inner/outer decoder receiver structures that include one or more of the following: 1) an inner decoder that includes a linear front-end followed by a limited tree-search based on a soft-output M-algorithm; 2) a conventional near-optimal or optimal decoder for the outer binary code; and 3) iterative decoding (ID), whereby decoding (output) information is passed from one decoder module as input to the other and used to refine and improve the inner/outer decoding module outputs.

[0030] Also described herein is a design of the inner decoding module that may reside in a linear front-end, and in techniques to jointly adapt and optimize the tree search through the use of this front-end. This may improve the receiver performance in terms of reduced bit or symbol or block-error rates (for a given received signal-to-noise ratio) over previous front-ends for a given receiver complexity, or reduce the receiver complexity required to achieve a target performance. In one embodiment, adaptation and optimization may occur in each iteration in the inner/outer decoding algorithm. Performance improvements may be seen with iterative decoding as the number of iterations increases.

[0031] The described schemes achieve advantageous performance-complexity trade-offs by exploiting, at the inner decoder module, the information provided by the outer decoder module in order to adaptively optimize the linear filtering operation. In one embodiment, the structures implicitly make use of the information provided by the outer decoder regarding the reliability of each symbol, and combine it with measurement and channel state information to define the detection tree and select the tree-search order in a systematic manner at each iteration. Then a reduced tree-search on this tree is conducted via a soft-output M-algorithm in order to generate soft-output information.

[0032] The jointly optimized operations allow these receiver structures to yield bit-error rate performance that improves with increasing number of iterations. Furthermore, the bit-error-rate performance gracefully degrades as the M values in the M-algorithm are reduced.

[0033] In the following description, numerous specific details are set forth. However, embodiments of the invention may be practiced without these specific details. In other instances, well-known circuits, structures and techniques have not been shown in detail in order not to obscure the understanding of this description.

[0034] Some portions of the detailed descriptions which follow are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

[0035] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0036] The present invention also relates to apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, or it may comprise a general purpose computer selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a computer readable storage medium, such as, but is not limited to, any type of disk including floppy disks, optical disks, CD-ROMs, and magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic or optical cards, or any type of media suitable for storing electronic instructions, and each coupled to a computer system bus.

[0037] The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct more specialized apparatus to perform the required method steps. The required structure for a variety of these systems will appear from the description below. In addition, the present invention is not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the invention as described herein.

Introduction

[0038] A system design and process that allows the operation of iterative receiver structures for coded OFDM/MIMO/QAM systems with BICM are described. In one embodiment, the receivers have an inner/outer decoder structure, whereby multiple iterations are performed in decoding following the turbo decoding principle. As the complexity of these structures is dominated by the inner decoder, any existing soft-output channel decoder can be employed, for example, optimal (MAP), or near-optimal (e.g., MaxLogMAP) receivers. However, as described in greater detail below, the inner decoder structure has the ability to adapt and optimize its performance at each iteration, subject to the inherent receiver constraints on computational complexity.

[0039] In one embodiment, the receiver structure falls within the class of receivers that can be represented in the block diagram form shown in Figure 2. The receiver may include OFDM front-end on each receive antenna and iterative decoding between an inner demapper and an outer channel decoder. One embodiment of the inner demapper structure that may be utilized in this OFDM setting is further detailed in Figure 3. As Figures 2 and 3 illustrate, during any given iteration of the decoding operation, there is one demapping (inner-decoding) operation performed on each OFDM tone in the system.

[0040] Figure 2 illustrates a general decoding structure that includes an inner decoder (MIMO demapper 220) that provides demodulation of the parallel received signal. The demodulated signal is converted to a serial signal by parallel to serial converter 230. The serial signal is deinterleaved by deinterleaver 240 and sent to an outer decoder (MAP 250). The decoded signal may be interleaved by interleaver 260 and converted to a parallel signal by serial to parallel converter 270.

[0041] Figure 3 is a block diagram of one embodiment of joint demapper units for a receiver in a single-user MIMO system based on OFDM. In one embodiment, N_t receive antennae 310 may receive OFDM signals from a transmitting device (not illustrated in Figure 3). The parallel received signals, labeled observed vectors (y) 320, are provided to parallel MIMO demappers 330. As described in greater detail below, MIMO demappers 330 may receive extrinsic (e.g., reliability) information from an outer decoder. This information may be utilized to control SOMA tree search parameters. The output from MIMO demappers 330 is provided to serial to parallel converter 340. Output form serial to parallel converter 340 is provided to an outer decoder as soft output estimates.

[0042] The architecture described herein provides performance improvements when iterative decoding is used. This may be accomplished by exploiting, at the inner decoder module, information provided by the outer decoder module in order to adaptively optimize the linear front-end, the SOMA tree, and the symbol order selected for the SOMA tree search in the inner decoder module. In one embodiment, the front end is affine. In one embodiment, the linear front-end filters the measurements in such a way that allows the computation of the soft-output values for the inner decoding module on a tree with N levels, where N is the number of symbols (or symbol streams) simultaneously transmitted in this MIMO system and satisfies $N=N_t$.

[0043] The computation outcome at any given node at full depth of the tree provides a reliability metric for a specific codeword, where a codeword is a specific combination of values for the N transmitted symbols. In one embodiment, together with the linear front-end filtering operation, the module also selects a SOMA tree together with a specific symbol order based on which the metric computations will be performed on a tree by use of a soft-output M-algorithm.

[0044] In one embodiment, at depth one, partial metrics are computed for partial codewords depending only on the first-ordered symbol. A subset (e.g., the "best M") of these metrics are used at depth two to compute new partial metrics for all combinations of the associated first-ordered symbol values with all second-ordered symbol values. In one embodiment, this process is repeated until at the full depth N in the tree is reached, at which point path metrics have been computed for a subset of all possible full-length codewords. This technique controls operation of the front-end filter and chooses the way the SOMA tree is constructed and the symbol order for the tree search so as to optimize the performance of the SOMA-based inner decoder. The overall system decoding performance is thus optimized by the choice of the linear front-end and of the decoding order.

[0045] In one embodiment, at each iteration and on each OFDM tone, the following is used as an input: 1) a receive vector including measurements collected by the receiver antennas on the given OFDM tone; 2) channel coefficients between transmit and receive antennas; and 3) output information provided by the outer decoder about the reliability of the bits comprising the symbols in the codewords for which the inner decoder is to produce soft output.

[0046] The linear front-end can then be selected. One embodiment of this process is illustrated in Figure 5, which is an expansion of the Front-End module in Figure 4. A more detailed description of the front end is given in Figure 6 and may provide the following combination of principles: 1) obtain mean and variance estimate of each symbol in the codeword based on use of the output information from the outer decoder; use this mean estimate and the channel coefficients to subtract the mean contribution from the OFDM tone; 2) compute the conditional linear Mean-Square error (LMSE) based on the OFDM tone and the channel coefficients; 3) in an iterative manner select a symbol order and obtain a corresponding QR decomposition; 4) use the resulting QR decomposition on the measurements to setup the soft-output computation as a tree; and 5) perform a limited-tree search by means of a soft-output M-algorithm in order to generate soft-output information. In one embodiment, the parameters in the soft-output M-algorithm may also be adapted with iterations and with tree depth. In one embodiment, even if the chosen order for the tree is the same between iterations, the method for construction the three and the tree itself changes with each iteration.

[0047] In one embodiment, the front-end operations to the SOMA search 1) – 4) listed above, allow these receiver structures to yield bit-error rate performance that improves with increasing number of iterations and gracefully degrades as the M values in the M-algorithm are reduced. In addition, the architectures described herein implicitly make good use of the information provided by the outer decoder regarding the reliability of each symbol, and combine it with the measurement and channel state information to construct the tree together with the tree-search order and the branch metric computations in a systematic manner.

[0048] The description that follows focuses on the description of the inner decoding module (inner demapper) on an arbitrary but fixed OFDM tone (i.e., the description of one of the inner decoding modules shown in Figure 3). Note that, as shown in Figures 1 and 3, there are N_t transmit antennas and N_r receive antennas in the system.

[0049] Figure 4 is a flow diagram of one embodiment of a MIMO demapper operation on a sample OFDM tone n. This may be performed by the MIMO demapper illustrated in Figure 2 or Figure 3, for example, and in that case F decoding operations of the form shown in Figure 4 are applied in parallel, one for each subchannel/tone n. In one embodiment, for the first iteration (k=1) 410, the front end utilizes channel information (H) on the given tone n for the iteration, extrinsic information from the previous decoding iteration on the symbols transmitted on the given tone n and the received signal on tone n to calculate a front end value for the current iteration, 420. In one embodiment the front end value is a signal estimate described in greater detail below. The front end value is used as an input to the SOMA stage 430. SOMA is performed on the iteration 440 to generate at least reliability information for symbols on the current tone. This reliability information is collected over all tones for the given iteration, it is then deinterleaved via module 240, and is then sent to an outer decoder 250. In the next iteration, the output of the outer decoder is then re-interleaved via module 260 and used to provide the input extrinsic information for each tone demapper for the next iteration. Note that, during any given (and fixed) iteration, the F demmaping operations 420 in Figure 4 can be performed in series or in parallel.

[0050] Figure 5 is a block diagram of one embodiment of a front end. The block diagram of Figure 5 provides an expansion of the front end of Figure 4 and its interaction with the SOMA decoder. In one embodiment, for any given tone the front end receives an observed received signal vector (y), extrinsic information, $L_a(b,k)$, at each iteration and a matrix of channel coefficients, H all pertinent to that tone.

[0051] In one embodiment, for each symbol of the tone, the front end selects a conditional MMSE filter 510 based on y, $L_a(b,k)$, and H. The front end uses y, $L_a(b,k)$, and the selected conditional MMSE filter to create signal estimates 520 (filtered signal estimates). In one embodiment, the front end also creates a modified QR decomposition and/or selects the symbol order for the SOMA tree and the SOMA tree itself, using the selected MMSE filter 540. In one embodiment, the front end may process the extrinsic information, $L_a(b,k)$, to generate modified bit priors 530.

[0052] The front end provides the modified bit priors, the filtered signal estimates and/or subspaces and order (to define the SOMA tree), to the SOMA decoder 550. In one embodiment, the SOMA decoder 550 provides a soft output estimate for the current iteration.

[0053] Figure 6 is a block diagram of one embodiment of an inner demapper structure. This inner demapper may be the MIMO demapper for subchannel n illustrated in Figure 3. The inner demapper takes as input an $N_r \times 1$ vector of observations **y**, corresponding to the N_r (complex-valued) scalar measurements collected across all N_r receive antennas on the given OFDM tone. These measurements are related to the $N_t \times 1$ vector

$$\mathbf{s} = [s_1\ s_2 \ldots s_N]^T,$$

representing the $N=N_t$ QAM symbols transmitted by the N_t transmit antennas on the given OFDM tone as follows:

$$\mathbf{y} = \mathbf{H}\,\mathbf{s} + \mathbf{w}\,.$$

[0054] The $N_r \times 1$ vector **w** represents the effects of noise and interference on each of the N_r receive antennas, and **H** is a matrix with dimensions $N_r \times N_t$. The entry of **H** on the i-th row and the j-th column equals the channel (complex-valued) scaling coefficient (on the given OFDM tone) between the j-th transmit antenna and the i-th receive antenna. As shown in Figure 6, the inner decoder also takes as input the channel coefficient matrix **H**. An estimate of the channel coefficient matrix **H** is obtained at the receiver via pilot-assisted channel estimation, i.e., by signaling known signals (pilots) for **s** and using the resulting observation vector **y** at the receiver for channel estimation in a manner well known in the art.

[0055] Each of the $N_t=N$ QAM symbols, $s_1\, s_2 \ldots s_N$, can take one of Q possible complex values, with $Q=2^B$, and where B denotes the number of bits per QAM symbol. Let also

$$\mathbf{b}_k = [b_k^1\; b_k^2 \ldots b_k^B]$$

denote the set of B bits that are mapped to the QAM symbol s_k at the transmitter. Let also the $BN_t \times 1$ vector

$$\mathbf{b} = [\mathbf{b}_1\; \mathbf{b}_2 \ldots \mathbf{b}_N]^T$$

denote the collection of all the bits encoded on the given OFDM tone (and thus representing the QAM symbol vector **s**).

[0056] As shown in Figure 6, in one embodiment, at the k-th iteration the inner decoder also takes as input, extrinsic information produced by the outer decoder on the previous iteration, about the reliability of each bit in the vector **b**. This quantity is summarized by the $BN_t \times 1$ vector $\mathbf{L}_a(\mathbf{b};k)$. The i-th entry of this vector is an estimate of the reliability of the estimate of the i-th entry of the vector **b,** produced as output by the channel decoder on the preceding iteration. These reliability quantities are log-likelihood ratio estimates for each of the bits comprising the vector **b**. In one embodiment, on the first iteration, the entries of $\mathbf{L}_a(\mathbf{b};k)$ are initialized to the value 0.

[0057] The output of the decoder in Figure 6 is a $BN_t \times 1$ vector $\mathbf{L}(\mathbf{b};k)$, which contains new reliability values for the bits in the vector **b**. One embodiment for generation of this vector $\mathbf{L}(\mathbf{b};k)$ is produced at each iteration k is shown schematically in Figure 6.

[0058] In one embodiment, the extrinsic information vector $\mathbf{L}_a(\mathbf{b};k)$ is used to produce estimates of the conditional mean and variance of the QAM symbols comprising the vector **s**. To this end "priors" are first generated for each of the bits in the vector **b** based on the log-likelihood information $\mathbf{L}_a(\mathbf{b};k)$ (input to the inner decoder on the k-th iteration). The discounting factor function F_1 is an odd-valued function for which $0 \le F_1(x) < x$ for all $x>0$, and has the effect of making the bit priors produced by $\mathbf{L}_a(\mathbf{b};k)$ more robust. In one embodiment, $F_1(x) = f_1\, x$, with $0 \le f_1 < 1$. The resulting bit priors for the set of bits $\mathbf{b}_n$ comprising the QAM symbol s_n implicitly produce a prior distribution for QAM symbol s_n (n-th entry of the vector **s**) and are used to compute the mean (denoted via $\bar{s}_n[k]$) and the standard deviation (denoted via $d_n[k]$) of s_n with respect to this prior distribution.

[0059] Next, the conditional MMSE filter is designed, 610. First let $\mathbf{C}[k]$ denote the $N_t \times N_t$ diagonal matrix whose i-th entry on the diagonal equals the inverse of $d_i[k]$. Then the conditional MMSE filter $\mathbf{W}[k]$ is given by

$$\mathbf{W}[k] = [\mathbf{H}^{H}\,\mathbf{H} + N_o\,\mathbf{C}^2[k]]^{-1}\,\mathbf{H}^{H}$$

As the above equation for generating $\mathbf{W}[k]$ suggests, the filter $\mathbf{W}[k]$ on the specific tone, in general, changes with iterations. In particular, note that, although the channel term **H** on the tone stays fixed with iteration index "k", **W**[k] changes with "k" through **C**[k], which captures the effect of the extrinsic information on the symbols on iteration "k".

[0060] The scalar number N_o represents the effective power of noise and interference in each of the entries of the interference vector **w**, while the superscript ^{H} denotes the Hermitian (conjugation and transposition) operation. In addition an augmented matrix $\mathbf{G}[k]$ is constructed by the module as follows:

$$\mathbf{G}[k] = \begin{bmatrix} \mathbf{H}[k] \\ \sqrt{N_o}\,\mathbf{C}[k] \end{bmatrix}.$$

[0061] The matrix $\mathbf{W}[k]$ produced by the MMSE filter design module 610 is provided as input to the MMSE filleting module 620. The MMSE filter module 620 then produces as its output an $N_t \times 1$ vector $\hat{\mathbf{s}}[k]$, which is a linear soft estimate of the vector $\tilde{\mathbf{s}}[k] = \mathbf{s} - \bar{\mathbf{s}}[k]$ as follows:

$$\hat{\mathbf{s}}[k] = \mathbf{W}[k](\mathbf{y} - \mathbf{H}\bar{\mathbf{s}}[k]).$$

As discussed above, the linear soft estimate above changes as a function of iteration "k" via the extrinsic information provided by the outer decoder on the coded bits on the given tone on iteration "k", through **W**[k] and $\bar{s}[k]$ above.

[0062] In one embodiment, the QR decomposition block 630 takes as input the augmented matrix $\mathbf{G}[k]$ produced by the MMSE filter module 610. The QR decomposition module 630 then generates as its output a good symbol order $\boldsymbol{\pi}[k] = [\boldsymbol{\pi}_1[k]\ \boldsymbol{\pi}_2[k] \ldots \boldsymbol{\pi}_N[k]]$ for the SOMA tree search, 640, along with a lower triangular $N_t \times N_t$ matrix $\mathbf{R}[k]$ (i.e., a matrix whose entry on the i-th row and the j-th column equals zero if i<j). The vector $\boldsymbol{\pi}[k]$ is a permutation of the integers 1, 2, …, N, (with N=N_t). Its n-th element, i.e., $\boldsymbol{\pi}_n[k]$, denotes that symbol s_m is the n-th symbol in the tree-search (i.e., the symbol introduced in the search at depth n), and where m=$\pi_n[k]$.

[0063] Given a symbol order $\boldsymbol{\pi}$, let $\mathbf{s}_\pi$ denote the $N \times 1$ vector whose n-th entry is s_m for $m=\pi_n$. We also let $\mathbf{P}_\pi$ denote the permutation matrix associated with a given order $\boldsymbol{\pi}$. Specifically, $\mathbf{P}_\pi$ is the $N_t \times N_t$ permutation matrix with the following property: the vector resulting by multiplying $\mathbf{s}$ from the left with $\mathbf{P}_\pi$ (i.e. the vector $\mathbf{P}_\pi\mathbf{s}$) equals $\mathbf{s}_\pi$, i.e., $\mathbf{P}_\pi\mathbf{s}=\mathbf{s}_\pi$. At the k-th inner decoder iteration, the QR decomposition box 630 produces such a symbol-order $\boldsymbol{\pi}[k]$ (or equivalently a permutation matrix $\mathbf{P}[k]=\mathbf{P}_{\pi[k]}$) and a corresponding $N \times N$ lower triangular matrix $\mathbf{R}[k]$ from the QR decomposition associated with this order.

[0064] For illustration, when the symbol order is the natural order $\boldsymbol{\pi}[k]$=[1 2 … N] (in which case $\mathbf{P}[k]$ is the identity matrix), the resulting $\mathbf{R}[k]$ is the lower triangular matrix associated with the QR decomposition of $\mathbf{G}[k]$, i.e., the QR decomposition module 630 finds a unitary $\mathbf{Q}$[k] and a lower triangular $\mathbf{R}$[k], such that $\mathbf{G}[k] = \mathbf{Q}[k]\mathbf{R}[k]$. For the case that $\boldsymbol{\pi}[k]$ equals some arbitrary but fixed symbol order $\boldsymbol{\pi}$, the matrix $\mathbf{R}[k]$ is the lower triangular matrix in the QR decomposition of the matrix that is the product $\mathbf{G}[k]\ (\mathbf{P}_\pi)^T$, i.e., the QR decomposition module finds a unitary $\mathbf{Q}[k]$ and a lower triangular matrix $\mathbf{R}[k]$, such that

$$\mathbf{G}[k]\ (\mathbf{P}[k])^T = \mathbf{Q}[k]\mathbf{R}[k], \qquad \text{Eqn (1)}$$

and where $\mathbf{P}[k] = \mathbf{P}_{\pi[k]}$ and the superscript T denotes transposition.

[0065] In one embodiment, the order π[k] is selected by the QR decomposition module 630. In one embodiment, a random order is selected. In another embodiment, the order is selected recursively by adding one symbol at the time in the order. To select the first symbol in the order, each symbol is considered as being the first symbol in the order. Then the QR decomposition and the magnitude of the (1,1) entry in the associated $\mathbf{R}[k]$ matrix is computed for each choice of a "first symbol in the order".

[0066] The symbol choice yielding the highest magnitude (1,1) entry is chosen as the first symbol index in the order. The process is repeated to add the rest of the symbols in the symbol order recursively. Given that the n first symbols have been selected, each of the remaining *N-n* symbols is considered as the next symbol in the symbol-order. The magnitude of the $(n+1,n+1)$ entry in the resulting $\mathbf{R}[k]$ from the associated QR decomposition is computed for each choice of next symbol in the order. These magnitudes are then compared and the symbol yielding the largest magnitude is chosen as the next symbol in the order. When the process is completed and the order $\pi[k]$ (or, equivalently, $\mathbf{P}[k]$) is produced, then the associated $\mathbf{R}[k]$ is computed from Eqn. (1) and provided as input to the soft-output algorithm component 640.

[0067] Another component in the inner-decoder module is a controlled tree-search soft-output M-algorithm module 640. The algorithm takes as input a set of symbol priors, a symbol order $\pi[k]$ and an associated lower triangular matrix $\mathbf{R}[k]$, a linear MMSE estimate $\hat{\mathbf{s}}[k]$, the mean vector $\bar{\mathbf{s}}[k]$, and the standard deviation vector $\mathbf{d}[k]$.

[0068] The set of priors that are inputs to the algorithm are produced by a discount-factor function F_2 that operates in a manner similar to F_1 (660). The discounting factor function F_2 (665) is also an odd-valued function for which $0<F_2(x) \leq x$ for all $x>0$, and has the effect of making the bit priors produced by $\mathbf{L}_a(\mathbf{b};k)$ more robust. In one embodiment, $F_2(x) = f_2\, x$, with $0 < f_2 \leq 1$.

[0069] In one embodiment, a set of equations may be used to set up the SOMA tree search at the *k*-th iteration assuming the symbol-order in the tree search is the natural order $\pi[k] = [1\ 2\ \ldots\ N]$. The set of equations in the general case involving a general $\pi[k]$, can be obtained from the natural-order algorithm by replacing s_i, $\hat{s}_i$, $\bar{s}_i$, d_i, $\mathbf{b}_i$ with s_m, $\hat{s}_m$, $\bar{s}_m$, d_m, $\mathbf{b}_m$ and where $m = \pi_i[k]$. To describe the tree on which the limited search will be performed by the soft-output M-algorithm, it is convenient to consider the operation of the exhaustive MaxLogMAP algorithm in the *k*-th iteration and express it as an exhausted tree-search computation. This MaxLogMAP algorithm computes for all values of m and n (i.e., all choices of m and n integers such that $1 \leq m \leq N$ and $1 \leq n \leq B$), the following log-likelihood ratio values

$$L(b_m^n) = ll_o(b_m^n = 1; k) - ll_o(b_m^n = 0; k)$$

where

$$ll_o(b_m^n = u; k) = \max_{\mathbf{s}:\mathbf{b}(\mathbf{s}) \in B_u^{m,n}} -\|\mathbf{y} - \mathbf{Hs}\|^2 / N_o + ll_a(\mathbf{b}(\mathbf{s}); k) = -\min_{\mathbf{s}:\mathbf{b}(\mathbf{s}) \in B_u^{m,n}} \left[\|\mathbf{y} - \mathbf{Hs}\|^2 / N_o - ll_a(\mathbf{b}(\mathbf{s}); k)\right]$$

and where $ll_a(\mathbf{b}(\mathbf{s}); k)$ are the log-likelihood priors at the k-th iteration, i.e., the output of the discount factor function F_2, on the k-th iteration.

[0070] In computing $ll_o(b_m^n = u; k)$, for u=0, 1, the following representation can be exploited:

$$\begin{aligned}
-N_o ll_o(b_m^n = u; k) &= \min_{\mathbf{s}:\mathbf{b}(\mathbf{s}) \in B_u^{m,n}} \|\mathbf{y} - \mathbf{Hs}\|^2 - N_o\, ll_a(\mathbf{b}(\mathbf{s}); k) \\
&= C + \min_{\mathbf{s}:\mathbf{b}(\mathbf{s}) \in B_u^{m,n}} \left\|\mathbf{R}[k]\left(\hat{\mathbf{s}}[k] - (\mathbf{s} - \bar{\mathbf{s}}[k])\right)\right\|^2 - \|\mathbf{C}[k](\mathbf{s} - \bar{\mathbf{s}}[k])\|^2 - N_o ll_a(\mathbf{b}(\mathbf{s}); k) \\
&= C + \min_{\mathbf{s}:\mathbf{b}(\mathbf{s}) \in B_u^{m,n}} \sum_{i=1}^{N} \left(\left| \mathbf{R}_{ii}[k]\left(\hat{s}_i[k] - (s_i - \bar{s}_i[k])\right) + \sum_{1<j<i} \mathbf{R}_{ij}[k]\left(\hat{s}_j[k] - (s_j - \bar{s}_j[k])\right) \right|^2 - N_o \frac{|s_i - \bar{s}_i[k]|^2}{d_i^2[k]} - N_o ll_a(\mathbf{b}_i(s_i); k) \right)
\end{aligned}$$

This is the set of equations based on which the SOMA tree, along with its branch metric computations is defined for the given symbol order. To see how the tree is defined, consider the last equation above. Note that on the reduced tree search, the "min" operation listed happens over a subset of all paths i.e., not for all paths. For each such path considered by the "min" operation, in full length on the tree we would compute the big outer sum. The index "i" in that sum reflects the depth in the tree. The ith term in the sum shows the branch metric computed at depth "i" for that path. As the equation reveals, this ith term depends only on symbols 1,2,…i , i.e., only on the part of the path through the tree so far up to depth i. On the tree at depth "i", this branch metric would be first computed and then added to the partial path metric so far, that is, the sum of all branch metrics 1 to i-1 (already computed at the previous depth for this path), in order to produce the metric of the partial path up to depth i. Note that at full length, N, the path metric gives the whole sum from 1 to N.

Note also that even if the symbol order is kept the same on a tone from one iteration to the next, the decomposition of the computations on the tree can be different.

[0071] In the above representations, the constant C does not depend on $\mathbf{s}$. If the above representation is used to conduct the exhaustive MaxLogMAP computation, the metrics that are computed for each vector candidate **s** can be computed on a tree. Indeed, the metric for a specific value of the codeword **s** can be computed as the sum of N "branch" metrics, whereby the mth metric depends only in the first m elements of **s.** T

[0072] This tree is thus the tree used for conducting the reduced-search on the tree via a soft-output M-algorithm. Note that the above approach can be used with any soft-output M-algorithm structure. For instance, it can be used in conjunction with soft-output M-algorithms that use *a priori* chosen M values, and the M value can be potentially different from one depth level in the tree to the next and from one iteration to the next. In another embodiment, channel-adaptive SOMA implementations are used, where channel knowledge at the receiver is exploited to choose the M value adaptively over tones, iterations, and tree depth. In addition, in each case one may employ forward-pass only SOMA algorithms, or forward-backward pass soft-output algorithms.

[0073] A class of embodiments involves the following choice for the discount factor functions $F_k(x) = f_k x$, with $0 \leq f_1 < 1$ and $0 < f_2 \leq 1$. In one embodiment, f_1=0. In this case, the MMSE filter, the QR decomposition, the symbol order on the tree, and thus the tree on which the tree-search takes place do not change from iteration to iteration. As a result, there are no more front-end computations after the first iteration. The only component changing in the operation of the inner decoder in subsequent iterations is the priors provided by the outer decoder. When f_1=1, these are used in the SOMA algorithm in the standard practice without discounting.

[0074] Another embodiment involves the case where an f_1 is used satisfying $0< f_1 <1$, and where f_2=1. In that case "conservative" priors are used for forming the conditional mean and conditional variance estimates (the smaller the f_1 value used the higher the degree of conservatism). In this case the MMSE filter, the QR decomposition, the symbol order on the tree, and thus the tree on which the tree-search takes place do change from iteration to iteration. Yet another preferred embodiment involves the case where an f_1 is used satisfying $0<f_1<1$, and whereby and where $f_2=f_1$. In that case, the same "conservative" priors used for computing the conditional mean and variance are also used in the SOMA tree-search.

[0075] Another embodiment involves the use of a simplified conditional-variance computation. In particular, in this embodiment a vector $\mathbf{d}[k]$ is generated by the inner decoder with all-equal entries, i.e., a vector of the form $\mathbf{d}[k] = [d[k]\ d[k]\ \ldots\ d[k]]^T$ is produced by the module computing it. The advantage of this scheme is in the computations needed to generate the MMSE filter used for each iteration. Specifically, in computing the MMSE filter a computation of the inverse of a matrix is only required on the first operation. In subsequent operations, the new MMSE filter can be computed by means of simply updating the MMSE filter from the previous iteration (i.e., without computing the inverse of a new matrix). An alternative interpretation can be obtained by considering the eigenvalue decomposition of $H^H H = V\Lambda V^H$, where $\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_N]$ is a unitary matrix and $\mathbf{\Lambda}$ is a diagonal matrix $\mathbf{\Lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \ldots, \lambda_N)$, with $\lambda_k \geq 0$. In this case the MMSE filter at the k-th iteration can be expressed as

$$\mathbf{W}[k] = (\textstyle\sum_{1\leq i\leq N} \rho_i[k]\ \mathbf{v}_i\ \mathbf{v}_i^H)\mathbf{H}^H,$$

with $\rho_i[k] = 1/(\lambda_i + d^2[k]N_o)$. Once the eigen-decomposition of $H^H H$ is computed (which in a computational sense is equivalent to a matrix-inversion computation) all the MMSE filters can be computed without requiring any more eigen-decompositions or matrix inversions. In one variation of this embodiment, the QR decomposition module outputs the same symbol order $\boldsymbol{\pi}[k] = \boldsymbol{\pi}[1]$ for all iterations, but a new $\mathbf{R}[k]$ is recomputed for each k, based on the associated $\mathbf{G}[k]$.

[0076] Several simplified versions of the QR decomposition module can be constructed. In one case, the symbol order $\boldsymbol{\pi}[k]$ is not updated at every iteration, but every K iterations, for some $K>1$. The associated lower triangular matrix $\mathbf{R}[k]$ is recomputed by the QR decomposition module for each new choice of $\mathbf{W}[k]$. In one special case of interest, the decoder uses $K \rightarrow \infty$. In that case the same symbol order $\boldsymbol{\pi}[1]$, computed on the first iteration, is subsequently used for all iterations.

[0077] In one embodiment, the symbol order $\boldsymbol{\pi}[k]$ and the associated $\mathbf{R}[k]$ (computed by the QR decomposition module, and the filter $\mathbf{W}[k]$ (computed by the

MMSE filter design module) are updated every K iterations. In another embodiment, the $\mathbf{d}[k]$ estimate vector produced by the QAM Priors Computation module 670 is set at iteration k to the same value as $\mathbf{d}[k-1]$, unless a sufficient change in the elements from iteration k-1 to iteration k has been recorded. Thus, computation complexity reduction may be accomplished, since in the event that $\mathbf{d}[k] = \mathbf{d}[k-1]$, the MMSE filter calculation and QR decomposition computations stay the same at iteration k.

[0078] The examples that follow provide a number of embodiments involving the operation of the SOMA module in the inner decoding module. One embodiment uses the variance estimate, $(d_m[k])^2$, as an indicator of the reliability of the m-th symbol at iteration k, as a method of tailoring the complexity of the search associated with that symbol in the SOMA tree. In one extreme, a symbol with sufficiently low variance estimate can be viewed as a symbol that can be decoded correctly with very high probability and can then be "cancelled/subtracted off" from the aggregate signal. The resulting "N-1"-level problem can be then treated as in the preceding embodiments.

[0079] In one embodiment, parts of the adaptivity may be selectively updated on a tone-by-tone basis on each iteration. In one embodiment, the front-end and tree decomposition updates for tones may be performed only when there is a sufficiently large change in extrinsic information from the previous iteration. For instance for those tones for which there is a small change in the extrinsic information from iteration "k" to iteration "k+1", the tree decomposition shown in the equation set above from k=k may be used. Specifically, the last equation shown in paragraph 0066 also describes the tree decomposition for iteration "k+1" on those tones, provided $ll_{\mathrm{a}}(\cdot, \mathrm{k})$ is changed to $ll_{\mathrm{a}}(\cdot, \mathrm{k+1})$.

[0080] In one embodiment, if the "prior" reliability for a given bit (i.e., the associated discounted soft-output from the outer decoder) is above a given threshold value, the bit can be viewed as one that can be decoded correctly with very high probability. In that case, the SOMA tree search can be simplified (without appreciable loss in performance) at the three depth at which the QAM symbol associated with the given bit is considered. Specifically, at that depth, only candidates for which the associated QAM symbol takes values in agreement to the most likely value for the given bit are considered and expanded/evaluated on the tree.

An Example of a System

[0081] Figure 7 is a block diagram of one embodiment of an electronic (e.g., computer) system that may include a MIMO decoder as described herein. Referring to Figure 7, computer system 700 may comprise an exemplary client or server computer system. Computer system 700 comprises a communication mechanism or bus 711 for communicating information, and a processor 712 coupled with bus 711 for processing information. Processor 712 includes a microprocessor, but is not limited to a microprocessor, such as, for example, Pentium™, PowerPC™, Alpha™, etc.

[0082] System 700 further comprises a random access memory (RAM), or other dynamic storage device 704 (referred to as main memory) coupled to bus 711 for storing information and instructions to be executed by processor 712. Main memory 704 also may be used for storing temporary variables or other intermediate information during execution of instructions by processor 712.

[0083] Computer system 700 also comprises a read only memory (ROM) and/or other static storage device 706 coupled to bus 711 for storing static information and instructions for processor 712, and a data storage device 707, such as a magnetic disk or optical disk and its corresponding disk drive. Data storage device 707 is coupled to bus 711 for storing information and instructions.

[0084] Computer system 700 may further be coupled to a display device 721, such as a cathode ray tube (CRT) or liquid crystal display (LCD), coupled to bus 711 for displaying information to a computer user. An alphanumeric input device 722, including alphanumeric and other keys, may also be coupled to bus 711 for communicating information and command selections to processor 712. An additional user input device is cursor control 723, such as a mouse, trackball, trackpad, stylus, or cursor direction keys, coupled to bus 711 for communicating direction information and command selections to processor 712, and for controlling cursor movement on display 721.

[0085] Another device that may be coupled to bus 711 is hard copy device 724, which may be used for marking information on a medium such as paper, film, or similar types of media. Another device that may be coupled to bus 711 is a wired/wireless communication capability 725 to communication to a phone or handheld palm device.

[0086] A machine-readable medium includes any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computer). For example, a machine-readable medium includes read only memory ("ROM"); random access memory ("RAM"); magnetic disk storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other form of propagated signals (e.g., carrier waves, infrared signals, digital signals, etc.); etc.

[0087] Note that any or all of the components of system 700 and associated hardware may be used. However, it can be appreciated that other configurations of the computer system may include some or all of the devices.

[0088] Whereas many alterations and modifications of the present invention will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that any particular embodiment shown and described by way of illustration is in no way intended to be considered limiting. Therefore, references to details of various embodiments are not intended to limit the scope of the claims which in themselves recite only those features regarded as essential to the invention.

CLAIMS

We claim:

1. A receiver for use in an orthogonal frequency division multiplexing (OFDM) wireless communication system to receive signals from a transmitter that transmits the signals using OFDM and bit interleaved coded modulation, the receiver comprising:

an inner decoder structure having an adaptive front end, the inner decoder communicatively coupled to receive extrinsic information, the adaptive front end to utilize the extrinsic information from one or more prior decoder iterations and channel information corresponding to a portion of the received signals, to generate one or more filtered signal estimates, and to receive the one or more filtered signal estimates, the inner decoder having a soft output M-algorithm (SOMA) based multiple-in multiple-out (MIMO) demapper that utilizes the one or more filtered signal estimates to perform inner demapping over each tone; and

an outer decoder communicatively coupled with the inner decoder to perform iterative decoding and to provide extrinsic information related to the iterative decoding to the adaptive front end.

2. A method for iterative decoding of orthogonal frequency division multiplexing (OFDM) wireless signals received from a transmitter that transmitted the signals using OFDM and bit interleaved coded modulation, the method comprising:

determining channel coefficients corresponding to the signals;

receiving extrinsic information from one or more prior decoding iterations;

generating one or more filtered signal estimates based, at least in part, on the extrinsic information;

performing a SOMA-based multiple-input/multiple-output (MIMO) detection process over each tone of the signals by searching a detection tree for each tone, where tree search parameters are selected based on the one or more filtered signal estimates and at least in part on the extrinsic information.

3. An apparatus for decoding orthogonal frequency division multiplexing (OFDM) wireless signals received from a transmitter that transmitted the signals using OFDM and bit interleaved coded modulation, the apparatus comprising:

means for determining channel coefficients corresponding to the signals;

means for receiving extrinsic information from one or more prior decoding iterations;

means for generating one or more filtered signal estimates based, at least in part, on the extrinsic information;

means for performing a SOMA-based multiple-input/multiple-output (MIMO) detection process over each tone of the signals by searching a detection tree for each tone, where tree search parameters are selected based on the one or more filtered signal estimates and at least in part on the extrinsic information.

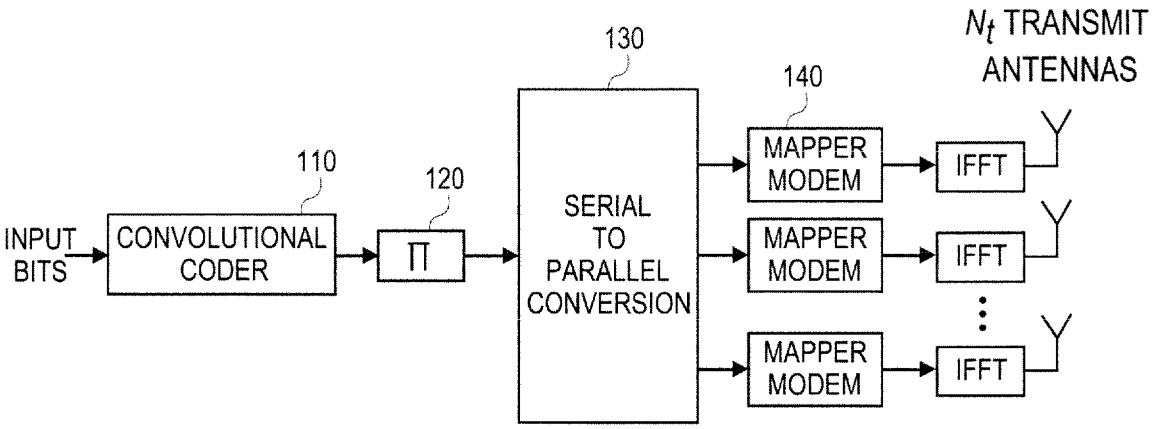
N_t TRANSMIT ANTENNAS
130
140
110
120
INPUT BITS
CONVOLUTIONAL CODER
Π
SERIAL TO PARALLEL CONVERSION
MAPPER MODEM
MAPPER MODEM
MAPPER MODEM
IFFT
IFFT
IFFT

FIG. 1

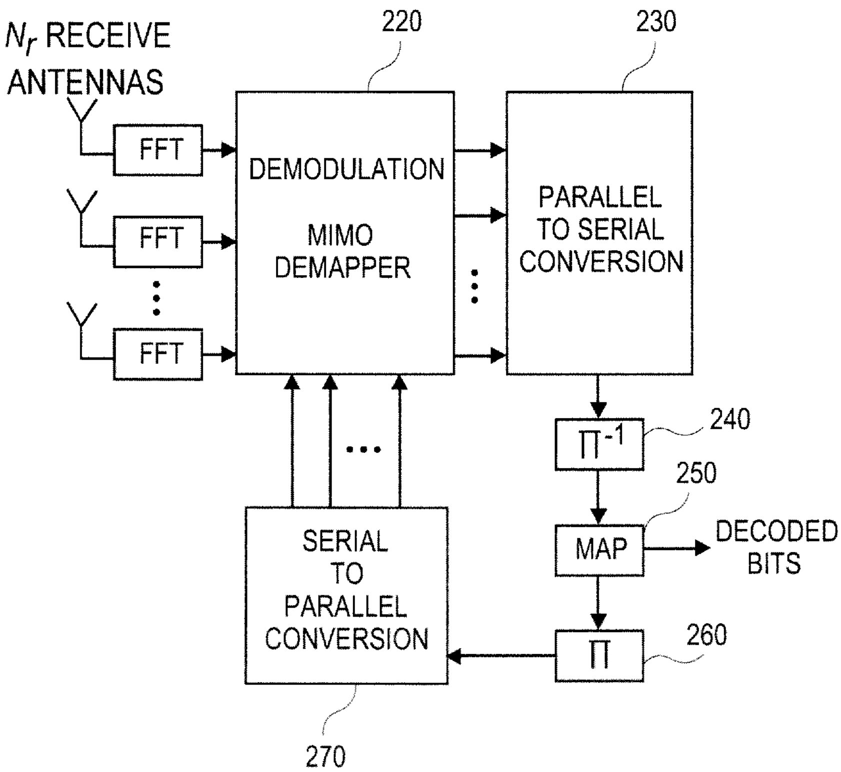
N_r RECEIVE ANTENNAS
220
230
FFT
FFT
FFT
DEMODULATION
MIMO DEMAPPER
PARALLEL TO SERIAL CONVERSION
$Π^{-1}$
240
250
MAP
DECODED BITS
Π
260
SERIAL TO PARALLEL CONVERSION
270

FIG. 2

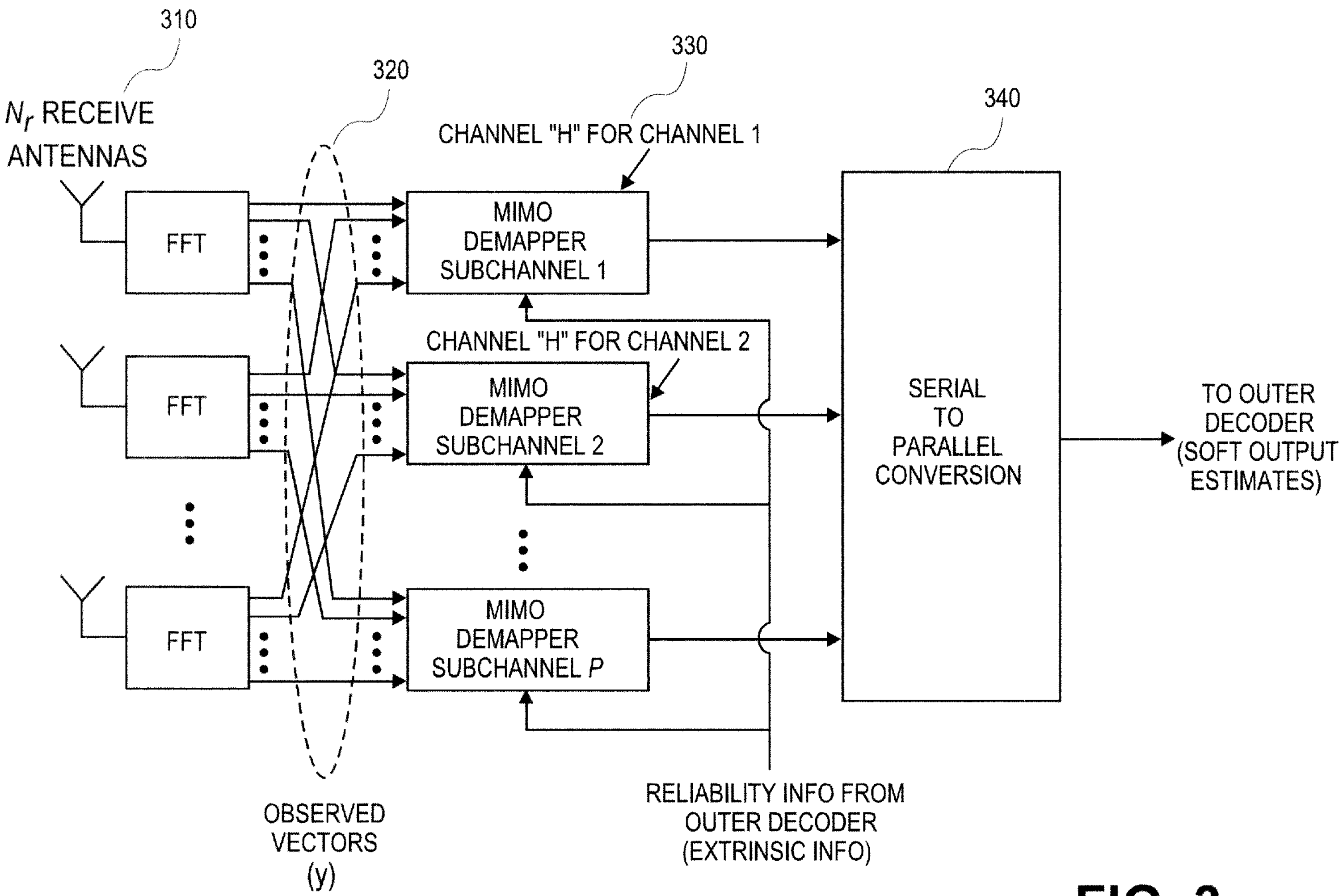
310
320
330
340
N_r RECEIVE ANTENNAS
FFT
FFT
FFT
CHANNEL "H" FOR CHANNEL 1
MIMO DEMAPPER SUBCHANNEL 1
CHANNEL "H" FOR CHANNEL 2
MIMO DEMAPPER SUBCHANNEL 2
MIMO DEMAPPER SUBCHANNEL P
SERIAL TO PARALLEL CONVERSION
TO OUTER DECODER (SOFT OUTPUT ESTIMATES)
OBSERVED VECTORS (y)
RELIABILITY INFO FROM OUTER DECODER (EXTRINSIC INFO)

FIG. 3

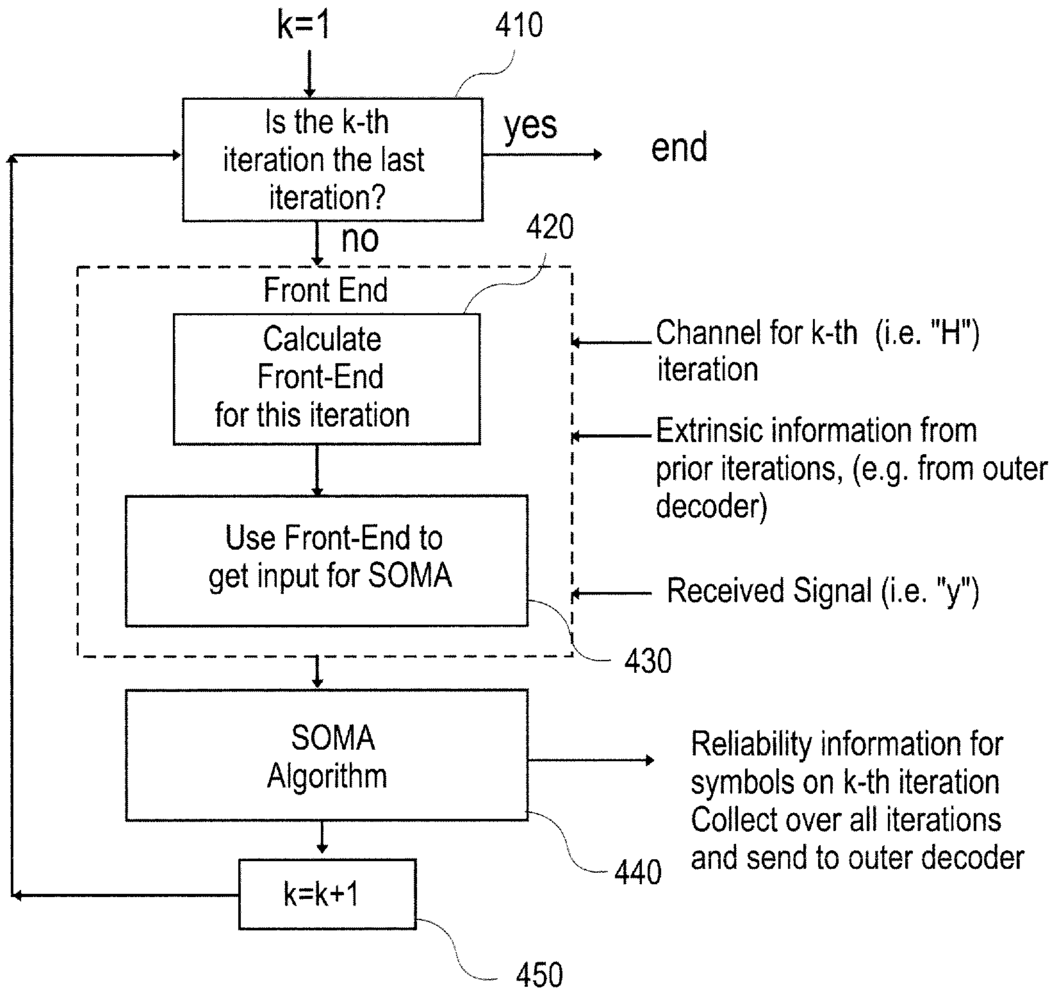
k=1
410
Is the k-th iteration the last iteration?
yes
end
no
420
Front End
Calculate Front-End for this iteration
Channel for k-th (i.e. "H") iteration
Extrinsic information from prior iterations, (e.g. from outer decoder)
Use Front-End to get input for SOMA
Received Signal (i.e. "y")
430
SOMA Algorithm
Reliability information for symbols on k-th iteration Collect over all iterations and send to outer decoder
440
k=k+1
450

FIG. 4

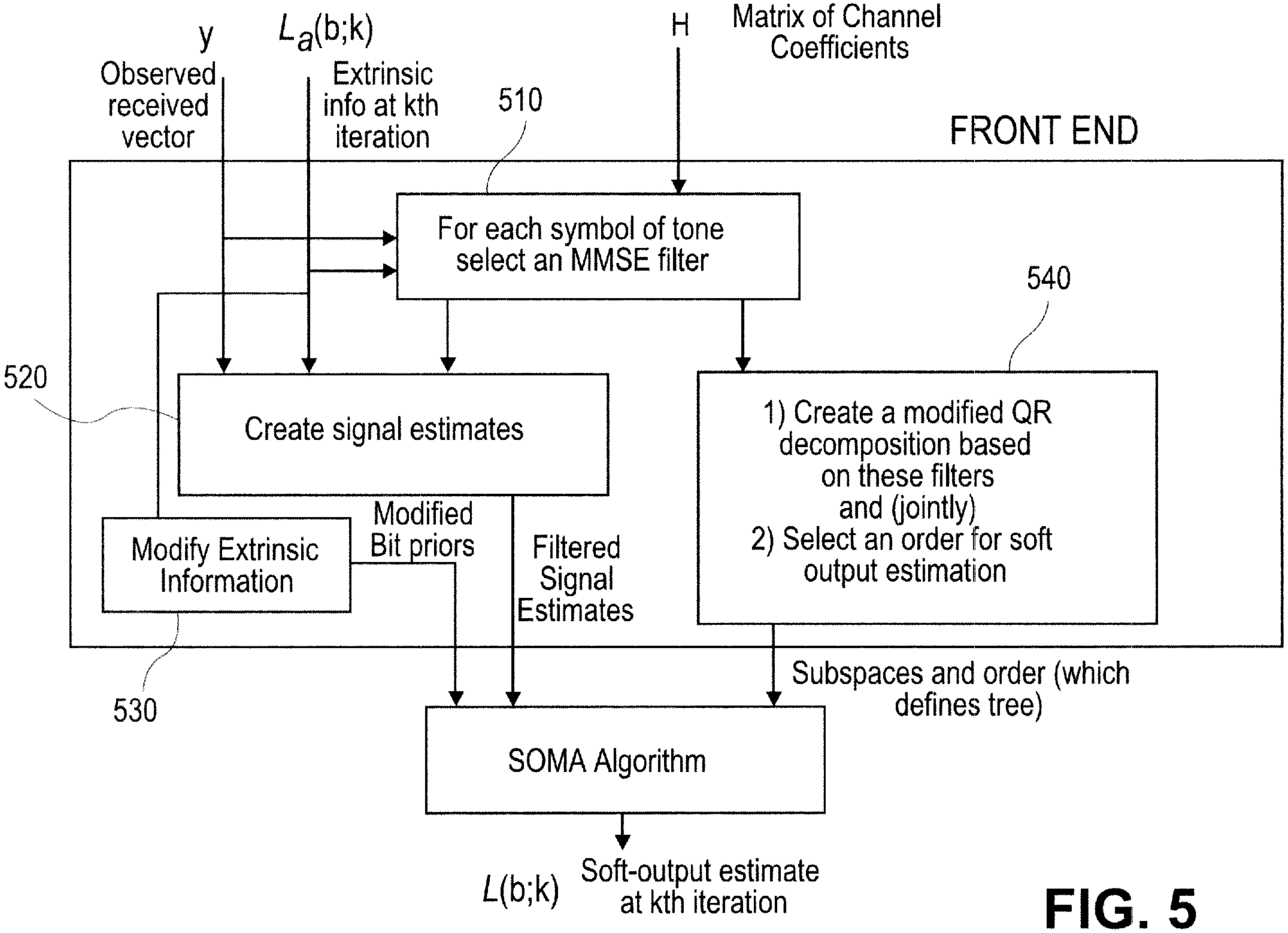
y
Observed received vector
$L_a(b;k)$
Extrinsic info at kth iteration
H
Matrix of Channel Coefficients
510
FRONT END
For each symbol of tone select an MMSE filter
540
520
Create signal estimates
1) Create a modified QR decomposition based on these filters and (jointly)
2) Select an order for soft output estimation
Modify Extrinsic Information
Modified Bit priors
Filtered Signal Estimates
530
Subspaces and order (which defines tree)
SOMA Algorithm
$L(b;k)$
Soft-output estimate at kth iteration

FIG. 5

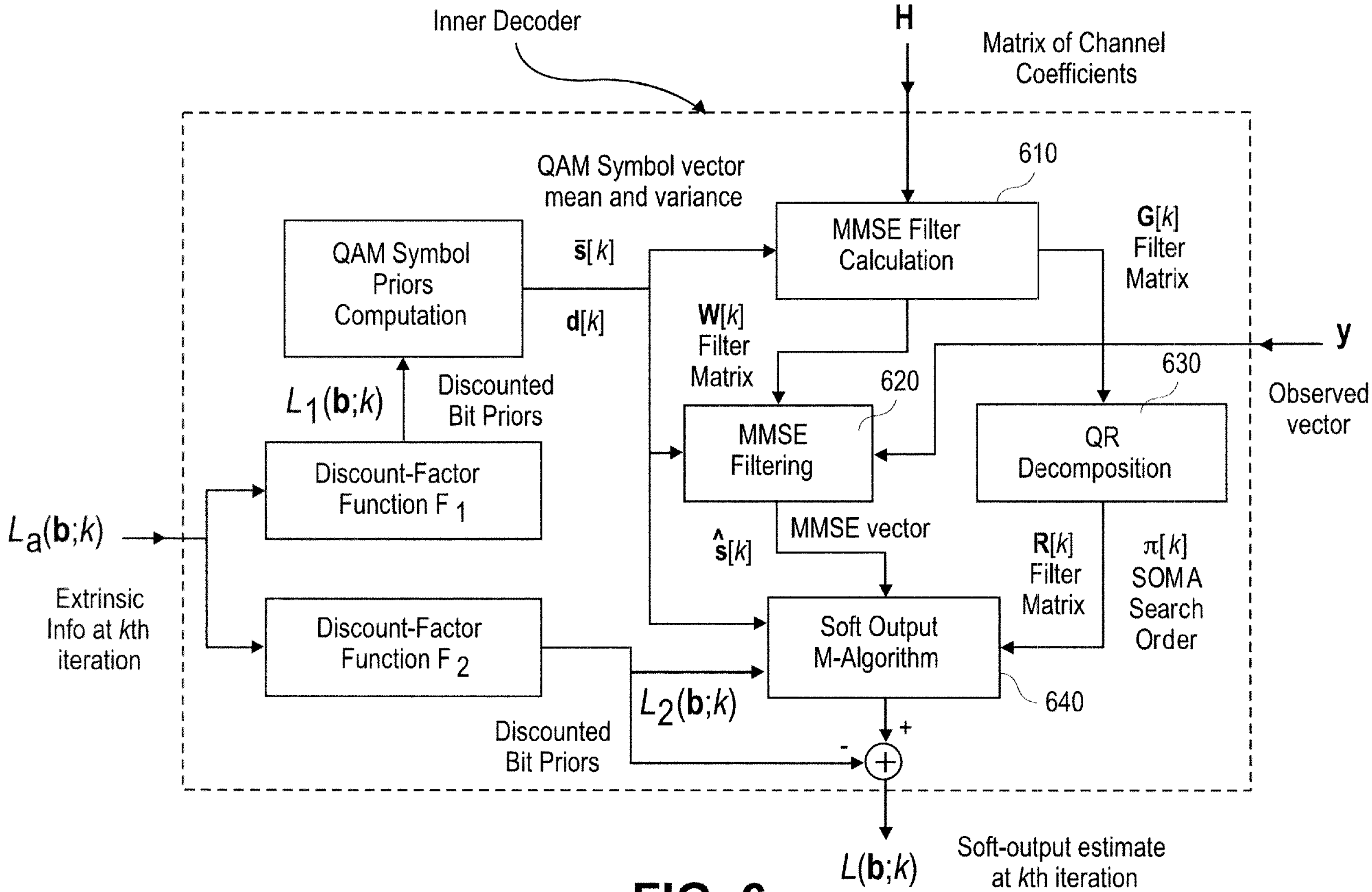
Inner Decoder
H
Matrix of Channel Coefficients
QAM Symbol vector mean and variance
610
QAM Symbol Priors Computation
s̄[k]
d[k]
MMSE Filter Calculation
G[k] Filter Matrix
W[k] Filter Matrix
y
Observed vector
620
630
MMSE Filtering
QR Decomposition
L1(b;k)
Discounted Bit Priors
Discount-Factor Function F 1
La(b;k)
Extrinsic Info at kth iteration
ŝ[k]
MMSE vector
R[k] Filter Matrix
π[k] SOMA Search Order
Discount-Factor Function F 2
Soft Output M-Algorithm
640
L2(b;k)
Discounted Bit Priors
+
-
L(b;k)
Soft-output estimate at kth iteration

FIG. 6

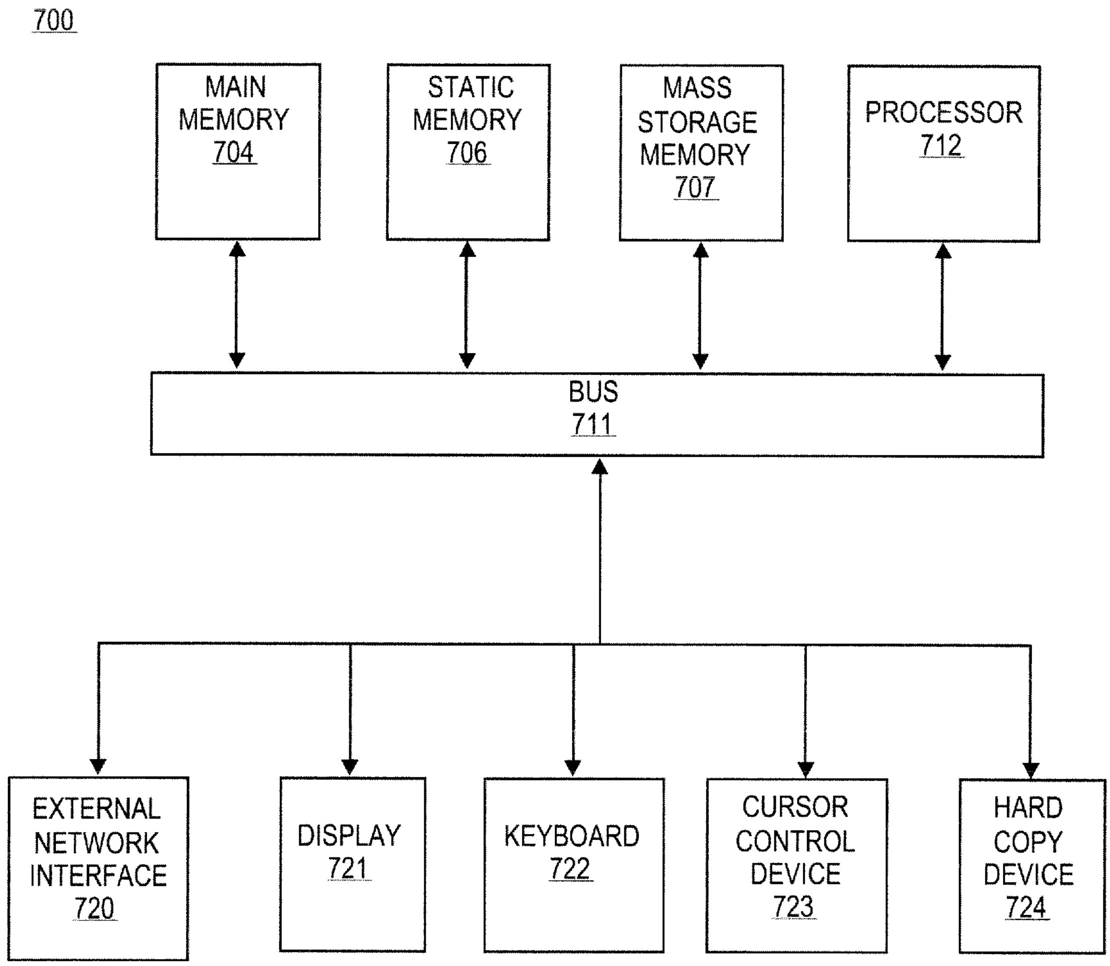
700
MAIN MEMORY 704
STATIC MEMORY 706
MASS STORAGE MEMORY 707
PROCESSOR 712
BUS 711
EXTERNAL NETWORK INTERFACE 720
DISPLAY 721
KEYBOARD 722
CURSOR CONTROL DEVICE 723
HARD COPY DEVICE 724

FIG. 7