DERIVATION AND FEEDBACK OF TRANSMIT STEERING MATRIX

[0001] The present application claims priority to provisional U.S. Application Serial No. 60/802,682, entitled "JACOBI ITERATIONS FOR EIGENVECTOR DECOMPOSITION AND FEEDBACK REDUCTION," filed May 22, 2006, assigned to the assignee hereof and incorporated herein by reference.

BACKGROUND

I. Field

[0002] The present disclosure relates generally to communication, and more specifically to techniques for sending feedback for a multiple-input multiple-output (MIMO) transmission.

II. Background

[0003] In a wireless communication system, a transmitter may utilize multiple (T) transmit antennas for data transmission to a receiver equipped with multiple (R) receive antennas. The multiple transmit and receive antennas form a MIMO channel that may be used to increase throughput and/or improve reliability. For example, the transmitter may transmit up to T data streams simultaneously from the T transmit antennas to improve throughput. Alternatively, the transmitter may transmit a single data stream from all T transmit antennas to improve reception by the receiver.

[0004] Good performance (e.g., high throughput) may be achieved by transmitting data on eigenmodes of the MIMO channel. The eigenmodes may be viewed as orthogonal spatial channels. The receiver may estimate the MIMO channel response, derive a transmit steering matrix based on a MIMO channel response matrix, and send the transmit steering matrix to the transmitter. The transmitter may then perform spatial processing with the transmit steering matrix to send data on the eigenmodes.

[0005] Valuable radio resources are used to send the transmit steering matrix from the receiver to the transmitter. There is therefore a need in the art for techniques to efficiently send the transmit steering matrix so that overhead may be reduced.

SUMMARY

[0006] Techniques for efficiently deriving a transmit steering matrix and sending feedback for this matrix are described herein. In one design, a receiver may determine a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to the receiver. The receiver may derive the transmit steering matrix based on a plurality of transformation matrices, which may be used for multiple iterations of Jacobi rotation to zero out off-diagonal elements of a channel matrix. The receiver may determine the set of parameters based on the transformation matrices. The set of parameters may comprise at least one angle, at least one value, at least one index, etc., for each transformation matrix. The receiver may send the set of parameters defining the transmit steering matrix (instead of elements of the transmit steering matrix) to the transmitter for use by the transmitter to derive the transmit steering matrix.

[0007] Various aspects and features of the disclosure are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 shows a block diagram of an access point and a terminal.

[0009] FIG. 2 illustrates eigenvalue decomposition for multiple subcarriers.

[0010] FIG. 3 illustrates feedback of a transmit steering matrix.

[0011] FIG. 4 shows a process performed by a receiver.

[0012] FIG. 5 shows an apparatus for the receiver.

[0013] FIG. 6 shows another process performed by the receiver.

[0014] FIG. 7 shows a process performed by a transmitter.

[0015] FIG. 8 shows a process to derive a transmit steering matrix by the transmitter.

[0016] FIG. 9 shows an apparatus for the transmitter.

DETAILED DESCRIPTION

[0017] The techniques described herein may be used for various wireless communication networks such as wireless wide area networks (WWANs), wireless metropolitan area networks (WMANs), wireless local area networks (WLANs), etc. The terms "network" and "system" are often used interchangeably. The techniques may also be used for various multiple access schemes such as Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), Spatial Division Multiple Access (SDMA), Orthogonal FDMA (OFDMA), Single-Carrier FDMA (SC-FDMA), etc. An OFDMA system utilizes Orthogonal Frequency Division Multiplexing (OFDM). An SC-FDMA system utilizes Single-Carrier Frequency Division Multiplexing (SC-FDM). OFDM and SC-FDM partition the system bandwidth into multiple (K) orthogonal subcarriers, which are also referred to as tones, bins, etc. Each subcarrier may be modulated with data. In general, modulation symbols are sent in the frequency domain with OFDM and in the time domain with SC-FDM. An OFDMA system may implement a radio technology such as Long Term Evolution (LTE), Ultra Mobile Broadband (UMB), IEEE 802.20, IEEE 802.16 (which is also referred to as WiMAX), IEEE 802.11 (which is also referred to as Wi-Fi), Flash-OFDM®, etc. These various radio technologies and standards are known in the art.

[0018] FIG. 1 shows a block diagram of a design of an access point 110 and a terminal 150 in a wireless communication network. An access point is a station that communicates with the terminals. An access point may also be called, and may contain some or all of the functionality of, a base station, a Node B, an evolved Node B (eNode B), etc. A terminal may also be called, and may contain some or all of the functionality of, a mobile station, a user equipment, an access terminal, an user terminal, a subscriber station, a station, etc. Terminal 150 may be a cellular phone, a personal digital assistant (PDA), a wireless communication device, a handheld device, a wireless modem, a laptop computer, a cordless phone, etc. Access point 110 is equipped with multiple (N_{ap}) antennas that may be used for data transmission and reception. Terminal 150 is equipped with multiple (N_{ut}) antennas that may be used for data transmission and reception.

[0019] On the downlink, at access point 110, a transmit (TX) data processor 114 may receive traffic data from a data source 112 and/or other data from a controller/ processor 130. TX data processor 114 may process (e.g., format, encode, interleave, and symbol map) the received data and generate data symbols, which are modulation symbols for data. A TX spatial processor 120 may multiplex the data symbols with pilot symbols, perform transmitter spatial processing with one or more downlink (DL) transmit steering matrices, and provide N_{ap} streams of output symbols to N_{ap} modulators (MOD) 122a through 122ap. Each modulator 122 may process its output symbol stream (e.g., for OFDM, SC-FDM, CDMA, etc.) to generate an output chip stream. Each modulator 122 may further condition (e.g., convert to analog, amplify, filter, and upconvert) its output chip stream to generate a downlink signal. N_{ap} downlink signals from modulators 122a through 122ap may be transmitted from antennas 124a through 124ap, respectively.

[0020] At terminal 150, N_{ut} antennas 152a through 152ut may receive the downlink signals from access point 110, and each antenna 152 may provide a received signal to a respective demodulator (DEMOD) 154. Each demodulator 154 may perform processing complementary to the processing performed by modulators 122 and provide received symbols. A receive (RX) spatial processor 160 may perform spatial matched filtering on the received symbols from all demodulators 154a through 154ut and provide data symbol estimates, which are estimates of the data symbols transmitted by access point 110. An RX data processor 170 may further process (e.g., symbol demap, deinterleave, and decode) the data symbol estimates and provide decoded data to a data sink 172 and/or a controller/processor 180.

[0021] A channel processor 178 may process pilot symbols received on the downlink from access point 110 and may estimate the downlink MIMO channel response. Processor 178 may decompose a downlink channel response matrix for each subcarrier of interest, as described below, to obtain a DL transmit steering matrix and eigenvalues for that subcarrier. Processor 178 may also derive a DL spatial filter matrix for each subcarrier of interest based on the transmit steering matrix and eigenvalues for that subcarrier. Processor 178 may provide the DL spatial filter matrices to RX spatial processor 160 for downlink spatial matched

filtering and may provide the DL transmit steering matrices to controller/processor 180 for feedback to access point 110.

[0022] The processing for the uplink may be the same as or different from the processing for the downlink. Traffic data from a data source 186 and/or other data from controller/processor 180 may be processed (e.g., encoded, interleaved, and modulated) by a TX data processor 188, and multiplexed with pilot symbols and spatially processed by TX spatial processor 190 with one or more uplink (UL) transmit steering matrices. The output symbols from TX spatial processor 190 may be further processed by modulators 154a through 154ut to generate N_{ut} uplink signals, which may be transmitted via antennas 152a through 152ut.

[0023] At access point 110, the uplink signals from terminal 150 may be received by antennas 124a through 124ap and processed by demodulators 122a through 122ap to obtain received symbols. An RX spatial processor 140 may perform spatial matched filtering on the received symbols and provide data symbol estimates. An RX data processor 142 may further process the data symbol estimates and provide decoded data to a data sink 144 and/or controller/processor 130.

[0024] A channel processor 128 may process pilot symbols received on the uplink from terminal 150 and may estimate the uplink MIMO channel response. Processor 128 may decompose an uplink channel response matrix for each subcarrier of interest to obtain an UL transmit steering matrix and eigenvalues for that subcarrier. Processor 128 may also derive an UL spatial filter matrix for each subcarrier of interest. Processor 128 may provide the UL spatial filter matrices to RX spatial processor 140 for uplink spatial matched filtering and may provide the UL transmit steering matrices to controller/processor 130 for feedback to terminal 150.

[0025] Controllers/processors 130 and 180 may control the operation at access point 110 and terminal 150, respectively. Memories 132 and 182 may store data and program codes for access point 110 and terminal 150, respectively.

[0026] The techniques described herein may be used for MIMO transmission on the downlink as well as the uplink. The techniques may be performed by terminal 150 to derive transmit steering matrices for the downlink and to send these matrices to access point 110 for MIMO transmission on the downlink. The

techniques may also be performed by access point 110 to derive transmit steering matrices for the uplink and to send these matrices to terminal 150 for MIMO transmission on the uplink.

[0027] A MIMO channel formed by multiple (T) transmit antennas at a transmitter and multiple (R) receive antennas at a receiver may be characterized by an $R \times T$ channel response matrix $\underline{\mathbf{H}}$, which may be given as:

$$\underline{\mathbf{H}} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,T} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{R,1} & h_{R,2} & \cdots & h_{R,T} \end{bmatrix}, \qquad \text{Eq (1)}$$

where entry $h_{i,j}$, for $i = 1, ..., R$ and $j = 1, ..., T$, denotes the coupling or complex channel gain between transmit antenna j and receive antenna i. For downlink transmission, access point 110 is the transmitter, terminal 150 is the receiver, $T = N_{ap}$ and $R = N_{ut}$. For uplink transmission, terminal 150 is the transmitter, access point 110 is the receiver, $T = N_{ut}$ and $R = N_{ap}$.

[0028] The channel response matrix $\underline{\mathbf{H}}$ may be diagonalized to obtain multiple (S) eigenmodes of $\underline{\mathbf{H}}$, where $S \leq \min\{T, R\}$. The diagonalization may be achieved by performing eigenvalue decomposition of a correlation matrix of $\underline{\mathbf{H}}$.

[0029] The eigenvalue decomposition may be expressed as:

$$\underline{\mathbf{R}} = \underline{\mathbf{H}}^H \underline{\mathbf{H}} = \underline{\mathbf{V}} \underline{\Lambda} \underline{\mathbf{V}}^H, \qquad \text{Eq (2)}$$

where $\underline{\mathbf{R}}$ is a $T \times T$ correlation matrix of $\underline{\mathbf{H}}$,

$\underline{\mathbf{V}}$ is a $T \times T$ unitary matrix whose columns are eigenvectors of $\underline{\mathbf{R}}$,

$\underline{\Lambda}$ is a $T \times T$ diagonal matrix of eigenvalues of $\underline{\mathbf{R}}$, and

"^{H}" denotes a conjugate transpose.

[0030] Unitary matrix $\underline{\mathbf{V}}$ is characterized by the property $\underline{\mathbf{V}}^H \underline{\mathbf{V}} = \underline{\mathbf{I}}$, where $\underline{\mathbf{I}}$ is the identity matrix. The columns of a unitary matrix are orthogonal to one another, and each column has unit power. Diagonal matrix $\underline{\Lambda}$ contains possible

non-zero values along the diagonal and zeros elsewhere. The diagonal elements of $\underline{\Lambda}$ are eigenvalues of $\underline{\mathbf{R}}$. These eigenvalues represent the power gains of the S eigenmodes. $\underline{\mathbf{R}}$ is a Hermitian matrix whose off-diagonal elements have the following property: $r_{i,j} = r_{j,i}^*$, where " * " denotes a complex conjugate.

[0031] The transmitter may perform transmitter spatial processing based on the eigenvectors in $\underline{\mathbf{V}}$ to transmit data on the eigenmodes of $\underline{\mathbf{H}}$, as follows:

$$\underline{\mathbf{x}} = \underline{\mathbf{V}}\,\underline{\mathbf{s}} , \qquad \text{Eq (3)}$$

where $\underline{\mathbf{s}}$ is a $T \times 1$ vector with S data symbols to be sent on S eigenmodes, and

$\underline{\mathbf{x}}$ is a $T \times 1$ vector with T output symbols to be sent from the T transmit antennas.

[0032] The spatial processing in equation (3) may also be referred to as beamforming, precoding, etc. The transmitter may also perform beamsteering by (i) scaling each element of $\underline{\mathbf{V}}$ to obtain a matrix $\underline{\tilde{\mathbf{V}}}$ with unit-magnitude elements and (ii) performing transmitter spatial processing with $\underline{\tilde{\mathbf{V}}}$ instead of $\underline{\mathbf{V}}$. In any case, beamforming and beamsteering may provide better performance than simply transmitting data from the T transmit antennas without any spatial processing.

[0033] The receiver may obtain received symbols from the R receive antennas, which may be expressed as:

$$\underline{\mathbf{r}} = \underline{\mathbf{H}}\,\underline{\mathbf{x}} + \underline{\mathbf{n}} , \qquad \text{Eq (4)}$$

where $\underline{\mathbf{r}}$ is an $R \times 1$ vector with R received symbols from the R receive antennas, and

$\underline{\mathbf{n}}$ is an $R \times 1$ noise vector.

[0034] The receiver may perform spatial matched filtering on the received symbols, as follows:

$$\hat{\underline{\mathbf{s}}} = \underline{\Lambda}^{-1}\,\underline{\mathbf{V}}^{H}\,\underline{\mathbf{H}}^{H}\,\underline{\mathbf{r}} , \qquad \text{Eq (5)}$$

where $\hat{\underline{\mathbf{s}}}$ is a $T \times 1$ vector of data symbol estimates, which are estimates of the data symbols in $\underline{\mathbf{s}}$. The receiver may also perform receiver spatial processing in other manners.

[0035] As shown in equation (3), matrix $\underline{\mathbf{V}}$ may be used by the transmitter for spatial processing for data transmission. As shown in equation (5), matrix $\underline{\mathbf{V}}$ may also be used by the receiver for spatial processing for data reception. $\underline{\mathbf{V}}$ may be derived by performing eigenvalue decomposition of $\underline{\mathbf{R}}$ or singular value decomposition of $\underline{\mathbf{H}}$.

[0036] Eigenvalue decomposition of $\mathrm{T} \times \mathrm{T}$ complex Hermitian matrix $\underline{\mathbf{R}}$ may be performed with an iterative process that uses Jacobi rotation repeatedly to zero out off-diagonal elements in $\underline{\mathbf{R}}$. Jacobi rotation is also commonly referred to as Jacobi method, Jacobi transformation, etc. For a 2×2 complex Hermitian matrix, one iteration of the Jacobi rotation is sufficient to obtain two eigenvectors and two eigenvalues for this matrix. For a larger complex Hermitian matrix with dimension greater than 2×2, the iterative process performs multiple iterations of the Jacobi rotation to obtain the eigenvectors and eigenvalues for the larger complex matrix.

[0037] In the following description, index i denotes iteration number and is initialized as $i = 0$. $\underline{\mathbf{R}}$ is a $\mathrm{T} \times \mathrm{T}$ Hermitian matrix to be decomposed, where $\mathrm{T} > 2$. A $\mathrm{T} \times \mathrm{T}$ matrix $\underline{\mathbf{D}}_i$ is an approximation of diagonal matrix $\underline{\Lambda}$ of eigenvalues of $\underline{\mathbf{R}}$ and may be initialized as $\underline{\mathbf{D}}_0 = \underline{\mathbf{R}}$. A $\mathrm{T} \times \mathrm{T}$ matrix $\underline{\mathbf{V}}_i$ is an approximation of matrix $\underline{\mathbf{V}}$ of eigenvectors of $\underline{\mathbf{R}}$ and may be initialized as $\underline{\mathbf{V}}_0 = \underline{\mathbf{I}}$.

[0038] A single iteration of the Jacobi rotation to update matrices $\underline{\mathbf{D}}_i$ and $\underline{\mathbf{V}}_i$ may be performed as follows. First, a 2×2 Hermitian matrix $\underline{\mathbf{D}}_{pq}$ may be formed based on the current $\underline{\mathbf{D}}_i$, as follows:

$$\underline{\mathbf{D}}_{pq} = \begin{bmatrix} d_{pp} & d_{pq} \\ d_{qp} & d_{qq} \end{bmatrix}, \qquad \text{for } 1 \le p < \mathrm{T} \text{ and } p < q \le \mathrm{T}, \qquad \text{Eq (6)}$$

where d_{pq} is the element at location (p,q) in $\underline{\mathbf{D}}_i$.

[0039] $\underline{\mathbf{D}}_{pq}$ is a 2×2 submatrix of $\underline{\mathbf{D}}_i$. The four elements of $\underline{\mathbf{D}}_{pq}$ are four elements at locations (p,p), (p,q), (q,p) and (q,q) in $\underline{\mathbf{D}}_i$. Indices p and q may be selected as described below.

[0040] Eigenvalue decomposition of $\underline{\mathbf{D}}_{pq}$ may be performed to obtain a 2×2 unitary matrix $\underline{\mathbf{V}}_{pq}$ of eigenvectors of $\underline{\mathbf{D}}_{pq}$. The elements of $\underline{\mathbf{V}}_{pq}$ may be computed directly from the elements of $\underline{\mathbf{D}}_{pq}$, as follows:

$$d = \sqrt{(\mathrm{Re}\{d_{pq}\})^2 + (\mathrm{Im}\{d_{pq}\})^2}\ , \qquad \text{Eq (7a)}$$

$$c_1 = \frac{\mathrm{Re}\{d_{pq}\}}{d} = \cos(\angle d_{pq})\ , \qquad \text{Eq (7b)}$$

$$s_1 = \frac{\mathrm{Im}\{d_{pq}\}}{d} = \sin(\angle d_{pq})\ , \qquad \text{Eq (7c)}$$

$$g_1 = c_1 - js_1\ , \qquad \text{Eq (7d)}$$

$$\tau = \frac{d_{qq} - d_{pp}}{2\cdot d}\ , \qquad \text{Eq (7e)}$$

$$x = \sqrt{1+\tau^2}\ , \qquad \text{Eq (7f)}$$

$$t = \frac{1}{|\tau| + x}\ , \qquad \text{Eq (7g)}$$

$$c = \frac{1}{\sqrt{1+t^2}}\ , \qquad \text{Eq (7h)}$$

$$s = t\cdot c = \sqrt{1-c^2}\ , \qquad \text{Eq (7i)}$$

if $(d_{qq} - d_{pp}) < 0$,

$$\text{then } \underline{\mathbf{V}}_{pq} = \begin{bmatrix} v_{pp} & v_{pq} \\ v_{qp} & v_{qq} \end{bmatrix} = \begin{bmatrix} c & -s \\ g_1\cdot s & g_1\cdot c \end{bmatrix}\ , \qquad \text{Eq (7j)}$$

$$\text{else } \underline{\mathbf{V}}_{pq} = \begin{bmatrix} v_{pp} & v_{pq} \\ v_{qp} & v_{qq} \end{bmatrix} = \begin{bmatrix} s & c \\ g_1\cdot c & -g_1\cdot s \end{bmatrix}\ , \qquad \text{Eq (7k)}$$

where d is the magnitude of d_{pq}, $\angle d_{pq}$ is the phase of d_{pq}, g_1 is a complex value, and c and s are real values with unit power, or $c^2 + s^2 = 1$.

[0041] Equation set (7) performs a Jacobi rotation on 2×2 Hermitian matrix $\underline{\mathbf{D}}_{pq}$ to obtain matrix $\underline{\mathbf{V}}_{pq}$ of eigenvectors of $\underline{\mathbf{D}}_{pq}$. The computations in equation set (7) are designed to avoid trigonometric functions such as arc-tangent, cosine, and sine.

[0042] A $\mathrm{T} \times \mathrm{T}$ transformation matrix $\underline{\mathbf{T}}_i$ may be formed with matrix $\underline{\mathbf{V}}_{pq}$. $\underline{\mathbf{T}}_i$ is an identity matrix with the four elements at locations (p,p), (p,q), (q,p) and (q,q) replaced with the (1,1), (1,2), (2,1) and (2,2) elements, respectively, of $\underline{\mathbf{V}}_{pq}$. $\underline{\mathbf{T}}_i$ has the following form:

$$\underline{\mathbf{T}}_i = \begin{bmatrix} 1 & & & & & & \\ & \ddots & & & & & \\ & & v_{pp} & \cdots & v_{pq} & & \\ & & \vdots & 1 & \vdots & & \\ & & v_{qp} & \cdots & v_{qq} & & \\ & & & & & \ddots & \\ & & & & & & 1 \end{bmatrix}. \qquad \text{Eq (8)}$$

[0043] All of the other off-diagonal elements of $\underline{\mathbf{T}}_i$ not shown in equation (8) are zeros. Equations (7j) and (7k) indicate that $\underline{\mathbf{T}}_i$ is a complex matrix containing complex values for v_{qp} and v_{qq}.

[0044] Matrix $\underline{\mathbf{D}}_i$ may be updated as follows:

$$\underline{\mathbf{D}}_{i+1} = \underline{\mathbf{T}}_i^H \, \underline{\mathbf{D}}_i \, \underline{\mathbf{T}}_i \; . \qquad \text{Eq (9)}$$

Equation (9) performs Jacobi rotation with $\underline{\mathbf{T}}_i$ to zero out two off-diagonal elements d_{pq} and d_{qp} at locations (p,q) and (q,p) in $\underline{\mathbf{D}}_i$. The computation may alter the values of other off-diagonal elements in $\underline{\mathbf{D}}_i$.

[0045] Matrix $\underline{\mathbf{V}}_i$ may also be updated as follows:

$$\underline{\mathbf{V}}_{i+1} = \underline{\mathbf{V}}_i \, \underline{\mathbf{T}}_i \; . \qquad \text{Eq (10)}$$

$\underline{\mathbf{V}}_i$ is a cumulative transformation matrix that contains all of the transformation matrices $\underline{\mathbf{T}}_i$ used on $\underline{\mathbf{D}}_i$.

[0046] Transformation matrix $\underline{\mathbf{T}}_i$ may also be expressed as a product of (i) a diagonal matrix with $T-1$ ones elements and one complex-valued element and (ii) a real-valued matrix with $T-2$ ones along the diagonal, two real-valued diagonal elements, two real-valued off-diagonal elements, and zeros elsewhere. As an example, for $p=1$ and $q=2$, $\underline{\mathbf{T}}_i$ may be expressed as:

$$\underline{\mathbf{T}}_i = \begin{bmatrix} c & -s & 0 & \cdots & 0 \\ g_1 s & g_1 c & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & g_1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c & -s & 0 & \cdots & 0 \\ s & c & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}, \quad \text{Eq (11)}$$

where g_1 is a complex value and c and s are real values given in equation set (7).

[0047] Each iteration of the Jacobi rotation zeros out two off-diagonal elements of $\underline{\mathbf{D}}_i$. Multiple iterations of the Jacobi rotation may be performed for different values of indices p and q to zero out all of the off-diagonal elements of $\underline{\mathbf{D}}_i$. Indices p and q may be selected in various manners.

[0048] In one design, for each iteration, the largest off-diagonal element of $\underline{\mathbf{D}}_i$ may be identified and denoted as d_{pq}. The iteration may then be performed with $\underline{\mathbf{D}}_{pq}$ containing this largest off-diagonal element d_{pq} and three other elements at locations (p,p), (q,p) and (q,q) in $\underline{\mathbf{D}}_i$. The iterative process may be performed for any number of iterations until a termination condition is encountered. The termination condition may be completion of a predetermined number of iterations, satisfaction of an error criterion, etc. For example, the total error or the power in all off-diagonal elements of $\underline{\mathbf{D}}_i$ may be computed and compared against an error threshold, and the iterative process may be terminated if the total error is below the error threshold.

[0049] In another design, indices p and q may be selected in a predetermined manner, e.g., by sweeping through all possible values of these indices. A single sweep across all possible values for indices p and q may be performed as follows.

Index p may be stepped from 1 through $T-1$ in increments of one. For each value of p, index q may be stepped from $p+1$ through T in increments of one. An iteration of the Jacobi rotation to update $\underline{\mathbf{D}}_i$ and $\underline{\mathbf{V}}_i$ may be performed for each combination of values for p and q, as described above. For a given combination of values for p and q, the Jacobi rotation to update $\underline{\mathbf{D}}_i$ and $\underline{\mathbf{V}}_i$ may be skipped if the magnitude of the off-diagonal elements at locations (p,q) and (q,p) in $\underline{\mathbf{D}}_i$ is below a predetermined threshold.

[0050] A sweep consists of $T \cdot (T-1)/2$ iterations of the Jacobi rotation to update $\underline{\mathbf{D}}_i$ and $\underline{\mathbf{V}}_i$ for all possible values of p and q. Each iteration of the Jacobi rotation zeros out two off-diagonal elements of $\underline{\mathbf{D}}_i$ but may alter other elements that might have been zeroed out earlier. The effect of sweeping through indices p and q is to reduce the magnitude of all off-diagonal elements of $\underline{\mathbf{D}}_i$, so that $\underline{\mathbf{D}}_i$ approaches diagonal matrix $\underline{\Lambda}$. $\underline{\mathbf{V}}_i$ contains an accumulation of all transformation matrices that collectively give $\underline{\mathbf{D}}_i$. Thus, $\underline{\mathbf{V}}_i$ approaches $\underline{\mathbf{V}}$ as $\underline{\mathbf{D}}_i$ approaches $\underline{\Lambda}$. Any number of sweeps may be performed to obtain more and more accurate approximations of $\underline{\mathbf{V}}$ and $\underline{\Lambda}$.

[0051] Regardless of how indices p and q may be selected, upon termination of the iterative process, the final $\underline{\mathbf{V}}_i$ is a good approximation of $\underline{\mathbf{V}}$ and is denoted as $\underline{\hat{\mathbf{V}}}$, and the final $\underline{\mathbf{D}}_i$ is a good approximation of $\underline{\Lambda}$ and is denoted as $\underline{\hat{\Lambda}}$. The columns of $\underline{\hat{\mathbf{V}}}$ may be used as eigenvectors of $\underline{\mathbf{R}}$, and the diagonal elements of $\underline{\hat{\Lambda}}$ may be used as eigenvalues of $\underline{\mathbf{R}}$.

[0052] In another design, the iterative process to drive $\underline{\hat{\mathbf{V}}}$ may be performed based on singular value decomposition of $\underline{\mathbf{H}}$. For this design, $T \times T$ matrix $\underline{\mathbf{V}}_i$ is an approximation of $\underline{\mathbf{V}}$ and may be initialized as $\underline{\mathbf{V}}_0 = \underline{\mathbf{I}}$. An $R \times T$ matrix $\underline{\mathbf{W}}_i$ may be initialized as $\underline{\mathbf{W}}_0 = \underline{\mathbf{H}}$.

[0053] A single iteration of the Jacobi rotation to update matrices $\underline{\mathbf{V}}_i$ and $\underline{\mathbf{W}}_i$ may be performed as follows. First, a 2×2 Hermitian matrix $\underline{\mathbf{M}}_{pq}$ may be formed based on the current $\underline{\mathbf{W}}_i$. $\underline{\mathbf{M}}_{pq}$ is a 2×2 submatrix of $\underline{\mathbf{W}}_i^H \underline{\mathbf{W}}_i$ and

contains four elements at locations (p,p), (p,q), (q,p) and (q,q) in $\underline{\mathbf{W}}_i^H \underline{\mathbf{W}}_i$. $\underline{\mathbf{M}}_{pq}$ may be decomposed, e.g., as shown in equation set (7), to obtain 2×2 matrix $\underline{\mathbf{V}}_{pq}$. Transformation matrix $\underline{\mathbf{T}}_i$ may be formed based on $\underline{\mathbf{V}}_{pq}$ as shown in equation (8). Matrix $\underline{\mathbf{V}}_i$ may then be updated with $\underline{\mathbf{T}}_i$ as shown in equation (10). Matrix $\underline{\mathbf{W}}_i$ may also be updated based on $\underline{\mathbf{T}}_i$, as follows:

$$\underline{\mathbf{W}}_{i+1} = \underline{\mathbf{W}}_i \underline{\mathbf{T}}_i \ . \qquad \text{Eq (12)}$$

[0054] The iterative process may be performed until a termination condition is encountered. For each iteration, indices p and q may be selected based on the largest element in $\underline{\mathbf{W}}_i$ or in a predetermined order.

[0055] For both eigenvalue decomposition and singular value decomposition, the receiver may send back all $\mathrm{T} \cdot \mathrm{T}$ complex-valued elements in $\underline{\hat{\mathbf{V}}}$ to the transmitter. If each complex-valued element is quantized with b bits for the real part and b bits for the imaginary part, then the receiver may send the entire $\underline{\hat{\mathbf{V}}}$ with $2b \cdot \mathrm{T} \cdot \mathrm{T}$ bits.

[0056] In an aspect, the receiver may send back parameters defining $\underline{\hat{\mathbf{V}}}$ instead of the elements of $\underline{\hat{\mathbf{V}}}$. As shown in equation (10), inherent in the iterative process to derive $\underline{\hat{\mathbf{V}}}$ is a representation of $\underline{\hat{\mathbf{V}}}$ as a product of transformation matrices. Each transformation matrix $\underline{\mathbf{T}}_i$ may be formed based on a simple 2×2 unitary matrix $\underline{\mathbf{V}}_{pq}$. Each 2×2 unitary matrix includes one complex value g_1 and two real values c and s. Each transformation matrix may be defined by one complex value g_1, two real values c and s, and the values of indices p and q if these indices are not selected in a predetermined manner. The parameters defining $\underline{\mathbf{T}}_i$ may be sent in fewer bits than the complex-valued elements of $\underline{\hat{\mathbf{V}}}$.

[0057] In one design, the values of the elements of each transformation matrix $\underline{\mathbf{T}}_i$ may be quantized and sent back. As an example, for each $\underline{\mathbf{T}}_i$, the real and imaginary parts of g_1 may each be sent with b bits, c may be sent with b bits, and s may be sent with b bits, or a total of $4b$ bits. In general, g_1 may be sent with the same or different resolution as c and s. If the values of indices p and q are not

known *a priori* by the transmitter, then $\ell = \lceil \log_2 \ T \cdot (T-1)/2 \rceil$ bits may be used to convey the p and q values. For example, if $\underline{\mathbf{R}}$ is a 4×4 matrix, then there are six possible combinations of p and q values, which may be conveyed with $\ell = 3$ bits.

[0058] In another design, the angles of the elements of each transformation matrix $\underline{\mathbf{T}}_i$ may be quantized, and two real-valued angle parameters may be sent back. As shown in equation set (7), c and s may be calculated as functions of only τ even though intermediate values x and t are used to simplify notation. Since $|\tau|$ ranges from 0 to ∞, c ranges from 0.707 to 1.0, and s ranges from 0.707 to 0.0. Furthermore, since $s = \sqrt{1-c^2}$, c and s may be specified by an angle θ between 0 and 45 degrees, or 0 to $\pi/4$. Thus, c may be given as $c = \cos\theta$, and s may be given as $s = \sin\theta$, for $0 \le \theta \le \pi/4$. Likewise, g_1 may be specified by the angle of d_{pq}, or $\phi = \angle d_{pq}$, which is an angle between 0 and 360 degrees, or 0 to 2π.

[0059] In one design, each transformation matrix $\underline{\mathbf{T}}_i$ may be given by (i) the sign of $(d_{qq} - d_{pp})$, which determines the form of $\underline{\mathbf{V}}_{pq}$ as shown in equations (7j) and (7k), (ii) angle ϕ for complex value g_1, and (iii) angle θ for real values c and s. One bit may be used to specify the sign of $(d_{qq} - d_{pp})$. The number of bits to use for quantization of angles ϕ and θ may be selected based on how much quantization error is acceptable for the desired system performance.

[0060] In one design, angle ϕ for g_1 and angle θ for c and s are given with uniform quantization. In this design, b bits may be used to specify angle ϕ for g_1 over a range of 0 to 2π, and $b-3$ bits may be used to specify angle θ for c and s over a range of 0 to $\pi/4$. The number of bits to send for each $\underline{\mathbf{T}}_i$ may then be given as $b + (b-3) + 1 = 2b - 2$. For example, $b = 5$ bits may be used for quantization of angles ϕ and θ to 32 uniformly spaced angles from 0 to 2π. If 10 iterations are performed to obtain $\underline{\hat{\mathbf{V}}}$, then the number of bits to send for 10 transformation matrices $\underline{\mathbf{T}}_i$ for the 10 iterations may be given as $10 \cdot [(2 \cdot 5 - 2) + 3] = 110$ bits. In comparison, if $\underline{\hat{\mathbf{V}}}$ is a 4×4 matrix and the real and imaginary parts of the complex-valued elements of $\underline{\hat{\mathbf{V}}}$ are each quantized to 5 bits, then the number of

bits used to send 16 complex-valued elements of $\underline{\hat{\mathbf{V}}}$ may be given as $16 \cdot 2 \cdot 5 = 160$ bits.

[0061] In another design, angle ϕ for g_1 and angle θ for c and s are given with non-uniform quantization. Angles ϕ and θ may be derived based on Coordinate Rotational Digital Computer (CORDIC) computation, which implements an iterative algorithm that allows for fast hardware calculation of trigonometric functions such as sine, cosine, magnitude, and phase using simple shift, add and subtract operations. A complex number $R = R_I \pm j\, R_Q$ may be rotated by up to 90 degrees by multiplying R with a complex number C_m having the form $C_m = 1 \pm j\, B_m$, where $B_m = 2^{-m}$ and m is an index defined as $m = 0,\ 1,\ 2,\ \ldots$.

[0062] R may be rotated counter-clockwise if $C_m = 1 + j\, B_m$, and the rotated result may be expressed as:

$$Y_I = R_I - B_m \cdot R_Q = R_I - 2^{-m} \cdot R_Q \ , \text{ and} \qquad \text{Eq (13)}$$

$$Y_Q = R_Q + B_m \cdot R_I = R_Q + 2^{-m} \cdot R_I \ .$$

[0063] R may be rotated clockwise if $C_m = 1 - j\, B_m$, and the rotated result may be expressed as:

$$Y_I = R_I + B_m \cdot R_Q = R_I + 2^{-m} \cdot R_Q \ , \text{ and} \qquad \text{Eq (14)}$$

$$Y_Q = R_Q - B_m \cdot R_I = R_Q - 2^{-m} \cdot R_I \ .$$

[0064] The counter-clockwise rotation of R in equation set (13) and the clockwise rotation of R in equation set (14) via multiplication with C_m may be achieved by (i) shifting both R_I and R_Q by m bit positions, (ii) adding/subtracting the shifted R_Q to/from R_I to obtain Y_I, and (iii) adding/subtracting the shifted R_I to/from R_Q to obtain Y_Q. No multiplies are needed to perform the rotation.

[0065] Table 1 shows the value of B_m, the complex number C_m, the phase of C_m, and the magnitude of C_m for each value of m from 0 through 5. As shown in Table 1, for each value of m, the phase of C_m is slightly more than half the phase of C_{m-1}.

Table 1

m	$B_m = 2^{-m}$	$C_m = 1 + j\,B_m$	Phase of C_m	Magnitude of C_m
0	1.0	$1 + j1.0$	45.00000	1.41421356
1	0.5	$1 + j0.5$	26.56505	1.11803399
2	0.25	$1 + j0.25$	14.03624	1.03077641
3	0.125	$1 + j0.125$	7.12502	1.00778222
4	0.0625	$1 + j0.0625$	3.57633	1.00195122
5	0.03125	$1 + j0.03125$	1.78991	1.00048816

[0066] The magnitude and phase of R may be determined by iteratively rotating R counter-clockwise and/or clockwise with successively smaller phases until the phase of the rotated R approaches zero and the rotated R lies mostly on the x-axis. A phase variable φ_{total} may be initialized to zero, and a variable $R_m = R_{I,m} + j\,R_{Q,m}$ representing the rotated R may be initialized as $R_0 = R$. For each iteration starting with $m = 0$, R_m has a positive phase if $R_{Q,m}$ is positive or a negative phase if $R_{Q,m}$ is negative. If the phase of R_m is negative, then R_m is rotated counter-clockwise by φ_m by multiplying R_m with $C_m = 1 + j\,B_m$, as shown in equation set (13). Conversely, if the phase of R_m is positive, then R_m is rotated clockwise by φ_m by multiplying R_m with $C_m = 1 - j\,B_m$, as shown in equation set (14). φ_{total} is updated by $+\varphi_m$ if R_m is rotated counter-clockwise and by $-\varphi_m$ if R_m is rotated clockwise. φ_{total} represents the cumulative phase that has been added to or subtracted from the phase of R to zero out the phase of R_m.

[0067] The final result becomes more accurate as more iterations are performed. After all of the iterations are completed, the phase of R_m should be close to zero, the imaginary part of R_m should be approximately zero, and the real part of R_m is equal to the magnitude of R scaled by a CORDIC gain. The CORDIC gain asymptotically approaches 1.646743507 for large values of m and may be accounted for by other circuit blocks. The final value of φ_{total} is an approximation of the phase of R. φ_{total} may be represented by a sequence of sign bits, $z_0 z_1 z_2 \ldots$, where $z_m = 1$ if φ_m was subtracted from φ_{total} and $z_m = -1$ if φ_m was added to φ_{total}.

[0068] Angle ϕ for g_1 may be given by a bit sequence $z_0 z_1 z_2 \ldots$ obtained from the CORDIC computation of d_{pq}. Angle θ for c and s may be given by another bit sequence $z_0 z_1 z_2 \ldots$ obtained from the CORDIC computation of $c + js$. Alternatively, a τ look-up table may be used to produce angle θ for c and s and may store the CORDIC shifts for angle θ and bypass c and s. At the transmitter, a CORDIC processor may reverse the CORDIC shifts to obtain c and s.

[0069] The techniques described herein may be used for single-carrier systems, systems that utilize OFDM, systems that utilize SC-FDM, etc. For a system that utilizes OFDM or SC-FDM, multiple channel response matrices $\underline{\mathbf{H}}(k)$ may be obtained for multiple subcarriers. The iterative process may be performed for each channel response matrix $\underline{\mathbf{H}}(k)$ to obtain matrices $\hat{\underline{\mathbf{V}}}(k)$ and $\hat{\underline{\Lambda}}(k)$, which are approximations of matrix $\underline{\mathbf{V}}(k)$ of eigenvectors and matrix $\underline{\Lambda}(k)$ of eigenvalues for that $\underline{\mathbf{H}}(k)$. A high degree of correlation may exist between the channel response matrices for nearby subcarriers. This correlation may be exploited by the iterative process to reduce the computation to derive $\hat{\underline{\mathbf{V}}}(k)$ and $\hat{\underline{\Lambda}}(k)$ for all subcarriers of interest.

[0070] FIG. 2 illustrates eigenvalue decomposition for multiple subcarriers. The iterative process may be performed for one subcarrier at a time. For the first subcarrier k_1, matrix $\underline{\mathbf{V}}_i(k_1)$ may be initialized to the identity matrix, or $\underline{\mathbf{V}}_0(k_1) = \underline{\mathbf{I}}$, and matrix $\underline{\mathbf{D}}_i(k_1)$ may be initialized to $\underline{\mathbf{R}}(k_1)$, or $\underline{\mathbf{D}}_0(k_1) = \underline{\mathbf{R}}(k_1) = \underline{\mathbf{H}}^H(k_1)\,\underline{\mathbf{H}}(k_1)$. The iterative process may then operate on the initial solutions $\underline{\mathbf{V}}_0(k_1)$ and $\underline{\mathbf{D}}_0(k_1)$ for subcarrier k_1 until a termination condition is encountered. The iterative process may provide the final $\underline{\mathbf{V}}_i(k_1)$ and $\underline{\mathbf{D}}_i(k_1)$ as $\hat{\underline{\mathbf{V}}}(k_1)$ and $\hat{\underline{\Lambda}}(k_1)$, respectively, for subcarrier k_1.

[0071] For the next subcarrier k_2, which may be adjacent to or nearby subcarrier k_1, matrix $\underline{\mathbf{V}}_i(k_2)$ may be initialized to the final result for subcarrier k_1, or $\underline{\mathbf{V}}_0(k_2) = \hat{\underline{\mathbf{V}}}(k_1)$, and matrix $\underline{\mathbf{D}}_i(k_2)$ may be initialized as $\underline{\mathbf{D}}_0(k_2) = \underline{\mathbf{V}}_0^H(k_2)\,\underline{\mathbf{R}}(k_2)\,\underline{\mathbf{V}}_0(k_2)$. The iterative process may then operate on the initial solutions $\underline{\mathbf{V}}_0(k_2)$ and $\underline{\mathbf{D}}_0(k_2)$ for subcarrier k_2 until a termination condition

is encountered. The iterative process may provide the final $\underline{\mathbf{V}}_i(k_2)$ and $\underline{\mathbf{D}}_i(k_2)$ as $\underline{\hat{\mathbf{V}}}(k_2)$ and $\underline{\hat{\Lambda}}(k_2)$, respectively, for subcarrier k_2.

[0072] For each subsequent subcarrier k, the final results obtained for the nearest subcarrier may be used as the initial solutions $\underline{\mathbf{V}}_0(k)$ and $\underline{\mathbf{D}}_0(k)$ for subcarrier k. The iterative process may then operate on the initial solutions to obtain the final results for subcarrier k.

[0073] The receiver may perform decomposition for a set of subcarriers. This set may include consecutive subcarriers, or subcarriers spaced apart by some uniform or non-uniform spacing, or specific subcarriers of interest. The receiver may send feedback information (e.g., parameters used to derive $\underline{\hat{\mathbf{V}}}(k)$) for this set of subcarriers.

[0074] The concept described above may also be used across time. For each time interval t, the final solutions obtained for a prior time interval may be used as the initial solutions for the current time interval t. The iterative process may then operate on the initial solutions for time interval t until a termination condition is encountered. The concept may also be extended across both frequency and time.

[0075] In general, the receiver may derive a transmit steering matrix in any manner. A transmit steering matrix may be any matrix usable for spatial processing by a transmitter. A transmit steering matrix may be a matrix of eigenvectors for a MIMO channel, some other unitary matrix that may provide good performance, etc. A transmit steering matrix may also be referred to as a steering matrix, a precoding matrix, eigenvectors, etc. The receiver may derive a transmit steering matrix based on any type of transformation, e.g., eigenvalue decomposition, singular value decomposition, iterative Jacobi rotation, etc. The parameters defining the transmit steering matrix, which may be dependent on the type of transformation used to derive the transmit steering matrix, may be sent to the transmitter. The parameters may be represented in various forms, e.g., with real and/or complex values, angles, format indicator, row and column indices, etc.

[0076] **FIG. 3** illustrates example feedback sent by the receiver to the transmitter for a transmit steering matrix, e.g., matrix $\underline{\hat{\mathbf{V}}}$. The feedback information may include parameters for N transformation matrices used to derive the transmit

steering matrix, instead of elements of the transmit steering matrix. The parameters for each transformation matrix may comprise (i) values of elements of the transformation matrix, e.g., g_1, c and s, (ii) angles of elements of the transformation matrix, e.g., ϕ and θ, (iii) row and column indices of elements of the transformation matrix, e.g., p and q, (iv) the form of the transformation matrix, e.g., a sign bit to indicate whether to use the form shown in equation (7j) or (7k), and/or (v) some other information. The row and column indices may be omitted if the elements are selected in a predetermined order that is known *a priori* by the transmitter.

[0077] In general, various parameters may be conveyed to allow the transmitter to derive the transmit steering matrix. The parameters to convey may be dependent on various factors such as the type of transformation being performed (e.g., iterative Jacobi rotation), the manner in which the transformation is performed, the manner in which the elements of each transformation matrix are represented, etc. The parameters to send as feedback may be encoded or compressed to further reduce the number of bits to send for the parameters.

[0078] FIG. 4 shows a design of a process 400 performed by a receiver. A set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to the receiver may be determined (block 410). For block 410, the transmit steering matrix may be derived based on a plurality of transformation matrices, which may be formed in any manner. The set of parameters may then be determined based on the plurality of transformation matrices. The set of parameters may be sent to the transmitter for use by the transmitter to derive the transmit steering matrix (block 412).

[0079] FIG. 5 shows a design of an apparatus 500 for a receiver. Apparatus 500 includes means for determining a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to the receiver (module 510) and means for sending the set of parameters to the transmitter for use by the transmitter to derive the transmit steering matrix (module 512). Modules 510 and 512 may comprise processors, electronics devices, hardware devices, electronics components, logical circuits, memories, etc., or any combination thereof.

[0080] FIG. 6 shows a design of a process 600 performed by a receiver. A plurality of iterations of Jacobi rotation may be performed on a channel matrix (e.g., $\underline{\mathbf{D}}_i$) with a plurality of transformation matrices (e.g., $\underline{\mathbf{T}}_i$) to zero out off-diagonal elements of the channel matrix (block 610). The channel matrix may be a correlation matrix $\underline{\mathbf{R}}$, a channel response matrix $\underline{\mathbf{H}}$, or some other matrix derived based on a channel response estimate. The transmit steering matrix may be initialized to an identity matrix, a transmit steering matrix obtained for another subcarrier, a transmit steering matrix obtained for another time interval, etc. (block 612)

[0081] For each iteration of the Jacobi rotation, indices p and q may be determined, e.g., by sweeping through the elements of the channel matrix in a predetermined order, or by identifying the largest off-diagonal element of the channel matrix (block 614). A submatrix (e.g., $\underline{\mathbf{D}}_{pq}$) of the channel matrix may be formed based on elements of the channel matrix at indices p and q (block 616). The submatrix may be decomposed to obtain an intermediate matrix (e.g., $\underline{\mathbf{V}}_{pq}$) of eigenvectors of the submatrix, e.g., as shown in equation set (7) (block 618). A transformation matrix (e.g., $\underline{\mathbf{T}}_i$) may be formed based on the intermediate matrix (block 620), and parameters of the transformation matrix may be saved (block 622). The channel matrix may be updated based on the transformation matrix, e.g., as shown in equation (9) (block 624). The transmit steering matrix may also be updated based on the transformation matrix, e.g., as shown in equation (10) (block 626).

[0082] If a termination condition is not encountered, as determined in block 628, then the process returns to block 614 for the next iteration of the Jacobi rotation. Otherwise, parameters for all transformation matrices used to derive the transmit steering matrix may be sent to the transmitter (block 630). These parameters may comprise, for each transformation matrix, at least one angle, at least one value, at least one index, an indication of the form of the transformation matrix, etc. The at least one angle may be given with uniform or non-uniform quantization, e.g., non-uniform quantization obtained from CORDIC computation.

[0083] FIG. 7 shows a design of a process 700 performed by a transmitter. A set of parameters defining a transmit steering matrix may be received from a receiver

(block 710). The transmit steering matrix may be derived based on the set of parameters (block 712). For block 712, a plurality of transformation matrices may be formed based on the set of parameters. The transmit steering matrix may then be updated with each of the transformation matrices. The transmit steering matrix may be used for transmission from the transmitter to the receiver (block 714).

[0084] FIG. 8 shows a design of a process for block 712 in FIG. 7. The transmit steering matrix may be initialized to an identity matrix, a transmit steering matrix for another subcarrier, a transmit steering matrix for another time interval, etc. (block 810). A transformation matrix may be formed based on parameters received for the transformation matrix (block 812). For example, at least one angle may be received for the transformation matrix, and CORDIC computation may be performed on the at least one angle to obtain at least one element of the transformation matrix. The transmit steering matrix may be updated with the transformation matrix (block 814). If all transformation matrices have not been applied, then the process returns to block 812 to form and apply the next transformation matrix. Otherwise, the process terminates.

[0085] FIG. 9 shows a design of an apparatus 900 for a transmitter. Apparatus 900 includes means for receiving a set of parameters defining a transmit steering matrix from a receiver (module 910), means for deriving the transmit steering matrix based on the set of parameters (module 912), and means for using the transmit steering matrix for transmission from the transmitter to the receiver (module 914). Modules 910 to 914 may comprise processors, electronics devices, hardware devices, electronics components, logical circuits, memories, etc., or any combination thereof.

[0086] The techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, firmware, software, or a combination thereof. For a hardware implementation, the processing units used to perform the techniques may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, electronic devices, other electronic units designed to perform the functions described herein, a computer, or a combination thereof.

[0087] For a firmware and/or software implementation, the techniques may be implemented with modules (e.g., procedures, functions, etc.) that perform the functions described herein. The firmware and/or software instructions may be stored in a memory (e.g., memory 132 or 182 in FIG. 1) and executed by a processor (e.g., processor 130 or 180). The memory may be implemented within the processor or external to the processor. The firmware and/or software instructions may also be stored in other processor-readable medium such as random access memory (RAM), read-only memory (ROM), non-volatile random access memory (NVRAM), programmable read-only memory (PROM), electrically erasable PROM (EEPROM), FLASH memory, compact disc (CD), magnetic or optical data storage device, etc.

[0088] The previous description of the disclosure is provided to enable any person skilled in the art to make or use the disclosure. Various modifications to the disclosure will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other variations without departing from the spirit or scope of the disclosure. Thus, the disclosure is not intended to be limited to the examples described herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. An apparatus comprising:

at least one processor configured to determine a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to a receiver, and to send the set of parameters to the transmitter for use by the transmitter to derive the transmit steering matrix; and

a memory coupled to the at least one processor.

2. The apparatus of claim 1, wherein the at least one processor is configured to derive the transmit steering matrix based on a plurality of transformation matrices, and to determine the set of parameters based on the plurality of transformation matrices.

3. The apparatus of claim 2, wherein the at least one processor is configured to perform a plurality of iterations of Jacobi rotation on a channel matrix with the plurality of transformation matrices to zero out off-diagonal elements of the channel matrix.

4. The apparatus of claim 3, wherein for each iteration of the Jacobi rotation the at least one processor is configured to derive a transformation matrix based on the channel matrix, to update the channel matrix based on the transformation matrix, and to update the transmit steering matrix based on the transformation matrix.

5. The apparatus of claim 4, wherein for each iteration of the Jacobi rotation, the at least one processor is configured to form a submatrix of the channel matrix, to decompose the submatrix to obtain an intermediate matrix of eigenvectors of the submatrix, and to form the transformation matrix based on the intermediate matrix.

6. The apparatus of claim 4, wherein for each iteration of the Jacobi rotation, the at least one processor is configured to identify a largest off-diagonal

element of the channel matrix, and to derive the transformation matrix based on row and column indices of the largest off-diagonal element.

7. The apparatus of claim 4, wherein the at least one processor is configured to select elements of the channel matrix in a predetermined order for the plurality of iterations of the Jacobi rotation, and to derive the transformation matrix for each iteration of the Jacobi rotation based on elements of the channel matrix selected for the iteration.

8. The apparatus of claim 4, wherein the at least one processor is configured to initialize the transmit steering matrix to an identity matrix, a transmit steering matrix for another subcarrier, or a transmit steering matrix for another time interval prior to the plurality of iterations of the Jacobi rotation.

9. The apparatus of claim 4, wherein the at least one processor is configured to derive the channel matrix based on a channel response estimate.

10. The apparatus of claim 4, wherein the at least one processor is configured to derive a correlation matrix for a channel response matrix and to use the correlation matrix as the channel matrix.

11. The apparatus of claim 2, wherein the set of parameters comprises at least one angle for at least one element of each of the transformation matrices.

12. The apparatus of claim 11, wherein the at least one processor is configured to obtain the at least one angle for each transformation matrix with uniform quantization.

13. The apparatus of claim 11, wherein the at least one processor is configured to obtain the at least one angle for each transformation matrix with non-uniform quantization from CORDIC computation.

14. The apparatus of claim 2, wherein the set of parameters comprises at least one value for at least one element of each transformation matrix, at least one index for the at least one element of each transmit, an indication of a form of each transformation matrix, or a combination thereof.

15. A method comprising:

determining a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to a receiver; and

sending the set of parameters to the transmitter for use by the transmitter to derive the transmit steering matrix.

16. The method of claim 15, wherein the determining the set of parameters comprises

deriving the transmit steering matrix based on a plurality of transformation matrices, and

determining the set of parameters based on the plurality of transformation matrices.

17. The method of claim 16, wherein the deriving the transmit steering matrix comprises

performing a plurality of iterations of Jacobi rotation on a channel matrix with the plurality of transformation matrices, and

for each iteration of the Jacobi rotation,

deriving a transformation matrix based on the channel matrix,

updating the channel matrix based on the transformation matrix, and

updating the transmit steering matrix based on the transformation matrix.

18. The method of claim 16, wherein the determining the set of parameters based on the plurality of transformation matrices comprises

forming the set of parameters with at least one angle for at least one element of each transformation matrix.

19. An apparatus comprising:

means for determining a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to a receiver; and

means for sending the set of parameters to the transmitter for use by the transmitter to derive the transmit steering matrix.

20. The apparatus of claim 19, wherein the means for determining the set of parameters comprises

means for deriving the transmit steering matrix based on a plurality of transformation matrices, and

means for determining the set of parameters based on the plurality of transformation matrices.

21. The apparatus of claim 20, wherein the means for deriving the transmit steering matrix comprises

means for performing a plurality of iterations of Jacobi rotation on a channel matrix with the plurality of transformation matrices, and

means for, for each iteration of the Jacobi rotation,

deriving a transformation matrix based on the channel matrix,

updating the channel matrix based on the transformation matrix, and

updating the transmit steering matrix based on the transformation matrix.

22. The apparatus of claim 20, wherein the means for determining the set of parameters based on the plurality of transformation matrices comprises

means for forming the set of parameters with at least one angle for at least one element of each transformation matrix.

23. A processor-readable medium including instructions stored thereon, comprising:

a first instruction set for determining a set of parameters defining a transmit steering matrix to be used for transmission from a transmitter to a receiver; and

a second instruction set for sending the set of parameters to the transmitter for use by the transmitter to derive the transmit steering matrix.

24. The processor-readable medium of claim 23, wherein the first instruction set comprises

a third instruction set for deriving the transmit steering matrix based on a plurality of transformation matrices, and

a fourth instruction set for determining the set of parameters based on the plurality of transformation matrices.

25. The processor-readable medium of claim 24, wherein the fourth instruction set comprises

a fifth instruction set for forming the set of parameters with at least one angle for at least one element of each transformation matrix.

26. An apparatus comprising:

at least one processor configured to receive a set of parameters defining a transmit steering matrix, to derive the transmit steering matrix based on the set of parameters, and to use the transmit steering matrix for transmission from a transmitter to a receiver; and

a memory coupled to the at least one processor.

27. The apparatus of claim 26, wherein the at least one processor is configured to initialize the transmit steering matrix, to form a plurality of transformation matrices based on the set of parameters, and to update the transmit steering matrix with each of the transformation matrices.

28. The apparatus of claim 27, wherein the at least one processor is configured to obtain at least one angle for at least one element of each transformation matrix from the set of parameters, and to form each transformation matrix based on the at least one angle for the transformation matrix.

29. The apparatus of claim 28, wherein the at least one processor is configured to derive the at least one element of each transformation matrix by performing CORDIC computation based on the at least one angle for the transformation matrix.

30. The apparatus of claim 27, wherein the at least one processor is configured to initialize the transmit steering matrix to an identity matrix, a transmit steering matrix for another subcarrier, or a transmit steering matrix for another time interval.

31. A method comprising:

receiving a set of parameters defining a transmit steering matrix;

deriving the transmit steering matrix based on the set of parameters; and

using the transmit steering matrix for transmission from a transmitter to a receiver.

32. The method of claim 31, wherein the deriving the transmit steering matrix comprises

initializing the transmit steering matrix,

forming a plurality of transformation matrices based on the set of parameters, and

updating the transmit steering matrix with each of the transformation matrices.

33. The method of claim 32, wherein the forming the plurality of transformation matrices comprises

obtaining at least one angle for at least one element of each transformation matrix from the set of parameters, and

forming each transformation matrix based on the at least one angle for the transformation matrix.

34. An apparatus comprising:

means for receiving a set of parameters defining a transmit steering matrix;

means for deriving the transmit steering matrix based on the set of parameters; and

means for using the transmit steering matrix for transmission from a transmitter to a receiver.

35. The apparatus of claim 34, wherein the means for deriving the transmit steering matrix comprises

means for initializing the transmit steering matrix,

means for forming a plurality of transformation matrices based on the set of parameters, and

means for updating the transmit steering matrix with each of the transformation matrices.

36. The apparatus of claim 35, wherein the means for forming the plurality of transformation matrices comprises

means for obtaining at least one angle for at least one element of each transformation matrix from the set of parameters, and

means for forming each transformation matrix based on the at least one angle for the transformation matrix.

37. A processor-readable medium including instructions stored thereon, comprising:

a first instruction set for receiving a set of parameters defining a transmit steering matrix;

a second instruction set for deriving the transmit steering matrix based on the set of parameters; and

a third instruction set for using the transmit steering matrix for transmission from a transmitter to a receiver.

38. The processor-readable medium of claim 37, wherein the second instruction set comprises

a fourth instruction set for initializing the transmit steering matrix,

a fifth instruction set for forming a plurality of transformation matrices based on the set of parameters, and

a sixth instruction set for updating the transmit steering matrix with each of the transformation matrices.

39. The processor-readable medium of claim 38, wherein the fifth instruction set comprises

a seventh instruction set for obtaining at least one angle for at least one element of each transformation matrix from the set of parameters, and

an eighth instruction set for forming each transformation matrix based on the at least one angle for the transformation matrix.