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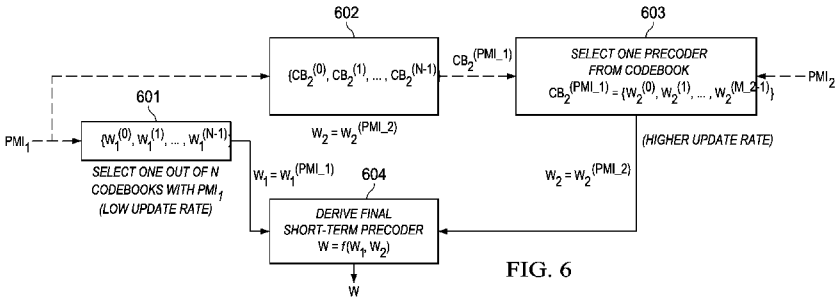

FIG. 6

(57) Abstract: Channel state information (CSI) feedback in a wireless communication system is disclosed. A precoding matrix is generated for multi-antenna transmission based on precoding matrix indicator (PMI) feedback, wherein the PMI indicates a choice of precoding matrix derived from a matrix multiplication of two matrices from a first codebook W1 and a second codebook W2. In one embodiment, the first codebook W1 comprises at least a first precoding matrix PMI1 constructed with a first group of adjacent Discrete-Fourier-Transform (DFT) vectors. In another embodiment, the first codebook W1 comprises at least a second precoding matrix PMI2 constructed with a second group of uniformly distributed non-adjacent DFT vectors. In yet another embodiment, the first codebook W1 comprises at least a first precoding matrix PMI1 and a second precoding matrix PMI2, where said first precoding matrix PMI1 is constructed with a first group of adjacent DFT vectors, and said second precoding matrix PMI2 is constructed with a second group of uniformly distributed non-adjacent DFT vectors.

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4TX CODEBOOK ENHANCEMENT IN LTE

[0001] This relates to wireless communication such as wireless telephony.

BACKGROUND

[0002] The disclosed embodiments relate to wireless communication systems and, more particularly, to the precoding of Physical Downlink Shared Channel (PDSCH) data and dedicated reference signals with codebook-based feedback for multi-input multi-output (MIMO) transmissions.

[0003] With Orthogonal Frequency Division Multiplexing (OFDM), multiple symbols are transmitted on multiple carriers that are spaced apart to provide orthogonality. An OFDM modulator typically takes data symbols into a serial-to-parallel converter, and the output of the serial-to-parallel converter is considered as frequency domain data symbols. The frequency domain tones at either edge of the band may be set to zero and are called guard tones. These guard tones allow the OFDM signal to fit into an appropriate spectral mask. Some of the frequency domain tones are set to values which will be known at the receiver. Among these are Channel State Information Reference Signals (CSI-RS) and Dedicated or Demodulating Reference Signals (DMRS). These reference signals are useful for channel estimation at the receiver.

[0004] In multi-input multi-output (MIMO) communication systems with multiple transmit/receive antennas, the data transmission is performed via precoding. Here, precoding refers to a linear (matrix) transformation of L-stream data into P-stream where L denotes the number of layers (also termed the transmission rank) and P denotes the number of transmit antennas. With the use of dedicated (*i.e.* user-specific) DMRS, a transmitter, such as a base station or eNodeB (eNodeB), can perform precoding operations that are transparent to user equipment (UE) acting as receivers. It is beneficial for the base station to obtain a precoding matrix recommendation from the user equipment. This is particularly the case for frequency-division duplexing (FDD) where the uplink and downlink channels occupy different parts of the frequency bands, *i.e.* the uplink and downlink are not reciprocal. Hence, a codebook-based feedback from the UE to the eNodeB is preferred. To enable a codebook-based feedback, a precoding codebook needs to be designed.

[0005] The Long-Term Evolution (LTE) specification includes codebooks for 2-antenna, 4-antenna, and 8-antenna transmissions. While those codebooks are designed efficiently, the present inventors recognize that still further improvements in downlink (DL) spectral efficiency are possible. Accordingly, the preferred embodiments described below are directed toward these problems as well as improving upon the prior art.

SUMMARY

[0006] Systems and methods for channel state information (CSI) and precoding matrix indicator (PMI) feedback in a wireless communication system are disclosed. A precoding matrix is generated for multi-antenna transmission based on a precoding matrix indicator (PMI) feedback from at least one remote receiver wherein the PMI indicates a choice of precoding matrix derived from a matrix multiplication of two matrices from a first codebook and a second codebook. One or more layers of a data stream are precoded with the precoding matrix and transmitted to the remote receiver.

[0007] In one embodiment, a method of CSI feedback and transmitting data in a wireless communication system comprises receiving one or more precoding matrix indicator (PMI) signals from a remote transceiver. The PMI signals indicating a choice of a precoding matrix W. The system generates the precoding matrix W from a matrix multiplication of two matrices W_1 and W_2. Matrix W is termed the composite precoder. Matrix W1 targets wideband/long-term channel properties, and matrix W2 targets frequency-selective/short-term channel properties. Each of the components W1, W2 is assigned a codebook. Hence, two distinct codebooks are needed: C_1 and C_2. Matrix W_1 is selected from a first codebook C_1 based on a first group of bits in the PMI signals, and matrix W_2 is selected from a second codebook C_2 based on a second group of bits in the PMI signals.

[0008] Proposed first and second codebooks C_1 and C_2 are defined below for different ranks and different PMI bit lengths.

[0009] In one embodiment, one or more layers of a data stream are precoded by multiplication with the precoding matrix W. The precoded layers in the data stream are then transmitted to the remote receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 illustrates an example wireless telecommunications network.

[0011] FIG. 2 illustrates a uniform linear array (ULA) or four pairs of ULA elements.

[0012] FIG. 3 illustrates four pairs of cross-polarized arrays.

[0013] FIG. 4 illustrates an example in which a grid of beams is shifted by m = 2 beams.

[0014] FIG. 5 illustrates an example of using a row selection vector to prune antenna pairs in an 8Tx array.

[0015] FIG. 6 illustrates the technique used in downlink LTE-Advanced (LTE-A).

[0016] FIG. 7 is a block diagram illustrating internal details of a mobile UE and an eNodeB in an example network system.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0017] FIG. 1 illustrates an example wireless telecommunications network 100. Network 100 includes a plurality of base stations 101, 102 and 103. In operation, a telecommunications network necessarily includes many more base stations. Each base station 101, 102 and 103 (eNodeB) is operable over corresponding coverage areas 104, 105 and 106. Each base station's coverage area is further divided into cells. In the illustrated network, each base station's coverage area is divided into three cells 104a-c, 105a-c, 106a-c. User equipment (UE) 107, such as telephone handset, is shown in Cell A 104a. Cell A 104a is within coverage area 104 of base station 101. Base station 101 transmits to and receives transmissions from UE 107. As UE 107 moves out of Cell A 104a and into Cell B 105b, UE 107 may be handed over to base station 102. Because UE 107 is synchronized with base station 101, UE 107 can employ non-synchronized random access to initiate handover to base station 102.

[0018] Non-synchronized UE 107 also employs non-synchronous random access to request allocation of uplink 108 time or frequency or code resources. If UE 107 has data ready for transmission, which may be traffic data, measurements report, tracking area update, UE 107 can transmit a random access signal on uplink 108. The random access signal notifies base station 101 that UE 107 requires uplink resources to transmit the UEs data. Base station 101 responds by transmitting to UE 107 via downlink 109, a message containing the parameters of the resources allocated for UE 107 uplink transmission along with a possible timing error correction. After receiving the resource allocation and a possible timing advance message transmitted on downlink 109 by base station 101, UE 107 optionally adjusts its transmit timing and transmits the data on uplink 108 employing the allotted resources during the prescribed time interval.

[0019] Base station 101 configs UE 107 for periodic uplink sounding reference signal (SRS) transmission. Base station 101 estimates uplink channel quality information (CSI) from the SRS transmission. The preferred embodiments of the present invention provide improved communication through precoded multi-antenna transmission with codebook-based feedback. In a cellular communication system, a UE is uniquely connected to and served by a single cellular base station or eNodeB at a given time. An example of such a system is the 3GPP LTE system, which includes the LTE-Advanced (LTE-A) system. With an increasing number of transmit antennas at the eNodeB, the task of designing an efficient codebook with desirable properties is challenging.

[0020] CSI consists of Channel Quality Indicator (CQI), precoding matrix indicator (PMI), precoding type indicator (PTI), and/or rank indication (RI). The time and frequency resources that can be used by the UE to report CSI are controlled by the eNodeB.

[0021] In one embodiment, a dual-stage codebook for CSI feedback is based on the product structure proposed in:

$$W=W_1W_2 \quad (1)$$

where W_1 targets wideband/long-term channel properties and W_2 targets frequency-selective/short-term channel properties. Each of the components W_1, W_2 is assigned a codebook. Hence, two distinct codebooks are needed: CB_1 and CB_2. W is termed the composite precoder. The choice of W_1 and W_2 are indicated via PMI_1 and PMI_2.

[0022] The following principles are enforced for codebook designs:

[0023] (1) Finite alphabet for W: each matrix element belongs to a finite set of values or constellation (*e.g.,* M-PSK alphabet).

[0024] (2) Constant modulus for W: all elements in a precoding matrix have the same magnitude. This is important to facilitate power amplifier (PA) balance property in all scenarios. Note that constant modulus is a sufficient condition for PA balance, but not a necessary condition. However, enforcing constant modulus property tends to result in a simpler codebook design. Note also that while the precoding codebook (for feedback) conforms to the constant modulus property, this does not restrict the eNodeB from using non-constant modulus precoder. This is possible due to the use of UE-specific RS for demodulation.

[0025] (3) Nested property for W: every matrix/vector of rank-n is a sub-matrix of a rank-(n+1) precoding matrix, n=1, 2, ..., N-1 where N is the maximum number of layers. While

this property is desirable as it allows to reduce the complexity of PMI selection, it is not necessary to facilitate rank override if UE-specific RS is used.

[0026] (4) The associated feedback signaling overhead should be minimized. This is achieved by a balance between the overhead associated with W_1 (wideband, long-term) and W_2 (sub-band, short-term). Here, both the time (feedback rate) and frequency (feedback granularity) dimensions are important.

[0027] (a) Blindly increasing the size of CB_1 (while reducing the size of CB_2) does not guarantee reducing the overall feedback overhead if a certain level of performance is expected. If the codebook CB_1 is meant to cover a certain precoder sub-space with a given spatial resolution, increasing the size of CB_1 demands an increase in feedbacks signaling associated with W_1, both in time and frequency. This is because CB_1 starts to capture shorter-term channel properties, which are meant to be parts of CB_2.

[0028] (b) To ensure that CB_1 does not need to be updated too frequently (in time and frequency), CB_1 should capture long-term channel properties such as the antenna setup and a range of values of angle of departure (AoD) which are associated with spatial correlation.

[0029] (c) The design should strive to keep the maximum overhead associated with W_2/CB_2 the same as the Release 8 PMI overhead (*i.e.*, $\leq$4 bits).

[0030] (5) Unitary precoder for W: (the column vectors of a precoder matrix must be pair-wise orthogonal to one another), while not necessary, is a sufficient condition for maintaining constant average transmitted power. This constraint is also used in designing the codebook at least for some relevant ranks.

[0031] The design of a 4Tx codebook for LTE disclosed herein targets an enhancement for multi-user (MU) MIMO over the 4Tx codebook in LTE Release 8. Rather than redesigning the 4Tx codebook, the enhancements disclosed herein focus on enhancing the MU-MIMO performance because the LTE Release 8 4Tx codebook was already designed to offer competitive performance for single-user (SU) MIMO (while keeping MU-MIMO in mind with the support of 8 discrete Fourier transform (DFT) vectors in the rank-1 codebook). Based on this consideration, the 4Tx enhancement focuses on rank-1 and at most rank-2 where MU-MIMO becomes relevant.

[0032] In terms of antenna setups, three setups may be considered:

- two dual-polarized elements with $\lambda/2$ (half wavelength) spacing between two elements,

- two dual-polarized elements with 4λ (larger) spacing between two elements, and
- uniform linear array (ULA) with λ/2 (half wavelength) spacing.

[0033] The first and the second setups have the highest priority. Good performance should be ensured for dual (*i.e.*, cross) polarized antenna arrays with both small and large spacing.

[0034] The antenna element indexing shown in FIGS. 2 and 3 is use enumerate the spatial channel coefficients $H_{n,m}$, where n and m are the receiver and transmitter antenna indices, respectively. FIG. 2 illustrates a ULA or four pairs of ULA elements indexed 1-8. FIG. 3 illustrates four pairs of cross-polarized arrays. The indexing for the four pairs of cross-polarized antennas represents grouping two antennas with the same polarization, which tend to be more correlated. This is analogous to the indexing of 4 pairs of ULA in FIG. 2.

Proposed Codebook Structure

[0035] The following notation is used to define the codebooks below:

W: 4Tx feedback precoding matrix.

W_1: first feedback precoding matrix

W_2: second feedback precoding matrix

i_1: PMI index of W_1

i_2: PMI index of W_2

N: maximum number of layers

N_{TXA}: number of transmit antennas

I_k: (k×k)-dimensional identity matrix

[0036] Following the guideline of using the same principle for 4Tx enhancement and 8Tx, the block diagonal grid-of-beam (GoB) structure is used. This structure is common between 4Tx and 8Tx.

[0037] W_1 and the associated codebook can be written as follows:

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{N-1} \end{bmatrix} \tag{2}$$

$$[\mathbf{B}]_{1+m,1+n} = e^{j\frac{2\pi mn}{N}}, \quad m = 0,1,\cdots,\frac{N_{TXA}}{2}-1 \quad n = 0,1,\cdots,N-1 \tag{3}$$

$$\mathbf{X}^{(k)} \in \left\{ \left[\mathbf{b}_{(N_b k) \bmod N} \quad \mathbf{b}_{(N_b k+1) \bmod N} \quad \cdots \quad \mathbf{b}_{(N_b k+N_b-1) \bmod N} \right] : k = 0,1,\cdots, \frac{N}{N_b} - 1 \right\} \tag{4}$$

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \quad , \quad C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \cdots, \mathbf{W}_1^{(N/N_b)-1} \right\} \tag{5}$$

[0038] Here, different W_1 matrices represent a partitioning (without overlap) in terms of beam angles:

- W_1 is a block diagonal matrix of size X where X is a $(N_{TXA}/2) \times Nb$ matrix. Nb denotes the number of adjacent $(N_{TXA}/2)$-Tx DFT beams contained in X. Such a design is able to synthesize N $(N_{TXA}/2)$-Tx DFT beams within each polarization group. For a given N, the spatial oversampling factor is essentially (N/2). The overall $(N_{TXA}/2)$-Tx DFT beam collections are captured in the $(N_{TXA}/2)$xN matrix B.
- By using co-phasing in W_2 (described below), the composite precoder W can synthesize up to N DFT beams.
- For 4Tx, it should be noted that the Release 8 rank-1 codebook already contains eight 4Tx DFT beams.
- The set of W_1 matrices represents (N/Nb)-level partitioning (hence non-overlapping) of the N beam angles (in X, *i.e.* each polarization group).
- This design results in a codebook size of (N/Nb) for W_1.

[0039] If some overlap in the set of beam angles is desired between two different W_1 matrices, the above formulation can be slightly modified such that two consecutive X matrices consists of some overlapping beam angles. Overlapping in beam angles may be beneficial to reduce "edge effects", *i.e.* to ensure that a common W_1 matrix can be better chosen for different resource blocks (RBs) within the same precoding sub-band when sub-band precoding or CSI feedback is used. Herein a sub-band refers to a set of continuous physical resource blocks (PRB). With overlapping,

$$\mathbf{X}^{(k)} \in \left\{ \left[\mathbf{b}_{(N_b k/2) \bmod N} \quad \mathbf{b}_{(N_b k/2+1) \bmod N} \quad \cdots \quad \mathbf{b}_{(N_b k/2+N_b-1) \bmod N} \right] : k = 0,1,\cdots, \frac{2N}{N_b} - 1 \right\} \tag{6}$$

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \quad , \quad C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \cdots, \mathbf{W}_1^{(2N/N_b)-1} \right\} \tag{7}$$

[0040] This enhancement targets MU-MIMO improvement and, therefore, is designed for rank-1 (and at most rank-2). At the same time, the Release 8 4Tx codebook should still be used at least for SU-MIMO. Keeping in mind that dynamic switching (switching without RRC configuration) between SU-MIMO and MU-MIMO is the baseline assumption for Release 12, an eNodeB should be able to use the Release 8 4Tx and the enhanced components interchangeably (*i.e.* the switching between the two components should be dynamic). Thanks to the dual-stage feedback structure and in particular the $W=W_1*W_2$ structure, this can be realized in a simple and natural manner. The enhanced component can be augmented or combined with the Release 8 codebook as follows:

- the Release 8 4Tx codebook is used as the codebook for W_2 and associated with W_1 = identity matrix;
- when PMI_1 indicates that W_1 = identity matrix is chosen, CB_2 is chosen as the original Rel-8 codebook;
- else, when PMI_1 indicates some other W_1, W_1 and CB_2 are chosen as the enhanced component.

[0041] The above switching/augmentation mechanism features the following:

- best possible 4Tx MU-MIMO codebook enhancement opportunity. This is because the optimization effort for the new components can be focused on improving MU-MIMO without the need for considering the SU-MIMO performance (which is covered by the Release 8 4Tx codebook). Furthermore, the new components can be designed "from scratch" as the above augmentation mechanism with Release 8 4Tx codebook can be done without constraining any of the structures of the new components.
- maintain best possible performance for 4Tx SU-MIMO without additional standardization effort. This comes from the use of Release 8 4Tx codebook. It is noted that the Release 8 4Tx codebook offers competitive performance in various antenna and channel setups including dual-polarized arrays as pointed out partly due to the inherent block diagonal structure in a number of the precoder matrices/vectors.

- achieve flexible frequency-selective precoding with physical uplink shared channel (PUSCH) mode 3-2. If Release 8 codebook is not re-used and the new codebook is entirely based on the $W=W_1W_2$ structure, all subband PMI must fall in the same Grid-of-Beam (GoB) due to the wideband W_1 constraint. This inevitably limits the precoding gains of mode 3-2 and system performance. On the contrary, by augmenting the Release 8 codebook, all Release 8 PMI vectors can be used on each subband independently without any constraint. This is critical to ensure flexible subband precoding.

[0042] The design for W_2 (based on co-phasing and selection) follows the structure used for 8Tx codebook design. Co-phasing allows some phase adjustment between the two polarization groups and generation of 4Tx DFTTx DFT vectors from two block diagonal 2Tx DFTTx DFT matrices. The (group) selection operation allows refinement/adjustment of beam angles across RBs within the same sub-band thereby maximizing frequency-selective precoding gain.

[0043] The combination of beam selection and co-phasing in W_2 – combined with W_1 – should result in a unitary precoder $W=W_1W_2$.

[0044] An example of a complete design with non-overlapping block diagonal GoB augmentation of (N,Nb) codebook is given in the subsequent sections. It is straightforward to extend the proposed designs to include adjacent W_1 matrix overlapping, but is omitted here due to simplicity.

$$\mathbf{B}=\begin{bmatrix}\mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{N-1}\end{bmatrix} \quad , \quad [\mathbf{B}]_{l+m,l+n}=e^{j\frac{2\pi mn}{N}}, \quad m=0,1 \quad n=0,1,\cdots,N-1 \tag{8}$$

$$\mathbf{X}^{(k)} \in \left\{\begin{bmatrix}\mathbf{b}_{(N_b k)\bmod N} & \mathbf{b}_{(N_b k+1)\bmod N} & \cdots & \mathbf{b}_{(N_b k+N_b-1)\bmod N}\end{bmatrix} : k=0,\ldots N/N_b-1\right\} \tag{9}$$

Rank-1

[0045] Assuming (N, Nb) = (8,4) as an example.

$$\mathbf{W}_1 \in C_1=\left\{\mathbf{I}_4,\begin{bmatrix}\mathbf{X}^{(0)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(0)}\end{bmatrix},\begin{bmatrix}\mathbf{X}^{(1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(1)}\end{bmatrix}\right\} \tag{10}$$

→ size-3 (Rel-8 codebook augmented with block diagonal GoB).

[0046] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r1}$, where $C_{2,R8Tx4r1}$ denotes the Release 8 4Tx rank-1 codebook used for W_2.

[0047] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} (k = 0,1)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ \mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ j\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -j\mathbf{Y} \end{bmatrix} \right\}, \quad \mathbf{Y} \in \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}$$

[0048] The rank-1 PMI overhead for this example is shown in Table 1.

	W1 overhead (wideband)	W2 overhead (subband)
Rank-1	log2(3)-bits	4-bit

TABLE 1

[0049] Other values of (N, Nb) are not precluded if justified by sufficient system performance gain and reasonable feedback overhead.

[0050] Note that the block-diagonal enhancement components are sub-matrices of a subset of the Release 10 8Tx codebook. As such, the 4Tx GoB components can be obtained by pruning the 8Tx codebook for 4Tx MIMO feedback. This is discussed in more detail below.

[0051] N, Nb can also take other values. For example if (N, Nb) = (16, 4).

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(1)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(1)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(2)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(3)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(3)} \end{bmatrix} \right\} \tag{11}$$

→ size-5 (Rel-8 codebook augmented with block diagonal GoB).

[0052] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r1}$, where $C_{2,R8Tx4r1}$ denotes the Release 8 4Tx rank-1 codebook used for W_2.

[0053] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} (k = 0,1,2,3)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ \mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ j\mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -\mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -j\mathbf{Y}\end{bmatrix} \right\}, \quad \mathbf{Y} \in \left\{ \begin{bmatrix}1\\0\\0\\0\end{bmatrix}, \begin{bmatrix}0\\1\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\0\\0\\1\end{bmatrix} \right\}$$

[0054] The rank-1 PMI overhead for this example is shown in Table 2.

	W1 overhead (wideband)	W2 overhead (subband)
Rank-1	log2(5)-bits	4-bit

TABLE 2

[0055] It is possible in some embodiments that the Release 12 4Tx codebook does not comprise the Release 8 codebook. In that case, the identity matrix I_4 is removed from the W_1 codebook C_1.

[0056] It is also possible to increase the value of N (*e.g.* to 32 or 64). This however increases the C_1 codebook size and feedback overhead, and reduces the span of angular spread that Nb adjacent beams can cover.

Rank-2:

[0057] Assuming (N,Nb) = (8,4) as an example:

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix}\mathbf{X}^{(0)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(0)}\end{bmatrix}, \begin{bmatrix}\mathbf{X}^{(1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(1)}\end{bmatrix} \right\} \tag{12}$$

→ size-3 (Rel-8 codebook augmented with block diagonal GoB).

[0058] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r2}$, where $C_{2,R8Tx4r2}$ denotes the Release 8 4Tx rank-2 codebook used for W_2.

[0059] When $\mathbf{W}_1 = \begin{bmatrix}\mathbf{X}^{(k)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(k)}\end{bmatrix} (k = 0,1)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} & \mathbf{Y} \\ \mathbf{Y} & -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} & \mathbf{Y} \\ j\mathbf{Y} & -j\mathbf{Y} \end{bmatrix} \right\}, \quad \mathbf{Y} \in \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}$$

[0060] One minor shortcoming of this design is that the W_2 overhead is not constant, but varying dependent on the W_1 matrix. In particular,

- if $W_1 = I$, W_2 overhead is 4-bits per subband; and
- if W_1 corresponds to the block-diagonal component, W_2 overhead is 3-bits per subband.

[0061] Because W_1 and W_2 are jointly encoded in the PUSCH feedback mode, joint blind decoding of W_1/W_2 is required at the eNodeB, which may increase the eNodeB implementation complexity.

[0062] As one solution, the two columns in a rank-2 precoding matrix W may be chosen from different beams in one grid.

[0063] As an example, the following design is possible.

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(1)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(1)} \end{bmatrix} \right\} \tag{13}$$

→ size-3 (Rel-8 codebook augmented with block diagonal GoB).

[0064] When $\mathbf{W}_1 = \mathbf{I}_4$:then $\mathbf{W}_2 \in C_{2,R8Tx4r2}$, where $C_{2,R8Tx4r2}$ denotes the Release 8 4Tx rank-2 codebook used for W_2.

[0065] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0,1)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4), (e_1^4, e_2^4), (e_2^4, e_3^4), (e_1^4, e_4^4), (e_2^4, e_4^4) \right\}$$

where e_q^p is a $p \times 1$ column vector with all elements equivalent to zero, except the q-th element which is 1. The W_2 overhead is 4-bits per subband, consistent with the Release 8 codebook overhead. Note that any other $(\mathbf{Y}_1, \mathbf{Y}_2)$ pair, denoted by (e_m^4, e_n^4), are equally applicable, where $1 \le m \le 4, 1 \le n \le 4, m \ne n$.

[0066] Note that in any of the (Y_1, Y_2) pair above, the two selection vectors inside the brackets [ ] can be permuted. For example, (e_1^4, e_2^4) can be replaced by (e_2^4, e_1^4), and the resulting codebook is equivalently applicable.

[0067] It should be noted that that the block-diagonal enhancement components are sub-matrices of a subset of the Release 10 8Tx codebook.

[0068] As another solution, it can be resolved by adopting a (N, Nb) = (16, 8) codebook enhancement.

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(1)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(1)} \end{bmatrix} \right\} \tag{14}$$

→ size-3 (Rel-8 codebook augmented with block diagonal GoB).

[0069] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r2}$, where $C_{2,R8Tx4r2}$ denotes the Release 8 4Tx rank-2 codebook used for W_2.

[0070] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0,1)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} & \mathbf{Y} \\ \mathbf{Y} & -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} & \mathbf{Y} \\ j\mathbf{Y} & -j\mathbf{Y} \end{bmatrix} \right\}, \quad \mathbf{Y} \in \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \right\}$$

[0071] The rank-2 PMI overhead for this example is shown in Table 3.

	W1 overhead (wideband)	W2 overhead (subband)
Rank-2	log2(3)-bit	4-bit

TABLE 3

[0072] Alternatively, it is possible that the Release 12 4Tx codebook does not comprise of the Release 8 codebook. In that case, the identity matrix is removed from the W_1 codebook C_1.

[0073] Another possible design is to use (N,Nb) = (16,4) as

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(1)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(1)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(2)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(2)} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^{(3)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(3)} \end{bmatrix} \right\} \quad (15)$$

→ size-5 (Rel-8 codebook augmented with block diagonal GoB).

[0074] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r2}$, where $C_{2,R8Tx4r2}$ denotes the Release 8 4Tx rank-2 codebook used for W_2.

[0075] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0,...,3)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4), (e_1^4, e_2^4), (e_2^4, e_3^4), (e_1^4, e_4^4), (e_2^4, e_4^4) \right\}$$

[0076] It is also possible to increase the value of N (*e.g.* to 32 or 64). This however increases the C_1 codebook size and feedback overhead, and reduces the span of angular spread that Nb adjacent beams can cover.

Rank-3:

[0077] The simplest solution is to reuse the Release 8 codebook as-is for Release 12.

$$\mathbf{W}_1 = \mathbf{I}_4 \quad (16)$$

→ size-1 (Rel-8 codebook only).

$\mathbf{W}_2 \in C_{2,R8Tx4r3}$, where $C_{2,R8Tx4r3}$ denotes the Release 8 4Tx rank-3 codebook used for W_2.

[0078] If enhancement based on (N,Nb) structure is warranted by sufficient performance gain, it can be done in a similar fashion as for rank-1 and rank-2. For instance, based on a (N,Nb) = (4,4) design:

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix} \right\} \quad (17)$$

→ size-2 (Rel-8 codebook augmented with block diagonal GoB).

[0079] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r3}$, where $C_{2,R8Tx4r3}$ denotes the Release 8 4Tx rank-3 codebook used for W_2.

[0080] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \begin{matrix} (e_1^4,[e_1^4,e_3^4]),(e_2^4,[e_2^4,e_4^4]),(e_3^4,[e_1^4,e_3^4]),(e_4^4,[e_2^4,e_4^4]), \\ ([e_1^4,e_3^4],e_1^4),([e_2^4,e_4^4],e_2^4),([e_1^4,e_3^4],e_3^4),([e_2^4,e_4^4],e_4^4) \end{matrix} \right\},$$

corresponding to $i_2 = 0, \ldots, 7$.

[0081] To make the W_2 overhead consistent for different W_1 matrices, $i_2 = 8, \ldots, 15$ shall be reserved for W_2 corresponding to W_1 matrices that are enhancement components (*e.g.* block diagonal).

[0082] Alternatively, when $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \begin{matrix} (e_1^4,[e_1^4,e_3^4]),(e_2^4,[e_2^4,e_4^4]),(e_3^4,[e_1^4,e_3^4]),(e_4^4,[e_2^4,e_4^4]), \\ ([e_1^4,e_3^4],e_1^4),([e_2^4,e_4^4],e_2^4),([e_1^4,e_3^4],e_3^4),([e_2^4,e_4^4],e_4^4) \end{matrix} \right\}.$$

In this case W2 overhead is 4-bits per sub-band.

[0083] The rank-3 PMI overhead for this example is shown in Table 4.

	W1 overhead (wideband)	W2 overhead (subband)
Rank-3	0-bit (w/o augmentation) 1-bit (w/ augmentation)	4-bit

TABLE 4

[0084] It is possible that the Release 12 4Tx codebook does not comprise of the Release 8 codebook. In that case, the identity matrix is removed from the W_1 codebook C_1.

[0085] Note that in any of the (Y_1, Y_2) pairs above, the two selection vectors inside the brackets can be permuted. For example, $(e_1^4,[e_1^4,e_3^4])$ can be replaced by $(e_1^4,[e_3^4,e_1^4])$, and the resulting codebook is equivalently applicable.

[0086] It is not precluded that the Release 12 4Tx rank-3 codebook is redesigned using the GoB component as proposed above, and not include any Release 8 4Tx rank-3 precoding matrices.

[0087] Another alternative GoB design is (N,Nb) = (8,8), where

$$\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} (k = 0), \text{ and}$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\} \text{ , or}$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \begin{Bmatrix} (e_1^4, [e_1^4, e_5^4]), (e_2^4, [e_2^4, e_6^4]), (e_3^4, [e_3^4, e_7^4]), (e_4^4, [e_4^4, e_8^4]), \\ (e_5^4, [e_1^4, e_5^4]), (e_6^4, [e_2^4, e_6^4]), (e_7^4, [e_3^4, e_7^4]), (e_3^4, [e_4^4, e_8^4]), \\ ([e_1^4, e_5^4], e_1^4), ([e_2^4, e_6^4], e_2^4), ([e_3^4, e_7^4], e_3^4), ([e_4^4, e_8^4], e_4^4), \\ ([e_1^4, e_5^4], e_5^4), ([e_2^4, e_6^4], e_6^4), ([e_3^4, e_7^4], e_7^4), ([e_4^4, e_8^4], e_8^4), \end{Bmatrix}$$

Rank-4:

[0088] The simplest solution is to reuse Release 8 codebook as-is for Release 12.

$$\mathbf{W}_1 = \mathbf{I}_4 \qquad (18)$$

→ Size-1 (Rel-8 codebook only).

$\mathbf{W}_2 \in C_{2,R8Tx4r4}$, where $C_{2,R8Tx4r4}$ denotes the Release 8 4Tx rank-4 codebook used for W_2.

[0089] If enhancement based on (N,Nb) structure is warranted by sufficient performance gain, it can be done in a similar fashion as for rank-1 and rank-2. For instance, based on a (N,Nb) = (4,4) design,

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix} \right\} \qquad (19)$$

→ Size-2 (Rel-8 codebook augmented with block diagonal GoB)

[0090] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r4}$, where $C_{2,R8Tx4r4}$ denotes the Release 8 4Tx rank-4 codebook used for W_2.

[0091] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} (k = 0)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

where

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \begin{matrix} ([e_1^4, e_3^4], [e_1^4, e_3^4]), ([e_2^4, e_4^4], [e_2^4, e_4^4]), \\ ([e_1^4, e_3^4], [e_2^4, e_4^4]), ([e_2^4, e_4^4], [e_1^4, e_3^4]) \end{matrix} \right\},$$

corresponding to $i_1 = 0, \ldots, 7$.

[0092] Note there are a total of 8 W_2 matricess ($i_2 = 0, \ldots, 7$) for $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$. To make the W_2 overhead consistent across all W_1, W_2 can be reserved for $i_2 = 8, \ldots, 15$.

[0093] Alternatively, one may adopt a (N, Nb) = (8,8) codebook as below:

$$\mathbf{W}_1 \in C_1 = \left\{ \mathbf{I}_4, \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix} \right\} \tag{20}$$

→ Size-2 (Rel-8 codebook augmented with block diagonal GoB).

[0094] When $\mathbf{W}_1 = \mathbf{I}_4$, then $\mathbf{W}_2 \in C_{2,R8Tx4r4}$, where $C_{2,R8Tx4r4}$ denotes the Release 8 4Tx rank-4 codebook used for W_2.

[0095] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = 0)$, then

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \text{ and}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \begin{matrix} ([e_1^8, e_5^8], [e_1^8, e_5^8]), ([e_2^8, e_6^8], [e_2^8, e_6^8]), ([e_3^8, e_7^8], [e_3^8, e_7^8]), ([e_4^8, e_8^8], [e_4^8, e_8^8]), \\ ([e_1^8, e_5^8], [e_2^8, e_6^8]), ([e_1^8, e_5^8], [e_3^8, e_7^8]), ([e_2^8, e_6^8], [e_4^8, e_8^8]), ([e_3^8, e_7^8], [e_4^8, e_8^8]) \end{matrix} \right\}.$$

[0096] Note that in any of the $(\mathbf{Y}_1, \mathbf{Y}_2)$ pair above, the two selection vectors inside the brackets [ ] can be permuted.

[0097] Also note that any $(\mathbf{Y}_1, \mathbf{Y}_2)$ pair above can be replaced by a different pair denoted as $([e_m^{N_b}, e_{m+N/2}^{N_b}], [e_n^{N_b}, e_{n+N/2}^{N_b}])$, where $1 \le m \le N/2, \quad 1 \le n \le N/2$.

[0098] The rank-4 PMI overhead for this example is shown in Table 5.

	W1 overhead (wideband)	W2 overhead (sub-band)
Rank-4	0-bit (w/o augmentation) 1-bit (w/ augmentation)	4-bit

TABLE 5

[0099] It is possible that the Release 12 4Tx codebook does not comprise of the Release 8 codebook. In that case, the identity matrix is removed from the W_1 codebook C_1.

[00100] It is not precluded that the Release 12 4Tx rank-4 codebook is redesigned using the GoB component as proposed above, and not includes any Release 8 4Tx rank-4 precoding matrices.

[00101] The final 4Tx codebook comprises of rank-r codebook, r = 1, 2, 3, 4. For each rank r, the corresponding rank-r codebook can be constructed by methods discussed above regarding rank-1 to rank-4 codebooks. It is not precluded that codebook is enhanced for certain rank(s), while for the other ranks, Release 8 codebook is reused.

Reformulation of Proposed Rank-1 to Rank-4 Codebooks

[00102] Using (N, Nb) = (16,4) as an example, the proposed codebook in the sections above may be re-formulated by the equations shown in the tables below. It should be noted that these tables can be easily extended to other (N, Nb) values.

Rank-1 and Rank-2

[00103] If Release 12 4Tx codebook for rank-1 and rank-2 is redesigned by the GoB framework with adjacent beams overlapping, and does not include the Release 8 codebook, the 4Tx codebooks can be expressed by equations in Tables 6-1 and 6-2.

[00104] A first PMI value of $n_1 \in \{0,1,\cdots,f(\upsilon)-1\}$ and a second PMI value of $n_2 \in \{0,1,\cdots,g(\upsilon)-1\}$ correspond to the codebook indices ^{n1} and ^{n2} given in Table.6-*j*, where υ is equal to the associated rank value and where j = υ, $f(\upsilon)=\{8,8\}$ and $g(\upsilon)=\{16,16\}$. Interchangeably, the first and second precoding matrix indicators are expressed by i_1 and i_2.

[00105] The quantities φ_n and v_m are expressed by

$$\varphi_n = e^{j\pi n/2} \tag{21}$$

$$v_m = \left[1;\quad e^{j2\pi m/16}\right] \tag{22}$$

[00106] Table 6-1 illustrates a codebook for 1-layer CSI reporting according to one embodiment.

i_1	i_2							
	0	1	2	3	4	5	6	7
0-7	$W^{(1)}_{2i_1,0}$	$W^{(1)}_{2i_1,1}$	$W^{(1)}_{2i_1,2}$	$W^{(1)}_{2i_1,3}$	$W^{(1)}_{2i_1+1,0}$	$W^{(1)}_{2i_1+1,1}$	$W^{(1)}_{2i_1+1,2}$	$W^{(1)}_{2i_1+1,3}$
i_1	i_2							
	8	9	10	11	12	13	14	15
0-7	$W^{(1)}_{2i_1+2,0}$	$W^{(1)}_{2i_1+2,1}$	$W^{(1)}_{2i_1+2,2}$	$W^{(1)}_{2i_1+2,3}$	$W^{(1)}_{2i_1+3,0}$	$W^{(1)}_{2i_1+3,1}$	$W^{(1)}_{2i_1+3,2}$	$W^{(1)}_{2i_1+3,3}$
where $W^{(1)}_{m,n} = \frac{1}{\sqrt{4}}\begin{bmatrix} v_m \\ \varphi_n v_m \end{bmatrix}$								

TABLE 6-1

[00107] Table 6-2 illustrates a codebook for 2-layer CSI reporting according to one embodiment.

i_1	i_2			
	0	1	2	3
0 – 7	$W^{(2)}_{2i_1,2i_1,0}$	$W^{(2)}_{2i_1,2i_1,1}$	$W^{(2)}_{2i_1+1,2i_1+1,0}$	$W^{(2)}_{2i_1+1,2i_1+1,1}$
i_1	i_2			
	4	5	6	7
0 – 7	$W^{(2)}_{2i_1+2,2i_1+2,0}$	$W^{(2)}_{2i_1+2,2i_1+2,1}$	$W^{(2)}_{2i_1+3,2i_1+3,0}$	$W^{(2)}_{2i_1+3,2i_1+3,1}$
i_1	i_2			
	8	9	10	11
0 – 7	$W^{(2)}_{2i_1,2i_1+1,0}$	$W^{(2)}_{2i_1,2i_1+1,1}$	$W^{(2)}_{2i_1+1,2i_1+2,0}$	$W^{(2)}_{2i_1+1,2i_1+2,1}$
i_1	i_2			
	12	13	14	15
0 – 7	$W^{(2)}_{2i_1,2i_1+3,0}$	$W^{(2)}_{2i_1,2i_1+3,1}$	$W^{(2)}_{2i_1+1,2i_1+3,0}$	$W^{(2)}_{2i_1+1,2i_1+3,1}$
where $W^{(2)}_{m,m',n} = \frac{1}{\sqrt{8}}\begin{bmatrix} v_m & v_{m'} \\ \varphi_n v_m & -\varphi_n v_{m'} \end{bmatrix}$				

TABLE 6-2

[00108] If the Release 12 4Tx codebook for rank-1 and rank-2 is designed by augmenting the existing Release 8 codebook with GoB components, then the Release 12 4Tx codebook can be expressed as in Table 6-3 and Table 6-4.

[00109] Table 6-3 illustrates a codebook for 1-layer CSI reporting according to one embodiment.

i_1	i_2															
0	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Use precoding matrix of index i_2 of Release 8 4Tx rank-1 codebook															
i_1	i_2															
1-8	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Corresponding to i_1 = 0-7 in table 6-1															

TABLE 6-3

[00110] Table 6-4 illustrates a codebook for 2-layer CSI reporting according to one embodiment.

i_1	i_2															
0	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Use precoding matrix of index i_2 of Release 8 4Tx rank-1 codebook															
i_1	i_2															
1-8	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Corresponding to i_1 = 0-7 in table 6-2															

TABLE 6-4

Rank-3 and Rank-4

[00111] If the Release 12 4Tx codebook for rank-3 and rank-3 is redesigned by the GoB framework with adjacent beams overlapping, and not includes the Release 8 codebook, the 4Tx codebooks can be expressed by equations in Table 6-5 and 6-6.

[00112] Table 6-5 illustrates a codebook for 3-layer CSI reporting according to one embodiment.

i_1	i_2			
	0	1	2	3
0	$W^{(3)}_{16i_1,16i_1,16i_1+8,0}$	$W^{(3)}_{16i_1,16i_1,16i_1+8,1}$	$W^{(3)}_{16i_1+4,16i_1+4,16i_1+12,0}$	$W^{(3)}_{16i_1+4,16i_1+4,16i_1+12,1}$
i_1	i_2			
	4	5	6	7
0	$W^{(3)}_{16i_1+8,16i_1,16i_1+8,0}$	$W^{(3)}_{16i_1+8,16i_1,16i_1+8,1}$	$W^{(3)}_{16i+12_1,16i_1+4,16i_1+12,0}$	$W^{(3)}_{16i_1+12,16i_1+4,16i_1+12,1}$
i_1	i_2			
	8	9	10	11
0	$\tilde{W}^{(3)}_{16i_1,16i_1+8,16i_1,0}$	$\tilde{W}^{(3)}_{16i_1,16i_1+8,16i_1,1}$	$\tilde{W}^{(3)}_{16i_1+4,16i_1+12,16i_1+4,0}$	$\tilde{W}^{(3)}_{16i_1+4,16i_1+12,16i_1+4,1}$
i_1	i_2			
	12	13	14	15
0	$\tilde{W}^{(3)}_{16i_1,16i_1+8,16i_1+8,0}$	$\tilde{W}^{(3)}_{16i_1,16i_1+8,16i_1+8,1}$	$\tilde{W}^{(3)}_{16i_1+4,16i_1+12,16i_1+12,0}$	$\tilde{W}^{(3)}_{16i_1+4,16i_1+12,16i_1+12,1}$
where $W^{(3)}_{m,m',m'',n} = \frac{1}{\sqrt{12}}\begin{bmatrix} v_m & v_{m'} & v_{m''} \\ \varphi_n v_m & -\varphi_n v_{m'} & -\varphi_n v_{m''} \end{bmatrix}$, $\tilde{W}^{(3)}_{m,m',m'',n} = \frac{1}{\sqrt{12}}\begin{bmatrix} v_m & v_{m'} & v_{m''} \\ \varphi_n v_m & \varphi_n v_{m'} & -\varphi_n v_{m''} \end{bmatrix}$				

TABLE 6-5

[00113] Table 6-6 illustrates a codebook for 4-layer CSI reporting according to one embodiment.

i_1	i_2			
	0	1	2	3
0	$W^{(4)}_{16i_1,16i_1+8,16i_1,16i_1+8,0}$	$W^{(4)}_{16i_1,16i_1+8,16i_1,16i_1+8,1}$	$W^{(4)}_{16i_1+4,16i_1+12,16i_1+4,16i_1+12,0}$	$W^{(4)}_{16i_1+4,16i_1+12,16i_1+4,16i_1+12,1}$
i_1	i_2			
	4	5	6	7
0	$W^{(4)}_{16i_1,16i_1+8,16i_1+4,16i_1+12,0}$	$W^{(4)}_{16i_1,16i_1+8,16i_1+4,16i_1+12,1}$	$W^{(4)}_{16i_1+4,16i_1+12,16i_1,16i_1+8,0}$	$W^{(4)}_{16i_1+4,16i_1+12,16i_1,16i_1+8,1}$
where $W^{(4)}_{m,m',m'',m''',n} = \frac{1}{\sqrt{16}}\begin{bmatrix} v_m & v_{m'} & v_{m''} & v_{m'''} \\ \varphi_n v_m & \varphi_n v_{m'} & -\varphi_n v_{m''} & -\varphi_n v_{m'''} \end{bmatrix}$				

TABLE 6-6

[00114] If the Release 12 4Tx codebook for rank-3 and rank-3 is designed by augmenting the existing Release 8 codebook with GoB components, the Release 12 4Tx codebook can be expressed as in Table 6-7and Table 6-8.

[00115] Table 6-7 illustrates a codebook for 3-layer CSI reporting according to one embodiment.

i_1	i_2															
0	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Use precoding matrix of index i_2 of Release 8 4Tx rank-3 codebook															
i_1	i_2															
1-8	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Corresponding to i_1 = 0-7 in Table 6-5.															

TABLE 6-7

[00116] Table 6-8 illustrates a codebook for 4-layer CSI reporting according to one embodiment.

i_1	i_2															
0	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Use precoding matrix of index i_2 of Release 8 4Tx rank-4 codebook															
i_1	i_2															
1-8	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	For i_2 = 0 – 7: corresponding to i_1 = 0-7 in Table 6-6. For i_2 = 8 – 15: reserved.															

TABLE 6-8

Alternative Codebook Designs

[00117] For the W_1 codebook C_1 proposed above, the GoB component is expressed in the form of a block diagonal matrix as

$$\mathbf{W}_1 \in C_1 = \left\{ \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \right\} \tag{23}$$

where without overlapping:

$$\mathbf{X}^{(k)} \in \left\{ \left[\mathbf{b}_{(N_b k) \bmod N} \quad \mathbf{b}_{(N_b k+1) \bmod N} \quad \cdots \quad \mathbf{b}_{(N_b k+N_b-1) \bmod N} \right] : k = 0,1,\cdots, \frac{N}{N_b} - 1 \right\}, \tag{24}$$

and with overlapping:

$$\mathbf{X}^{(k)} \in \left\{ \left[\mathbf{b}_{(N_b k/2) \bmod N} \quad \mathbf{b}_{(N_b k/2+1) \bmod N} \quad \cdots \quad \mathbf{b}_{(N_b k/2+N_b-1) \bmod N} \right] : k = 0,1,\cdots, \frac{2N}{N_b} - 1 \right\}. \tag{25}$$

Each $\mathbf{X}^{(k)}$ represents a group of Nb adjacent beams that model a certain angle of arrival and angular spread.

[00118] Alternative designs are possible where the block diagonal sub-matrix of W_1 (*i.e.* $\mathbf{X}^{(k)}$) is replaced by linear or non-linear transformations of $\mathbf{X}^{(k)}$, for example:

$$\mathbf{W}_1(n,m,k) \in C_1 = \left\{ \begin{bmatrix} f_n\left(\mathbf{X}^{(k)}\right) & \mathbf{0} \\ \mathbf{0} & g_m\left(\mathbf{X}^{(k)}\right) \end{bmatrix}, k = 0,... \right\}, \tag{26}$$

where $f_n(\ )$, $g_m(\ )$, $n = 0,....,m = 0,...$ are linear/non-linear transformation functions.

[00119] In the following section several such possible designs are described assuming (N,Nb) = (16,4) as an example, but extension to other (N, Nb) values are straightforward.

[00120] It is also assumed that the Release 12 4Tx codebook is redesigned using the GoB structure and does not include the Release 8 4Tx codebook; however it is straightforward to augment the Release 8 4Tx codebook by the designs proposed below.

Example 1: Beam Shifting

[00121] In one embodiment,

$$\mathbf{W}_1(n,m,k) \in C_1 = \left\{ \begin{bmatrix} f_n\left(\mathbf{X}^{(k)}\right) & \mathbf{0} \\ \mathbf{0} & g_m\left(\mathbf{X}^{(k)}\right) \end{bmatrix}, k = 0,... \right\} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{D}(m)\mathbf{X}^{(k)} \end{bmatrix}. \tag{27}$$

Alternatively,

$$C_1 = \begin{bmatrix} \mathbf{D}(m)\mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}. \tag{28}$$

$\mathbf{D}(m)$ $(m = 0,1...N-1)$ is a Nt/2×Nt/2 diagonal matrix, in the case of Nt $= 4$ denoted as

$$\mathbf{D}=\begin{bmatrix}1 & 0\\ 0 & e^{j\frac{2\pi m}{N}}\end{bmatrix}. \qquad (29)$$

Herein $\mathbf{D}(m)$ performs beam shifting. For instance, as the first sub-matrix $\mathbf{X}^{(k)}$ comprises of Nb adjacent beams $\mathbf{b}_{(N_b k)\bmod N}$ $\mathbf{b}_{(N_b k+1)\bmod N}$ $\cdots$ $\mathbf{b}_{(N_b k+N_b-1)\bmod N}$, the second sub-matrix $\mathbf{D}(m)\mathbf{X}^{(k)}$ comprises a different grid of Nb beams as

$$\mathbf{b}_{(N_b k+m)\bmod N}\quad \mathbf{b}_{(N_b k+1+m)\bmod N}\quad \cdots\quad \mathbf{b}_{(N_b k+N_b-1+m)\bmod N}.$$

In other words, the second grid of beam is shifted by m beams, where m can take values from 0 to N-1. If m = 0, .. N-1, the W_1 codebook size is increased to $N\frac{N}{N_b}$ without W_1 overlapping, and $N\frac{2N}{N_b}$ with W_1 overlapping. Note that the codebook proposed in the initial sections above is a special case where m = 0, in which case there is no beam shifting.

[00122] FIG. 4 illustrates an example in which a grid of beams is shifted by m = 2 beams. A first grid of Nb beams 401 is selected from N beams 402. The second grid of beams 403 is selected from the N beams 402, but is shifted by two beams 404, 405 relative to the first grid of beams 401.

[00123] It is not precluded that a subset of $\mathbf{D}(m)$ matrices are used in constructing codebook C_1, where $m\in\Pi$, $\Pi\subseteq\{0,....N-1\}$. For instance, when $\Pi=\{1\}$, the Nb beams in the second grid of beams (*e.g.,* for the vertical polarization array 402) are all shifted by 1 beam, which is half of the number of overlapping beams (Nb/2 = 2) between two consecutive W_1 matrices. As another example, when $\Pi=\{0,1\}$, the second grid of Nb beams may be unshifted, or shifted by one beam.

[00124] In another embodiment, both the first and second grid of beams may be shifted. This is expressed as:

$$\mathbf{W}_1(n,m,k)\in C_1=\left\{\begin{bmatrix}f_n\left(\mathbf{X}^{(k)}\right) & \mathbf{0}\\ \mathbf{0} & g_m\left(\mathbf{X}^{(k)}\right)\end{bmatrix},k=0,...\right\}=\begin{bmatrix}\mathbf{G}(n)\mathbf{X}^{(k)} & \mathbf{0}\\ \mathbf{0} & \mathbf{D}(m)\mathbf{X}^{(k)}\end{bmatrix}, \qquad (30)$$

where $\mathbf{G}(n)=\begin{bmatrix}1 & 0\\ 0 & e^{j\frac{2\pi n}{N}}\end{bmatrix},(n=0,1...N-1)$, $\mathbf{D}(m)=\begin{bmatrix}1 & 0\\ 0 & e^{j\frac{2\pi m}{N}}\end{bmatrix},(m=0,1...N-1)$.

Similarly, it is possible to use a subset of $\mathbf{G}(n)$ and $\mathbf{D}(m)$ matrices in generating the codebook C_1.

Example 2: Beam Permutation

[00125] It is further possible to permute the selected beams in one or both sub-matrices of W_1. As one example, the W_1 codebook is expressed as:

$$\mathbf{W}_1(l,m,k) \in C_1 = \left\{ \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{D}(m)\mathbf{X}^{(k)}\mathbf{P}(l) \end{bmatrix} \right\}, \quad (31)$$

where $\mathbf{P}(l)$ is a 4×4 column permutation of an $N_b \times N_b$ identity matrix $\mathbf{I}_{N_b}$.

One example of $\mathbf{P}(l)$ is $\mathbf{P}(l) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$.

By multiplying $\mathbf{P}(l)$ to $\mathbf{D}(m)\mathbf{X}^{(k)}$, the Nb beams in the second sub-matrix $\mathbf{D}(m)\mathbf{X}^{(k)}$ are permuted before being co-phased with the first grid of beam $\mathbf{X}^{(k)}$, providing further diversity gain in the W_1 codebook.

[00126] Permutation can be performed for both sub-matrices of W_1. In another example, the W_1 codebook is expressed as

$$\mathbf{W}_1(j,l,n,m,k) \in C_1 = \left\{ \begin{bmatrix} f_n\left(\mathbf{X}^{(k)}\right)\mathbf{P}_1(j) & \mathbf{0} \\ \mathbf{0} & g_m\left(\mathbf{X}^{(k)}\right)\mathbf{P}_2(l) \end{bmatrix}, k = 0,... \right\} = \begin{bmatrix} \mathbf{D}(n)\mathbf{X}^{(k)}\mathbf{P}_1(j) & \mathbf{0} \\ \mathbf{0} & \mathbf{D}(m)\mathbf{X}^{(k)}\mathbf{P}_2(l) \end{bmatrix}$$

(32)

where $\mathbf{P}_1(j)$ and $\mathbf{P}_2(l)$ perform column permutations for the first and the second grid of beams, respectively. Note that the permutation operation $\mathbf{P}(l)$ can be applied without beam shifting (*e.g.* $\mathbf{D}(m)$).

Example 3: Phase Rotation

[00127] In another embodiment,

$$\mathbf{W}_1(n,m,k) \in C_1 = \left\{ \begin{bmatrix} f_n\left(\mathbf{X}^{(k)}\right) & \mathbf{0} \\ \mathbf{0} & g_m\left(\mathbf{X}^{(k)}\right) \end{bmatrix}, k = 0,... \right\} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)}\mathbf{D}(m) \end{bmatrix} \quad (33)$$

Alternatively,

$$C_1 = \begin{bmatrix} \mathbf{X}^{(k)}\mathbf{D}(m) & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \tag{34}$$

$\mathbf{D}(m)$ $(m = 0,1...N-1)$ is a Nb x Nb diagonal matrix denoted as

$$\mathbf{D} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\frac{2\pi m}{N}} & 0 & 0 \\ 0 & 0 & \ldots & \\ 0 & 0 & 0 & e^{j\frac{2\pi(N_b-1)m}{N}} \end{bmatrix}. \tag{35}$$

Herein $\mathbf{D}(m)$ performs phase correction to the Nb beams. For instance, as the first sub-matrix $\mathbf{X}^{(k)}$ comprises Nb adjacent beams defined as:

$$\mathbf{b}_{(N_b k)\bmod N} \quad \mathbf{b}_{(N_b k+1)\bmod N} \quad \cdots \quad \mathbf{b}_{(N_b k+N_b-1)\bmod N},$$

the second sub-matrix $\mathbf{D}(m)\mathbf{X}^{(k)}$ comprises a different grid of Nb beams defined as

$$\mathbf{b}_{(N_b k+m)\bmod N} \quad e^{j\frac{2\pi m}{N}}\mathbf{b}_{(N_b k+1)\bmod N} \quad \cdots \quad e^{j\frac{2\pi(N_b-1)m}{N}}\mathbf{b}_{(N_b k+N_b-1)\bmod N}.$$

In other words, the m-th beam in the second grid (m = 0, 1, …, Nb-1) is phase rotated by $\frac{2\pi(N_b-1)m}{N}$ degrees. It is also possible to apply the phase rotation to both the first and the second grid of beams.

[00128] An alternative formulation of the phase rotation matrix $\mathbf{D}(m)$ is given as

$$\mathbf{D} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\frac{\pi}{2N_b}} & 0 & 0 \\ 0 & 0 & \ldots & \\ 0 & 0 & 0 & e^{j\frac{(N_b-1)\pi}{2N_b}} \end{bmatrix} \tag{36}$$

where Nb phase correction components (*e.g.*, 1, $e^{j\frac{\pi}{2N_b}}$, … $e^{j\frac{(N_b-1)\pi}{2N_b}}$) uniformly sample a 90-degree sector. As such, co-phasing between two grids of beams is no longer limited to the QPSK alphabet as in the W*2* codebook, but can take values of $\{0, \frac{\pi}{2N_b}, \ldots \frac{(N_b-1)\pi}{2N_b}\}+\{0, \pi/2, \pi, , 3\pi/2,\}$.

[00129] It will be further understood that combination of beam shifting, beam permutation, and/or phase rotation schemes can be used in constructing the W_1 codebook.

Pruning the 8Tx Codebook for 4Tx MIMO

[00130] The LTE Release 10 8Tx codebook is designed using the GoB structure. Specifically:

- each 4Tx polarization array is over-sampled by N DFT beams'
- each wideband W_1 matrix comprises Nb adjacent DFT beams to cover a certain AoD and angular spread, and
- narrowband W_2 performs beam selection and co-phasing.

As such, the 4Tx GoB codebook components can be selected as sub-matrices of a subset of the 8Tx codebook in Release 12. In other words, each 4Tx GoB precoder may correspond to four selected rows of a Release 10 8Tx precoder (*i.e.*, pruning the 8Tx codebook down to four rows).

[00131] To illustrate this pruning, the Release 10 8Tx codebook is denoted as $C^{(8)} = C_1^{(8)} \times C_2^{(8)}$, where $C^{(8)} = \{\mathbf{W}^{(8)}\}$, $C_1^{(8)} = \{\mathbf{W}_1^{(8)}\}$ and $C_2^{(8)} = \{\mathbf{W}_2^{(8)}\}$ are the first and second codebook. Subsequently, the 4Tx GoB codebook can be written as

$$C^{(4)} == \{\mathbf{W}^{(4)}\} = C_1^{(4)} \times C_2^{(4)}, \tag{37}$$

where $C^{(4)} = \{\mathbf{W}^{(4)}\} \subseteq \{\mathbf{W}^{(8)}_{[(n1,n2,n3,n4),:]}\}$, and where, for an $8 \times R$ matrix $\mathbf{H}$, $\mathbf{H}_{(n_i,:)}$ denotes the ni-th row of $\mathbf{H}$,

$$\mathbf{H}_{[(n1,n2,n3,n4),:]} = \begin{pmatrix} \mathbf{H}_{(n1,:)} \\ \mathbf{H}_{(n2,:)} \\ \mathbf{H}_{(n3,:)} \\ \mathbf{H}_{(n4,:)} \end{pmatrix},$$

and $(n1,n2,n3,n4)$ is the row selection vector for codebook pruning.

[00132] The 4Tx GoB codebooks proposed above may be pruned from the Release 10 8Tx codebook. The following notations are used herein:

i_1^4 : index of first precoder W_1 for 4Tx

i_2^4 index of second precoder W_2 for 4Tx

i_1^8 index of first precoder W_1 for 8Tx

i_2^8 index of second precoder W_1 for 8Tx

As such, each 8Tx precoding matrix $\mathbf{W}^{(8)}=\mathbf{W}_1^{(8)}\mathbf{W}_2^{(8)}$ is denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), and each 4Tx precoding matrix $\mathbf{W}^{(4)}=\mathbf{W}_1^{(4)}\mathbf{W}_2^{(4)}$ is denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4),

Rank-1

[00133] For a (N,Nb) = (N,Nb) 4Tx GoB codebook with overlapping beams, where N<= 32, Nb = 4, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), where $i_1^4=\frac{32}{N}i_1^8$, $i_2^4=i_2^8$, $i_2^4=0, \ldots, 15$.

[00134] More specifically:

[00135] For (N,Nb) = (8,4) 4Tx codebook with overlapping, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), as given in Table 7.

4Tx indices	i_1^4	i_2^4							
	0-3	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-3	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	8	9	10	11	12	13	14	15

TABLE 7

[00136] For a (N,Nb) = (16,4) 4Tx codebook with overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 8.

4Tx indices	i_1^4	i_2^4							
	0-7	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-7	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	8	9	10	11	12	13	14	15

TABLE 8

[00137] For (N,Nb) = (32,4) 4Tx codebook with overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 9.

.

4Tx indices	i_1^4	i_2^4							
	0-15	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	i_1^4	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-15	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	i_1^4	8	9	10	11	12	13	14	15

TABLE 9

[00138] For a (N,Nb) = (N,Nb) 4Tx codebook without overlapping beams, where N<= 32, and Nb = 4, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), where $i_1^4 = \frac{64}{N} i_1^8$, $i_2^4 = i_2^8$, $i_2^4 = 0, \ldots, 15$.

[00139] More specifically:

[00140] For a (N,Nb) = (8,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 10.

4Tx indices	i_1^4	i_2^4							
	0-1	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$8i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-1	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	$8i_1^4$	8	9	10	11	12	13	14	15

TABLE 10

[00141] For a (N,Nb) = (16,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 11.

4Tx indices	i_1^4	i_2^4							
	0-3	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-3	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	8	9	10	11	12	13	14	15

TABLE 11

[00142] For a (N,Nb) = (32,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-1 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 12.

4Tx indices	i_1^4	i_2^4							
	0-7	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-7	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	8	9	10	11	12	13	14	15

TABLE 12

Rank-2

Example Codebook 1

[00143] In this section, we assume the following 4Tx rank-2 codebook, where the W_2 codebook is size-8.

$$\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}, \tag{38}$$

where $(k = 0,....N/N_b - 1)$ without overlapping beams, and $(k = 0,....2N/N_b - 1)$ with overlapping beams.

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\} , \tag{39}$$

where $(\mathbf{Y}_1, \mathbf{Y}_2) \in \{(e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4)\}$.

[00144] For a (N,Nb) = (N,Nb) 4Tx GoB codebook with overlapping beams, where N<= 32, Nb = 4, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), where $i_1^4 = \frac{32}{N} i_1^8$, $i_2^4 = i_2^8$, i_2^4=0, …, 7

[00145] More specifically:

[00146] For a (N,Nb) = (8,4) 4Tx codebook with overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 13.

4Tx indices	i_1^4	i_2^4							
	0-3	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	0	1	2	3	4	5	6	7

TABLE 13

[00147] For a (N,Nb) = (16,4) 4Tx codebook with overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 14.

4Tx indices	i_1^4	i_2^4							
	0-7	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	0	1	2	3	4	5	6	7

TABLE 14

[00148] For a (N,Nb) = (32,4) 4Tx codebook with overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 15.

4Tx indices	i_1^4	i_2^4							
	0-15	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	i_1^4	0	1	2	3	4	5	6	7

TABLE 15

[00149] For a (N,Nb) = (N,Nb) 4Tx codebook without overlapping beams, where N<= 32, Nb = 4, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), where $i_1^4 = \frac{64}{N} i_1^8$, $i_2^4 = i_2^8$, $i_2^4 = 0, \ldots, 7$.

[00150] More specifically:

[00151] For a (N,Nb) = (8,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 16.

4Tx indices	i_1^4	i_2^4							
	0-1	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$8i_1^4$	0	1	2	3	4	5	6	7

TABLE 16

[00152] For a (N,Nb) = (16,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 17.

4Tx indices	i_1^4	i_2^4							
	0-3	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$4i_1^4$	0	1	2	3	4	5	6	7

TABLE 17

[00153] For a (N,Nb) = (32,4) 4Tx codebook without overlapping beams, each 4Tx precoding matrix denoted by (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by (i_1^8, i_2^8), as given in Table 18.

4Tx indices	i_1^4	i_2^4							
	0-7	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	$2i_1^4$	0	1	2	3	4	5	6	7

TABLE 18

Example Codebook 2

[00154] In this section, we assume the following 4Tx GoB codebook where the W_2 codebook is size-16.

$$\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}, \tag{40}$$

where $(k = 0,....N/N_b - 1)$ without overlapping beams, and $(k = 0,....2N/N_b - 1)$ with overlapping beams.

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \tag{41}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4), (e_1^4, e_2^4), (e_2^4, e_3^4), (e_1^4, e_4^4), (e_2^4, e_4^4) \right\}.$$

[00155] Such a 4Tx codebook cannot be completely pruned out of the 8Tx codebook unless the oversampling rate is N = 32, which is equivalent to the 8Tx oversampling rate. In this case, when there is W_1 overlapping for 4Tx, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), as given in Table 19, where $i_1^4 = i_1^8$, $i_1^4 = 0, \ldots 15$, $i_2^4 = i_2^8$, $i_2^4 = 0, .., 15$.

4Tx indices	i_1^4	i_2^4							
	0-15	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8							
	i_1^4	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4							
	0-15	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8							
	i_1^4	8	9	10	11	12	13	14	15

TABLE 19

[00156] For a (N,Nb) = (32,4) 4Tx GoB codebook without overlapping beams, each 4Tx precoding matrix denoted by a pair of 4Tx codebook indices (i_1^4, i_2^4) can be pruned from a corresponding 8Tx rank-2 precoding matrix denoted by a pair of 8Tx codebook indices (i_1^8, i_2^8), as given in Table 20, where $i_1^4 = 2i_1^8$, $i_1^4 = 0, \ldots, 7$, $i_2^4 = i_2^8$, $i_2^4 = 0, \ldots, 15$.

4Tx indices	i_1^4	i_2^4						
	0-7	0	1	2	3	4	5	6	7
Corresponding 8Tx indices	i_1^8	i_2^8						
	$2i_1^4$	0	1	2	3	4	5	6	7
4Tx indices	i_1^4	i_2^4						
	0-7	8	9	10	11	12	13	14	15
Corresponding 8Tx indices	i_1^8	i_2^8						
	$2i_1^4$	8	9	10	11	12	13	14	15

TABLE 20

Rank-3

[00157] A rank-3 4Tx GoB codebook cannot be pruned from the rank-3 8Tx codebook. This can be seen from the 8Tx design, which followed the (N,Nb) = (16,8) structure, where

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{15} \end{bmatrix}, \quad [\mathbf{B}]_{1+m,1+n} = e^{j\frac{2\pi mn}{16}}, \quad m = 0,1,2,3,\ n = 0,1,\cdots,15$$

$$\mathbf{X}^{(k)} \in \left\{ \begin{bmatrix} \mathbf{b}_{4k \bmod 32} & \mathbf{b}_{(4k+1) \bmod 32} & \mathbf{b}_{(4k+2) \bmod 32} & \mathbf{b}_{(4k+3) \bmod 32} & \mathbf{b}_{(4k+4) \bmod 32} & \mathbf{b}_{(4k+5) \bmod 32} & \mathbf{b}_{(4k+6) \bmod 32} & \mathbf{b}_{(4k+7) \bmod 32} \end{bmatrix} \right\}_{k=0,..3}$$

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}, \text{Codebook 1:} \quad C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \mathbf{W}_1^{(3)} \right\} \tag{42}$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\}, \tag{43}$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{\begin{array}{l}(e_1^4,[e_1^4,e_5^4]),(e_2^4,[e_2^4,e_6^4]),(e_3^4,[e_3^4,e_7^4]),(e_4^4,[e_4^4,e_8^4]),\\(e_5^4,[e_1^4,e_5^4]),(e_6^4,[e_2^4,e_6^4]),(e_7^4,[e_3^4,e_7^4]),(e_3^4,[e_4^4,e_8^4]),\\([e_1^4,e_5^4],e_1^4),([e_2^4,e_6^4],e_2^4),([e_3^4,e_7^4],e_3^4),([e_4^4,e_8^4],e_4^4),\\([e_1^4,e_5^4],e_5^4),([e_2^4,e_6^4],e_6^4),([e_3^4,e_7^4],e_7^4),([e_4^4,e_8^4],e_8^4),\end{array}\right\}. \quad (44)$$

[00158] The column vectors of each rank-3 8Tx precoding matrix comprise critically sampled (*e.g.* sampling rate 4) 4Tx DFT vectors in order to ensure that a rank-3 8Tx precoding matrix satisfies the unitary constraint. For 4Tx, in order to achieve the unitary constraint, column vectors of each rank-3 4Tx precoding matrix must comprise critically sampled (*e.g.* sampling rate 2) 2Tx DFT vectors. As such, the column vectors of any 4Tx GoB matrix will always span across different W_1 matrices of the 8Tx codebook, leaving it impossible to construct the rank-3 4-Tx codebook by pruning the 8Tx codebook.

[00159] However the rank-3 4Tx GoB component can be pruned from the rank-6 8Tx codebook, where

$$C^{(4)}=\left\{\mathbf{W}^{(4)}\right\}_{rank3}\subseteq\left\{\mathbf{W}^{(8)}_{[(n1,n2,n3,n4),(m1,m2,m3)]}\right\}_{rank6} \quad (45)$$

e.g., the $(n1,n2,n3,n4)$-th row and $(m1,m2,m3)$-th column of a rank-6 8Tx precoding matrix corresponding to a pair of codebook index (i_1^8,i_2^8) are used to construct a 4Tx precoding matrix corresponding to a pair of codebook indices (i_1^4,i_2^4).

[00160] For instance, for the (N,Nb) = (4,4) GoB codebook, the pruning shown in Table 21 is possible:

4Tx indices	i_1^4	i_2^4
	0	arbitrary
Corresponding 8Tx indices	i_1^8	i_2^8
	0	0

TABLE 21

[00161] Note that the column-selection method $(m1,m2,m3)$ may depend on the 4Tx GoB precoding matrix. For instance:

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{(e_1^4,[e_1^4,e_3^4])\right\}\Rightarrow(m1,m2,m3)=(1,2,6) \quad (46)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{(e_3^4,[e_1^4,e_3^4])\right\}\Rightarrow(m1,m2,m3)=(5,2,6) \quad (47)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_1^4,e_3^4],e_1^4)\right\}\Rightarrow(m1,m2,m3)=(1,5,2) \quad (48)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_1^4,e_3^4],e_3^4)\right\}\Rightarrow(m1,m2,m3)=(1,5,6) \quad (49)$$

Rank-4

[00162] Similarly, the rank-4 4Tx GoB component cannot be pruned from the rank-4 8Tx codebook. However, a rank-4 4Tx GoB component can be pruned from the rank-8 8Tx codebook, where

$$C^{(4)}=\left\{\mathbf{W}^{(4)}\right\}_{rank-4}\subseteq\left\{\mathbf{W}^{(8)}_{[(n1,n2,n3,n4),(m1,m2,m3,m4)]}\right\}_{rank-8} \quad (50)$$

e.g., the $(n1,n2,n3,n4)$-th row and $(m1,m2,m3,m4)$-th column of a rank-8 8Tx precoding matrix corresponding to a pair of codebook index (i_1^8,i_2^8) is used to construct a 4Tx precoding matrix corresponding to a pair of codebook indices (i_1^4,i_2^4). For instance for the (N,Nb) = (4,4) GoB codebook, the pruning shown in Table 22 is possible.

4Tx indices	i_1^4	i_2^4
	0	arbitrary
Corresponding 8Tx indices	i_1^8	i_2^8
	0	0

TABLE 22

[00163] Note that the column -selection method $(m1,m2,m3,m4)$ may depend on the 4Tx GoB precoding matrix. For instance:

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_1^4,e_3^4],[e_1^4,e_3^4])\right\}\Rightarrow(m1,m2,m3,m4)=(1,5,2,6) \quad (51)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_2^4,e_4^4],[e_2^4,e_4^4])\right\}\Rightarrow(m1,m2,m3,m4)=(3,7,4,8) \quad (52)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_1^4,e_3^4],[e_2^4,e_4^4])\right\}\Rightarrow(m1,m2,m3,m4)=(1,5,4,8) \quad (53)$$

$$(\mathbf{Y}_1,\mathbf{Y}_2)\in\left\{([e_2^4,e_4^4],[e_1^4,e_3^4],)\right\}\Rightarrow(m1,m2,m3,m4)=(3,7,2,6) \quad (54)$$

Row Selection Vector ($n1$,$n2$,$n3$,$n4$) for Pruning

[00164] In one embodiment, the row selection vector $(n1,n2,n3,n4)$ is hard-coded / fixed in the specification, and is not signalled to the UE. FIG. 5 illustrates an example of using a row selection vector to prune antenna pairs in an 8Tx array. Eight antennas 1-8 are arranged in four cross-polarized pairs 501-504. Using the row selection vector $(n1,n2,n3,n4) = [1,2,5,6]$ prunes the first two cross-polarized antenna pairs 501, 502 from the 8Tx array 505 for a 4Tx deployment 506.

[00165] In another embodiment, the row selection vector $(n1,n2,n3,n4)$ may be semi-statically radio resource control (RRC)-configd for a UE, and can be different for different UEs. There are multiple possible methods for RRC signalling $(n1,n2,n3,n4)$

Example 1:

[00166] For the k-th antenna port of a 4-Tx MIMO system (k = 1, 2, 3, 4), the eNodeB signals the corresponding virtual antenna port index n_k in an 8-Tx MIMO system. This requires a signaling overhead of log2(8) x 4 = 12 bits.

Example 2:

[00167] As there are a total of $C_4^8 = 70$ ways of choosing 4-antenna ports out of an 8-antenna port system, log2(70) = 7-bits are used to signal the combinatorial index of the antenna selection vector $(n1,n2,n3,n4)$. This achieves 5-bits of overhead savings.

[00168] It is further possible to down-size the set of candidate antenna selection vectors $\{(n1,n2,n3,n4)\}$, which may further reduce the RRC signalling overhead. For instance, the eNodeB may use 1-bit to config the UE to assume $(n1,n2,n3,n4) = [1,2,5,6]$ or $(n1,n2,n3,n4) = [1,4,5,8]$. With $(n1,n2,n3,n4) = [1,4,5,6]$, two adjacent cross-polarized antenna pairs are configd, which models 4Tx cross-polarized antennas with small antenna spacing. With $(n1,n2,n3,n4) = [1,4,5,8]$, two antenna pairs with large antenna spacing are modelled. This may be important for some wireless operators that must deploy wide antenna spacing due to their GSM/HSPA/LTE spectrum farming limitation, where two separate antenna radomes with large spacing are used for 4Tx MIMO.

[00169] For a UE configd in transmission mode 10, where the UE is configd with multiple CSI-RS resources, the row selection vector $(n1,n2,n3,n4)$ can be independently configd for each 4-Tx CSI-RS resource.

Example of 4Tx codebook from 8Tx pruning

[00170] Using the methods proposed above for rank-1,2,3,4Tx GoB codebooks, one example of a 4Tx codebook is summarized below.

[00171] Release 12 enhancement is achieved by augmenting the Release 8 codebook with double-codebook (DCB) components.

- component 1 (Release 8): W1 = identity matrix, W2 selected from Release 8 codebook,

- component 2 (DCB):…pruned Release 10 8Tx codebook,

select four rows out of eight rows from the 8Tx precoding matrices (*i.e.*, a subset of the 8Tx matrices).

Rank-1:

Component 1: Release 8

$W_1 = I_4$, (55)

$\mathbf{W}_2 \in C_{2,R8-4Tx-R1}$ (56)

Component 2: DCB:

W_1: $i_1 = 0,...15$, each W_1 is the $(1,2,5,6)^{th}$ row of the $(i_1)^{th}$ 8Tx W_1 codebook.

W_2: $i_2 = 0,...15$, same as 8Tx W_2 codebook

Note: the 4Tx DCB components are the $(1,2,5,6)^{th}$ row of the 8Tx DCB codebook. This is equivalent to a (N,Nb) = (32,4) codebook with adjacent W_1 overlapping.

Rank-2:

Component 1: Release 8

$W_1 = I_4$, (57)

$\mathbf{W}_2 \in C_{2,R8-4Tx-R2}$ (58)

Component 2: DCB:

W1: $i_1 = 0,...15$, each W_1 is the $(1,2,5,6)^{th}$ row of the $(i_1)^{th}$ 8Tx W_1 codebook.

W2: $i_2 = 0,...15$, same as 8Tx W_2 codebook.

Note: the 4Tx DCB components are the $(1,2,5,6)^{th}$ row of the 8Tx DCB codebook. This is equivalent to a (N,Nb) = (32,4) codebook with adjacent W_1 overlapping.

Rank-3/Rank-4:

[00172] Re-use the Release 8 codebook.

[00173] Further enhancement of 4Tx codebook

[00174] Any of the codebooks proposed above can be further enhanced by adding more 4Tx precoding matrices. Note that in the sections above, the Release 8 4Tx codebook is inherited in Release 12 4Tx codebook in the form of $W = W_1 W_2$, where W_1 is a 4x4 identity matrix and W_2 are taken from Release 8 codebook. An extension of this design is possible, where the W_1 codebook not only includes the 4x4 identity matrix I_4, but also includes other size 4x4 matrices. One example extension is where the W_1 codebook comprises of a set of diagonal matrices, where each diagonal element performs phase rotation for each row of W_2 matrix.

[00175] Following this design principle, an example of a further-enhanced 4Tx codebook is given below.

Rank-1/Rank-2:

$$C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \cdots, \mathbf{W}_1^{N-1} \right\}, \tag{59}$$

where:

[00176] For $i_1 = 0, ..., N/2-1$, $\mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)} \ldots \mathbf{W}_1^{(N/2-1)}$ are diagonal matrices (*e.g.* performing phase rotation), and W_2 inherits the Release 8 4Tx codebook. In particular, for $i_1 = 0$, $\mathbf{W}_1^{(0)} = \mathbf{I}_4$. This allows the Release 8 codebook to be re-used without change in Release 12.

[00177] When i_1 = (N/2), …, N-1, then $\mathbf{W}_1^{(N/2)} \ldots \mathbf{W}_1^{(N-1)}$ are block diagonal matrices designed with double-codebook structure. In this case, W_1 and W_2 can use any of the DCB codebook components proposed in the sections above. As one example, W_1/W_2 may be pruned 8Tx codebooks, where N = 32, and W_1: $i_1 = 16,...31$, each W_1 is the $(1,2,5,6)^{th}$ row of the $(i_1 - 15)^{th}$ 8Tx W_1 matrix, W_2: $i_2 = 0,...15$, same as 8Tx W_2 codebook.

[00178] Herein, the W_1 overhead is 5-bit, and W_2 overhead is 4-bits per subband.

[00179] Rank-3 and rank-4 may follow the same enhancement design if necessary.

Alternative Design for Rank-2

[00180] The GoB designs proposed above assumed that each W_1 matrix comprises a group of adjacent DFT beams. It is noted that the beams in each W_1 grid are not necessarily adjacent,

which makes other designs possible. In this section we propose an example rank-2 design with non-adjacent beams in W_1.

[00181] To recapture the notations, note that

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \tag{60}$$

where $\mathbf{X}^{(k)}$ comprises of multiple 2x1 DFT beams, $k = i_1$. In the following section, we assume an over-sampling ratio N = 16, but the proposed design can be easily generalized to other N values.

Alternative Design 1

[00182] It is noted that an N-times oversampled 2×1 DFT beam expressed as

$$\mathbf{b}_{l \bmod N} = \begin{bmatrix} 1 \\ e^{j2\pi l/N} \end{bmatrix}, l = 0,...N-1$$

is orthogonal to

$$\mathbf{b}_{(l+N/2) \bmod N}.$$

Therefore each W_1 grid may comprise two orthogonal DFT beams expressed as

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}, \tag{61}$$

$$\mathbf{X}^{(k)} = [\mathbf{b}_{l \bmod N}, \mathbf{b}_{(l+N/2) \bmod N}], \text{ k=l.} \tag{62}$$

[00183] The W_2 codebook may comprise beam selection and co-phasing matrixes, for example, denoted as:

$$\mathrm{W}_2 = C_2 = \Omega \circ \left\{ \begin{pmatrix} e_1 & e_2 \\ e_1 & e_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ e_1 & -e_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ -e_1 & e_2 \end{pmatrix}, \begin{pmatrix} e_1 & e_2 \\ -e_1 & -e_2 \end{pmatrix} \right\} \tag{63}$$

where $\circ$ denotes the Schur product, e_i^2 is a 2×1 column vector with all zero entries except the i-th element being 1, and

$$\Omega = \left\{ \begin{pmatrix} \mathbf{I}_2 & \\ & e^{j2\pi k/N}\mathbf{I}_2 \end{pmatrix} \right\}_{k=\Xi} \tag{64}$$

are diagonal matrices that perform co-phasing.

[00184] As an example,

$$\Omega=\left\{\begin{pmatrix}\mathbf{I}_2 & \\ & \mathbf{I}_2\end{pmatrix},\begin{pmatrix}\mathbf{I}_2 & \\ & -\mathbf{I}_2\end{pmatrix},\begin{pmatrix}\mathbf{I}_2 & \\ & j\mathbf{I}_2\end{pmatrix},\begin{pmatrix}\mathbf{I}_2 & \\ & -j\mathbf{I}_2\end{pmatrix},\right\}, \tag{65}$$

which results in a 4-bits W_2 codebook. Correspondingly, for each $\mathbf{X}^{(k)}=[\mathbf{b}_{l \bmod N},\mathbf{b}_{(l+N/2) \bmod N}]$, $k=l=i_1$, the corresponding sixteen composite matrices $\mathbf{W}=\mathbf{W}_{i_1,i_2}$, $i_2=0,...15$ are expressed as shown in Table 23.

$i_2=0,...,3$	$\mathbf{W}_{k,0}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,1}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ \mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,2}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ -\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,3}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ -\mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$
$i_2=4,...,7$	$\mathbf{W}_{k,4}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ -\mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,5}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ -\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,6}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ \mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,7}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$
$i_2=8,...,11$	$\mathbf{W}_{k,8}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,9}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,10}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\\ -j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$

	$\mathbf{W}_{k,11}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$
$i_2=12,...,15$	$\mathbf{W}_{k,12}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,13}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,14}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,15}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$

TABLE 23

[00185] It is noted that $\mathbf{W}_{i_1,i_2}, i_2=4,...,7$ are identical to $\mathbf{W}_{i_1,i_2}, i_2=0,...,3$, and $\mathbf{W}_{i_1,i_2}$, $i_2=12,...,15$ are identical to $\mathbf{W}_{i_1,i_2}, i_2=8,...,11$. Therefore it's possible to reduce the W_2 size to 3-bits ($i_2=0,...,7$), where

$$\Omega=\left\{\begin{pmatrix}\mathbf{I}_2 & \\ & \mathbf{I}_2\end{pmatrix},\begin{pmatrix}\mathbf{I}_2 & \\ & j\mathbf{I}_2\end{pmatrix}\right\}, \tag{66}$$

and the composite precoder $\mathbf{W}=\mathbf{W}_{i_1,i_2}$ is given by the values shown in Table 24.

$i_2=0,...,3$	$\mathbf{W}_{k,0}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,1}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ \mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,2}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$ $\mathbf{W}_{k,3}=\begin{pmatrix}\mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -\mathbf{b}_{l \bmod N} & -\mathbf{b}_{(l+N/2) \bmod N}\end{pmatrix}$

$i_2 = 4,...,7$	$\mathbf{W}_{k,4} = \begin{pmatrix} \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N} \end{pmatrix}$ $\mathbf{W}_{k,5} = \begin{pmatrix} \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N} \end{pmatrix}$ $\mathbf{W}_{k,6} = \begin{pmatrix} \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -j\mathbf{b}_{l \bmod N} & j\mathbf{b}_{(l+N/2) \bmod N} \end{pmatrix}$ $\mathbf{W}_{k,7} = \begin{pmatrix} \mathbf{b}_{l \bmod N} & \mathbf{b}_{(l+N/2) \bmod N} \\ -j\mathbf{b}_{l \bmod N} & -j\mathbf{b}_{(l+N/2) \bmod N} \end{pmatrix}$

TABLE 24

[00186] Note that other co-phasing methods Ω are possible, for example

$$\Omega = \left\{ \begin{pmatrix} \mathbf{I}_2 & \\ & \mathbf{I}_2 \end{pmatrix}, \begin{pmatrix} \mathbf{I}_2 & \\ & j\mathbf{I}_2 \end{pmatrix}, \begin{pmatrix} \mathbf{I}_2 & \\ & e^{j\frac{\pi}{4}}\mathbf{I}_2 \end{pmatrix}, \begin{pmatrix} \mathbf{I}_2 & \\ & e^{j\frac{3\pi}{4}}\mathbf{I}_2 \end{pmatrix}, \right\}. \quad (67)$$

[00187] In this case, the W_2 codebook size is 4-bits.

Generalization

[00188] The precoders proposed above as alternative design 1 may be combined with the precoders in the previous sections to construct the final rank-2 codebook. For example, assuming over-sampling ratio N (e.g. N = 16), $N_b = 4$, the rank-2 codebook may be expressed as

$$\mathbf{W}_1 \in C_1 = \left\{ \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}. \right\}, i_1 = k = 0,...2N/N_b - 1 \quad (68)$$

-> size $N/2$

[00189] When $i_2 = 0,...,7$:

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(N_b k/2) \bmod N} & \mathbf{b}_{(N_b k/2+1) \bmod N} & \cdots & \mathbf{b}_{(N_b k/2+N_b-1) \bmod N} \end{bmatrix} \quad (69)$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \quad (70)$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4) \right\} \quad (71)$$

[00190] When $i_2 = 8,...,15$:

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(k-N/2) \bmod N}, \mathbf{b}_{k \bmod N} \end{bmatrix} \quad (72)$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \frac{1}{\sqrt{2}} \times \left\{ \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \quad (73)$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^2, e_2^2) \right\} \quad (74)$$

[00191] The W_1 overhead is log2(N/2) = 3-bits, and the W_2 overhead is 4-bits.

[00192] Note that the combined codebook can be re-expressed below.

$$\mathbf{W}_1 \in C_1 = \left\{ \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \ldots \begin{bmatrix} \mathbf{X}^{(N-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(N-1)} \end{bmatrix} \right\} \quad (75)$$

→ size N

[00193] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = i_1 = 0, \ldots N/2 - 1)$: (76)

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(N_b k/2) \bmod N} & \mathbf{b}_{(N_b k/2+1) \bmod N} & \cdots & \mathbf{b}_{(N_b k/2+N_b-1) \bmod N} \end{bmatrix} \quad (77)$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\} \quad (78)$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4) \right\} \quad (79)$$

[00194] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = i_1 = \frac{N}{2}, \ldots, N-1)$: (80)

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(k-N/2) \bmod N}, \mathbf{b}_{k \bmod N} \end{bmatrix} \quad (81)$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \frac{1}{\sqrt{2}} \times \left\{ \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \quad (82)$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^2, e_2^2) \right\} \quad (83)$$

[00195] In this case, the W_1 overhead is log2(N) = 4-bits, and the W_2 overhead is 3-bits.

[00196] Another possible combinatorial design is

$$\mathbf{W}_1 \in C_1 = \left\{ \begin{bmatrix} \mathbf{X}^{(0)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(0)} \end{bmatrix}, \ldots \begin{bmatrix} \mathbf{X}^{(N-1} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(N-1)} \end{bmatrix} \right\} \tag{84}$$

→ size N

[00197] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = i_1 = 0, \ldots N/2-1)$: (85)

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(N_b k/2) \bmod N} & \mathbf{b}_{(N_b k/2+1) \bmod N} & \cdots & \mathbf{b}_{(N_b k/2+N_b-1) \bmod N} \end{bmatrix} \tag{86}$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \tag{87}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^4, e_1^4), (e_2^4, e_2^4), (e_3^4, e_3^4), (e_4^4, e_4^4), (e_1^4, e_2^4), (e_2^4, e_3^4), (e_1^4, e_4^4), (e_2^4, e_4^4) \right\} \tag{88}$$

[00198] When $\mathbf{W}_1 = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix}$ $(k = i_1 = \frac{N}{2}, \ldots, N-1)$: (89)

$$\mathbf{X}^{(k)} = \begin{bmatrix} \mathbf{b}_{(k-N/2) \bmod N}, \mathbf{b}_{k \bmod N} \end{bmatrix} \tag{90}$$

$$\mathbf{W}_2 \in \mathbf{CB}_2 =$$

$$\frac{1}{\sqrt{2}} \times \left\{ \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \right.$$
$$\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \tag{91}$$
$$\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ e^{j\frac{\pi}{4}}\mathbf{Y}_1 & e^{j\frac{\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ e^{j\frac{\pi}{4}}\mathbf{Y}_1 & -e^{j\frac{\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -e^{j\frac{\pi}{4}}\mathbf{Y}_1 & e^{j\frac{\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -e^{j\frac{\pi}{4}}\mathbf{Y}_1 & -e^{j\frac{\pi}{4}}\mathbf{Y}_2 \end{bmatrix},$$
$$\left. \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ e^{j\frac{3\pi}{4}}\mathbf{Y}_1 & e^{j\frac{3\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ e^{j\frac{3\pi}{4}}\mathbf{Y}_1 & -e^{j\frac{3\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -e^{j\frac{3\pi}{4}}\mathbf{Y}_1 & e^{j\frac{3\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -e^{j\frac{3\pi}{4}}\mathbf{Y}_1 & -e^{j\frac{3\pi}{4}}\mathbf{Y}_2 \end{bmatrix}, \right\}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (e_1^2, e_2^2) \right\} \tag{92}$$

[00199] The W_1 overhead is log2(N) = 4-bits, and the W_2 overhead is 4-bits.

Inheritance of the Release 8 Codebook in Release 12

Using Release 8 Precoders for W_2

[00200] As proposed in the previous sections, it is possible for the Release 12 codebook to inherit the Release 8 codebook as a subset. This can be achieved by using the Release 8 4Tx precoder as the codebook for W_2 which is associated with $W_1 = 4 \times 4$ identity matrix I_4. This is applicable for rank-1 to rank-4, where the subband W_2 overhead is 4-bits per subband.

[00201] It is also possible to divide the Release 8 precoders into N groups, where each group has 16/N Release 8 precoders that form a different W_2 codebook. For each W_2 codebook, the W_1 matrix is equivalent to a 4×4 identity matrix. The subband W_2 overhead will therefore be reduced to log2(16/N) bits.

[00202] For example:

- The Release 8 codebook is inherited in Release 12 codebook, corresponding to two W_1 matrices, *e.g.*, $W_1^k = \mathbf{I}_4$, k = 0, 1, For W_1^0, the W_2 codebook comprises the first eight Release 8 precoders. For W_1^1, the W_2 codebook comprises the last eight Release 8 precoders.
- Other values of N are possible to adapt the subband PMI bit-width. For example, N = 2 corresponds to a subband size of log2(8) = 3-bits, N = 4 corresponds to a subband size of log2(4) = 2 bits.
- The above designs can be applied for rank-1, rank-2, rank-3, and rank-4.

Constructing W_1 with Release 8 Precoders and W_2 with Column Selection

[00203] It is further possible to inherit the Release 8 codebook in Release 12 by constructing the W_1 matrix with Release 8 precoders, and constructing the W_2 codebook with column selection matrices.

[00204] For example:

- For rank-1, W_1 includes all or a subset of Release 8 rank-1 vectors. The size of W_1 is given by 4×L, where 1<=L<=16 is the number of rank-1 Release 8 codebook vectors that are included in W_1. The W_2 codebook comprises L column-selection vectors [e_1, e_2 … e_L], where e_i is an L×1 vector of all zero entries, except for the i-th entry, which is equivalent to 1.
- For rank-r (r= 2, 3, 4), the columns of W_1 comprise all or a subset of Release 8 rank-r vectors, *e.g.* this may be denoted as

$$W_1 = \left[W_{s(0)}^{\mathrm{Re}l.8-rank-r} \quad W_{s(1)}^{\mathrm{Re}l.8-rank-r} \quad .. \quad W_{s(L-1)}^{\mathrm{Re}l.8-rank-r} \right] \tag{93}$$

where $W_{s(l)}^{\mathrm{Re}l.8-rank-r}$ is the s(l)-th Release 8 precoder. The size of W_1 is 4×rL, where 1<=L<=16 is the number of rank-r Release 8 codebook matrices in W_1. The W_2 codebook comprises L column-selection matrices, where the l-th W_2 matrix (1<= l <= L) is

$$W2 = \begin{bmatrix} \mathbf{0}_{r(l-1)\times r} \\ \mathbf{I}_{r\times r} \\ \mathbf{0}_{r(L-l)\times r} \end{bmatrix} \tag{94}$$

[00205] Alternatively, the W_1 matrix can be constructed in a block diagonal manner.

[00206] For example, for rank-1:

$$W_1 = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}, \tag{95}$$

where A and B are of sizes 2×16, where the l-th column of A is the first two rows of the l-th Release 8 precoder, and the l-th column of B is the last two rows of the l-th Release 8 precoder, l = 1, …, 16.

[00207] The W2 matrix can be written in the form of

$$W_2^k = \begin{bmatrix} e_k & 0 \\ 0 & e_k \end{bmatrix}, \text{k} = 1, \ldots, 16, \tag{96}$$

where e_k is the k-th column of a 16×16 identity matrix.

[00208] For rank–r, r = 2, …, 4:

$$W_1 = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}, \tag{97}$$

where A and B are of sizes $2 \times 16r$, and where

$A = \left[W_1^{\text{Rel.8-rank-}r} \quad W_2^{\text{Rel.8-rank-}r} \quad .. \quad W_{16}^{\text{Rel.8-rank-}r} \right]_{(1:2)}$, $P_{(1:2)}$ is the first and second row of matrix P, and

$B = \left[W_1^{\text{Rel.8-rank-}r} \quad W_2^{\text{Rel.8-rank-}r} \quad .. \quad W_{16}^{\text{Rel.8-rank-}r} \right]_{(3:4)}$, $P_{(3:4)}$ is the third and fourth row of matrix P.

[00209] For the W_2 codebook,

$$W_2^k = \begin{bmatrix} e_k & 0 \\ 0 & e_k \end{bmatrix}, \text{k} = 1, \ldots 16, \tag{98}$$

where $e_k = \begin{bmatrix} \mathbf{0}_{r(k-1)\times r} \\ \mathbf{I}_{r\times r} \\ \mathbf{0}_{r(L-k)\times r} \end{bmatrix}$.

4Tx Codebook Enhancements for LTE

[00210] In the following section, possible 4Tx codebook enhancement alternatives for LTE Release 12 are disclosed. In these examples, $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

Rank-1/Rank-2

[00211] For a rank-1/2 codebook, the following two alternatives are possible.

Alternative-1:

[00212] Reusing the 8Tx GoB design with N = 32 over-sampled beams and 4 adjacent beams per grid, the following 4Tx codebook can be considered.

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{31} \end{bmatrix} \quad , \quad [\mathbf{B}]_{l+m,l+n} = e^{j\frac{2\pi mn}{32}}, \quad m = 0,\ldots\frac{N_t}{2}-1, n = 0,1,\cdots,31 \tag{99}$$

$$\mathbf{X}^{(k)} \in \left\{ \begin{bmatrix} \mathbf{b}_{2k \bmod 32} & \mathbf{b}_{(2k+1) \bmod 32} & \mathbf{b}_{(2k+2) \bmod 32} & \mathbf{b}_{(2k+3) \bmod 32} \end{bmatrix} : k = 0,1,\cdots,15 \right\} \tag{100}$$

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix} \tag{101}$$

$$\text{Codebook1:} \quad C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \cdots, \mathbf{W}_1^{(15)} \right\} \tag{102}$$

Rank-1: (4-bit)

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ \mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ j\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -j\mathbf{Y} \end{bmatrix} \right\} \tag{103}$$

$$\mathbf{Y} \in \left\{ \tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_4 \right\} \tag{104}$$

Rank-2: (4-bit)

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\} \tag{105}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\} \tag{106}$$

Rank-2: (3-bit)

[00213] For rank-2, if a (3-bit) W_2 is preferred, (Y1, Y2) can be changed to:

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4) \right\}. \tag{107}$$

Each W1 matrix is constructed by a set of adjacent DFT beams and covers a narrow range of angle-of-departures/arrivals. The fundamental consideration is based the feedback of wideband/long-term channel based on W_1 matrix, and the fed back W1 matrix in a properly

designed C1 codebook should be able to reflect the wideband AoA/AoDs with sufficient accuracy . For instance, most macro base stations in cellular communication systems are elevated on a cell tower and likely have a direct line-of-sign to the UE, where the angle of incoming radio signals to a UE is within in a small range. Hence, the wideband W1 comprising a set of adjacent beams can be used to cover the range of incoming radio signals on the wideband, whereas the narrowband W2 codebook can be used to select a specific beam on each subband. This W_1 design is particular suitable to macro base station with narrowly spaced antennas, propagation channel with sufficient line-of-sights, and perfectly calibrated base station antennas.

Alternative-2:

[00214] A rank-1/2 codebook comprises two components, where W_1 structures are different in each component. For the first 8 W_1 matrices, Xn comprise four adjacent DFT beams with over-sampling rate of N = 16. For the last 8 W_1 matrices, Xn comprise four distributed non-adjacent DFT beams uniformly sampling the [0, 360] angle of arrival sub-space. This provides wider angular spread coverage and may be beneficial to large timing misalignment error.

[00215] The W_1 codebook therefore can be given by:

$i_1 = 0,1,\cdots,7$:

$$\mathbf{X}^{(i_1)} \in \left\{ \left[\mathbf{b}_{2i_1 \bmod 16} \quad \mathbf{b}_{(2i_1+1) \bmod 16} \quad \mathbf{b}_{(2i_1+2) \bmod 16} \quad \mathbf{b}_{(2i_1+3) \bmod 16} \right] \right\}, \tag{108}$$

$$\mathbf{b}_n(m+1) = e^{j\frac{2\pi mn}{16}}, n = 0,1,\cdots,15 \quad , \mathrm{m} = 0,.1 \tag{109}$$

$i_1 = 8,9,\cdots,15$:

$$\mathbf{X}^{(i_1)} \in \left\{ \left[\mathbf{b}_{(i_1-8) \bmod 32} \quad \mathbf{b}_{(i_1-8)+8 \bmod 32} \quad \mathbf{b}_{(i_1-8)+16 \bmod 32} \quad \mathbf{b}_{(i_1-8)+24 \bmod 32} \right] \right\}, \tag{110}$$

$$\mathbf{b}_n(m+1) = e^{j\frac{2\pi mn}{32}}, n = 0,1,\cdots,31, \mathrm{m} = 0,.1 \tag{111}$$

[00216] As can be seen, for the last eight W_1 matrices, each W_1 matrix in codebook C_1 is comprised of four non-adjacent DFT beams. The four DFT beams in each W_1 matrix are widely spaced and uniformly distributed in the [0,360] DFT subspace to cover a wide range of angle-of-arrivals/departures. The DFT beams in a first W1 matrix are rotated by a small angle against four DFT beams in a second W_1 matrix. More specifically, the W1 matrices comprising widely spaced DFT beams are summarized as

$$\mathbf{X}_1^{(8)} \in \left\{\left[\mathbf{b}_0 \quad \mathbf{b}_8 \quad \mathbf{b}_{16} \quad \mathbf{b}_{24}\right]\right\}$$
$$\mathbf{X}_1^{(9)} \in \left\{\left[\mathbf{b}_1 \quad \mathbf{b}_9 \quad \mathbf{b}_{17} \quad \mathbf{b}_{25}\right]\right\} \tag{112}$$
$$\cdots$$
$$\mathbf{X}_1^{(15)} \in \left\{\left[\mathbf{b}_7 \quad \mathbf{b}_{15} \quad \mathbf{b}_{23} \quad \mathbf{b}_{31}\right]\right\}$$

[00217] Such a design framework is particularly beneficial in uses cases (*e.g.*, widely spaced antenna components, un-calibrated antenna array, rich multipath scattering environment) where the angle-of-arrival/departures of the incoming wireless signals are distributed in a wide range. For instance, in a heterogeneous deployment scenario where dense small cells are overlaid on top of macro base station on the same frequency, the multipath radio signals received by a UE are reflected by numerous scattering objects surrounding the UE (*e.g.*, building, cars). Have widely spaced and non-adjacent DFT beams in W1 ensures that all incoming signals from different angles can be properly captured. As another use case, it is noted that the transmitter timing at different antennas on a base station shall be synchronized by careful timing alignment calibration. In practice, perfect timing alignment cannot always be guaranteed at a base station, especially for low-cost low-power small base stations (*e.g.* pico-cells, femto-cells) with cheaper RF components. In 3GPP LTE, a maximum 65 nano-second downlink transmission timing misalignment requirement is set forth for all base stations. A consequence of misaligned antenna timing in the time domain is the increased channel variation on different OFDM subcarriers in the frequency domain, and the main DFT beam angle on one frequency subband can be significantly different than the main DFT beam angle on another subband. In this case, having non-adjacent widely spaced DFT beams in the W_1 matrix ensures that the wideband angle-of-arrival/departures can be more reliably covered, resulting in higher feedback accuracy.

[00218] The W_2 codebook for rank-1 (4-bit) may be given by:

$$\mathbf{W}_2 \in C_2 = \left\{\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ \mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ j\mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -\mathbf{Y}\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -j\mathbf{Y}\end{bmatrix}\right\}, \tag{113}$$

$$\mathbf{Y} \in \left\{\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_4\right\} \tag{114}$$

[00219] The W_2 codebook for rank-2 (4-bit) may be given by:

[00220] For W_2 corresponding to $i_1 = 0,1,\cdots,7$

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\}, \tag{115}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\} \tag{116}$$

[00221] If a (3-bit) W_2 is preferred, (Y1, Y2) may be changed to:

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4) \right\}. \tag{117}$$

[00222] For W_2 corresponding to $i_1 = 8,9,\cdots,15$

$$\mathbf{W}_2 \in C_2 = \left\{ \begin{array}{l} \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \\ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \end{array} \right\} \tag{118}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\} \tag{119}$$

[00223] If a (3-bit) W_2 is preferred, the W_2 codebook may be changed to

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\}, \tag{120}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\}, \tag{121}$$

or

$$\mathbf{W}_2 \in C_2 = \left\{ \begin{array}{l} \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \\ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \end{array} \right\} \tag{122}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3) \right\} or \left\{ (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\} \tag{123}$$

[00224] In one embodiment, the new rank-1/2 codebook designs set forth above may be incorporated into an LTE system complying with LTE Release 12. A subset of precoders in the proposed codebooks above may be used to construct a new Release 12 4Tx codebook, for either rank-1 or rank-2. For example, the W1 codebook may be constructed by W_1 matrices only comprising widely spaced DFT beams, e.g., i_2 = 8, 9, …15 in Equation (110) – (111).

[00225] FIG. 6 illustrates the precoding matrix/vector selection process according to one embodiment. The final precoding matrix/vector is a function of two PMIs:

$$W = f(PMI_1, PMI_2) \tag{124}$$

where PMI_1 is updated at a significantly less frequent rate than PMI_2. PMI_1 is intended for the entire system bandwidth while PMI_2 can be frequency-selective.

[00226] FIG. 6 illustrates the technique used in downlink LTE-Advanced (LTE-A). The UE selects PMI_1 and PMI_2 and hence W_1 and W_2 in a manner similar to the LTE feedback paradigm.

[00227] The UE first selects the first precoder codebook W_1 in block 601 based on the long-term channel properties such as spatial covariance matrix such as in a spatial correlation domain from an input of PMI_1. This is done in a long-term basis consistent with the fact that spatial covariance matrix needs to be estimated over a long period of time and in a wideband manner.

[00228] Conditioned upon W_1, the UE selects W_2 based on the short-term (instantaneous) channel. This is a two stage process. In block 602, a set of codebooks $CB_2^{(0)}$ to $CB_2^{(N-1)}$ is selected based upon the PMI_1 input. Block 603 selects one precoder corresponding to the selected codebook $CB_2^{(PMI_1)}$ and PMI_2. This selection may be conditioned upon the selected rank indicator (RI). Alternatively, RI can be selected jointly with W_2. Block 604 takes the selected W_1 and W_2 and forms the function $f(W_1, W_2)$.

[00229] PMI_1 and PMI_2 are reported to the base station (eNodeB) at different rates and/or different frequency resolutions.

[00230] Based on this design framework, several types of codebook design are described herein. While each type can stand alone, it is also possible to use different types in a single codebook design especially if the design is intended for different scenarios. A simple yet versatile design can be devised as follows:

PMI_1 selects one of the N codebooks W_1 as indicated above.

PMI_2 selects at least one of the column vectors of W, wherein the number of selected column vectors is essentially the recommended transmission rank (RI).

[00231] This design allows construction of N different scenarios where the codebook W_1 for each scenario is chosen to contain a set of basis vectors for a particular spatial channel characteristic W_2. While any two-dimensional function can be used in equation (124), this disclosure assumes a product (matrix multiplication) function f(x,y)=xy. Thus the final short-term precoding matrix/vector is computed as a matrix product of W_1 and W_2: $W = W_1 W_2$.

[00232] FIG. 7 is a block diagram illustrating internal details of a mobile UE 701 and an eNodeB 702 in the network system of FIG. 1. Mobile UE 701 may represent any of a variety of devices such as a server, a desktop computer, a laptop computer, a cellular phone, a Personal Digital Assistant (PDA), a smart phone or other electronic devices. In some embodiments, the electronic mobile UE 701 communicates with eNodeB 702 based on a LTE or Evolved Universal Terrestrial Radio Access Network (E-UTRAN) protocol. Alternatively, another communication protocol now known or later developed can be used.

[00233] Mobile UE 701 comprises a processor 703 coupled to a memory 704 and a transceiver 705. The memory 704 stores (software) applications 706 for execution by the processor 703. The applications could comprise any known or future application useful for individuals or organizations. These applications could be categorized as operating systems (OS), device drivers, databases, multimedia tools, presentation tools, Internet browsers, emailers, Voice-Over-Internet Protocol (VOIP) tools, file browsers, firewalls, instant messaging, finance tools, games, word processors or other categories. Regardless of the exact nature of the applications, at least some of the applications may direct the mobile UE 701 to transmit UL signals to eNodeB (base-station) 702 periodically or continuously via the transceiver 705. In at least some embodiments, the mobile UE 701 identifies a Quality of Service (QoS) requirement when requesting an uplink resource from eNodeB 702. In some cases, the QoS requirement may be implicitly derived by eNodeB 702 from the type of traffic supported by the mobile UE 701. As an example, VOIP and gaming applications often involve low-latency uplink (UL) transmissions while High Throughput (HTP)/Hypertext Transmission Protocol (HTTP) traffic can involve high-latency uplink transmissions.

[00234] Transceiver 705 includes uplink logic which may be implemented by execution of instructions that control the operation of the transceiver. Some of these instructions may be stored in memory 704 and executed when needed by processor 703. As would be understood by one of skill in the art, the components of the uplink logic may involve the physical (PHY) layer and/or the Media Access Control (MAC) layer of the transceiver 705. Transceiver 705 includes one or more receivers 707 and one or more transmitters 708.

[00235] Processor 703 may send or receive data to various input/output devices 709. A subscriber identity module (SIM) card stores and retrieves information used for making calls via the cellular system. A Bluetooth baseband unit may be provided for wireless connection to a

microphone and headset for sending and receiving voice data. Processor 703 may send information to a display unit for interaction with a user of mobile UE 701 during a call process. The display may also display pictures received from the network, from a local camera, or from other sources such as a Universal Serial Bus (USB) connector. Processor 703 may also send a video stream to the display that is received from various sources such as the cellular network via RF transceiver 705 or the camera.

[00236] During transmission and reception of voice data or other application data, transmitter 707 may be or become non-synchronized with its serving eNodeB. In this case, it sends a random access signal. As part of this procedure, it determines a preferred size for the next data transmission, referred to as a message, by using a power threshold value provided by the serving eNodeB, as described in more detail above. In this embodiment, the message preferred size determination is embodied by executing instructions stored in memory 704 by processor 703. In other embodiments, the message size determination may be embodied by a separate processor/memory unit, by a hardwired state machine, or by other types of control logic, for example.

[00237] eNodeB 702 comprises a processor 710 coupled to a memory 711, symbol processing circuitry 712, and a transceiver 713 via backplane bus 714. The memory stores applications 715 for execution by processor 710. The applications could comprise any known or future application useful for managing wireless communications. At least some of the applications 715 may direct eNodeB 702 to manage transmissions to or from mobile UE 701.

[00238] Transceiver 713 comprises an uplink Resource Manager, which enables eNodeB 702 to selectively allocate uplink Physical Uplink Shared CHannel (PUSCH) resources to mobile UE 701. As would be understood by one of skill in the art, the components of the uplink resource manager may involve the physical (PHY) layer and/or the Media Access Control (MAC) layer of the transceiver 713. Transceiver 713 includes at least one receiver 715 for receiving transmissions from various UEs within range of eNodeB 702 and at least one transmitter 716for transmitting data and control information to the various UEs within range of eNodeB 702.

[00239] The uplink resource manager executes instructions that control the operation of transceiver 713. Some of these instructions may be located in memory 711 and executed when needed on processor 710. The resource manager controls the transmission resources allocated to each UE 701 served by eNodeB 702 and broadcasts control information via the PDCCH.

[00240] Symbol processing circuitry 712 performs demodulation using known techniques. Random access signals are demodulated in symbol processing circuitry 712.

[00241] During transmission and reception of voice data or other application data, receiver 715 may receive a random access signal from a UE 701. The random access signal is encoded to request a message size that is preferred by UE 701. UE 701 determines the preferred message size by using a message threshold provided by eNodeB 702. In this embodiment, the message threshold calculation is embodied by executing instructions stored in memory 711 by processor 710. In other embodiments, the threshold calculation may be embodied by a separate processor/memory unit, by a hardwired state machine, or by other types of control logic, for example. Alternatively, in some networks the message threshold is a fixed value that may be stored in memory 711, for example. In response to receiving the message size request, eNodeB 702 schedules an appropriate set of resources and notifies UE 701 with a resource grant.

[00242] Those skilled in the art will appreciate that modifications may be made to the described embodiments, and also that many other embodiments are possible, within the scope of the claimed invention.

CLAIMS

1. A method of channel state information (CSI) feedback in a wireless communication system, comprising:

receiving one or more precoding matrix indicator (PMI) signals from a remote transceiver; and

generating a precoding matrix W derived from a matrix multiplication of two matrices W1 and W2, where said precoding matrix W is applicable to precoding one or more layers of data streams, matrix W1 selected from a first codebook C1 based on a first group of bits in the PMI signals, and matrix W2 selected from a second codebook C2 based on a second group of bits in the PMI signals, wherein the first codebook C1 comprises the following W1 matrices constructed by non-adjacent Discrete Fourier Transform (DFT) vectors:

$$\mathbf{B}=\begin{bmatrix}\mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{N-1}\end{bmatrix}, \quad [\mathbf{B}]_{l+m,l+n}=e^{j\frac{2\pi mn}{N}}, \quad m=0,\ldots\frac{N_t}{2}-1,\ n=0,1,\cdots,N-1,$$

$$\mathbf{X}^{(k)}\in\left\{\begin{bmatrix}\mathbf{b}_{k \bmod N} & \mathbf{b}_{(k+N/4) \bmod N} & \mathbf{b}_{(k+2\times N/4) \bmod 32} & \mathbf{b}_{(k+3\times N/4) \bmod 32}\end{bmatrix}: k=0,1,\cdots,\frac{N}{4}-1\right\},$$

$$\mathbf{W}_1^{(k)}=\begin{bmatrix}\mathbf{X}^{(k)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(k)}\end{bmatrix},$$

$$C_1=\left\{\mathbf{W}_1^{(0)},\mathbf{W}_1^{(1)},\mathbf{W}_1^{(2)},\cdots,\mathbf{W}_1^{(N/4-1)}\right\},$$

$N_t \geq 4$ is the number of transmit antennas corresponding to W,

N is an integer number greater than or equal to N_t.

2. The method of claim 1, wherein the number of layers of the data stream is one, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2\in C_2=\left\{\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ \mathbf{Y}\end{bmatrix},\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ j\mathbf{Y}\end{bmatrix},\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -\mathbf{Y}\end{bmatrix},\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{Y}\\ -j\mathbf{Y}\end{bmatrix}\right\},$$

$$\mathbf{Y}\in\left\{\tilde{\mathbf{e}}_1,\tilde{\mathbf{e}}_2,\tilde{\mathbf{e}}_3,\tilde{\mathbf{e}}_4\right\}, \text{ and}$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

3. The method of claim 1, wherein the number of layers of the data stream is two, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

4. The method of claim 1, wherein the number of layers of the data stream is two, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\}$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

5. The method of claim 1, wherein the number of layers of the data stream is two, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \begin{array}{l} \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \\ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \end{array} \right\}$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3) \right\} or \left\{ (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\}$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1

6. A method of channel state information (CSI) feedback in a wireless communication system, comprising:

receiving one or more precoding matrix indicator (PMI) signals from a remote transceiver; and

generating a precoding matrix W derived from a matrix multiplication of two matrices W1 and W2, where said precoding matrix W is applicable to precoding one or more layers of data streams, matrix W1 selected from a first codebook C1 based on a first group of bits in the PMI signals, and matrix W2 selected from a second codebook C2 based on a second group of bits in the PMI signals, wherein the first codebook C1 comprises at least a first W1 matrix and a second W1 matrix, wherein said at least first W1 matrix is constructed with a first group of adjacent Discrete Fourier Transform (DFT) vectors, and said at least second W1 matrix is constructed with a second group of non-adjacent DFT vectors, and

$$\mathbf{B}=\begin{bmatrix}\mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{31}\end{bmatrix} \quad , \quad [\mathbf{B}]_{l+m,l+n}=e^{j\frac{2\pi mn}{32}}, \quad m=0,...\frac{N_t}{2}-1, n=0,1,\cdots,31,$$

for $i_1=0,1,\cdots,7$:

$$\mathbf{X}^{(i_1)}\in\left\{\begin{bmatrix}\mathbf{b}_{2i_1 \bmod 16} & \mathbf{b}_{(2i_1+1)\bmod 16} & \mathbf{b}_{(2i_1+2)\bmod 16} & \mathbf{b}_{(2i_1+3)\bmod 16}\end{bmatrix}\right\},$$

$$\mathbf{b}_n(m+1)=e^{j\frac{2\pi mn}{16}}, n=0,1,\cdots,15 \quad , \mathrm{m}=0,.1$$

for $i_1=8,9,\cdots,15$:

$$\mathbf{X}^{(i_1)}\in\left\{\begin{bmatrix}\mathbf{b}_{(i_1-8)\bmod 32} & \mathbf{b}_{(i_1-8)+8\bmod 32} & \mathbf{b}_{(i_1-8)+16\bmod 32} & \mathbf{b}_{(i_1-8)+24\bmod 32}\end{bmatrix}\right\}$$

$$\mathbf{b}_n(m+1)=e^{j\frac{2\pi mn}{32}}, n=0,1,\cdots,31, \mathrm{m}=0,.1$$

$$\mathbf{W}_1^{(i_1)}=\begin{bmatrix}\mathbf{X}^{(i_1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{X}^{(i_1)}\end{bmatrix},$$

$$C_1=\left\{\mathbf{W}_1^{(0)},\mathbf{W}_1^{(1)},\mathbf{W}_1^{(2)},\cdots,\mathbf{W}_1^{(15)}\right\},$$

$N_t \geq 4$ is the number of transmit antennas corresponding to W.

7. The method of claim 6, further comprising:

precoding one or more layers of a data stream at a base station by multiplication with the precoding matrix W; and

transmitting the precoded layers in the data stream to the remote transceiver.

8. The method of claim 6, wherein the number of layers of the data stream is one, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ \mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ j\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -j\mathbf{Y} \end{bmatrix} \right\},$$

$\mathbf{Y} \in \left\{ \tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_4 \right\}$, and

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

9. The method of claim 6, wherein the number of layers of the data stream is two, and wherein $i_1 = 0,1,\cdots,7$, the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

10. The method of claim 6, wherein the number of layers of the data stream is two, and wherein $i_1 = 0,1,\cdots,7$, the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

11. The method of claim 6, wherein the number of layers of the data stream is two, and wherein $i_1 = 8,9,\cdots,15$, the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \begin{array}{l} \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \\ \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \end{array} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \left(\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3\right), \left(\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4\right) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

12. The method of claim 6, wherein the number of layers of the data stream is two, and wherein $i_1 = 8,9,\cdots,15$, the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \left(\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3\right), \left(\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4\right) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

13. The method of claim 6, wherein the number of layers of the data stream is two, and wherein $i_1 = 8,9,\cdots,15$, the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \begin{array}{l} \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & \mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -\mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \\ \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & j\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ -j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \end{array} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ \left(\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_3\right) \right\} or \left\{ \left(\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4\right) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

14. A method of channel state information (CSI) feedback in a wireless communication system, comprising:

receiving one or more precoding matrix indicator (PMI) signals from a remote transceiver; and

generating a precoding matrix W derived from a matrix multiplication of two matrices W1 and W2, where said precoding matrix W is applicable to precoding one or more layers of data streams, matrix W1 selected from a first codebook C1 based on a first group of bits in the PMI signals, and matrix W2 selected from a second codebook C2 based on a second group of bits in the PMI signals, wherein the first codebook C1 comprises at least the following matrix constructed by a set of adjacent Discrete Fourier Transform (DFT) vectors:

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_0 & \mathbf{b}_1 & \cdots & \mathbf{b}_{31} \end{bmatrix} \quad , \quad [\mathbf{B}]_{l+m,l+n} = e^{j\frac{2\pi mn}{32}} \quad , \quad m = 0,\ldots\frac{N_t}{2} - 1,\ n = 0,1,\cdots,31 \,,$$

$$\mathbf{X}^{(k)} \in \left\{ \begin{bmatrix} \mathbf{b}_{2k \bmod 32} & \mathbf{b}_{(2k+1) \bmod 32} & \mathbf{b}_{(2k+2) \bmod 32} & \mathbf{b}_{(2k+3) \bmod 32} \end{bmatrix} : k = 0,1,\cdots,15 \right\} \,,$$

$$\mathbf{W}_1^{(k)} = \begin{bmatrix} \mathbf{X}^{(k)} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}^{(k)} \end{bmatrix},$$

$$C_1 = \left\{ \mathbf{W}_1^{(0)}, \mathbf{W}_1^{(1)}, \mathbf{W}_1^{(2)}, \cdots, \mathbf{W}_1^{(15)} \right\},$$

$N_t = 4$ is the number of transmit antennas corresponding W.

15. The method of claim 14, further comprising:

precoding one or more layers of a data stream at a base station by multiplication with the precoding matrix W; and

transmitting the precoded layers in the data stream to the remote transceiver.

16. The method of claim 14, wherein the number of layers of the data stream is one, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ \mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ j\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -\mathbf{Y} \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y} \\ -j\mathbf{Y} \end{bmatrix} \right\},$$

$$\mathbf{Y} \in \left\{ \tilde{\mathbf{e}}_1 , \tilde{\mathbf{e}}_2 , \tilde{\mathbf{e}}_3 , \tilde{\mathbf{e}}_4 \right\}, \text{ and}$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

17. The method of claim 14, wherein the number of layers of the data stream is two, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_4), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_4) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

18. The method of claim 14, wherein the number of layers of the data stream is two, and wherein the second codebook C2 comprises at least the following matrix:

$$\mathbf{W}_2 \in C_2 = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ \mathbf{Y}_1 & -\mathbf{Y}_2 \end{bmatrix}, \frac{1}{\sqrt{2}} \begin{bmatrix} \mathbf{Y}_1 & \mathbf{Y}_2 \\ j\mathbf{Y}_1 & -j\mathbf{Y}_2 \end{bmatrix} \right\},$$

$$(\mathbf{Y}_1, \mathbf{Y}_2) \in \left\{ (\tilde{\mathbf{e}}_1, \tilde{\mathbf{e}}_1), (\tilde{\mathbf{e}}_2, \tilde{\mathbf{e}}_2), (\tilde{\mathbf{e}}_3, \tilde{\mathbf{e}}_3), (\tilde{\mathbf{e}}_4, \tilde{\mathbf{e}}_4) \right\},$$

wherein $\tilde{\mathbf{e}}_i$ is a 4×1 vector with all zero entries except for the i-th element which has value 1.

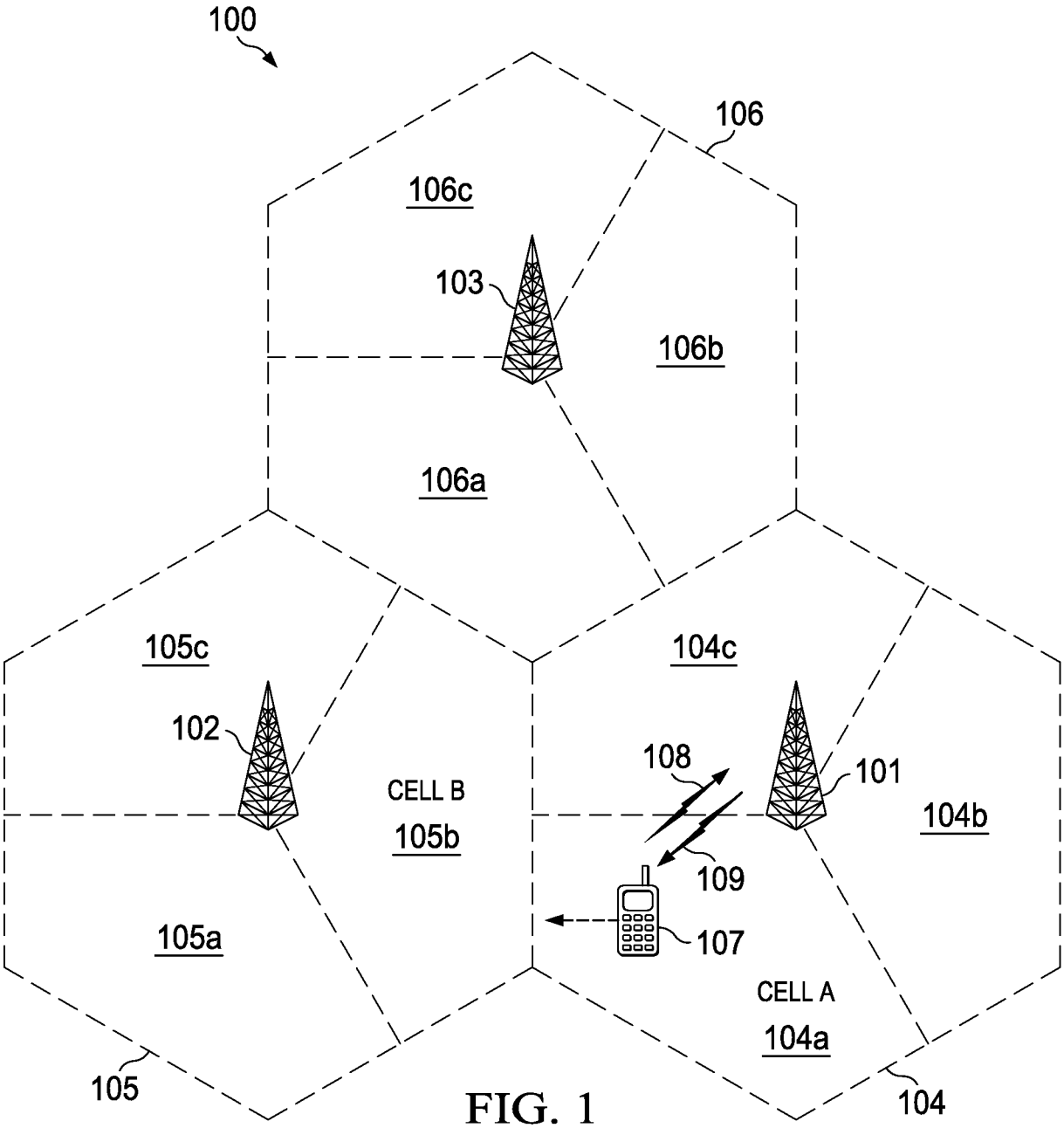

FIG. 1
(PRIOR ART)

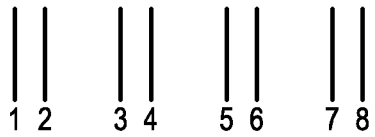

FIG. 2

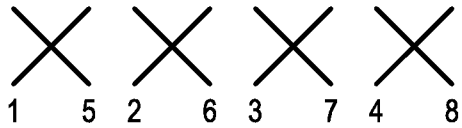

FIG. 3

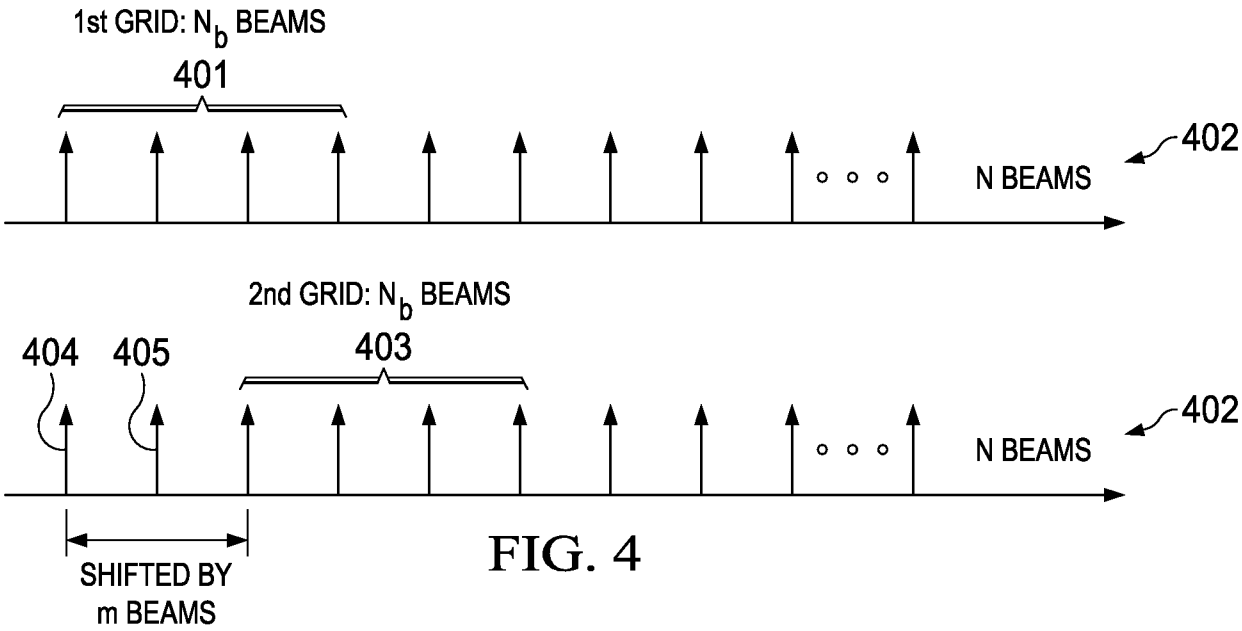

FIG. 4

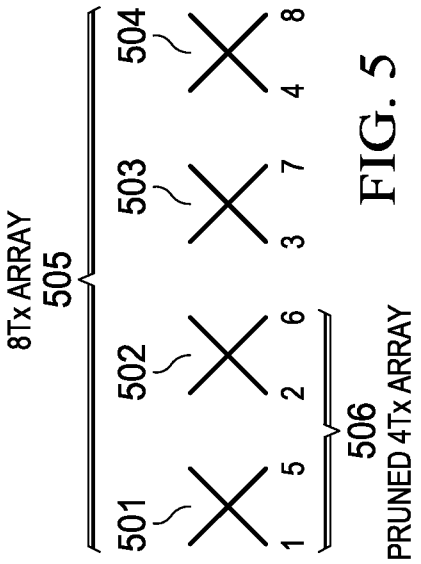
8Tx ARRAY
505
501
502
503
504
1
5
2
6
3
7
4
8
506
PRUNED 4Tx ARRAY

FIG. 5

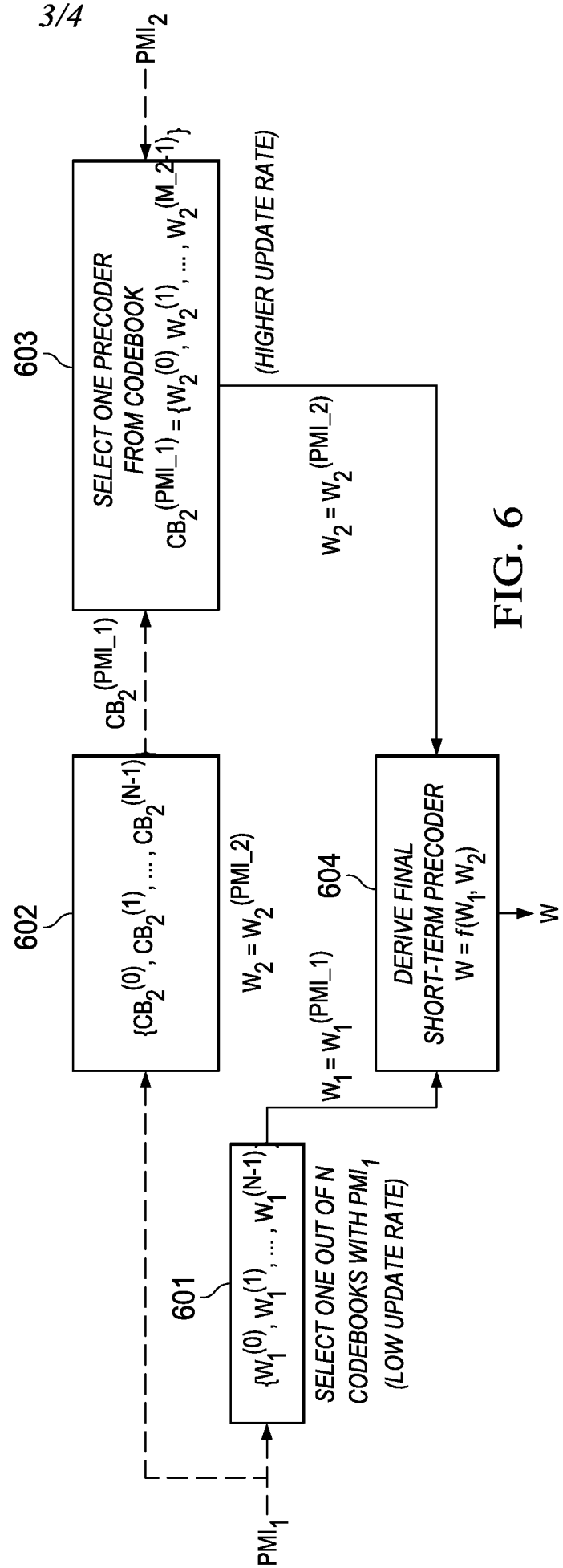
PMI_2
603
SELECT ONE PRECODER FROM CODEBOOK
$CB_2^{(PMI_1)} = \{W_2^{(0)}, W_2^{(1)}, \ldots, W_2^{(M_2-1)}\}$
(HIGHER UPDATE RATE)
$W_2 = W_2^{(PMI_2)}$
$CB_2^{(PMI_1)}$
602
$\{CB_2^{(0)}, CB_2^{(1)}, \ldots, CB_2^{(N-1)}\}$
$W_2 = W_2^{(PMI_2)}$
604
DERIVE FINAL SHORT-TERM PRECODER
$W = f(W_1, W_2)$
W
$W_1 = W_1^{(PMI_1)}$
601
$\{W_1^{(0)}, W_1^{(1)}, \ldots, W_1^{(N-1)}\}$
SELECT ONE OUT OF N CODEBOOKS WITH PMI_1
(LOW UPDATE RATE)
PMI_1

FIG. 6

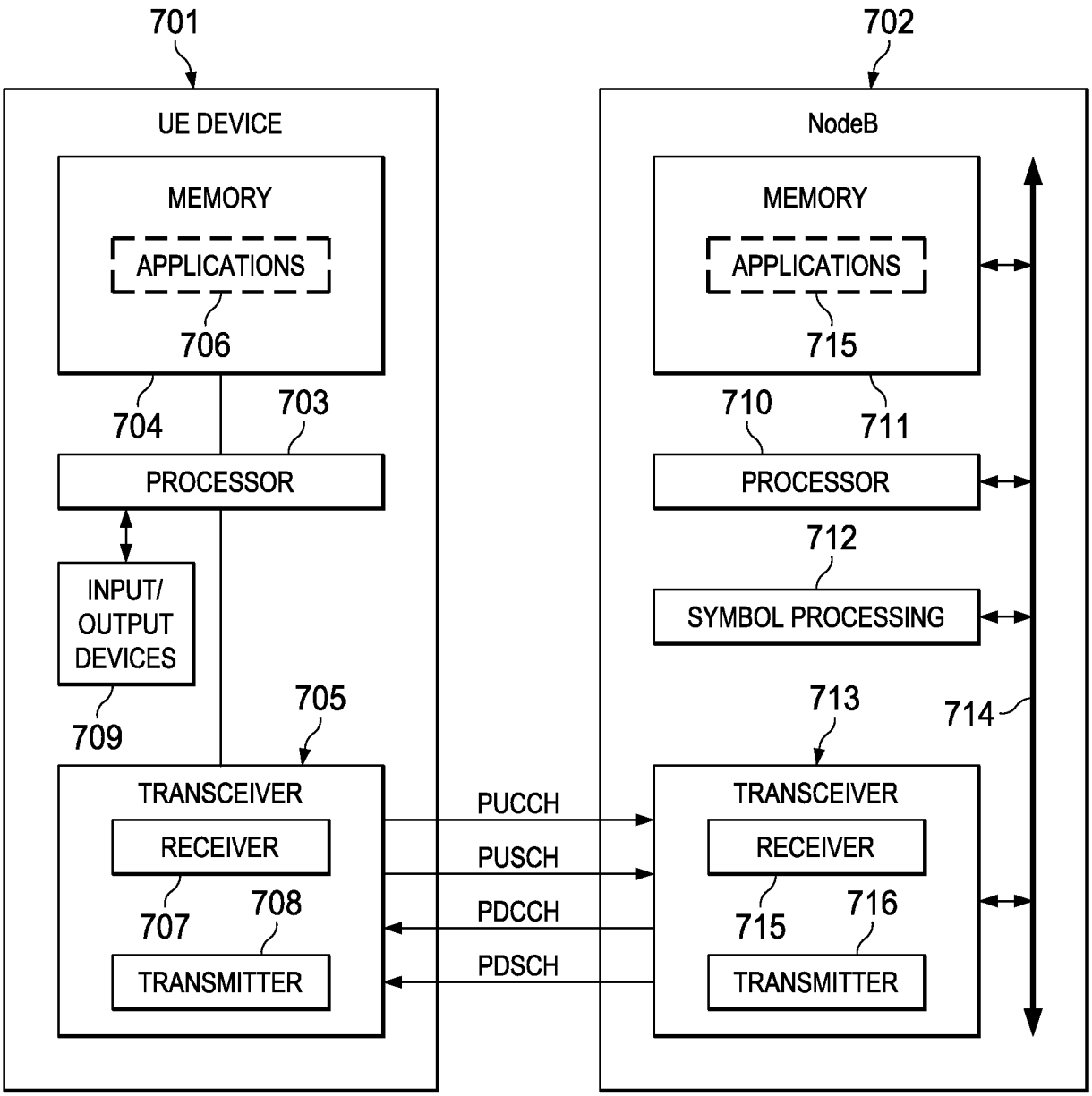
701
UE DEVICE
MEMORY
APPLICATIONS
706
704
703
PROCESSOR
INPUT/
OUTPUT
DEVICES
709
705
TRANSCEIVER
RECEIVER
707
708
TRANSMITTER
PUCCH
PUSCH
PDCCH
PDSCH
702
NodeB
MEMORY
APPLICATIONS
715
710
711
PROCESSOR
712
SYMBOL PROCESSING
713
714
TRANSCEIVER
RECEIVER
715
716
TRANSMITTER

FIG. 7