



(51) International Patent Classification:
H04L 25/02 (2006.01)

(21) International Application Number:
PCT/CN2020/082096

(22) International Filing Date:
30 March 2020 (30.03.2020)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/825,624 28 March 2019 (28.03.2019) US

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(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,

(54) Title: SYSTEM AND METHOD FOR REDUCED CSI FEEDBACK AND REPORTING USING TENSORS AND TENSOR DECOMPOSITION

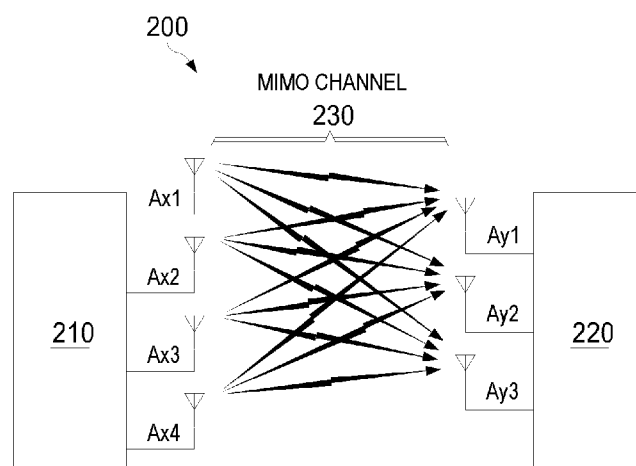


FIG. 2

(57) Abstract: A user equipment (UE) receives, through M antenna ports, a reference signal (RS) resource set transmitted from N antenna ports of a base station (BS) over K1 subcarriers on L1 OFDM symbols, and reports, to the BS, R sets of vectors that are obtained based on measurement of the RS resource set. Each set of vectors includes one or more vectors selected from a $N \times 1$ vector, a $M \times 1$ vector, a $K2 \times 1$ vector, and a $L2 \times 1$ vector, and the sum of R outer products of the respective R sets of vectors represents channel state information of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K2 subcarriers on L2 OFDM symbols. The BS reconstructs the channel by calculating an outer product of each set of vectors and summing up outer products of the respective R sets of vector.

TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

- *with international search report (Art. 21(3))*

System and Method for Reduced CSI Feedback and Reporting Using Tensors and Tensor Decomposition

TECHNICAL FIELD

[1] The present invention relates generally to wireless communications, and, in particular embodiments, to a system and method for reduced channel state information (CSI) feedback and reporting using tensors and tensor decomposition.

BACKGROUND

[2] Wireless communication systems typically include base stations communicating with user equipments (UEs). A communication channel from a base station to a UE is generally referred to as a downlink channel, and a transmission from the base station to the UE is a downlink transmission. A communication channel from a UE to a base station is generally referred to an uplink channel, and a transmission from the UE to the base station is an uplink transmission. Channel estimation may be performed to improve communications between base stations and UEs. In a time division duplex (TDD) system, a base station can exploit the channel reciprocity and measure the uplink channel to infer the downlink channel. In a frequency division duplex (FDD) system, separation between uplink transmissions and downlink transmissions is in frequency, and feedback may be required from receivers (UEs) to convey information regarding the downlink channel. The feedback would be substantial when the users are highly mobile and the communications system has a massive number of antennas. Therefore, knowledge of channel state information (CSI) at the base station with low feedback overhead is becoming increasingly important in wireless communication systems for achieving higher spectral efficiency.

SUMMARY

[3] According to one aspect of the present disclosure, a method is provided that includes: receiving, through M antenna ports of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted from N antenna ports of a base station (BS) over K_1 subcarriers on L_1 OFDM symbols, wherein each of the M , N , K_1 and L_1 is an integer greater than 0, and reporting, by the UE to the BS, R sets of vectors that are obtained based on measurement of the RS resource set, wherein each set of vectors comprises one or more vectors, the one or more vectors comprising a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector, a fourth $L_2 \times 1$ vector, or any combination thereof, wherein a sum of R outer products of the respective R sets of vectors represents channel state information of a channel between the N antenna ports of

the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols, and wherein each of the R, K_2 and L_2 is an integer greater than 0.

[4] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, resources carrying the RS resource set.

[5] Optionally, in any one of preceding aspects, the R sets of vectors are reported according to a configuration signaled by the BS.

[6] Optionally, in any one of preceding aspects, the method further includes: constructing, by the UE, a multi-dimensional tensor representing the channel based on the measurement of the RS resource set, and performing, by the UE, decomposition on the multi-dimensional tensor using a tensor decomposition technique, whereby generating factor matrices, wherein the R sets of vectors are obtained from the factor matrices.

[7] Optionally, in any one of preceding aspects, the multi-dimensional tensor is constructed based on the measurement of the RS resource set in a set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.

[8] Optionally, in any one of preceding aspects, the number of measurement domains in the set of measurement domains is configured by the BS.

[9] Optionally, in any one of preceding aspects, the set of measurement domains is configured by the BS.

[10] Optionally, in any one of preceding aspects, a factor matrix comprises a plurality of $N \times 1$ vectors, a plurality of $M \times 1$ vectors, a plurality of $K_2 \times 1$ vectors, or a plurality of $L_2 \times 1$ vector.

[11] Optionally, in any one of preceding aspects, the factor matrices are generated from Canonical Polyadic decomposition (CPD) of the multi-dimensional tensor.

[12] Optionally, in any one of preceding aspects, the R sets of vectors are a subset of a plurality of $N \times 1$ vectors, a plurality of $M \times 1$ vectors, a plurality of $K_2 \times 1$ vectors, and a plurality of $L_2 \times 1$ vectors that make up the factor matrices.

[13] Optionally, in any one of preceding aspects, information about R is configured by the BS.

[14] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, signaling indicating the one or more vectors to be reported.

[15] Optionally, in any one of preceding aspects, resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.

[16] Optionally, in any one of preceding aspects, the R sets of vectors that are reported comprises quantized amplitudes and phases of elements of vectors.

[17] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, configuration information for reporting the R sets of vectors in higher layer signaling, or a downlink control information (DCI) message.

[18] Optionally, in any one of preceding aspects, the configuration information comprises information triggering reporting of the R sets of vectors.

[19] In accordance with another aspects of the present disclosure, a method is provided that includes: transmitting, through N antenna ports of a base station (BS) to M antenna ports of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted over K₁ subcarriers on L₁ OFDM symbols, wherein each of the M, N, K₁ and L₁ is an integer greater than 0, receiving, by the BS from the UE, a channel state information (CSI) report measured based on the RS resource set, the CSI report comprising information of R sets of vectors, wherein each set of vectors comprises one or more vectors, the one or more vectors comprising a first N×1 vector, a second M×1 vector, a third K₂×1 vector, a fourth L₂×1 vector, or any combination thereof, and wherein a sum of R outer products of the respective R sets of vectors represents CSI of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K₂ subcarriers on L₂ OFDM symbols, each of the R, K₂ and L₂ being an integer greater than 0, and reconstructing, by the BS, the channel based on the R sets of vectors by calculating an outer product of each set of vectors and summing up outer products of the respective R sets of vector.

[20] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, resources carrying the RS resource set.

[21] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, information about R.

[22] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a set of measurement domains for the UE to measure the RS resource set in the set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.

[23] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, an order of the set of measurement domains for the UE to measure the RS resource set in the order of the set of measurement domains.

[24] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a number of measurement domains in the set of measurement domains.

[25] Optionally, in any one of preceding aspects, the method further includes configuring, by the BS for the UE, one or more measurement domains comprised in the set of measurement domains.

[26] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, signaling indicating the one or more vectors to be reported.

[27] Optionally, in any one of preceding aspects, resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.

[28] Optionally, in any one of preceding aspects, the R sets of vectors that are reported comprises quantized amplitudes and phases of elements of vectors.

[29] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a trigger triggering reporting of the CSI of the channel.

[30] Optionally, in any one of preceding aspects, the method further includes generating, by the BS to the UE, a transmission filter based on the CSI report.

[31] An apparatus and a system for performing the above aspects are also provided.

[32] In the forgoing aspects, a UE feeds back R sets of vectors to a BS, where a sum of R outer products of the respective R sets of vectors represents channel state information of a channel. Feeding back the R sets of vectors by the UE involves less CSI feedback overhead compared with feeding back all information about the channel, while the R sets of vectors that are fed back can be used by the BS to reconstruct the channel, which may further be used for performing downlink transmission over the channel. The forgoing aspects have an advantage of providing improved downlink beamforming, e.g., in single user (SU)-MIMO systems and multi-user (MU)-MIMO systems, with less CSI feedback overhead.

BRIEF DESCRIPTION OF THE DRAWINGS

[33] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[34] FIG. 1 illustrates a diagram of an embodiment wireless network;

[35] FIG. 2 illustrates a diagram of an embodiment multi-input multi-output (MIMO) communications system;

[36] FIG. 3 illustrates a diagram showing a communication channel between a transmitter and a receiver modeled using multipath components (MPCs) arriving in clusters;

[37] FIG. 4 illustrates a graph showing single user (SU)-MIMO capacity curves of a MIMO system;

[38] FIG. 5 illustrates a diagram of an embodiment method for channel state information (CSI) feedback in a MIMO communications system;

[39] FIG. 6 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[40] FIG. 7 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[41] FIG. 8 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[42] FIG. 9 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[43] FIG. 10 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[44] FIG. 11 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[45] FIG. 12 illustrates a flowchart of another embodiment method for CSI feedback in a MIMO communications system;

[46] FIG. 13 illustrates a flowchart of an embodiment method for CSI feedback in a communications system;

[47] FIG. 14 illustrates a flowchart of another embodiment method for CSI feedback in a communications system;

[48] FIG. 15 illustrates a diagram of an embodiment processing system; and

[49] FIG. 16 illustrates a diagram of an embodiment transceiver.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[50] In a wireless communications system, a base station (BS) transmits reference signals to user equipment (UEs) for measuring channels between the BS and the UEs. A UE measures a channel based on the reference signals, and feeds back channel state information (CSI) of the channel to the BS. If all information of the estimated channel can be fed back to the BS, the BS may obtain a more complete understanding of the channel condition and quality, and consequently perform generally optimal downlink transmissions. However, this involves very large CSI feedback overhead (e.g., transmission resources), especially in cases of multi-input and multi-output (MIMO) systems or massive MIMO systems, where the CSI scales with a large number of transmit antennas.

[51] Embodiments of the present disclosure provide methods for feeding back CSI by UEs based on tensors and tensor decomposition techniques. Specifically, a MIMO channel or a MIMO channel covariance may be modelled as a multi-dimensional tensor, which is decomposed using a tensor decomposition technique, such as Canonical Polyadic decomposition. The decomposition results in factor matrices. Because the factor matrices represent CSI of the MIMO channel or the MIMO channel covariance, information about all or partial of the factor matrices may be fed back to a BS, and the BS may reconstruct the MIMO channel based on the feedback, and perform downlink transmissions accordingly. The overhead for feeding back the factor matrices depends on the size of each factor matrix, which is much less compared with feeding back all measurement information of the MIMO channel. Thus, the embodiments reduce CSI feedback overhead, while still providing sufficient amount of information for a more accurate estimation of the MIMO channel.

[52] In some embodiments, a UE may receive, through M antenna ports, a reference signal (RS) resource set transmitted from N antenna ports of a BS over K_1 subcarriers on L_1 OFDM symbols, and report, to the BS, R sets of vectors that are obtained based on measurement of the RS resource set. Each set of vectors may include one or more vectors selected from a $N \times 1$ vector, a $M \times 1$ vector, a $K_2 \times 1$ vector, and a $L_2 \times 1$ vector, and the sum of R outer products of the respective R sets of vectors represents channel state information of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols. The BS may reconstruct the channel by calculating an outer product of each set of vectors and

summing up outer products of the respective R sets of vector. Details of the embodiments will be provided in the following description.

[53] FIG. 1 illustrates a network 100 for communicating data. The network 100 comprises a base station 110 having a coverage area 101, a plurality of mobile devices 120, and a backhaul network 130. As shown, the base station 110 establishes uplink (dashed line) and/or downlink (dotted line) connections with the mobile devices 120, which serve to carry data from the mobile devices 120 to the base station 110, and vice-versa. Data carried over the uplink/downlink connections may include data communicated between the mobile devices 120, as well as data communicated to/from a remote-end (not shown) by way of the backhaul network 130. As used herein, the term “base station” refers to any component (or collection of components) configured to provide wireless access to a network, such as, an access node, a Node B, an evolved Node B (eNB), a next generation (NG) Node B (gNB), a master eNB (MeNB), a secondary eNB (SeNB), a master gNB (MgNB), a secondary gNB (SgNB), a network controller, a control node, an access point, a transmission point (TP), a transmission-reception point (TRP), a cell, a carrier, a macro cell, a femto cell, a pico cell, a relay, a customer premises equipment (CPE), a Wi-Fi access point (AP), or other wirelessly enabled devices. Base stations may provide wireless access in accordance with one or more wireless communication protocols, e.g., long term evolution (LTE), LTE advanced (LTE-A), 3GPP Rel. 15 and subsequent release, high speed packet access (HSPA), Wi-Fi 802.11a/b/g/n/ac, ax and other 802.11xx standards. As used herein, the term “mobile device” refers to any component (or collection of components) capable of establishing a wireless connection with a base station, such as a user equipment (UE), a mobile station (STA), a mobile, a terminal, a user, a subscriber, a stations, a communication device, a CPE, a relay, an integrated access and backhaul (IAB) relay, and other wirelessly enabled devices. In some embodiments, the network 100 may comprise various other wireless devices, such as relays, low power nodes, In the device to device communication mode, such as the proximity services operating mode, direct communication between UEs is possible.

[54] The base station 110 may utilize channel state information (CSI) to adapt downlink transmission to a downlink channel between the base station 110 and a UE 120. The CSI may be estimated by the UE 120 and fed back to the base station 110. The design of a multi-input multi-output (MIMO) communication system depends on, at least in part, the accuracy of the knowledge of CSI. The theoretically best performance in terms of spectral efficiency may be achieved when perfect CSI is available at both communication nodes. However, imperfect CSI may arise due to channel estimation errors, quantization errors, and/or outdated channel estimates.

[55] In time division duplex (TDD) systems, where a base station and UEs use the same frequency band for transmission, the base station may take advantage of channel reciprocity to obtain downlink channel (also called forward channel) estimation from pilots received over the uplink channel (also called reverse channel). In this case, CSI may not need to be estimated and fed back by UEs to the base station. However, because measurement at the base station may not capture downlink interferences from co-scheduled UEs or from neighboring cells, and the downlink channel estimation may not accurately reflect the downlink channel conditions. Thus, in many cases, UEs may still need to feedback estimated CSI to the base station even for a TDD system.

[56] In frequency division duplex (FDD) systems, because uplink transmission and downlink transmission are performed using different frequencies, relying on the uplink channel solely may not be able to produce desirable performance in downlink transmission, e.g., in terms of spectral efficiency. Therefore, UEs may need to estimate the downlink channel and feedback estimated CSI to the base station for downlink transmission.

[57] Conventionally, a channel between two devices is estimated by having a first device transmit a known signal on a known time or frequency resource (s) to a second device, the received signal at the second device is expressible as

$$y = Hs + n, \quad (1)$$

where y is the received signal at the second device, s is the known signal (which may be a reference signal, a pilot, or a pilot signal), H is the channel model or channel impulse response (CIR), and n is the noise (and interference for some communication channels). In a MIMO system, where there are N_{tx} transmit antennas and N_{rx} receive antennas, H is a $N_{rx} \times N_{tx}$ matrix. Because s is known by the second device, it is possible for the second device to determine or estimate H from y . Accordingly, a base station may transmit reference signals s to a UE, and the UE may estimate the channel H , and feed back CSI information based on the estimated H to the base station.

[58] However, in a communications system with a large number of antennas, such as a massive MIMO communications system, H generally has to be estimated for every possible transmit-receive antenna pair. Therefore, antenna element to element channel estimation and feedback may be expensive in terms of computational resources, as well as communications overhead. It is noted that the concept of antenna, antenna element, and antenna port may be generally interchangeable, but in some specific scenarios, they can mean different but related subjects. For example, one transmit (Tx) antenna port may be formed (or virtualized) by multiple antenna elements or antennas, and the

receiver sees only the one Tx antenna port instead of each of the multiple antenna elements or antennas. The virtualization may be achieved via beamforming, for example.

[59] When precoding is applied to downlink signals, the received signal at the second device may be expressed as

$$y_1 = Hvs + n$$

where y_1 is the received signal at the second device, v is a transmit filter (or precoder), s is the known signal, H is the channel model or response, and n is the noise. The signal s is precoded by v and transmitted. The transmit filter v of dimension $N_{tx} \times N_s$ enables the transmitter to precode or beamform the transmitted signal, where N_s is the number of layers, streams, symbols, pilots, messages, or known sequences transmitted. The precoder (i.e., the transmit filter v) can be a digital precoder, analog precoder, or hybrid digital-analog precoder, in which case N_s is replaced by N_{RF} representing the number of RF chains and is either equal to or smaller than the number of transmit antennas or transmit antenna ports

[60] A MIMO orthogonal frequency division multiplexing (OFDM) system provides an additional mode (or a dimension, or a domain) to the $N_{Rx} \times N_{Tx}$ matrix of a MIMO system that may lead to a multi-dimensional (e.g., a tensor, a multi-mode, a multi-domain, an array with multiple dimensions). For example, the channel mode may be represented by

$$\mathcal{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx} \times N_K} . \quad (3)$$

In this case, the third additional dimension represents a subcarrier dimension (e.g., subbands, tones, resource blocks, frequencies) of an OFDM system. In this particular example, the number of subcarriers, tones, subbands, or resource blocks is represented by N_K .

[61] Various methods have been developed to conduct CSI estimation and feedback (or reporting). In Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) systems, CSI feedback includes feedback of a channel quality indicator (CQI), a precoding matrix indicator (PMI), a rank indicator (RI) and a precoding type indication (PTI). The transmitter uses the CQI to select one of 15 modulation alphabet and code rate combinations for transmission. The RI informs the transmitter about the number of useful transmission layers for the current MIMO channel. The PMI signals the codebook index of the preferred digital precoding matrix. These three values are used to optimize resource allocation among UEs. CSI-RS is the channel state information reference signal and is used by a UE to estimate and report the CQI to a base station. There are two types of CQI transmission: Periodic and Aperiodic. Periodic CQI is

transmitted periodically with a certain interval specified by a higher layer message, e.g., radio resource control (RRC), while Aperiodic CQI is transmitted by a special trigger (e.g., DCI, or a RACH Response). The CSI feedback parameters are transmitted on the physical uplink control channel (PUCCH) or physical uplink shared channel (PUSCH) depending on the CSI Report Type (Periodic or Aperiodic), and used for closed loop link adaptation. Both wideband and subband CQI are supported.

[62] Codebook based feedback is adopted by 3GPP. Other methods of CSI feedback include feedback of the MIMO matrix for each tone (e.g., each subband, or each subcarrier), a group of tones (or group of subbands), or feedback of a wideband MIMO matrix, after channel estimation is performed by the UE. Another method includes having the UE perform singular value decomposition (SVD) on the matrix, decompose the channel into parallel single output single output (SISO) subchannel with non-equal gains, and feedback the right singular matrix or a subset of the right singular matrix. Efficient quantization/encoding of the unitary matrix may be adopted.

[63] In the conventional close loop-MIMO (CL-MIMO) systems, if CSI feedback is non-codebook based, that is, if information of the entire estimated channel H may be fed back to the base station, the base station may be able to have a more complete understanding of the channel condition and quality, and thus perform generally optimal downlink transmission. In performing the downlink transmission, the base station may perform Eigen based beamforming, or SVD based beamforming, or compute the optimal downlink multi-user MIMO precoder with interference cancellation. However, this type of feedback may incur a large overhead (e.g., transmission resources) for feeding back the CSI, especially in cases of multi-input and multi-output (MIMO) systems or massive MIMO systems, where the CSI scales with the large number of transmit antennas. On the other hand, if precoding is codebook based, then the UE may feedback a codebook index of a codebook that maximizes a certain criteria such as throughput, or spectral efficiency. Although such precoding has a lower feedback overhead compared to non-codebook based feedback, the system's performance is generally suboptimal compared to the non-codebook based beamforming.

[64] Embodiments of the present disclosure provide methods for feeding back CSI by UEs based on tensors and tensor decomposition techniques. In the embodiments, the MIMO channel or the MIMO channel covariance may be modelled as a tensor, and tensor decomposition techniques may be applied to the channel or the channel covariance tensor. The decomposition results in factor matrices. The factor matrices (or a subset of the factor matrices depending on configurations from the network) may be fed back to a base station. That is, instead of feeding back the multi-dimensional downlink

MIMO channel, the constituent factor matrices obtained from the tensor decomposition are fed back to the network. In another embodiment, the network may reduce the feedback overhead by requiring feedback of codeword(s) indices from codebook (basis). In yet another embodiment, the feedback may be over a subset of the domains, instead of all configured domains. The embodiments are beneficial for providing improved downlink beamforming in single user (SU)-MIMO systems and multi-user (MU)-MIMO systems with less feedback overhead compared with conventional schemes, such as the conventional scheme where a UE feedbacks the $N_{Rx} \times N_{Tx} \times N_K$ downlink MIMO channel, or the conventional scheme where a UE feedbacks the right singular matrix $N_{Tx} \times N_{Tx}$ for each of the N_K subcarriers (tones, subbands, frequencies, or resource blocks). The embodiments also provide an improved performance in downlink beamforming compared with codebook based beamforming, such as that adopted by 3GPP.

[65] As used herein, a tensor is referred to as a multi-dimensional matrix, e.g., a 3-dimensional array, or a 4-dimensional array, or a higher dimensional array, which is used to mathematically represent a downlink MIMO channel between a base station and a UE in a MIMO system, or a covariance matrix of the downlink MIMO channel. As used herein, CSI feedback is generally referred to transmitting or reporting channel state information to a base station or a network entity. Those of ordinary skill in the art would recognize that a matrix is a tensor with two dimensions.

[66] FIG. 2 illustrates a diagram of an embodiment MIMO communications system 200. The MIMO communications system 200 includes a first device 210 and a second device 220. The first device may be a base station (or a UE), and the second device may be a UE (or a base station). FIG. 2 only shows two devices for illustrative convenience. The MIMO communications system 200 may have more than 2 devices for wireless communications. As shown, the first device 210 includes four (5) antenna for transmitting signals, i.e., Ax1, Ax2, Ax3 and Ax4, while the second device 220 includes three (4) antenna for receiving signals, i.e., Ar1, Ar2, and Ar3. The downlink channel from the first device 210 to the second device 220 may be generally referred to as a MIMO channel 230. The MIMO channel 230 includes multiple paths from each of the antennas at the first device 210 to each of the antennas at the second device 220. The MIMO channel 230 with four inputs and three outputs may be modeled as a 4x3 matrix

$$\begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} \\ H_{2,1} & H_{2,2} & H_{2,3} \\ H_{3,1} & H_{3,2} & H_{3,3} \\ H_{4,1} & H_{4,2} & H_{4,3} \end{bmatrix},$$

where $H_{i,j}$, $i = 1-4$, and $j = 1-3$, represents the channel model or response from the i th antenna at the first device 210 to the j th antenna at the second device 220. Generally,

when the first device 210 has N_{Tx} antennas for transmission (also referred to as transmit antennas) and the second device 220 has N_{Rx} antennas for receiving (also referred to as receive antennas), the MIMO channel between the first device 210 and the second device 220 may be represented by the following $N_{Tx} \times N_{Rx}$ matrix

$$\begin{bmatrix} H_{1,1} & \cdots & H_{1,N_{Rx}} \\ \vdots & \ddots & \vdots \\ H_{N_{Tx},1} & \cdots & H_{N_{Tx},N_{Rx}} \end{bmatrix}, \quad (2)$$

where $H_{i,j}$, $i = 1, 2, \dots, N_{Tx}$, and $j = 1, 2, \dots, N_{Rx}$, represents the channel model or response from the i th antenna at the first device 210 to the j th antenna at the second device 220.

The $N_{Tx} \times N_{Rx}$ matrix may be referred to as a MIMO channel matrix.

[67] In one example, when the first device 210 and the second device 220 communicate using multiple subbands (or subcarriers or tones of an orthogonal frequency division multiplexing (OFDM) system), e.g., N_K subbands, for each subband, there may be a corresponding MIMO channel matrix estimated and formed. Thus, there may be N_K MIMO channel matrices. The N_K MIMO channel matrices form a 3-dimensional tensor for the MIMO channel. The three dimensions include a transmit domain, a receive domain and a subband domain (or frequency domain). In another example, when the MIMO channel is estimated multiple times during a measurement time window, for each measurement time point, there may be a MIMO channel matrix estimated and formed. Thus, for N_T measurement time points, N_T MIMO channel matrices may be obtained. The N_T MIMO channel matrices form a 3-dimensional tensor for the MIMO channel. The three dimensions include a transmit domain, a receive domain and a time domain. In another example, for each of the N_K subbands and each of the N_T measurement time points, there may be a MIMO channel matrix estimated. In this case, $(N_K \times N_T)$ MIMO channel matrices may be obtained, and form a 4-dimensional tensor. The four dimensions include transmit domain, a receive domain, a frequency domain and a time domain. In this way, the downlink MIMO channel from the first device 210 to the second device 220 may be represented by a multi-dimensional tensor constructed based on channel measurements or estimation. Other domains (or dimensions) that may be used to construct the multi-dimensional tensor may include multiple base stations, distributed antennas, a uniform planar array, or a base station with multiple carriers. Those of ordinary skill in the art would recognize that various tensors using different domains may be formed to represent a MIMO channel without departing from the principle of the present disclosure. The terms of “domain”, “dimension” and “mode” may be used interchangeably in the disclosure in connection with forming a multi-dimensional tensor. The domains may also be referred to as

measurement domains in which reference signals are measured and used to form a multi-dimensional tensor.

[68] Let $\mathcal{H} \in \mathbb{C}^{I_1 \times I_2 \times \dots \times I_N}$ denote an N th order tensor. The order of the tensor refers to the number of dimensions. In an illustrative example, a 3-dimensional tensor (formed using three different domains) representing a downlink MIMO channel may be represented as

$$\mathcal{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx} \times N_K}, \quad (3)$$

In this example, the first dimension refers to the receive antenna dimension, the second dimension refers to the transmit antenna dimension, and the third dimension refers to the subband (subcarrier, tone, frequency, resource block) dimension. In another illustrative example, a tensor may be formed using four domains (or dimensions, modes) including the transmit domain, receive domain, frequency domain and a time domain. The 4-dimensional tensor may be represented as

$$\mathcal{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx} \times N_K \times N_T}, \quad (4)$$

where N_T represents the number of channel measurements in the time domain which may be related to the Doppler of a moving UE.

[69] In an example, the channel between a transmitter (e.g., the first device 210) and a receiver (e.g., the second device 220) may be modeled using multipath components (MPCs) arriving in clusters, which are formed by multiple reflections from objects in the vicinity of the receiver and the transmitter. FIG. 3 illustrates a diagram showing this channel model graphically. In this example, the frontal slabs of the tensor representing the channel may be mathematically represented as

$$H(k) = \sum_{n=1}^N \alpha_n \exp(j2\pi\lambda^{-1} \cos \theta_{AOA,n} d_{rx,u}) \exp(j2\pi\lambda^{-1} \cos \theta_{AOD,n} d_{tx,s}) \exp(-j2\pi\tau_n f_k), \quad (5)$$

where:

- τ_n denotes the cluster delay ,
- $\alpha_n = \sqrt{P_n} \exp(j\Phi_n)$,
- n denotes a cluster index ,
- P_n is the n th cluster power ,
- $d_{rx,u}$ is the location vector of receive antenna element u ,
- $d_{tx,s}$ is the location vector of transmit antenna element s ,
- $\theta_{AOA,n}$ is the angle of arrival and $\theta_{AOD,n}$ is the angle of departure for cluster n ,
- λ^{-1} is the wavelength of the carrier frequency,
- Φ_n is the cluster path phase,

- $k = 1, 2, \dots, N_K$,
- $l = 1, 2, \dots, N$, and
- N is the number of clusters in the MIMO channel.

[70] A MIMO channel tensor, such as the tensor represented by the mathematical expression (3) or (4), may be decomposed using a tensor decomposition technique, such as the Canonical Polyadic Decomposition (CPD), multilinear SVD (MLSVD) or the Higher Order SVD (HOSVD), to obtain the tensor's factor matrices. Taking CPD as an example, the factor matrices of the tensor, represented by the mathematical expression (3), may be obtained by solving the following optimization problem

$$\min_{A_T, A_R, C} \left\| \mathcal{H} - \sum_{l=1}^L a_l^R \otimes a_l^T \otimes c_l \right\|_F^2, \quad (6)$$

$$A_T = [a_1^T, a_2^T, \dots, a_L^T],$$

$$A_R = [a_1^R, a_2^R, \dots, a_L^R],$$

$$C = [c_1, c_2, \dots, c_L],$$

where F stands for Frobenius norm, $\otimes$ represents outer product, and A_T , A_R , and C are factor matrices of the tensor. Each factor matrix includes L vectors. L represents the CPD decomposition rank.

[71] In another example, a tensor may be formulated by stacking the frontal slabs in Equation (5). For example, a three dimensional tensor may be formulated in this way as shown below, which is expressed similarly to the expression (3):

$$\mathcal{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx} \times N_K}, \quad (7)$$

where N_{Rx} represents the number of receiver antennas, N_{Tx} represents the number of transmit antennas, and N_K represents the number of subcarriers or tones. This tensor may be represented in the CPD form, i.e. as the sum of rank one outer product, as provided in the following:

$$\mathcal{H} = \sum_{n=1}^N a_R(\theta_{AOD,n}) \otimes a_T(\theta_{AOA,n}) \otimes g(\alpha_n, \tau_n), \quad (8)$$

where $\otimes$ represents the outer product and

$$a_R(\theta_{AOD,n}) = [1, \exp(j2\pi\lambda^{-1} \cos \theta_{AOD,n} d_{rx,u=2}), \dots, \exp(j2\pi\lambda^{-1} \cos \theta_{AOD,n} d_{rx,u=N_{Tx}})]^T$$

$$a_T(\theta_{AOA,n}) = [1, \exp(j2\pi\lambda^{-1} \cos \theta_{AOA,n} d_{rx,u=2}), \dots, \exp(j2\pi\lambda^{-1} \cos \theta_{AOA,n} d_{rx,s=N_{Tx}})]^T$$

$$g(\alpha_n, \tau_n) = [\alpha_n \exp(-j2\pi\tau_n f_{k=1}), \dots, \alpha_n \exp(-j2\pi\tau_n f_{k=K})]^T$$

It should be noted that the channel in Equation (8) is a tensor of rank at most N. The CPD decomposition of the channel in Equation (8) may be performed by solving the following optimization problem:

$$\min_{\hat{A}, \hat{B}, \hat{C}} \|\mathcal{H} - \sum_{l=1}^L \hat{a}_l \odot \hat{b}_l \odot \hat{c}_l\|_F^2, \quad (9)$$

where $\hat{A} = [a_1, \dots, a_L]$, $\hat{B} = [b_1, \dots, b_L]$, $\hat{C} = [c_1, \dots, c_L]$ are matrices of dimension $N_{Rx} \times L$, $N_{Tx} \times L$, $N_K \times L$ respectively. The optimization problem may be solved by alternating the least square (ALS) procedure.

[72] The original factor matrices A, B, C and the estimated factor matrices obtained using (9) from the CPD operation may have a relationship that can be expressed as follows:

$$\hat{A} = A \Lambda_1 \pi + E_1, \quad (10)$$

$$\hat{B} = B \Lambda_2 \pi + E_2, \text{ and}$$

$$\hat{C} = C \Lambda_3 \pi + E_3,$$

where $\Lambda_1, \Lambda_2, \Lambda_3$ are scaling matrices, and π is permutation matrix.

[73] The CPD decomposition as represented by expression (6) may be referred to as a rank L CPD decomposition (or least square approximation). The decomposition decomposes the tensor into a sum of rank-one component tensors. The rank L may be referred to as a tensor decomposition rank. A_T , A_R , and C may be referred to as CPD representation of the tensor or factor matrices of the tensor. Consequently, the MIMO channel may be represented using the CPD representation, i.e., A_T , A_R , and C, of the tensor of the MIMO channel. The CPD representation of a channel is a low rank representation of the channel.

[74] In another illustrative example, the decomposition of the tensor in Equation (4) using CPD may result in four factor matrices, e.g., including A_T , A_R , C, and D, where $D = [d_1, d_2, \dots, d_L]$.

[75] The factor matrices (or subsets of the factor matrices) of the tensor may be used to reconstruct the tensor or to approximate the tensor, i.e., the MIMO channel or covariance of the MIMO channel, and are thus useful, if fed back by UEs as CSI, for a base station to schedule and perform downlink transmission and compute downlink precoders, e.g., for SU and MU-MIMO based communications. Further, the factor matrices of the tensor may include information about channel parameters that are useful for a base station. For example, the matrix A_T may include information about angles of

departure, the matrix A_R may include information about angles of arrival, and the matrix C may include information about cluster delay and cluster gain.

[76] The decomposition of the tensor results in compact representation of the channel, which may be used to represent the channel with reduced amount of information, compared with using the tensor to represent the channel. CSI may be reported based on decomposition of the tensor, and accordingly, CSI feedback overhead may be reduced, while sufficient channel state information is fed back for the transmitter to estimate the downlink channel and perform downlink transmission.

[77] The present disclosure provides embodiment methods of CSI feedback based on tensors and tensor decomposition. An embodiment method may generally include a configuration step, a measurement step and a feedback step. In the configuration step, the network (e.g., a base station) configures a UE with for constructing a tensor of multiple dimensions (or domains, modes), configures the UE with measurement resources for measuring the downlink MIMO channel between the network and the UE, and configures the UE with CSI feedback configurations for reporting (i.e., feeding back) CSI. In the measurement step, the UE measures the downlink MIMO channel (or the covariance matrix), constructs downlink MIMO channel tensor, and decomposes the tensor into factor matrices. In the feedback step, CSI is fed back based on the decomposed tensor and CSI feedback configurations. Having received the feedback from the UE, which may include matrices or vectors, the network may estimate (and/or create, compute, reassemble) the downlink MIMO channel by taking the sum of rank 1 outer product of the feedback vectors. More details about these steps will be provided in the following.

[78] In one embodiment, the network may use the feedback information to construct (estimate, reassemble) the downlink MIMO channel, i.e., $\widehat{\mathcal{H}}_{DL}$, e.g., by taking the sum of rank 1 outer product of the feedback vectors, as shown below:

$$\widehat{\mathcal{H}}_{DL} = \sum_{l=1}^L \mathbf{a}_l^R \odot \mathbf{a}_l^T \odot \mathbf{c}_l.$$

In another embodiment, the network may use a portion or a subset of the feedback information to construct the downlink MIMO channel.

[79] The configuration step may include configuring the structure of the tensor. The different dimensions that constitute the tensor may be configured by the network. Dimensions may also be referred to as domains or modes. The dimensions configured for constructing a tensor may also be referred to as tensor dimensions or tensor domains, or measurement domains in the following description, for the purpose of illustration convenience only. The different dimensions that may be used to construct the tensor may

not be limited to the transmit dimension, receive dimension, and frequency dimension, as discussed above. Other applicable dimensions, such as the time dimension, may also be used. Any permutation of the dimension is applicable. Any combination of the time, transmit, receive, frequency dimensions is also applicable in the present disclosure. As discussed above, reference signals may be measured in one or more configured measurement domains to construct the tensor. A number (quantity) of the measurement domains configured, and/or an order of the configured measurement domains in which reference signals are to be measured, may also be configured for constructing the tensor.

[80] In one embodiment, a tensor may be formed using two (tensor) domains (e.g., the transmit and frequency domains). In this case, the tensor may be referred to as a covariance tensor. In another embodiment, a tensor may be formed based on the transmit domain, the receive domain, the time domain, and a channel impulse response delay domain (i.e., path delay domain). Those of ordinary skill in the art would recognize that various tensors using different (tensor) domains may be formed to represent a MIMO channel without departing from the principle of the present disclosure. In yet another embodiment, in the case of CoMP, an additional dimension may be added to form the tensor to model the cooperation.

[81] The configuration step may include configuring measurement resources for channel or spatial covariance measurement. The measurement resources indicate resources that carry a reference signal resource set, or reference signals, e.g., CSI-RSs, for the UE to perform the measurement. In an embodiment, the measurement resources associated with signal reception may include at least non-zero power (NZP) channel state information reference signal (CSI-RS) resources configured for channel and interference measurement, or demodulation reference signal (DMRS) resources. The network may also configure feedback resources, which indicate resources that carry CSI that is fed back to the network. The network may further configure trigger information triggering the UE to feedback CSI. For example, the network may send a DCI message to trigger dynamic CSI feedback.

[82] The configuration step may include configuring the required feedback granularity in the tensor dimensions. Taking the tensor of the expression (3) as an example, where either a wideband or a subband representation may be used, the frequency dimension may be configured to include a certain number of resource blocks, or a number of subcarriers. The granularity in the frequency dimension may be configured by the network. The granularity configured may not be limited to the frequency dimension, and feedback granularity may be configured for any tensor dimension.

[83] In one embodiment, a tensor may be formed using multiple dimensions such as the transmit, receive, time and frequency dimensions. The network configures the tensor domains with a feedback granularity for each domain. The network then transmits reference signals to enable the UE to perform channel estimation. Reference signals such as CSI-RS may be used. In another embodiment, reference signals such as DMRS, or CRS may be used. Within resource blocks scheduled to UEs, the reference signals are transmitted. The reference signals may not be evenly spaced in the frequency (subcarrier, subband, tones) domain and/or in the time (OFDM, slot, symbol) domain. In one embodiment, the reference signals may be evenly spaced on resource block basis but not on subcarrier (tone) basis.

[84] The UE may then perform some interpolation to obtain the channel estimation over resource elements that may not contain the reference signals. In one embodiment, the UE may down sample received signals such that the channel estimate may be on smaller granularity than that used for transmitting the reference signals. For example, the reference signals may be transmitted on subcarrier basis, but the feedback may be over resource block granularity. In another embodiment, the UE may interpolate over the symbols (time domain) to obtain the channel estimate in resources which may not contain any reference signals. In yet another embodiment, the UE may search for codewords from a predefined codebook (codebook basis) to represent the time domain. In these described embodiments, it may be viewed that the granularity over which the reference signals are transmitted may be different than the granularity over which the feedback for the different dimensions is performed. The granularity may be signaled by the network.

[85] In one embodiment, assuming the reference signals are transmitted over K_1 subcarrier and L_1 symbols within a resource block. Then the feedback granularity may have dimensions $K_2 \leq K_1$ and $L_2 \leq L_1$ (where K_2 represents the number of subcarriers and L_2 represents the number of OFDM symbols). In another embodiment, the K_2 subcarriers and L_2 OFDM symbols are configured by the network or specified by standard specification. The subcarriers and symbols are not necessarily contiguous. In yet another embodiment, the K_2 subcarriers and the L_2 OFDM symbols are a CSI reference (according to TS 38.214, 5.2.2.1.1) associated with reporting.

[86] The configuration step may include, configuring the UE with dimensions (modes, or domains) in which CSI feedback is required. The CSI to be fed back in a domain includes information related to or about the domain. The configured dimensions may also be referred to as feedback dimensions or domains. The feedback dimensions include a subset of or all the tensor dimensions that are configured for constructing a

tensor. For example, for the channel in the expression (4), the network may require feedback over the second dimension only, i.e., the transmit domain only. In this case, the network may configure the UE with necessary signaling for feeding back CSI in this particular domain. The network may use the feedback as a basis for downlink CSI-RS transmission. In another embodiment, the network may require substantial channel information for better downlink precoding or for downlink beamforming training for MU-MIMO settings. In this case, the network may require feedback over all the tensor dimensions. The network may configure the UE with necessary signaling for feeding back CSI in all the tensor domains that form the tensor. The network may use the feedback to compute a downlink precoder, such as a zero forcing precoder. Any combination of the feedback dimensions is applicable. For example, the network may require feedback over the transmit and frequency dimensions, but not including the receive dimension. In this case, the network may configure the UE with necessary signaling to feedback CSI over these two dimensions. As an illustrative example, the network may configure the UE to report a number (quantity) of vectors of the factor matrix A_T (transmit domain) and A_R (receive domain) in the expression (6), respectively. The quantity of vectors from each factor matrix to be reported may also be configured, and details will be provided later in the description. E quantity may be greater than or equal to L in the expression (6). Those of ordinary skill in the art would recognize that various combinations of feedback dimensions may be configured for reporting CSI in the configured feedback dimensions.

[87] The configuration step may include configuring the rank L (may also be referred to as a CPD rank, an approximate tensor rank, an approximate low rank, a decomposition rank, a least square rank) in the optimization problem of (6). The terms of “rank L ” and “CPD rank” are used interchangeably in the present disclosure. In one embodiment, the network may use the estimated uplink channel, which may be estimated from the uplink SRS, to compute and set the CPD rank, when assuming there is some degree of reciprocity between the uplink and downlink channels. In another embodiment, the network may use a previous feedback of downlink CSI to determine the CPD rank.

[88] In the case where the rank L is not configured by the network, the UE may choose a CPD rank. In one embodiment, the CPD rank is related to the number of clusters in the downlink.

[89] The configuration step may include configuring the number of vectors R_f to be fed back out of the L vectors in each factor matrix. In one embodiment, the network may configure the UE for feeding back all of the L vectors (generally referred to as feedback quantities) in each of the factor matrices A_T , A_R , and C resulted from the CPD

decomposition in (6). That is, in this case, $R_f = L$. In another embodiment, the network may configure the UE for feeding back $R_f < L$ vectors in each of the factor matrices A_T , A_R , and C . The UE may choose R_f vectors according to criteria specified the network. In yet another embodiment, the UE may determine the R_f (the number of vectors) according to an optimization criteria that maximizes a utility, such as capacity, signal to noise ratio (SNR), signal to interference to noise ratio (SINR), throughput, or spectral efficiency. The number of vectors R_f may also be related to the number of layers for transmission (i.e., the transmission rank, or the rank of transmission). The UE may determine the feedback rank based on the transmission rank. The number of vectors R_f may be referred to as a feedback rank, or a feedback length.

[90] In some embodiments, the network may configure different feedback ranks for different factor matrices. That is, in this case, the network may configure different feedback lengths for different tensor domains, in which CSI is to be fed back to the network, because the factor matrices correspond to different tensor domains. For example, the network may configure a feedback length $R_{f,1}$ for A_T , a feedback length $R_{f,2}$ for A_R , and a feedback length $R_{f,3}$ for C .

[91] A base station may configure a UE with a greater feedback rank R_f , e.g., in an initial communication period of time or for multi-user (MU) communications, and thus, the base station may receive greater amount of CSI and obtain more knowledge of the downlink MIMO channel. This may help the base station improve communication performance in the downlink MIMO channel during a succeeding communication period or for MU communications. A base station may configure a smaller feedback R_f for SU communications after the initial communication period.

[92] In some embodiments, the network may configure which factor matrix is to be fed back by the UE. Taking the factor matrices A_T , A_R , C , and D as one example, the base station may pre-assign a matrix ID to each of the factor matrices, e.g., 0, 1, 2 and 3 are assigned to the factor matrices. For example, the base station may predefine that a first matrix is related to the transmit domain, i.e., A_T , a second matrix is related to the receive domain, i.e., A_R , a third matrix is related to the frequency domain, i.e., C , and a fourth matrix is related to the time domain, i.e., D . The base station may use 2-bit to indicate a factor matrix that is to be fed back. For example, "00", "01", "10" and "11" indicate the four respective factor matrices. The base station does not specify how the factor matrices are generated, i.e., using what tensor decomposition techniques. The base station may also configure what channel parameters are to be fed back. One of ordinary

skill in the art would recognize that various methods may be used for the base station to indicate or specify the CSI to be fed back to the base station.

[93] In the configuration step, the network may configure the UE to report different CSI for different ranks of MIMO transmissions. Please note that the rank of transmission represents the number of layers to be transmitted, while the CPD rank represents the number of vectors in the factor matrices obtained from the CPD decomposition. For example, for rank 1 transmission, the network may configure the UE to report only one vector from each factor matrix with the configuration $R_f = 1$. For rank 2 transmission, the network may configure the UE to report two vectors from each factor matrix with a configuration $R_f = 2$. The network may configure the CPD rank to be different for the two ranks of transmission. Based on the received multiple CSI reports, the network may choose a rank of transmission, and configures the UE with the chosen rank of transmission.

[94] In the configuration step, the network may configure the periodicity of the feedback of the domains. That is, the feedback over certain dimensions may be on a larger time scale, while the feedback over other dimensions may be on a smaller time scale. For example, the transmit and receive dimensions may be fed back on a longer time scale, while feedback over the frequency and time domain may be more dynamic. In this case, the time between two CSI reports for the is longer than that in the former case. In one embodiment, the feedback periodicity of CSI of a domain (mode, dimension) may be configured by higher layer signaling (e.g., RRC signaling, or RRC Connection Setup). In another embodiment, a more dynamic configuration may be employed for a UE to aperiodically update the CSI feedback of a domain using a special trigger, e.g., triggering the UE to report updated CSI in the domain by sending a downlink control information (DCI) message.

[95] In some embodiments, the network may specify different update periods for different domains. For example, the network may configure the UE with different reporting periods for different domains. In one example, the transmit domain may be reported on longer period, while the frequency domain may be reported on smaller time scale.

[96] As mentioned before, the factor matrices of the tensor may include information about channel parameters, such as angles of departure, angles of arrival, cluster delay and cluster gain. These channel parameters may be derived from the factor matrices. For such cases, the network may configure the UE to feedback a combination of analog feedback, in addition to tensor feedback as described with respect to the configuration step above. The analog feedback herein refers to feedback of analog angles

of arrival, angles of departure, delays, gains, or other channel parameters. The tensor feedback refers to feedback of factor matrices, a subset of factor matrices, vectors, etc. When channel parameters are to be fed back, the rank R_f represents the number of values of a channel parameter related to a domain. For example, a number R_f of AOD values estimated from the factor matrix A_T may be fed back. In the configuration step, the network may also configure the UE to feed back CSI parameters including RI, CQI, or PMI.

[97] As discussed above, the network may configure the UE with information, for the UE to measure the downlink MIMO channel, to form a tensor representing the downlink MIMO channel, and to feedback CSI of the downlink MIMO channel based on decomposition of the tensor. The information may be generally referred to as CSI measurement and feedback configuration information. (or CSI measurement and feedback parameters). The CSI measurement and feedback configuration information may include configuration of the domains for constructing a MIMO channel tensor, configuration of the domains to provide feedback upon, a decomposition rank (CPD rank L) indicating the number of vectors in each factor matrix of the tensor, feedback rank R_f , one or more channel parameters (some type of analog feedback), measurement resources, feedback resources, or any combination thereof.

[98] In other words, the CSI measurement and feedback configuration information may include configuration parameters. These configuration parameters may include, e.g., tensor domains (or dimensions), feedback granularity of a tensor domain, measurement resources, a feedback dimension, the rank L , the feedback rank, feedback periodicity, a channel parameter, and/or a CSI parameter, e.g., RI, CQI, PMI. The network may configure a UE with one, or more, or all of these configuration parameters. The network may configure RI, CQI, and/or PMI in the same configuration as or separate configuration from tensor based feedback. In another example, the network may configure the CPD rank and the feedback rank in the same configuration or in separate configurations.

[99] The base station may signal the CSI measurement and feedback configuration information using higher layer signaling, e.g., radio resource control (RRC) signaling, medium access control (MAC) signaling, e.g., a MAC control element (CE), or downlink control signaling, e.g., downlink control information (DCI) signaling. In one example, the base station may trigger, using DCI, a UE to measure and feed back CSI according to the signaled CSI measurement and feedback configuration. The DCI may or may not include the decomposition rank L . In another example, the UE may be configured to feed back CSI periodically according to the signaled CSI measurement and

feedback configuration. The base station may signal the CSI measurement and feedback configuration information in one or more messages to a UE. The base station may configure a UE for CSI measurement and feedback dynamically on demand.

In the measurement step, the UE may measure the downlink MIMO channel between the UE and the base station or covariance of the downlink MIMO channel from the measured downlink reference signals. The UE may construct a tensor representing the measured downlink MIMO channel after the channel measurement and estimation, e.g., the tensor represented by expression (3) or (4), and decompose the tensor using a tensor decomposition technique, e.g., CPD in expression (6), generating factor matrices. The UE may then, in the feedback step, feedback (or report) CSI based on the resulted factor matrices, e.g., A_T , A_R , and C and based on the configuration specified by the network. Generally, this approach may be generally referred to as a tensor-based CSI feedback scheme.

[100] The UE may use any applicable tensor decomposition technique, such as the Canonical Polyadic decomposition (CPD), the Tucker decomposition, the Higher Order SVD (HOSVD), or other tensor decomposition techniques, to decompose the MIMO channel tensor or the spatial covariance matrix of the MIMO channel into its constituent factor matrices. Those of ordinary skill in the art would recognize that various decomposition techniques may be used to decompose the tensor.

[101] In one embodiment, the Tucker decomposition or the multi-linear decomposition may be used to decompose the MIMO channel into factor matrices and a core tensor. The factor matrices may include information related to the domains of time, frequency, transmit, receive, and/or delay. The core tensor includes the strength of the interaction between the columns of the factor matrices. The UE may feedback the factor matrices and the core tensor, which may be used to reconstruct the MIMO channel at the network. In another embodiment, the UE may feedback a subset of vectors of the factor matrices and the corresponding relevant values from the core tensor.

[102] In another embodiment, the factor matrices resulted from the tensor decomposition or the multi-linear decomposition may be used as basis (referred to as basis matrices) for a codebook. In this case, the core tensor resulted from the Tucker decomposition or the multi-linear decomposition may be quantized, and the resulting quantized coefficients (after quantization) may be fed back to the network. The network may use the feedback information to compute a downlink codebook.

[103] In one embodiment, the network may use the quantized feedback information of the core tensor and the feedback representing the different dimensions to

compute the downlink precoding. The feedback representing the different dimensions may be an index of codebook (may also be referred to as basis) that is suitable for each dimension. That is, the UE may not feedback an actual vector or vectors of factor matrices, but a codeword index from a codebook. The codeword may then be selected based on the index. An optimal codeword may also be selected based on RSRP, capacity, or throughput optimization.

[104] In the feedback step, the UE transmits a CSI feedback report including feedback parameters that are configured by the network. For example, the feedback parameters may include a combination of CQI, RI, PMI, factor matrices or subsets of the factor matrices, a CPD rank, a feedback rank, and/or a MIMO transmission rank. The periodicity for transmitting the CSI feedback report may be configured by the network.

[105] In one embodiment, the UE may feedback all the factor matrices of the tensor according to the configuration signaled by the network. The network may receive the factor matrices that is reported, and reconstruct (e.g., compute, reassemble, estimate) the downlink MIMO channel by taking the sum of the outer product of the vectors of the factor matrices as shown in the following:

$$\widehat{\mathcal{H}}_{DL} = \sum_{l=1}^L \mathbf{a}_l^R \odot \mathbf{a}_l^T \odot \mathbf{c}_l.$$

[106] In one embodiment, the factor matrices coefficients may be quantized and the quantized coefficients may be fed back to the network. For example, the amplitude and phase values of the factor matrices coefficients may be quantized. In another example, vector quantization of the vectors themselves may be performed.

[107] In another embodiment, the network may directly use the factor matrices to compute the downlink precoder without computing (or reconstructing) the downlink MIMO channel. For example, if the feedback includes the factor matrix $\mathbf{A}_T$, the network may use this matrix as basis for downlink precoding of a CSI-RS.

[108] In one embodiment, the UE may feedback a single vector $\mathbf{a}_l^T$ from the factor matrix $\mathbf{A}_T$, a single vector $\mathbf{a}_l^R$ from the factor matrix $\mathbf{A}_R$, and a single vector $\mathbf{c}_l$ from the factor matrix $\mathbf{C}$. Having received the vectors from the UE, the network may be able to reconstruct part of the original downlink MIMO channel by taking the outer product of the three vectors $\widehat{\mathcal{H}}_{DL} = \mathbf{a}_l^T \odot \mathbf{a}_l^R \odot \mathbf{c}_l$. Based on the reconstructed part of the downlink MIMO channel, the base station may compute the downlink precoder per subcarrier, or per tone, or per subband. When the channel has multiple clusters, feeding back a single vector from each domain may not be sufficient to capture a good representation of the channel (e.g., to closely approximate the channel in terms of minimizing the least square error, or maximize the throughput). In this case, more vectors need to be fed back. The

network may configure how many vectors from each domain (i.e., one or more feedback ranks) may need to be fed back.

[109] FIG. 4 illustrates a graph 400 showing example SU-MIMO capacity curves of a MIMO system when using different CSI to reconstruct a downlink MIMO channel. The graph 400 includes curves 402, 404 and 406, each shows the SU-MIMO capacity, i.e., number of bits per second and per tone that varies with signal and noise ratio (SNR). The curve 402 shows the SU-MIMO capacity when a subband scheme is used, where precoding per subband is based on SVD decomposition of a MIMO channel matrix H per subband (e.g., the matrix H in the Equation (1)). The matrix H may be mathematically represented by $H(k) = U(k)\Lambda(k)V(k)^*$. The precoder for each subband is determined based on the SVD decomposition, specifically, based on $V(k)^*$. The curve 404 shows the SU-MIMO capacity when a wideband scheme is used, where a wideband precoding is applied based on an average covariance matrix over all subbands. The covariance matrix is represented by $R = \sum_{k=1}^{N_k} H^H(k)H(k) = U(k)DU(k)^H$. The curve 406 shows the SU-MIMO capacity when a CPD reconstruction (CPDR) scheme is used, where the downlink MIMO channel is reconstructed using CSI generated based on the CPD decomposition of a MIMO channel tensor. In this case, a UE forms a tensor as discussed above with respect to expressions (2)-(4), decomposes the tensor using CPD generating three factor matrices A_T , A_R , and C , and feeds back a subset of each factor matrices. A base station reconstructs the downlink MIMO channel using the fed back CSI, and applies per subband precoding to transmission signals. As can be seen, the CPDR scheme (curve 406) has about the same performance as the subband scheme (curve 402), but better than the wideband scheme (curve 404). However, the CPDR requires less CSI feedback overhead than the subband scheme. For feeding back the downlink MIMO tensor, the subband scheme needs to feed back $N_{Tx} * N_{Rx} * N_K$ amount of information for reconstructing the downlink MIMO. The wideband scheme needs to feed back $N_{Tx} * N_K$ amount of information. For the CPDR scheme, in a case of a rank R transmission (i.e., R is the rank of MIMO transmission, representing a number of streams to be transmitted), and when three vectors from the respective three factor matrices are to be fed, only $(N_{Tx} + N_{Rx} + N_K) * R_f$ amount of CSI information needs to be fed back, while achieving similar performance as the subband scheme.

[110] FIG. 5 illustrates a diagram of an embodiment method 500 for CSI feedback in a MIMO communications system. In this example, a base station 502 including multiple transmit antennas communicates with a UE 504 including multiple receive antennas. As shown, at step 512, the base station 502 determines a CSI measurement and feedback configuration, with which the base station 502 configures the UE 504 for

measuring a downlink MIMO channel between the base station 502 and the UE 504, and feeding back CSI of the downlink MIMO channel. The CSI measurement and feedback configuration may include information as discussed above, such as domains for constructing a MIMO channel tensor, decomposition rank L indicating the number of vectors in each factor matrix of the tensor, feedback rank R_f , one or more factor matrices, one or more channel parameters, measurement resources, feedback resources, periodicity for CSI feedback, or any combination thereof. At step 514, the UE 502 configures the UE 504 with the CSI measurement and feedback configuration. The base station 502 may signal the CSI measurement and feedback configuration to the UE 504 using higher layer signaling, DCI signaling, or MAC signaling. At step 516, the base station 502 transmits reference signals to the UE 504 for the UE 504 to measure the downlink MIMO channel. At step 518, the UE 504 measures the downlink MIMO channel using the reference signals, forms a multi-dimensional tensor according to the signaled CSI measurement and feedback configuration, and decomposes the tensor to generate factor matrices according to the signaled CSI measurement and feedback configuration. The UE 504 forms the tensor using the domains specified by the CSI measurement and feedback configuration. Decomposition of the tensor is performed based on the decomposition rank L specified by the CSI measurement and feedback configuration. Thus, each of the factor matrices includes L sets of data. At step 520, the UE 504 generates CSI that is to be fed back to the base station 502 according to the signaled CSI measurement and feedback configuration. For example, if the CSI measurement and feedback configuration specifies feeding back all factor matrices, the CSI includes all the factor matrices that are generated. If a subset of each factor matrix is specified by the CSI measurement and feedback configuration, e.g., if a feedback rank R_f is specified, the CSI includes R_f sets of data in the L sets of data of each factor matrix. If the CSI measurement and feedback configuration specifies feeding back a channel parameter, the CSI includes L (or R_f , if specified) sets of the channel parameter values. The CSI may also include RI, PMI or CQI. At step 522, the UE 504 transmits the generated CSI to the base station. At step 524, the base station performs downlink transmission with the UE 504 based on the received CSI. The base station 502 may reconstruct the downlink MIMO channel using all the factor matrices fed back, or reconstruct a portion of the downlink MIMO channel using subsets of the factor matrices. For example, the base station 502 may take outer product of all the factor matrices, or the subsets of the factor matrices. The result is a reconstructed channel or a reconstructed portion of the channel. The base station 502 may also estimate one or more channel parameters using the CSI that including information about the one or more channel parameters. The base station 502 may determine precoding parameters,

modulation parameters, and other parameters used for transmitting signals to the UE 504 according to the reconstructed channel, the reconstructed portion of the channel, or the estimated one or more channel parameters.

[111] FIG. 6 illustrates a flowchart of an embodiment method 600 for CSI feedback in a MIMO communications system. The embodiment method 600 may be performed by a UE communicating with a base station in the MIMO communications system. As shown, at step 602, the UE forms a tensor representing a measured downlink MIMO channel between the base station and the UE. The UE may form the tensor according to domains or dimensions or modes specified by a received CSI measurement and feedback configuration. For example, the UE may form a tensor $\mathcal{H} \in \mathbb{C}^{N_{Rx} \times N_{Tx} \times N_K}$ as described above. At step 604, the UE performs a rank L CPD on the tensor after channel measurement and estimation. The rank L CPD results in factor matrices. Each factor matrix includes L sets of data. At step 606, the UE generates a measurement report based on the factor matrices. The measurement report includes information indicating the downlink MIMO channel status. The measurement report may include the factor matrices, a subset of each factor matrix, and/or one or more parameters estimated based on the factor matrices. At step 608, the UE transmits the measurement report to the base station.

[112] FIG. 7 illustrates a flowchart of another embodiment method 700 for CSI feedback in a MIMO communications system. The embodiment method 700 may be performed by a UE communicating with a base station in the MIMO communications system. As shown, at step 702, the UE receives a configuration for CSI measurement and feedback. The configuration may include quantities (i.e., information) as discussed above with respect to the CSI measurement and feedback configuration information. In this example, the quantities include CSI-RS resources, CSI reporting resources and trigger information. The quantities may also include the decomposition rank L, and tensor domains, e.g., the transmit domain, the receive domain, the frequency domain, the time domain, or the delay domain, for constructing a tensor. At step 704, the UE performs channel measurement on the CSI-RS resources. This includes measuring CSI-RSs, estimating and forming a tensor representing a downlink MIMO channel between the base station and the UE. Step 704 may be triggered by a DCI message, or may be performed periodically as configured by the network. At step 706, the UE generates quantities representing the downlink MIMO channel according to the decomposition rank L. The UE may generate factor matrices by performing rank L decomposition on the tensor. The quantities may include at least one factor matrix or a subset of one factor matrix in one of the domains. At step 708, the UE generates a report based on the

quantities. The report may be in a predefined format, and includes CSI to be reported according to the configuration. At step 710, the UE transmits the report.

[113] FIG. 8 illustrates a flowchart of another embodiment method 800 for CSI feedback in a MIMO communications system. The embodiment method 800 may be performed by a UE communicating with a base station in the MIMO communications system. As shown, at step 802, the UE forms a channel tensor representing a downlink MIMO channel between the UE and the base station. At step 804, the UE performs rank L CPD on the tensor. The UE may alternatively perform rank L MLSVD on the tensor. At step 806, the UE obtains factor matrices resulted from decomposition of the tensor. At step 808, the UE generates a report including the obtained factor matrices. At step 810, the UE transmits the report.

[114] FIG. 9 illustrates a flowchart of another embodiment method 900 for CSI feedback in a MIMO communications system. The embodiment method 900 may be performed by a UE communicating with a base station in the MIMO communications system. As shown, at step 902, the UE forms a channel tensor representing a downlink MIMO channel between the UE and the base station. At step 904, the UE performs rank L CPD on the tensor. The UE may alternatively perform rank L MLSVD on the tensor. At step 906, the UE obtains factor matrices resulted from decomposition of the tensor. At step 908, the UE generates a report including a subset of vectors of each of the obtained factor matrices. At step 910, the UE transmits the report.

[115] FIG. 10 illustrates a flowchart of another embodiment method 1000 for CSI feedback in a MIMO communications system. The embodiment method 1000 may be performed by a UE communicating with a base station in the MIMO communications system. As shown, at step 1002, the UE forms a channel tensor representing a downlink MIMO channel between the UE and the base station. At step 1004, the UE performs rank L CPD on the tensor. The UE may alternatively perform rank L MLSVD on the tensor. At step 1006, the UE obtains factor matrices resulted from decomposition of the tensor. At step 1008, the UE obtains values of one or more channel parameters estimated based on the factor matrices. At step 1010, the UE generates a report including the values of the one or more channel parameters. At step 1012, the UE transmits the report.

[116] FIG. 11 illustrates a flowchart of another embodiment method 1100 for CSI feedback in a MIMO communications system. The embodiment method 1100 may be performed by a base station communicating in the MIMO communications system. As shown, at step 1102, the base station configures UEs for CSI measurement and feedback. The base station may signal, to UEs, CSI measurement and feedback configuration information, as discussed above. At step 1104, the base station transmits reference

signals on measurement resources for downlink MIMO channel measurements. At step 1106, the base station receives reports about downlink MIMO channel measurements. Each report may include information about factor matrices that is generated and fed back by a UE. Each report is associated with a downlink MIMO channel between the base station and a UE feeding back the report. Each of the factor matrices has a rank L . Each of the factor matrices has L sets of data. At step 1108, the base station reconstructs downlink MIMO channels using the reports. For example, the base station may reconstruct a downlink MIMO channel between the base station and a UE based on factor matrices in a report sent by the UE, e.g., by taking the outer product of the factor matrices. At step 1110, the base station performs downlink transmission to the UEs according to the reconstructed downlink MIMO channels.

[117] FIG. 12 illustrates a diagram of another embodiment method 1200 for CSI feedback in a MIMO communications system, with emphasis on configuration of feedback rank R_f . The method 1200 may be performed by a network device, such as a base station. As shown, at step 1212, a base station 1202 signals the feedback rank R_f to a UE 1204 for reporting CSI in a tensor-based CSI feedback scheme. The base station may have had signals other configuration information for the UE to form a tensor (e.g., domains) and decompose the tensor (e.g., the decomposition rank L). At step 1214, the UE 1204 generates factor matrices of rank L by decomposing the tensor using a tensor decomposition technique. At step 1216, the UE 1204 generates a CSI report according to the feedback rank R_f . For example, the CSI report may include the first R_f vectors in each factor matrix. In another example, the CSI report may include R_f values of a channel parameter related to a domain (i.e., estimated from a factor matrix related to the domain). At step 1218, the UE 1204 transmits the CSI report to the base station 1202. At step 1220, the base station 1202 transmits signals based on the CSI report.

[118] FIG. 13 illustrates a flowchart of an embodiment method 1300 for CSI feedback in a communications system. The method 1300 may be performed by a communication device, such as a user equipment (UE). As shown, at step 1302, the UE receives, through M antenna ports of the UE, a reference signal (RS) resource set, where the RS resource set is transmitted from N antenna ports of a base station (BS) over K_1 subcarriers on L OFDM symbols. Each of the M , N , K_1 and L_1 is an integer greater than 0. At step 1304, the UE reports, to the BS, R sets of vectors that are obtained based on measurement of the RS resource set, where each set of vectors comprises one or more vectors, and the one or more vectors comprise a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector, a fourth $L_2 \times 1$ vector, or any combination thereof, and where a sum of R outer products of the respective R sets of vectors represents channel state information

of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols. Each of the R , K_2 and L_2 is an integer greater than 0.

[119] FIG. 14 illustrates a flowchart of an embodiment method 1400 for CSI feedback in a communications system. The method 1400 may be performed by a network device, such as a base station (BS). As shown, at step 1402, the BS transmits, through N antenna ports of the BS to M antenna ports of a user equipment (UE), a reference signal (RS) resource set, where the RS resource set is transmitted over K_1 subcarriers on L_1 OFDM symbols. Each of the M , N , K_1 and L_1 is an integer greater than 0.

[120] At step 1404, the BS receives, from the UE, a channel state information (CSI) report measured based on the RS resource set, where the CSI report comprises information of R sets of vectors, where each set of vectors comprises one or more vectors, and the one or more vectors comprises a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector, a fourth $L_2 \times 1$ vector, or any combination thereof, and where a sum of R outer products of the respective R sets of vectors represents CSI of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols. Each of the R , K_2 and L_2 being an integer greater than 0. At step 1406, the BS reconstructs the channel based on the R sets of vectors by calculating an outer product of each set of vectors and summing up outer products of the respective R sets of vector.

[121] The following aspects are provided in the present disclosure.

[122] According to one aspect of the present disclosure, a method is provided that includes: receiving, through M antenna ports of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted from N antenna ports of a base station (BS) over K_1 subcarriers on L_1 OFDM symbols, wherein each of the M , N , K_1 and L_1 is an integer greater than 0, and reporting, by the UE to the BS, R sets of vectors that are obtained based on measurement of the RS resource set, wherein each set of vectors comprises one or more vectors selected from a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector and a fourth $L_2 \times 1$ vector, wherein a sum of R outer products of the respective R sets of vectors represents channel state information of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols, wherein each of the R , K_2 and L_2 is an integer greater than 0.

[123] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, resources carrying the RS resource set.

[124] Optionally, in any one of preceding aspects, the R sets of vectors are reported according to a configuration signaled by the BS.

[125] Optionally, in any one of preceding aspects, the method further includes: constructing, by the UE, a multi-dimensional tensor representing the channel based on the measurement of the RS resource set, and performing, by the UE, decomposition on the multi-dimensional tensor using a tensor decomposition technique, whereby generating factor matrices, wherein the R sets of vectors are obtained from the factor matrices.

[126] Optionally, in any one of preceding aspects, the R sets of vectors are a subset of the factor matrices.

[127] Optionally, in any one of preceding aspects, the R sets of vectors comprise all vectors of the factor matrices.

[128] Optionally, in any one of preceding aspects, the tensor decomposition technique comprises Canonical Polyadic decomposition (CPD), Tucker decomposition, higher order singular vector decomposition (SVD), or multilinear SVD.

[129] Optionally, in any one of preceding aspects, the factor matrices are generated from Canonical Polyadic decomposition (CPD) of the multi-dimensional tensor.

[130] Optionally, in any one of preceding aspects, the factor matrices are generated from Tucker Decomposition or multilinear decomposition of the multi-dimensional tensor.

[131] Optionally, in any one of preceding aspects, the multi-dimensional tensor is constructed based on the measurement of the RS resource set in a set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.

[132] Optionally, in any one of preceding aspects, the measurement of the RS resource set is performed in the set of measurement domains in an order of the set of measurement domains, wherein the order is configured by the BS.

[133] Optionally, in any one of preceding aspects, a number of measurement domains in the set of measurement domains is configured by the BS.

[134] Optionally, in any one of preceding aspects, one or more measurement domains included in the set of measurement domains are configured by the BS.

[135] Optionally, in any one of preceding aspects, a factor matrix comprises a plurality of $N \times 1$ vectors, a plurality of $M \times 1$ vectors, a plurality of $K \times 1$ vectors, or a plurality of $L \times 1$ vector.

[136] Optionally, in any one of preceding aspects, each set of vectors comprises the first $N \times 1$ vector, the second $M \times 1$ vector, the third $K_2 \times 1$ vector, and the fourth $L_2 \times 1$ vector.

[137] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, signaling indicating the one or more vectors to be reported.

[138] Optionally, in any one of preceding aspects, resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.

[139] Optionally, in any one of preceding aspects, the R sets of vectors that are reported comprises quantized amplitudes and phases of a vector in a set of vectors.

[140] Optionally, in any one of preceding aspects, the method further includes receiving, by the UE, configuration information for reporting the R sets of vectors in higher layer signaling, or a downlink control information (DCI) message.

[141] Optionally, in any one of preceding aspects, the configuration information comprises information triggering reporting of the R sets of vectors.

[142] In accordance with another aspects of the present disclosure, a method is provided that includes: transmitting, through N antenna ports of a base station (BS) to M antenna ports of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted over K_1 subcarriers on L OFDM symbols, wherein each of the M, N, K_1 and L is an integer greater than 0, receiving, by the BS from the UE, a channel state information (CSI) report measured based on the RS resource set, the CSI report comprising information of R sets of vectors, wherein each set of vectors comprises one or more vectors selected from a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector, and a fourth $L_2 \times 1$ vector, and a sum of R outer products of the respective R sets of vectors represents CSI of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols, each of the R, K_2 and L_2 being an integer greater than 0, and reconstructing, by the BS, the channel based on the R sets of vectors by calculating an outer product of each set of vectors and summing up outer products of the respective R sets of vector.

[143] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, resources carrying the RS resource set.

[144] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, information about R.

[145] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a set of measurement domains for the UE to measure

the RS resource set in the set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.

[146] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, an order of the set of measurement domains for the UE to measure the RS resource set in the order of the set of measurement domains.

[147] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a number of measurement domains in the set of measurement domains.

[148] Optionally, in any one of preceding aspects, the method further includes configuring, by the BS for the UE, one or more measurement domains comprised in the set of measurement domains.

[149] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, signaling indicating the one or more vectors to be reported.

[150] Optionally, in any one of preceding aspects, resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.

[151] Optionally, in any one of preceding aspects, the R sets of vectors that are reported comprises quantized amplitudes and phases of a vector in a set of vectors.

[152] Optionally, in any one of preceding aspects, the method further includes transmitting, by the BS to the UE, a trigger triggering reporting of the CSI of the channel.

[153] Optionally, in any one of preceding aspects, the method further includes generating, by the BS to the UE, a transmission filter based on the CSI report.

[154] An apparatus and a system for performing the above aspects are also provided.

[155] FIG. 15 illustrates a block diagram of an embodiment processing system 1500 for performing methods described herein, which may be installed in a host device. As shown, the processing system 1500 includes a processor 1504, a memory 1506, and interfaces 1510-1514, which may (or may not) be arranged as shown in FIG. 15. The processor 1504 may be any component or collection of components adapted to perform computations and/or other processing related tasks, and the memory 1506 may be any component or collection of components adapted to store programming and/or instructions for execution by the processor 1504. In an embodiment, the memory 1506

includes a non-transitory computer readable medium. The interfaces 1510, 1512, 1514 may be any component or collection of components that allow the processing system 1500 to communicate with other devices/components and/or a user. For example, one or more of the interfaces 1510, 1512, 1514 may be adapted to communicate data, control, or management messages from the processor 1504 to applications installed on the host device and/or a remote device. As another example, one or more of the interfaces 1510, 1512, 1514 may be adapted to allow a user or user device (e.g., personal computer (PC), etc.) to interact/communicate with the processing system 1500. The processing system 1500 may include additional components not depicted in FIG. 15, such as long term storage (e.g., non-volatile memory, etc.).

[156] In some embodiments, the processing system 1500 is included in a network device that is accessing, or part otherwise of, a telecommunications network. In one example, the processing system 1500 is in a network-side device in a wireless or wireline telecommunications network, such as a base station, a relay station, a scheduler, a controller, a gateway, a router, an applications server, or any other device in the telecommunications network. In other embodiments, the processing system 1500 is in a user-side device accessing a wireless or wireline telecommunications network, such as a mobile station, a user equipment (UE), a personal computer (PC), a tablet, a wearable communications device (e.g., a smartwatch, etc.), or any other device adapted to access a telecommunications network.

[157] In some embodiments, one or more of the interfaces 1510, 1512, 1514 connects the processing system 1500 to a transceiver adapted to transmit and receive signaling over the telecommunications network. FIG. 16 illustrates a block diagram of a transceiver 1600 adapted to transmit and receive signaling over a telecommunications network. The transceiver 1600 may be installed in a host device. As shown, the transceiver 1600 comprises a network-side interface 1602, a coupler 1604, a transmitter 1606, a receiver 1608, a signal processor 1610, and a device-side interface 1612. The network-side interface 1602 may include any component or collection of components adapted to transmit or receive signaling over a wireless or wireline telecommunications network. The coupler 1604 may include any component or collection of components adapted to facilitate bi-directional communication over the network-side interface 1602. The transmitter 1606 may include any component or collection of components (e.g., up-converter, power amplifier, etc.) adapted to convert a baseband signal into a modulated carrier signal suitable for transmission over the network-side interface 1602. The receiver 1608 may include any component or collection of components (e.g., down-converter, low noise amplifier, etc.) adapted to convert a carrier signal received over the network-side

interface 1602 into a baseband signal. The signal processor 1610 may include any component or collection of components adapted to convert a baseband signal into a data signal suitable for communication over the device-side interface(s) 1612, or vice-versa. The device-side interface(s) 1612 may include any component or collection of components adapted to communicate data-signals between the signal processor 1610 and components within the host device (e.g., the processing system 1500, local area network (LAN) ports, etc.).

[158] The transceiver 1600 may transmit and receive signaling over any type of communications medium. In some embodiments, the transceiver 1600 transmits and receives signaling over a wireless medium. For example, the transceiver 1600 may be a wireless transceiver adapted to communicate in accordance with a wireless telecommunications protocol, such as a cellular protocol (e.g., long-term evolution (LTE), etc.), a wireless local area network (WLAN) protocol (e.g., Wi-Fi, etc.), or any other type of wireless protocol (e.g., Bluetooth, near field communication (NFC), etc.). In such embodiments, the network-side interface 1602 comprises one or more antenna/radiating elements. For example, the network-side interface 1602 may include a single antenna, multiple separate antennas, or a multi-antenna array configured for multi-layer communication, e.g., single input multiple output (SIMO), multiple input single output (MISO), multiple input multiple output (MIMO), etc. In other embodiments, the transceiver 1600 transmits and receives signaling over a wireline medium, e.g., twisted-pair cable, coaxial cable, optical fiber, etc. Specific processing systems and/or transceivers may utilize all of the components shown, or only a subset of the components, and levels of integration may vary from device to device.

[159] It should be appreciated that one or more steps of the embodiment methods provided herein may be performed by corresponding units or modules. For example, a signal may be transmitted by a transmitting unit or a transmitting module. A signal may be received by a receiving unit or a receiving module. A signal may be processed by a processing unit or a processing module. Other steps may be performed by a generating unit/module, a calculating unit/module, a reporting unit/module, a measuring unit/module, a reconstructing unit/module, a decomposing unit/module, a constructing unit/module, a performing unit/module, a quantizing unit/module, a triggering unit/module, a signaling unit/module, and/or a setting unit/module. The respective units/modules may be hardware, software, or a combination thereof. For instance, one or more of the units/modules may be an integrated circuit, such as field programmable gate arrays (FPGAs) or application-specific integrated circuits (ASICs).

[160] While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.

WHAT IS CLAIMED IS:

1. A method comprising:
receiving, through M antenna ports of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted from N antenna ports of a base station (BS) over K₁ subcarriers on L₁ OFDM symbols, wherein each of the M, N, K₁ and L₁ is an integer greater than 0; and
reporting, by the UE to the BS, R sets of vectors that are obtained based on measurement of the RS resource set, wherein each set of vectors comprises one or more vectors, the one or more vectors comprising a first N_{x1} vector, a second M_{x1} vector, a third K_{2x1} vector, a fourth L_{2x1} vector, or any combination thereof, wherein a sum of R outer products of the respective R sets of vectors represents channel state information of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K₂ subcarriers on L₂ OFDM symbols, and wherein each of the R, K₂ and L₂ is an integer greater than 0.
2. The method of claim 1, further comprising:
receiving, by the UE, resources carrying the RS resource set.
3. The method as recited in any of claims 1-2, wherein the R sets of vectors are reported according to a configuration signaled by the BS.
4. The method as recited in any of claims 1-3, further comprising:
constructing, by the UE, a multi-dimensional tensor representing the channel based on the measurement of the RS resource set; and
performing, by the UE, decomposition on the multi-dimensional tensor using a tensor decomposition technique, whereby generating factor matrices, wherein the R sets of vectors are obtained from the factor matrices.
5. The method of claim 4, wherein the multi-dimensional tensor is constructed based on the measurement of the RS resource set in a set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.
6. The method of claim 5, wherein the number of measurement domains in the set of measurement domains is configured by the BS.

7. The method as recited in any of claims 5-6, wherein the set of measurement domains is configured by the BS.
8. The method as recited in any of claims 5-7, wherein a factor matrix comprises a plurality of $N \times 1$ vectors, a plurality of $M \times 1$ vectors, a plurality of $K \times 2 \times 1$ vectors, or a plurality of $L \times 2 \times 1$ vector.
9. The method as recited in any of claims 5-8, wherein the factor matrices are generated from Canonical Polyadic decomposition (CPD) of the multi-dimensional tensor.
10. The method as recited in any of claims 5-9, wherein the R sets of vectors are a subset of a plurality of $N \times 1$ vectors, a plurality of $M \times 1$ vectors, a plurality of $K \times 2 \times 1$ vectors, and a plurality of $L \times 2 \times 1$ vectors that make up the factor matrices.
11. The method as recited in any of claims 1-10, wherein information about R is configured by the BS.
12. The method as recited in any of claims 1-11, further comprising:
receiving, by the UE, signaling indicating the one or more vectors to be reported.
13. The method as recited in any of claims 1-12, wherein resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.
14. The method as recited in any of claims 1-13, wherein the R sets of vectors that are reported comprises quantized amplitudes and phases of elements of vectors.
15. The method as recited in any of claims 1-14, further comprising:
receiving, by the UE, configuration information for reporting the R sets of vectors in higher layer signaling, or a downlink control information (DCI) message.
16. The method of claim 15, wherein the configuration information comprises information triggering reporting of the R sets of vectors.
17. A method comprising:
transmitting, through N antenna ports of a base station (BS) to M antenna ports

of a user equipment (UE), a reference signal (RS) resource set, the RS resource set being transmitted over K_1 subcarriers on L_1 OFDM symbols, wherein each of the M , N , K_1 and L_1 is an integer greater than 0;

receiving, by the BS from the UE, a channel state information (CSI) report measured based on the RS resource set, the CSI report comprising information of R sets of vectors, wherein each set of vectors comprises one or more vectors, the one or more vectors comprising a first $N \times 1$ vector, a second $M \times 1$ vector, a third $K_2 \times 1$ vector, a fourth $L_2 \times 1$ vector, or any combination thereof, and wherein a sum of R outer products of the respective R sets of vectors represents CSI of a channel between the N antenna ports of the BS and the M antenna ports of the UE over K_2 subcarriers on L_2 OFDM symbols, each of the R , K_2 and L_2 being an integer greater than 0; and

reconstructing, by the BS, the channel based on the R sets of vectors by calculating an outer product of each set of vectors and summing up outer products of the respective R sets of vector.

18. The method of claim 17, further comprising:
transmitting, by the BS to the UE, resources carrying the RS resource set.
19. The method of claim 17 or 18, further comprising:
transmitting, by the BS to the UE, information about R .
20. The method as recited in any claims of 17-19, further comprising:
transmitting, by the BS to the UE, a set of measurement domains for the UE to measure the RS resource set in the set of measurement domains, the set of measurement domains comprising a transmit domain, a receive domain, a time domain, a frequency domain, a delay domain, or any combination thereof.
21. The method of claim 20, further comprising:
transmitting, by the BS to the UE, an order of the set of measurement domains for the UE to measure the RS resource set in the order of the set of measurement domains.
22. The method as recited in any of claims 20-21, further comprising:
transmitting, by the BS to the UE, a number of measurement domains in the set of measurement domains.

23. The method as recited in any of claims 20-22, further comprising:
configuring, by the BS for the UE, one or more measurement domains comprised in the set of measurement domains.
24. The method as recited in any claims 17-23, further comprising:
transmitting, by the BS to the UE, signaling indicating the one or more vectors to be reported.
25. The method as recited in any of claims 17-24, wherein resources for transmitting the RS resource set are non-zero-power CSI-RS resources that are configured by the BS for CSI reporting.
26. The method as recited in any of claims 17-25, wherein the R sets of vectors that are reported comprises quantized amplitudes and phases of elements of vectors.
27. The method as recited in any claims 17-26, further comprising:
transmitting, by the BS to the UE, a trigger triggering reporting of the CSI of the channel.
28. The method as recited in any claims 17-27, further comprising:
generating, by the BS to the UE, a transmission filter based on the CSI report.
29. An apparatus comprising:
a non-statutory memory storage comprising instruction; and
one or more processors in communication with the memory storage, wherein the one or more processors execute the instructions to:
perform a method as recited in any of claims 1-28.
30. A system comprising:
a base station configured to perform a method as recited in any of claims 17-28;
and
a user equipment configured to communicate with the base station, and to perform a method as recited in any of claims 1-16.

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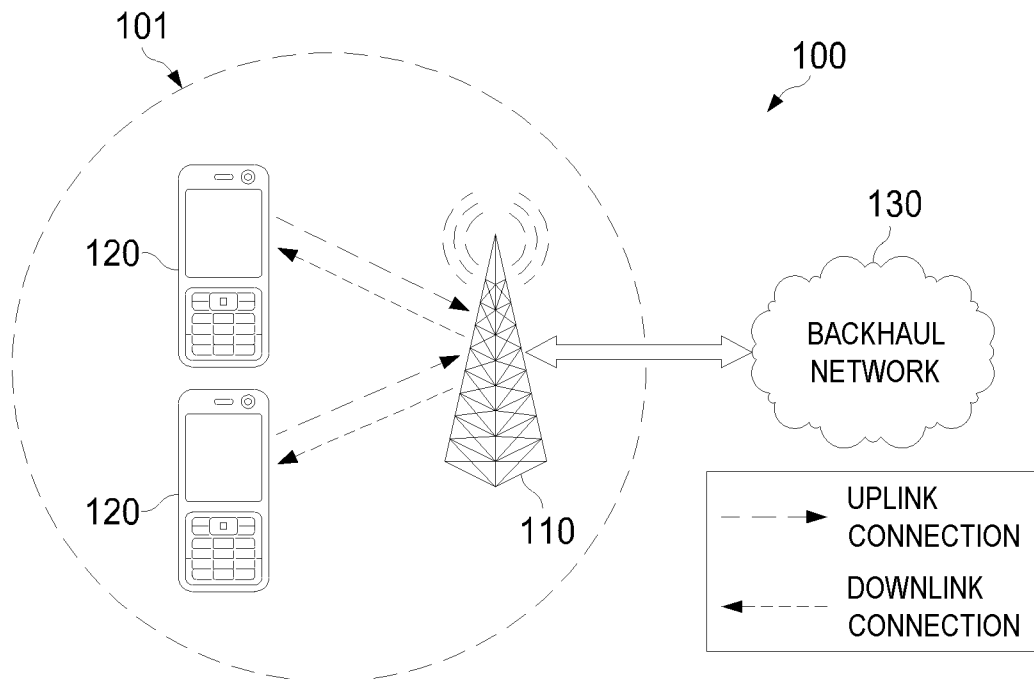


FIG. 1

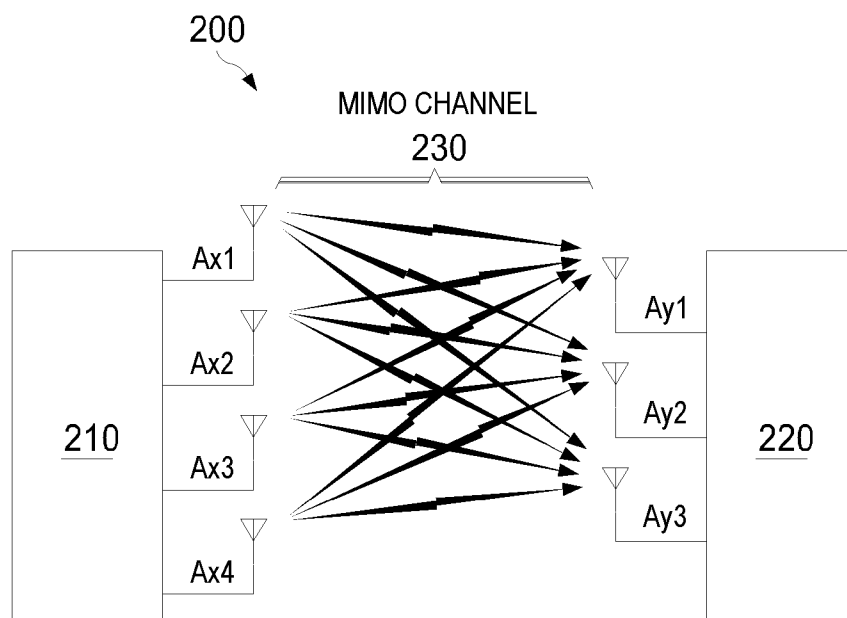


FIG. 2

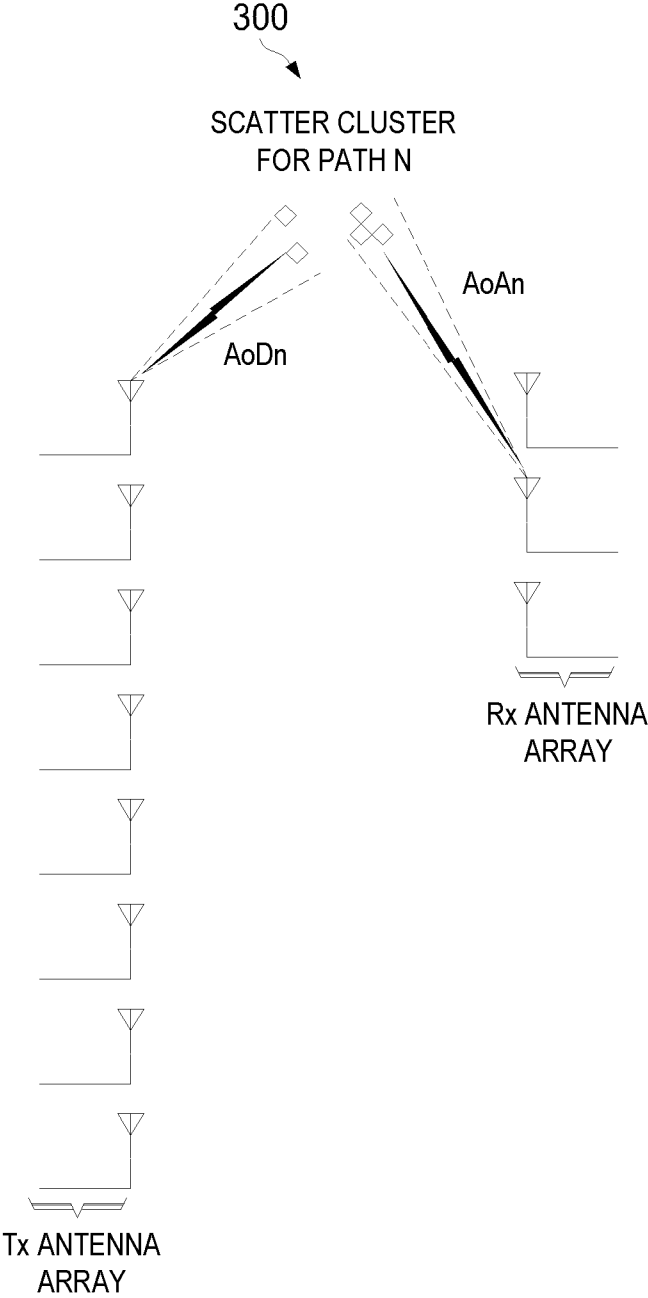
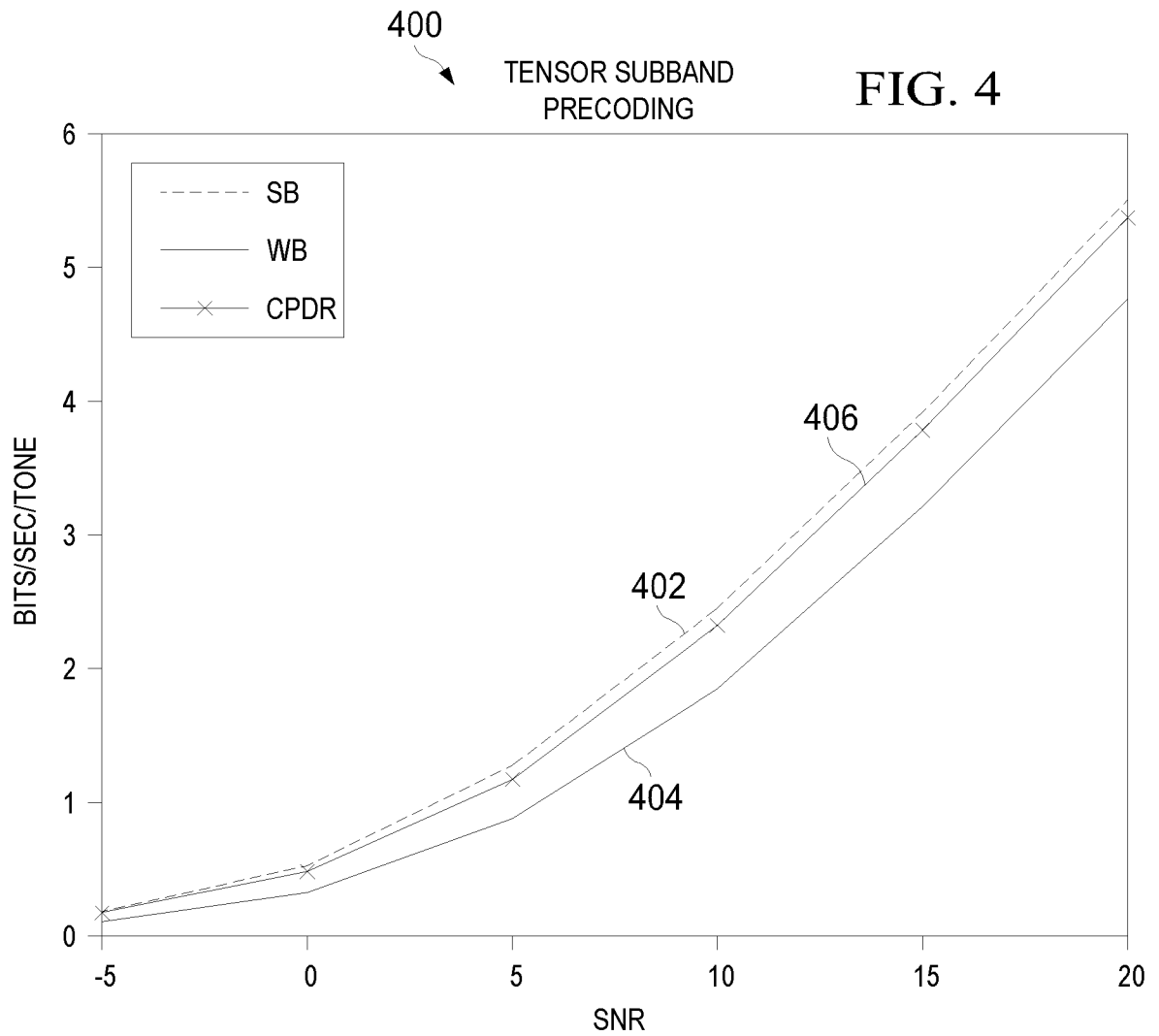


FIG. 3

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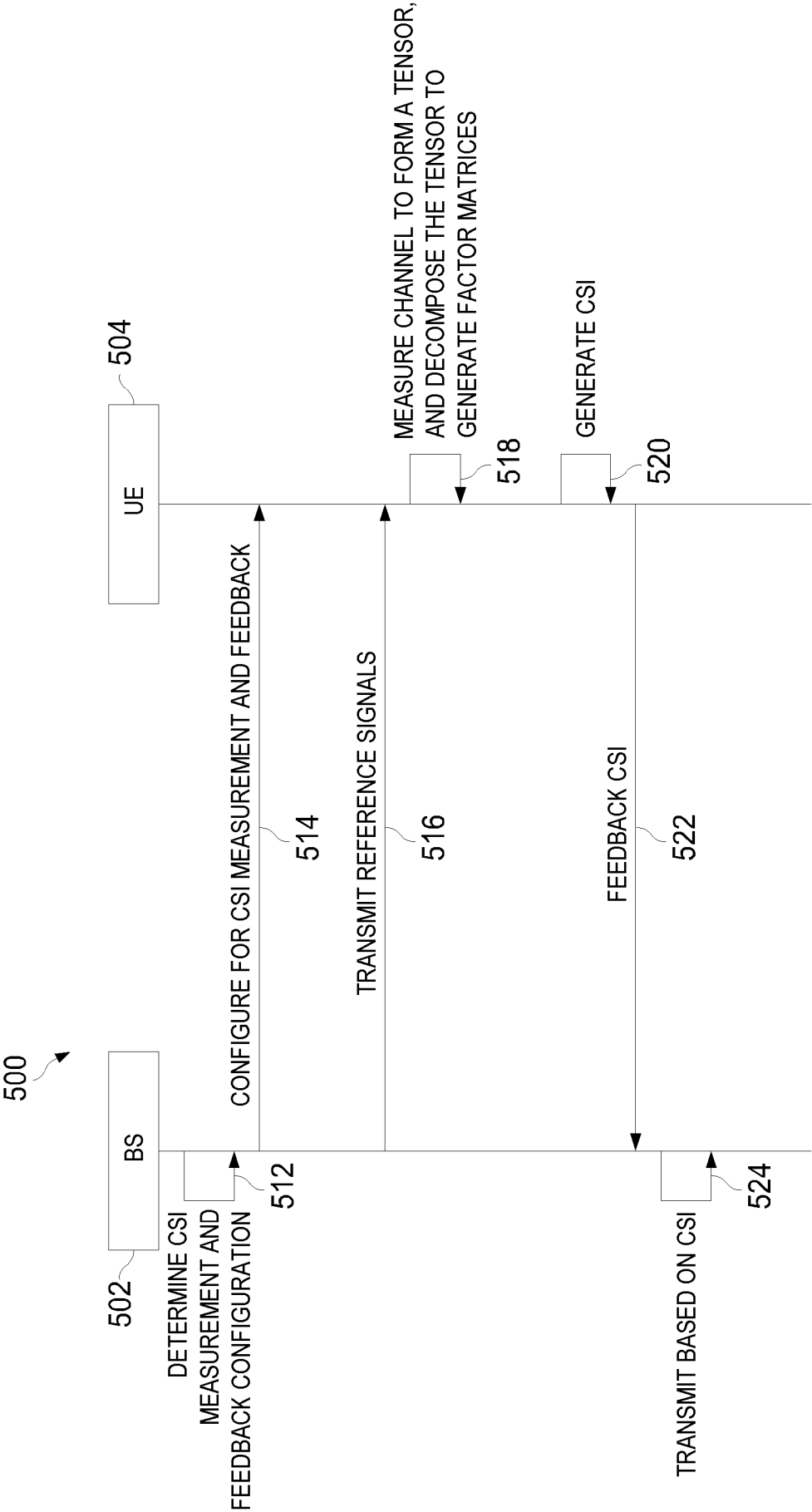


FIG. 5

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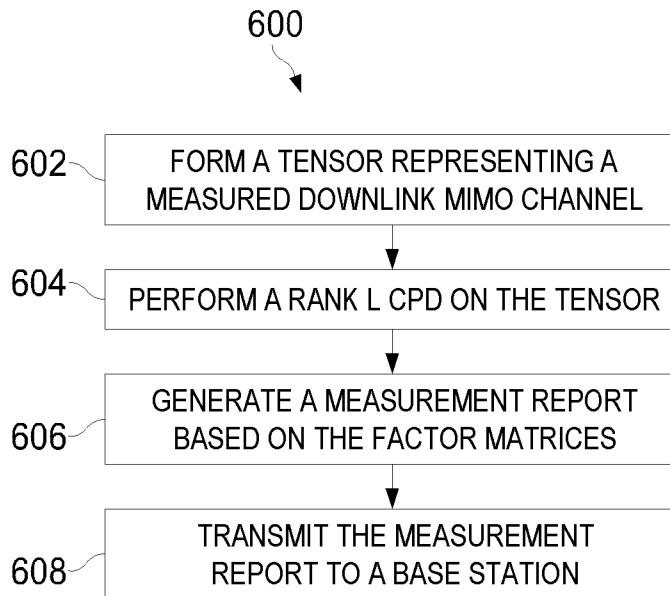


FIG. 6

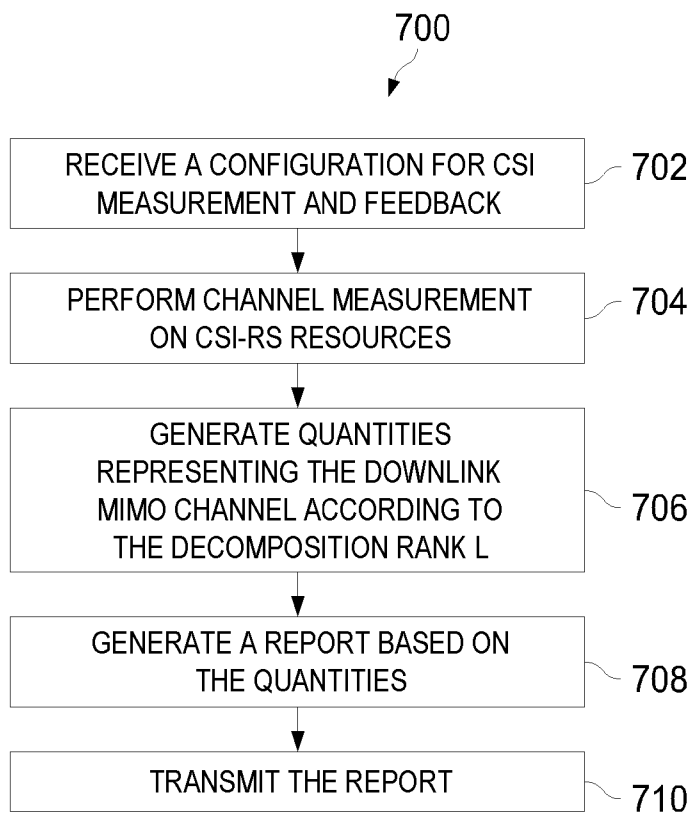


FIG. 7

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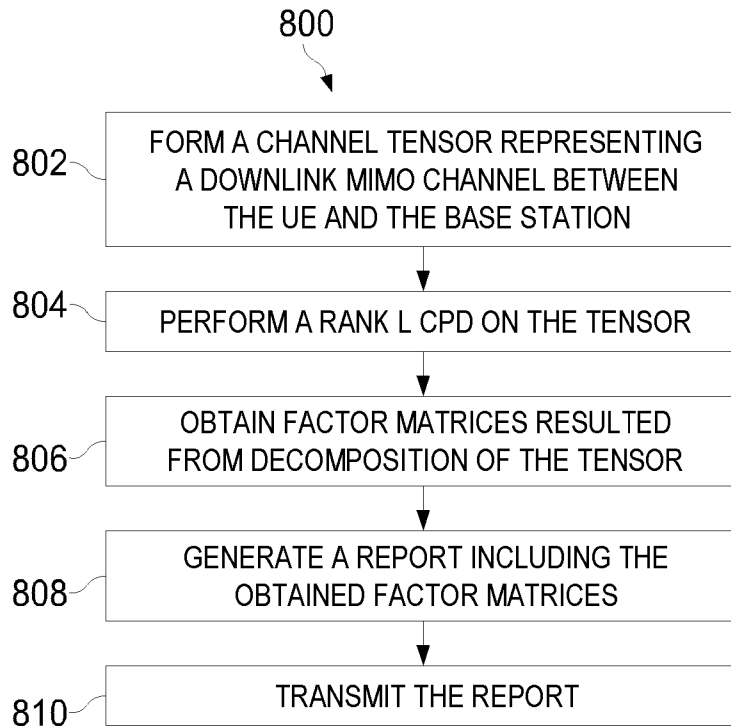


FIG. 8

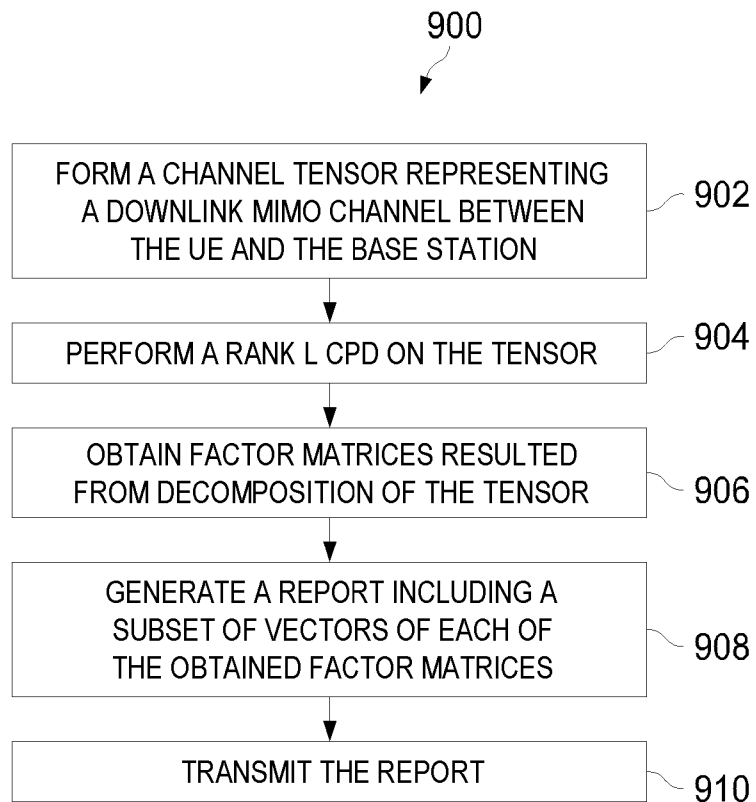


FIG. 9

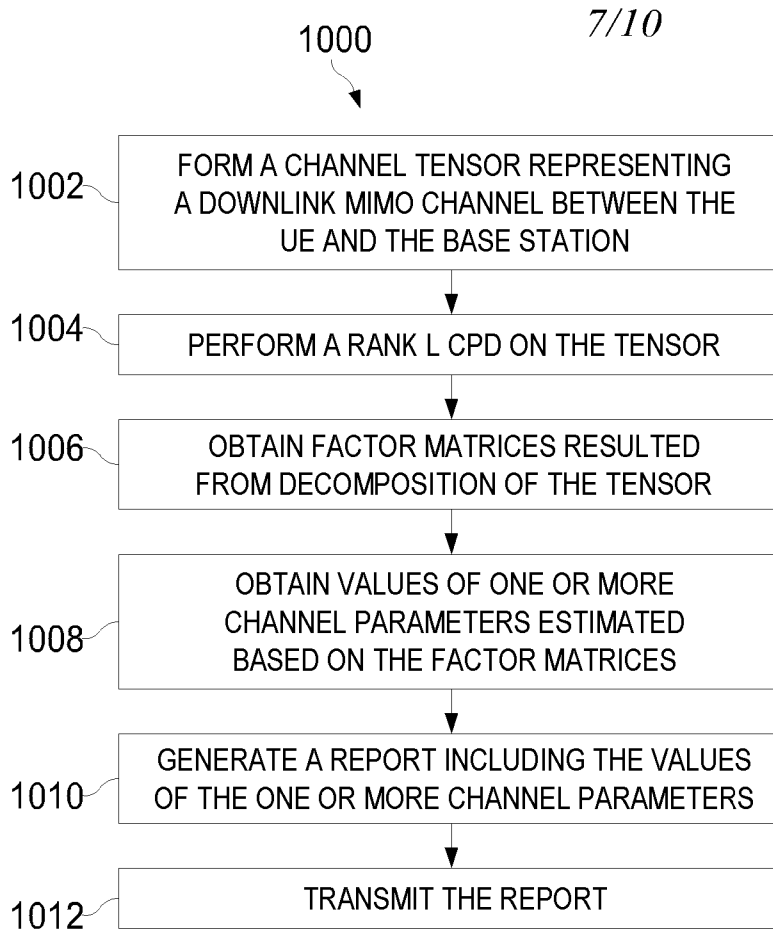


FIG. 10

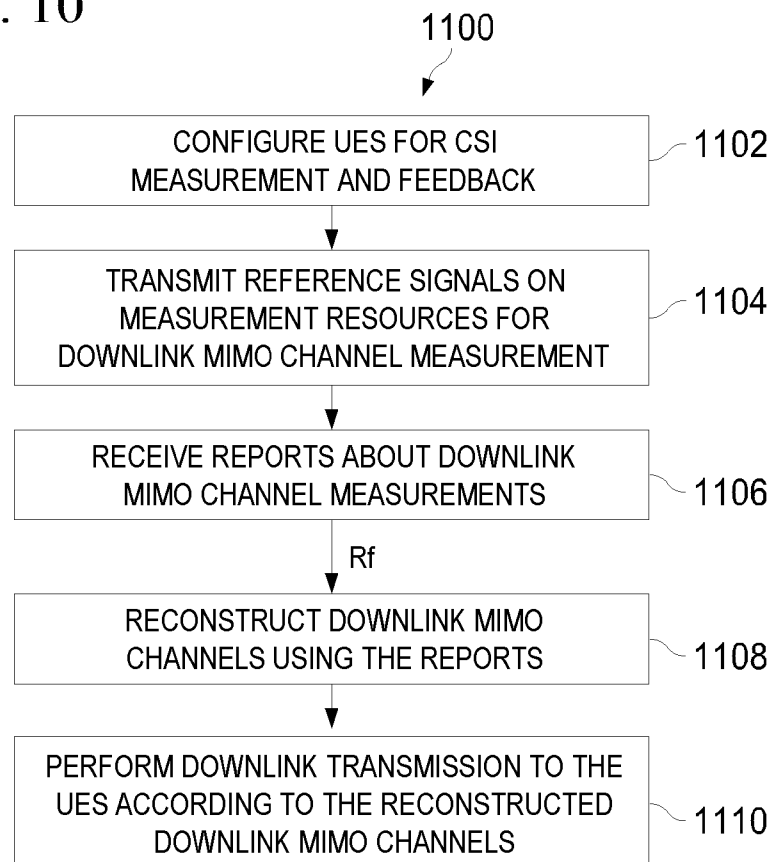


FIG. 11

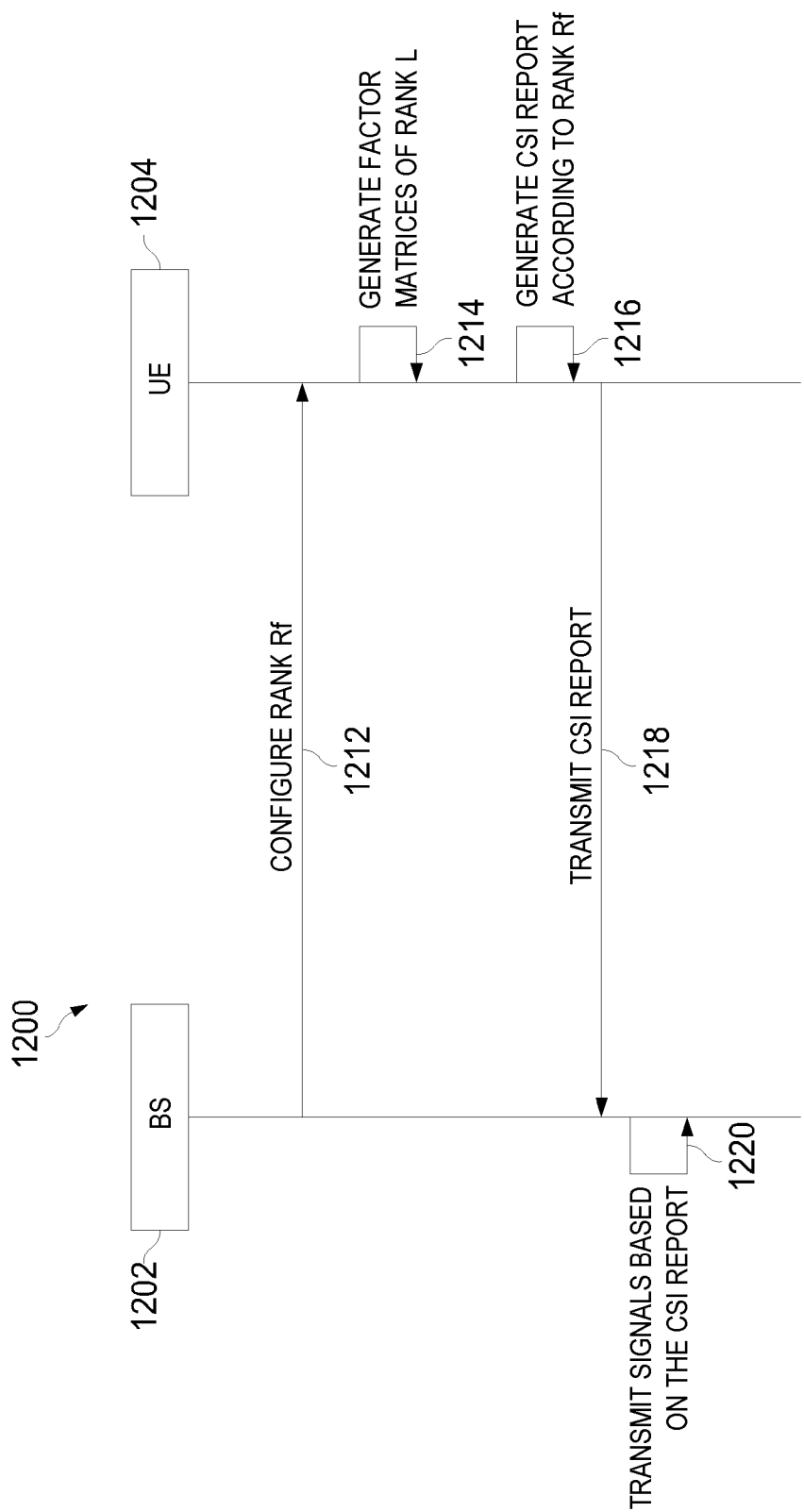


FIG. 12

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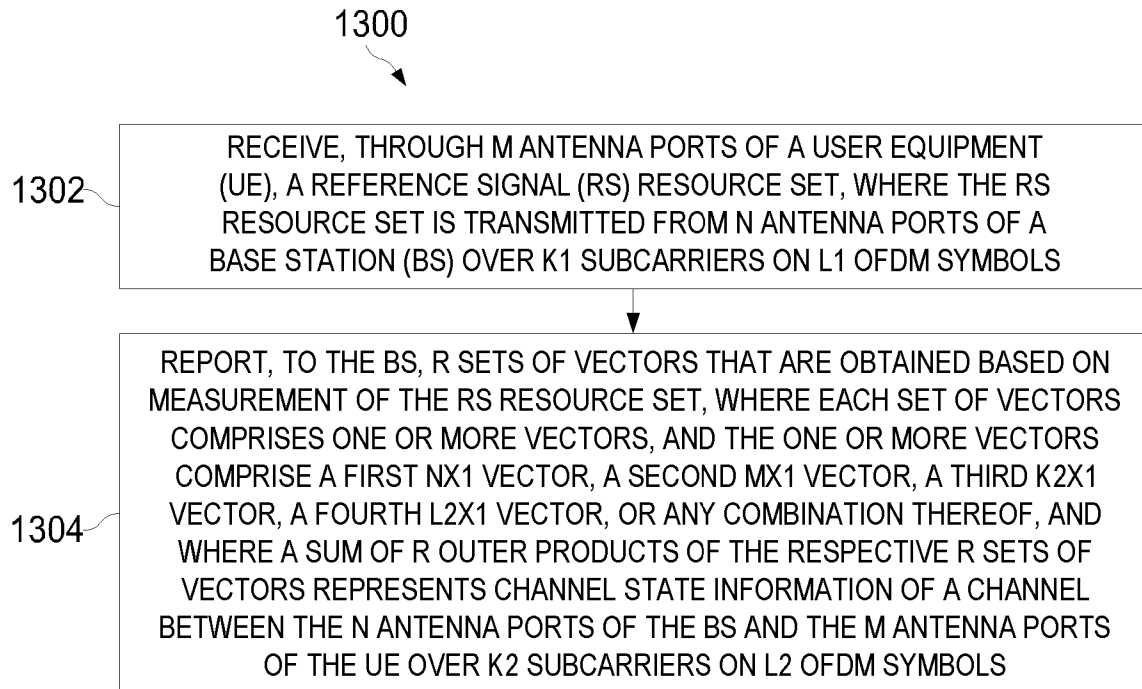


FIG. 13

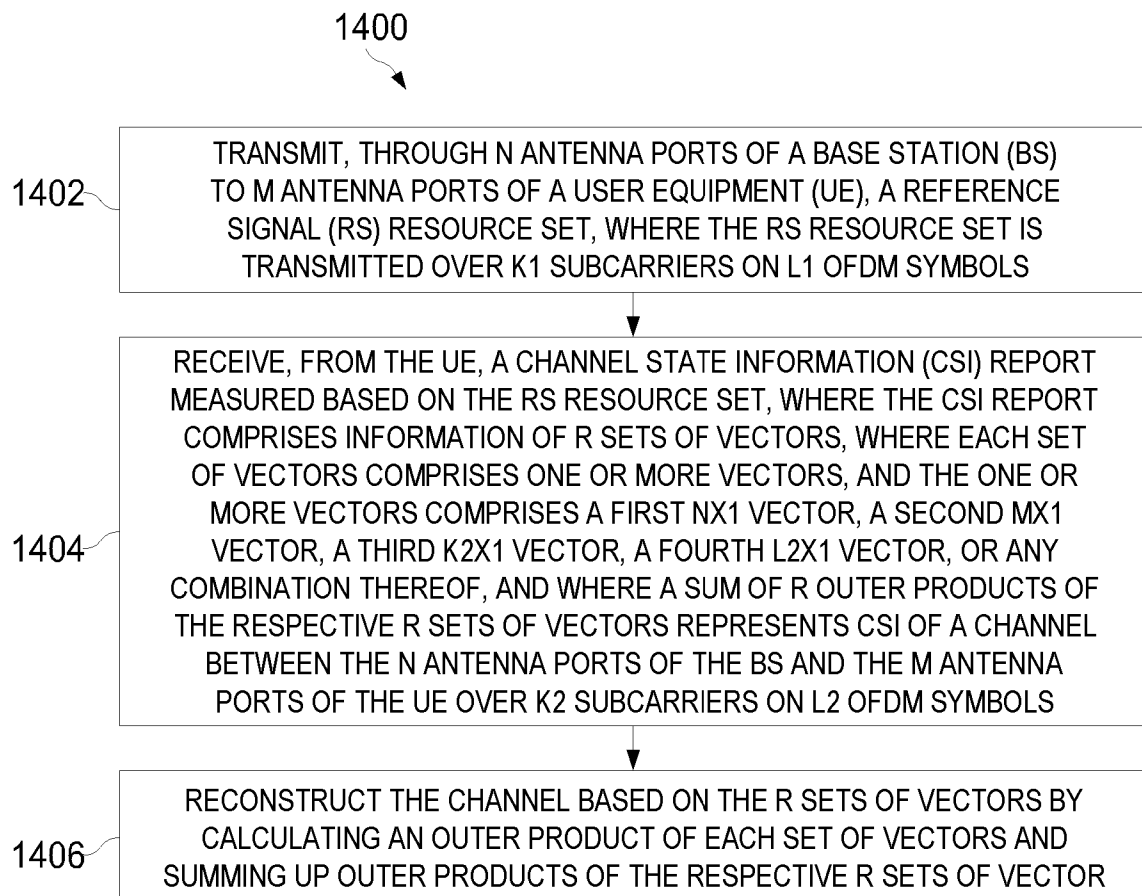


FIG. 14

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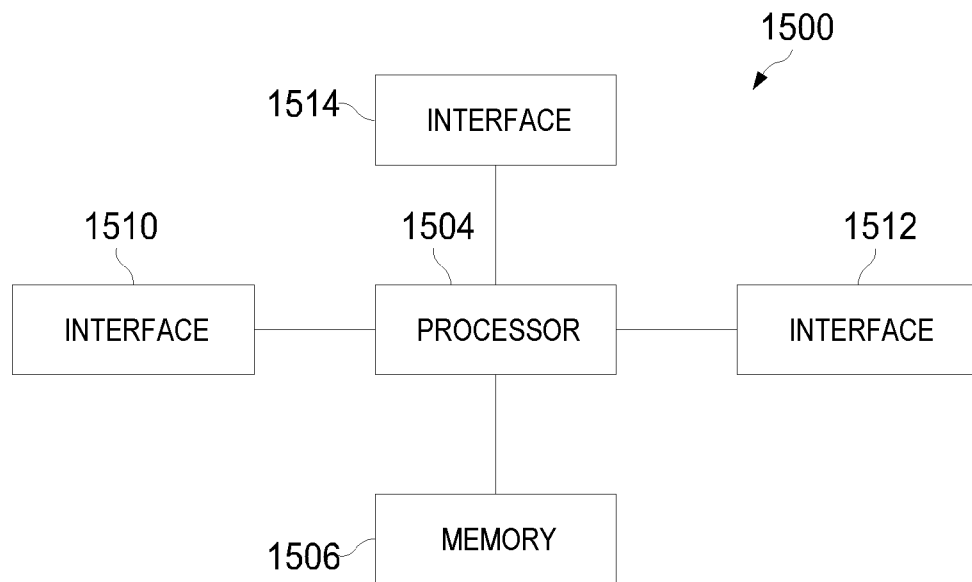


FIG. 15

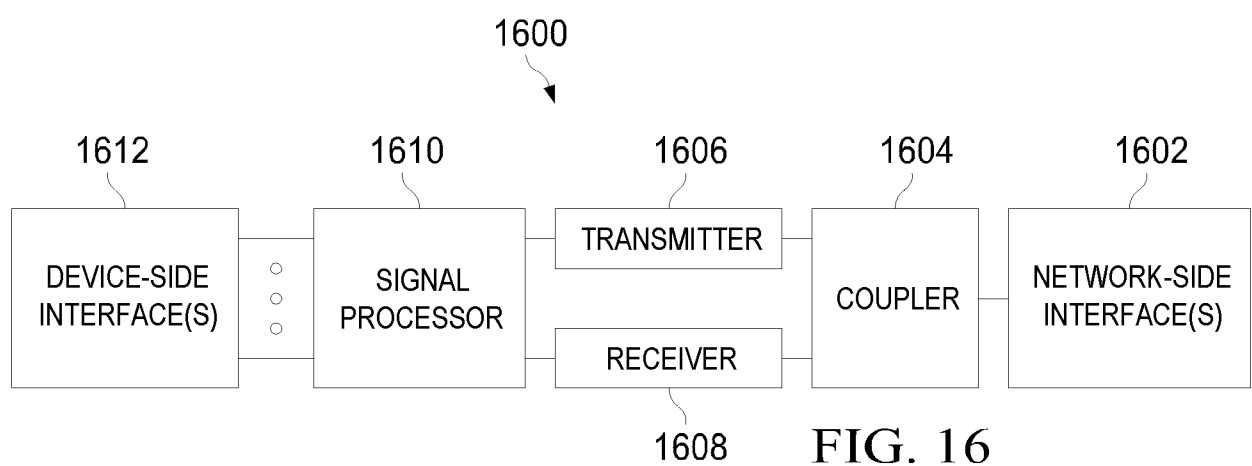


FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2020/082096

A. CLASSIFICATION OF SUBJECT MATTER H04L 25/02(2006.01)i According to International Patent Classification (IPC) or to both national classification and IPC																				
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H04L, H04W, H04B Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPI,EPODOC,CNPAT,CNKI,IEEE:channel, state, information, CSI, feedback, reduce, overhead, tensor, decomposition, outer, product, massive, MIMO																				
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>PX</td> <td>EP 3576361 A1 (FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG DER ANGEWANDTEN FORSCHUNG E.V.) 04 December 2019 (2019-12-04) description, paragraphs 0130-0178</td> <td>1-30</td> </tr> <tr> <td>A</td> <td>ZHU, Yu et al. "HOSVD-based Limited Feedback and Precoding Design for Massive MIMO Systems" <i>2016 IEEE/CIC International Conference on Communications in China (ICCC Workshops)</i>, 10 October 2016 (2016-10-10), section II, section III, abstract</td> <td>1-30</td> </tr> <tr> <td>A</td> <td>QIAN, Cheng et al. "Tensor-Based Channel Estimation for Dual-Polarized Massive MIMO Systems" <i>IEEE TRANSACTIONS ON SIGNAL PROCESSING</i>, Vol. 66, No. 24, 15 December 2018 (2018-12-15), the whole document</td> <td>1-30</td> </tr> <tr> <td>A</td> <td>EP 3459439 A1 (NOKIA TECHNOLOGIES OY) 27 March 2019 (2019-03-27) the whole document</td> <td>1-30</td> </tr> <tr> <td>A</td> <td>US 2018076871 A1 (SAMSUNG ELECTRONICS CO., LTD.) 15 March 2018 (2018-03-15) the whole document</td> <td>1-30</td> </tr> </tbody> </table>			Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	PX	EP 3576361 A1 (FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG DER ANGEWANDTEN FORSCHUNG E.V.) 04 December 2019 (2019-12-04) description, paragraphs 0130-0178	1-30	A	ZHU, Yu et al. "HOSVD-based Limited Feedback and Precoding Design for Massive MIMO Systems" <i>2016 IEEE/CIC International Conference on Communications in China (ICCC Workshops)</i> , 10 October 2016 (2016-10-10), section II, section III, abstract	1-30	A	QIAN, Cheng et al. "Tensor-Based Channel Estimation for Dual-Polarized Massive MIMO Systems" <i>IEEE TRANSACTIONS ON SIGNAL PROCESSING</i> , Vol. 66, No. 24, 15 December 2018 (2018-12-15), the whole document	1-30	A	EP 3459439 A1 (NOKIA TECHNOLOGIES OY) 27 March 2019 (2019-03-27) the whole document	1-30	A	US 2018076871 A1 (SAMSUNG ELECTRONICS CO., LTD.) 15 March 2018 (2018-03-15) the whole document	1-30
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A	US 2018076871 A1 (SAMSUNG ELECTRONICS CO., LTD.) 15 March 2018 (2018-03-15) the whole document	1-30																		
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Date of the actual completion of the international search 08 June 2020		Date of mailing of the international search report 30 June 2020																		
Name and mailing address of the ISA/CN National Intellectual Property Administration, PRC 6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088 China Facsimile No. (86-10)62019451		Authorized officer ZHANG,Wei Telephone No. 86-(10)-53961788																		

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2020/082096

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2020/082096

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
EP	3576361	A1	04 December 2019	WO	2019229095	A1	05 December 2019
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				WO	2018052255	A1	22 March 2018
				EP	3510707	A1	17 July 2019
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				RU	2011140623	A	20 April 2013