(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
23 October 2014 (23.10.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/170751 A2

(51) International Patent Classification: *H04L 5/00* (2006.01)

(21) International Application Number: PCT/IB2014/000656

(22) International Filing Date: 25 March 2014 (25.03.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
201310134377.1 17 April 2013 (17.04.2013) CN

(71) Applicant: ALCATEL LUCENT [FR/FR]; 3, avenue Octave Gréard, F-75007 Paris (FR).

(72) Inventor: WU, Keying; 388# Ningqiao RD, Shanghai, Shanghai 201206 (CN).

(74) Agent: THERIAS, Philippe; Alcatel-lucent International, 32 avenue Kléber, F-92700 Colombes (FR).

(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, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, 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, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, 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, 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, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) Title: CHANNEL DETECTION METHOD AND DEVICE IN LARGE-SCALE ANTENNA SYSTEM

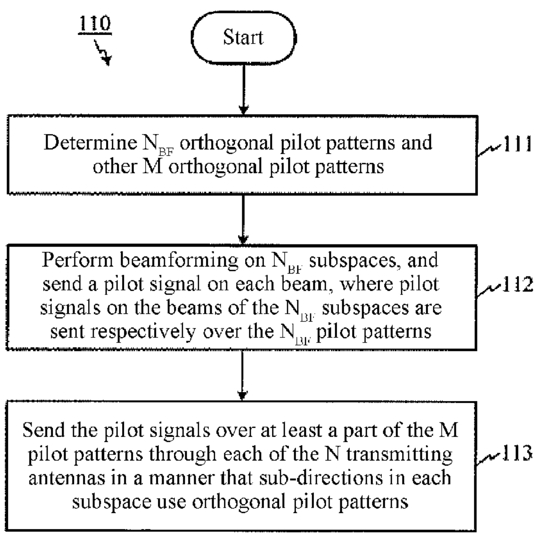

FIG. 1

(57) Abstract: The present invention relates to a channel detection method and device in a system having a large number of antennas. In an embodiment, a method used in a base station having N transmitting antennas in a multiple input multiple output (MIMO) system is provided, which includes: determining N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns; performing beamforming on N_{BF} subspaces, and sending a pilot signal on each beam, where pilot signals on the beams of the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns; and sending pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas, in a manner that sub-directions in each subspace use the orthogonal pilot patterns, where a value of N_{BF} is 10%~15% of N, and a value of M is 15%~50% of N. By using channel sparsity of the system having a large number of antennas, pilot overhead is reduced, and at least equivalent system performance can be achieved.

WO 2014/170751 A2

CHANNEL DETECTION METHOD AND DEVICE IN LARGE-SCALE ANTENNA SYSTEM

Background of the Invention

Field of the Invention

The present invention generally relates to the field of mobile communications technologies, and more particularly, to a Multiple User Multiple Input Multiple Output (MU MIMO) transmission technology.

Description of the Prior Art

Along with the increase of the number of base station antennas, pilot overhead becomes an increasingly severe problem, especially for downlink physical channel estimation in a frequency division duplexing (FDD) system, in which it is generally required that different antennas use orthogonal pilot patterns, and therefore, the pilot overhead increases linearly along with the increase of the number of the antennas, which significantly reduces capacity gain caused by more antennas. In a large-scale antenna system, more than 100 antennas may be used in a base station, and it is very difficult to allocate orthogonal pilot patterns for all the antennas. Therefore, precise downlink physical channel estimation and many subsequent downlink closed-loop MIMO operations, such as precoding and beamforming, become severe challenges, especially for the FDD.

Summary of the Invention

A major objective of the present invention is providing a new pilot signal sending solution and a new channel detection solution used for a multiple input multiple output (MIMO) system, so as to overcome the defects in the prior art. Current multi-antenna measurement and research show that radio channels of a large-scale antenna system are sparse in many situations, and channel capacity thereof is dominated by only a few degrees of freedom (far less than the number of antennas). Such sparsity allows significant reduction of pilot overhead while keeping precise channel estimation. By using a comprehensive sensing technology, the pilot overhead increases linearly only along with a dominant degree of freedom of the channel, instead of increasing along with the number of the antennas.

In an embodiment, a method used in a base station having N transmitting antennas in a MIMO system is provided, which includes: determining N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns; performing beamforming on N_{BF} subspaces, and sending a pilot signal on each beam, where pilot signals on the beams of the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns; and sending pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas, in a manner that sub-directions in each subspace use the orthogonal pilot patterns, where a value of N_{BF} is 10%~15% of N, and a value of M is 15%~50% of N. In some embodiments, the N_{BF} orthogonal pilot patterns and the M orthogonal pilot patterns determined by the base station are randomly distributed in a frequency domain.

Corresponding to the above embodiment, a method used in a user equipment in a MIMO system is further provided, which includes: receiving pilot signals from N_{BF} beams of N transmitting antennas of a base station; determining, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, positions where times of arrival of effective elements of a virtual channel matrix are located; separating components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determining, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong; receiving pilot signals from M pilot patterns on the N transmitting antennas of the base station; and separating components belonging to specific active subspaces from the pilot signals received from the M pilot patterns, and recovering a channel response matrix of corresponding active subspaces from the separated components.

In another embodiment, a method used in a base stating having N transmitting antennas in a MIMO system is provided, which includes: determining M orthogonal pilot patterns; and sending the pilot signals over at least a part of M pilot patterns through each of the N transmitting antennas, where a value of M is 15%~50% of N. In some embodiments, the M orthogonal pilot patterns determined by the base station are randomly distributed in a frequency domain.

Corresponding to the above embodiment, a method used in a user equipment in a MIMO system is further provided, which includes: receiving pilot signals from N transmitting antennas of a base station; determining, by using a sparse signal recovery algorithm from the received pilot signals, positions where times of arrival of effective elements of a virtual channel matrix are located; and separating components having specific directions of arrival from the received pilot signals, and determining, from the separated components, directions of arrival of the effective elements of the virtual channel matrix.

In still another embodiment, a device used in a base station having N transmitting antennas in a MIMO system is provided, which includes: a first device, configured to determine N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns; a second device, configured to perform beamforming on N_{BF} subspaces, and send a pilot signal on each beam, where pilot signals on the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns; and a third device, configured to send pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas, in a manner that sub-directions in each subspace use the orthogonal pilot patterns, where a value of N_{BF} is 10%~15% of N, and a value of M is 15%~50% of N. In some embodiments, the determined N_{BF} orthogonal pilot patterns and the determined M orthogonal pilot patterns are randomly distributed in a frequency domain.

Corresponding to the above embodiment, a device used in a user equipment in a MIMO system is further provided, which includes: a receiving device, configured to receive pilot signals from N_{BF} beams of N transmitting antennas of a base station and receive pilot signals from M pilot patterns of the N transmitting antennas; a time of arrival detecting device, configured to determine, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, positions where times of arrival of effective elements of a virtual channel matrix are located; a subspace detecting device, configured to separate components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determine, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong; and a channel recovering device, configured to separate components belonging to specific active subspaces from the pilot signals received from the M pilot patterns, and recover a channel response matrix of corresponding active subspaces from the separated components.

In yet another embodiment, a device used in a base station having N transmitting antennas in a MIMO system is provided, which includes: a first device, configured to determine M orthogonal pilot patterns; and a second device, configured to send the pilot signals over at least a part of M pilot patterns through each of the N transmitting antennas, where a value of M is 15%~50% of N. In some embodiments, the determined M orthogonal pilot patterns are randomly distributed in a frequency domain.

Corresponding to the above embodiment, a device used in a user equipment in a MIMO system is provided, which includes: a receiving device, configured to receive pilot signals from N transmitting antennas of a base station; a time of arrival detecting device, configured to determine, by using a sparse signal recovery algorithm from the received pilot signals, positions where times of arrival of effective elements of a virtual channel matrix are located; and a direction of arrival detecting device, configured to separate components having specific directions of arrival from the received pilot signals, and determine, from the separated components, directions of arrival of the effective elements of the virtual channel matrix.

The technical features and advantages of the present invention are briefly described in the foregoing to make following detailed descriptions of the present invention more comprehensible. Other features and advantages of the present invention are described in the following, which form a subject of claims of the present invention. Persons skilled in the art should understand that the disclosed concepts and embodiments may be easily used as a basis of modifying or designing other structures or procedures used for implementing the same objective of the present invention. The persons skilled in the art should further understand that the equivalent constructions do not depart from the spirit and scope of the accompanying claims.

Brief description of the drawings

Detailed descriptions of preferred embodiments of the present invention are more comprehensible with reference to accompanying drawings. The present invention is described by using examples, and is not limited to the accompanying drawings. Like reference numerals in the accompanying drawings indicate like elements.

FIG. 1 is a flowchart of a method used in a base station having N transmitting antennas in a multiple input multiple output (MIMO) system according to an embodiment of the present invention;

FIG. 2 is a flowchart of a method used in a user equipment in a MIMO system according to an embodiment of the present invention;

FIG. 3 is a flowchart of a method used in a base station having N transmitting antennas in a MIMO system according to another embodiment of the present invention;

FIG. 4 is a flowchart of a method used in a user equipment in a MIMO system according to another embodiment of the present invention;

FIG. 5 is a structural diagram of a device used in a base station having N transmitting antennas in a MIMO system according to an embodiment of the present invention;

FIG. 6 is a structural diagram of a device used in a user equipment in a MIMO system according to an embodiment of the present invention;

FIG. 7 is a structural diagram of a device used in a base station having N transmitting antennas in a MIMO system according to another embodiment of the present invention; and

FIG. 8 is a structural diagram of a device used in a user equipment in a MIMO system according to another embodiment of the present invention.

Detailed Description

The detailed descriptions of the accompanying drawings in tend to be used as descriptions of current preferred embodiments of the present invention, instead of representing the only form of implementing the present invention. It should be understood that, identical or equivalent functions may be implemented by different embodiments falling within the spirit and scope of the present invention.

Persons skilled in the art should understand that measures and functions that are described herein may be implemented by using a program-controlled microprocessor in combination with software functions of a computer, and/or implemented by using an application-specific integrated circuit (ASIC). It should be further understood that, although the present invention is described mainly in forms of method and device, the present invention may also be embodied as a computer program product and a system including a computer processor and a memory connected to the processor, where the memory is coded by using one or more programs capable of implementing functions disclosed herein.

Persons skilled in the art should understand that a base station or base station equipment in this text is, for example but not limited to, a Node B or an evolved Node B (eNB) in an LTE system or an LTE-A system, and technical solutions of the present invention are applicable to the LTE system or the LTE-A system, but the present invention is not limited thereto.

A first solution is applicable to a channel in which distribution of directions of arrival (DoA) has a clustering feature. One base station is configured with a linear antenna array having N transmitting antennas, and adopts an orthogonal frequency-division multiplexing (OFDM) system having sub-carriers with the number of N_{FFT}. A wireless multipath channel is formed by P propagation paths, a time of arrival (ToA) of each propagation path is τ_k, a DoA thereof is θ_k, a complex amplitude thereof is β_k (k=1~P). A frequency domain representation of channel response may be represented as

$$\mathbf{h}_j = \sum_{k=1}^{P} \mathbf{a}(\theta_k)\beta_k \exp(-i2\pi(j-1)W\tau_k / N_{FFT}),\ j = 1 \sim N_{FFT} \qquad (1\text{-}1),$$

where, $i=\sqrt{-1}$, $\mathbf{h}_j = [h(1,j)\cdots h(N,j)]^T$ is an N×1 vector, *h(n,j)* represents a channel coefficient of the nth antenna on the jth sub-carrier, W represents a system bandwidth, $\mathbf{a}(\theta_k) = [1, \exp(i2\pi\theta_k), \cdots, \exp(i(N-1)2\pi\theta_k]^T$ represents a steering vector, where $\theta_k = d\sin(\varphi_k)/\lambda = \alpha\sin(\varphi_k)$, φ_k represents a physical arrival angle of the k-th path, d represents a distance between antennas, λ represents a carrier wavelength for transmission, and $\alpha = d/\lambda$. In consideration of all the sub-carriers, the frequency domain channel response may be represented as the following matrix

$$\mathbf{H}=[\mathbf{h}_1\cdots\mathbf{h}_{N_{FFT}}]=\sum_{k=1}^{P}\mathbf{a}(\theta_k)\beta_k\mathbf{f}^H(\tau_k) \quad (1\text{-}2),$$

where,

$$\mathrm{f}(\tau_k)=[1,\exp(i2\pi W\tau_k/N_{FFT}),\cdots,\exp(i2\pi(N_{FFT}-1)W\tau_k/N_{FFT}]^T \quad (1\text{-}3).$$

By quantizing a spatial domain and a time domain into fixed and uniformly separated virtual angles and virtual delays, an expression of a virtual channel may be obtained.

$$\tilde{\theta}_q=-\alpha+\frac{(2q-1)}{2}\cdot\Delta\theta,\ q=1\sim N,\text{ and }\tilde{\tau}_l=(l-1)\cdot\Delta\tau,\ l=1\sim L+1 \quad (1\text{-}4),$$

where, $\tilde{\theta}_q$ and $\tilde{\tau}_l$ respectively represent the qth virtual angle and the lth virtual delay, $\Delta\theta=2\alpha/N$ is an interval between the virtual angels, $\Delta\tau=1/W=\tau_{max}/(L+1)$ is an interval between the virtual delays, and τ_{max} is the maximum delay spread. By using the definition in formula (1-4), the channel model in formula (2) may be converted to a virtual channel model through Fourier transform

$$\mathbf{H}^{(v)}=\mathbf{A}^H\mathbf{H}\mathbf{F}\text{ and }\mathbf{H}=\mathbf{A}\mathbf{H}^{(v)}\mathbf{F}^H \quad (1\text{-}5),$$

where $\mathbf{A}=[\mathbf{a}(\tilde{\theta}_1),\cdots,\mathrm{a}(\tilde{\theta}_N)]/\sqrt{N}$ and $\mathbf{F}=[\mathbf{f}(\tilde{\tau}_1),\cdots,\mathbf{f}(\tilde{\tau}_{L+1})]/\sqrt{N_{FFT}}$. The virtual channel matrix $\mathbf{H}^{(v)}$ is an $N\times(L+1)$ dimensional matrix, where an element located at the qth row and the lth column is represented as $h^{(v)}(q,l)$, which represents a complex amplitude of a virtual path having a delay $\tilde{\tau}_l$ and an angle $\tilde{\theta}_q$. $h^{(v)}(q,l)$ can be represented as

$$h^{(v)}(q,l)=\sum_{k=1}^{P}\beta_k\frac{\mathbf{a}^H(\tilde{\theta}_q)\mathbf{a}(\theta_k)}{\sqrt{N}}\frac{\mathbf{f}^H(\tau_k)\mathbf{f}(\tilde{\tau}_1)}{\sqrt{N_{FFT}}}\approx\sum_{k\in S(q,l)}\beta_k\sqrt{NN_{FFT}},\ q=1\sim N,l=1\sim L+1 \quad (1\text{-}6),$$

where, $S(q,l)$ is a group of transmission paths, and is defined as

$$S(q,l)=\{k|-\Delta\theta/2\le\tilde{\theta}_q-\theta_k<\Delta\theta/2,-\Delta\tau/2\le\tilde{\tau}_l-\tau_k<\Delta\tau/2\} \quad (1\text{-}7).$$

Because the number of the transmission paths is limited, that is, $P<<L+1$ and $P<<N$, and many elements in $S(q,l)$ are zero, the virtual channel matrix $\mathbf{H}^{(v)}$ has a feature of sparse approximation, in which most elements are zero or very close to zero.

$\mathbf{H}^{(v)}$ has sparsity in both the time domain and the spatial domain. Researches show that, the space sparsity of most channels generated by an actual channel model such as a spatial channel model (SCM) is weaker than the time sparsity thereof. Therefore, the performance of a compressive sensing technology used in the DoA detection is poorer than the performance thereof used in the ToA detection. The distribution of the DoAs has a clustering feature, and only a few clusters exist. The whole space of the DoAs is divided into several subspaces, the number of the subspaces is selected appropriately so as to ensure that each DoA cluster is distributed in at most two subspaces, and such subspaces are called active subspaces. The number of the clusters is small, and therefore, the number of the active subspaces is small. The subspace sparsity is quite beneficial to reduction of pilot overhead if it is utilized appropriately. Paths having different ToAs may have different active subspaces. Therefore, in order to increase sparsity of the subspace domain, transmission paths may be grouped according to the different ToAs, and active subspace detection is executed respectively for each group.

Make $S=[S(q,l)]$, and make K represent the number of non-zero rows in S, P transmission paths have K different quantized ToAs (obtained by uniformly quantizing actual ToAs by using granularity $\Delta\tau$). An ordinal number of the non-zero row is represented as

$$L=\{l(k)|k=1\sim K\} \quad (1\text{-}8),$$

where l(k) is the kth quantized ToA. After L is obtained, the channel may be grouped into K groups, and each group includes paths having the same quantized ToA. If the kth group has B_k active subspaces, an ordinal number of the active subspaces in the kth group is represented as

$$B_k=\{b_k(1),...,b_k(B_k)\},\ k=1\text{-}K \quad (1\text{-}9).$$

The following two-stage solution uses the DoA clustering feature to compensate the low sparsity of the spatial domain, so as to reduce the pilot overhead required by the large-scale antenna system. In the first stage, a location of an active subspace $\{B_k,k=1\sim K\}$ is detected; in the second stage, complex amplitudes of all sub-directions in the active subspace are detected. The procedure of the two-stage detection is divided into three parts: time domain ToA detection, spatial domain first-stage detection, and spatial domain second-stage detection.

In the time domain ToA detection, the compressive sensing technology is used to estimate the ToA of the channel. Therefore, pilots are inserted in the frequency domain discontinuously. Through researching, it is found that randomly inserting pilots can better utilize the time domain sparsity, and has more excellent performance as compared with the conventional pilot solution. In the following embodiments, a pilot pattern having a random frequency domain is used for ToA detection. It is assumed that channels corresponding to all antennas have the same ToA, so that during ToA detection, it is only need to send a pilot on one antenna, which means that pilot overhead does not increase along with the increase of the number of the antennas.

The length of a pilot sequence of the ToA detection is represented as $J^{(t)}$, and

$J^{(t)}=\{j^{(t)}(1),\ldots,j^{(t)}(J^{(t)})\}$ represents a set of ordinal numbers of pilot sub-carriers. A public pilot signal is represented as x_p. Without loss of generality, it is assumed that the pilot is sent from the first antenna. A received pilot signal is represented as

$$\vec{Y}^{(t)} = \vec{A}_1 \mathbf{H}^{(v)} \mathbf{F}^{(t)^H} x_p = \vec{H}^{(t-v)} \mathbf{F}^{(t)^H} x_p + \vec{N}^{(t)} \quad (1\text{-}10),$$

where, $\vec{Y}^{(t)}$ is a $1\times J^{(t)}$ vector of the received pilot, $\vec{A}_1$ is the first row of A in formula (1-5), $\mathbf{F}^{(t)}$ is obtained by removing rows in $\mathbf{F}$ that do not belong to $J^{(t)}$, $\vec{H}^{(t-v)} = \vec{A}_1 \mathbf{H}^{(v)}$ is a $1\times(L+1)$ vector, and $\vec{N}^{(t)}$ is Gaussian white noise vector. $\vec{H}^{(t-v)}$ is a sparse vector, and a non-zero element location thereof is L. Formula (1-10) is a typical compressive sensing problem, the non-zero element location of $\vec{H}^{(t-v)}$ can be recovered from $\vec{Y}^{(t)}$ by using various sparse signal recovery algorithms. By using Lasso algorithm as an example, the detection may be represented as

$$\hat{\vec{H}}^{(t-v)} = \arg\min_{\vec{H}^{(t-v)}} \{ \left\| \vec{H}^{(t-v)} \right\|_{l_1} + \delta \left\| \vec{H}^{(t-v)} \mathbf{F}^{(t)^H} x_p - \vec{Y}^{(t)} \right\|_{l_2} \} \quad (1\text{-}11),$$

where, $\hat{\vec{H}}^{(t-v)}$ represents an estimation of $\vec{H}^{(t-v)}$, and δ is a regularization parameter. Then, an estimation of the ToA may be generated by using threshold decision according to the following formula

$$\hat{\mathcal{L}} = \{\hat{l}(k)\} = \left\{ l \left| \left| \hat{\vec{h}}^{(t-v)}(l) \right|^2 > T_{thred}^{(t)} \right. \right\} \quad (1\text{-}12),$$

where, $\hat{\vec{h}}^{(t-v)}(l)$ is the l-th element of $\hat{\vec{H}}^{(t-v)}$, and $T_{thred}^{(t)}$ is a predetermined threshold.

The spatial domain detection is divided into two stages. In the first stage, the base station generates, by using a beamforming matrix, N_{BF} beams directing to N_{BF} subspaces. The beamforming matrix W is constructed by using the following formula

$$\mathbf{W}=\mathbf{BDA}^H \quad (1\text{-}13),$$

where **D** is a diagonal matrix, and **A** is the same as that in formula (5), and

$$\mathbf{B} = \begin{bmatrix} 1\ 1 \cdots 1 & & & 0 \\ & 1\ 1 \cdots 1 & & \\ & & \ddots & \\ 0 & & & 1\ 1 \cdots 1 \end{bmatrix} \quad (1\text{-}14),$$

B is an $N_{BF}\times N$ matrix, in which each row has $N_{DIR}=N/N_{BF}$ "1" (that is, the number of sub-directions in each subspace is N_{DIR}). The base station then sends pilots in the N_{BF} beams in an orthogonal manner. The number of pilots in one beam is represented as $J^{(s1)}$, and a set of ordinal numbers of pilot sub-carriers in the bth beam is represented as $J_b^{(s1)}=\{j_b^{(s1)}(1),\ldots,$

$j_b^{(s1)}(J^{(s1)})\}$, (b=1~N_{BF}). The pilot signal received at the bth beam is

$$\begin{aligned}\vec{Y}_b^{(s1)} &= \vec{W}_b \mathrm{A} \mathrm{H}^{(v)} \mathrm{F}_b^{(s1)^H} x_p + \vec{N}_b^{(s1)} = \vec{B}_b \mathrm{D} \mathrm{A}^H \mathrm{A} \mathrm{H}^{(v)} \mathrm{F}_b^{(s1)^H} x_p + \vec{N}_b^{(s1)} \\ &= \vec{B}_b \mathrm{D} \mathrm{H}^{(v)} \mathrm{F}_b^{(s1)^H} x_p + \vec{N}_b^{(s1)}\end{aligned}, b=1\sim N_{BF} \quad (1\text{-}15),$$

where, $\vec{Y}_b^{(s1)}$ is a $1\times J^{(s1)}$ vector of the pilot received at the bth beam, $\vec{W}_b$ and $\vec{B}_b$ are respectively the b-th rows of **W** and **B**, $\mathbf{F}_b^{(s1)}$ is obtained by removing rows in **F** that do not belong to $J_b^{(s1)}$, and $\vec{N}_b^{(s1)}$ represents Gaussian white noise.

It can be seen from formula (1-15) that, the b-th beam is a weighted linear superposition of all virtual paths in the b subspaces. A diagonal of a matrix D includes a weight coefficient, so that the matrix D can be considered as a weighted matrix. Statistically, only beams in the active subspaces have higher receiving power in a receiver, which allows a user equipment to detect locations of the active subspaces. Multiple weighted matrixes may be used to increase the precision of the detection, which is discussed in the following.

Before detecting the active subspaces, the received pilot is first filtered to leave paths having specific ToAs. The reason of performing the filtering operation is that paths having different ToAs may have different active subspaces, and therefore, extracting the paths having the same ToA through filtering can enhance sparsity of the subspace domain and improve performance of the active subspace detection. A filtering vector $\mathbf{v}_{b,k}$ is constructed as follows

$$\mathrm{v}_{b,k} = \frac{1}{\sqrt{N_{FFT}}} \left[\exp\left\{ -\frac{i2\pi(\ell(k)-1)(j_b^{(s1)}(1)-1)}{N_{FFT}} \right\}, \ldots, \exp\left\{ -\frac{i2\pi(\ell(k)-1)(j_b^{(s1)}(J^{(s1)})-1)}{N_{FFT}} \right\} \right]^H,$$

where b=1~N_{BF}, k=1~K (1-16).

where, $\{l(k)\}$ is replaced with an estimation thereof $\{\hat{\ell}(k)\}$ (generated in formula (1-12). The received pilot signal is multiplied by the filtering vector, so as to obtain the following formula

$$\begin{aligned}y_{b,k} &\equiv \vec{Y}_b^{s1} \mathbf{v}_{b,k} = \vec{B}_b \mathbf{D} \mathbf{H}^{(v)} \mathbf{F}_b^{(s1)^H} \mathbf{v}_{b,k} x_p + \vec{N}_b^{(s1)} \mathbf{v}_{b,k} \\ &= \vec{B}_b \mathbf{D} \mathbf{H}^{(v)} c_k x_p + \vec{B}_b \mathbf{D} \mathbf{H}^{(v)} \mathbf{e}_{b,k} x_p + \vec{N}_b^{(s1)} \mathbf{v}_{b,k}\end{aligned}, b=1\sim N_{BF} \text{ and } k=1\sim K \quad (1\text{-}17),$$

where, $\mathbf{c}_k=[c_k(l)]$ and

$$c_k(l) = \begin{cases} J^{(s1)} / N_{FFT}, & l = \ell(k) \\ 0, & otherwise \end{cases} \quad (1\text{-}18),$$

and $\mathbf{e}_{b,k} = [e_{b,k}(l)]$ represents interference from paths having other ToAs. Inter-path interference is a result of discontinuous insertion of pilots in the frequency domain, and distribution and power of the inter-path interference depend on the pilot pattern. By using a random pilot pattern as an example,

$$e_{b,k}(l)=\begin{cases}0 & if\ l=\ell(k)\\ e, & otherwise\end{cases} \quad (1\text{-}19),$$

where e is a zero mean random variable, and a variance thereof is $J^{(s1)}/N_{FFT}^2$ when $J^{(s1)} \ll N_{FFT}$. Comparing formula (1-18) and formula (1-19), when the random pilot pattern is used, the power of inter-path interference in formula (1-17) is far less than the signal power, and thus can be processed as additional noise. The active subspace may be detected through threshold decision as shown in the following formula

$$\hat{\mathcal{B}}_k=\{\hat{b}(k)\}=\{b\,\|y_{b,k}|^2>T_{thred}^{(s1)}\},k=1\sim K \quad (1\text{-}20),$$

where, $T_{thred}^{(s1)}$ is a predetermined threshold.

If pilots inserted periodically are used, e in formula (1-19) does not have the same distribution for used $l \neq l(k)$, which may be zero for some l, and may be very large for other l, depending on a value of $|l-\ell(k)|$. This means that when pilots are inserted periodically, paths having specific ToAs cannot be separated and must be processed together. Path grouping may require some modification to group the paths that cannot be separated into the same group. Then, the frequency filtering and the active subspace detection technologies described in the above can still be used. For simplicity, unless exception is stated explicitly, the random pilot pattern is used as an example in the following and less important details are ignored.

In order to improve the performance of the active subspace detection, different weighted matrixes may be used to construct multiple beamforming matrixes. The base station use the beamforming matrixes to pre-code pilot signals and send the pre-coded pilot signals in an orthogonal manner. Then, the user equipment receives multiple pilot sequences in each beam, performs the same filtering operation as described above for all the pilot sequences, and averages filtering results before comparison with the threshold.

In the second stage of the spatial domain detection, a precoding matrix is defined as follows

$$\mathbf{P}=(\mathbf{\Phi}\otimes\mathbf{I}_{N_{DIR}})\mathbf{A}^H=\tilde{\mathbf{\Phi}}\mathbf{A}^H \quad (1\text{-}21),$$

where, $\mathbf{\Phi}$ is an $M\times N_{BF}$ dimensional matrix, where elements are independent identically distributed random complex elements, $\mathbf{I}_{N_{DIR}}$ is an $N_{DIR}\times N_{DIR}$ dimensional unit matrix, and $\tilde{\mathbf{\Phi}}$ is an $MN_{DIR}\times N$ dimensional matrix and can be written as

$$\tilde{\Phi} = \Phi \otimes \mathrm{I}_{N_{DIR}} = \begin{bmatrix} \begin{bmatrix} \phi_{1,1} & & 0 \\ & \ddots & \\ 0 & & \phi_{1,1} \end{bmatrix} \cdots \begin{bmatrix} \phi_{1,N_{BF}} & & 0 \\ & \ddots & \\ 0 & & \phi_{1,N_{BF}} \end{bmatrix} \\ \vdots \qquad \ddots \qquad \vdots \\ \begin{bmatrix} \phi_{M,1} & & 0 \\ & \ddots & \\ 0 & & \phi_{M,1} \end{bmatrix} \cdots \begin{bmatrix} \phi_{M,N_{BF}} & & 0 \\ & \ddots & \\ 0 & & \phi_{M,N_{BF}} \end{bmatrix} \end{bmatrix} \qquad (1\text{-}22).$$

The base station use **P** to generate MN_{DIR} pre-coded pilot sequences and sends them in an orthogonal manner. Therefore, totally MN_{DIR} orthogonal pilot sequences are required. In each sub-direction, the base station, the base station sends M weighted pilots in an orthogonal manner. The sub-directions in the same subspace use orthogonal pilot patterns. Different subspaces share the same pilot pattern, so that the pilot signals are superposed. Each subspace corresponds to a beam in the beamforming.

The size of a pilot pattern is represented as $J^{(s2)}$, and a set of sequential numbers of pilot sub-carriers in the mth pilot pattern is represented as $\mathcal{J}_m^{(s2)} = \{ j_m^{(s2)}(1) \cdots j_m^{(s2)}(J^{(s2)}) \}, (m = 1 \sim MN_{DIR})$. A pilot received at the mth pilot pattern is

$$\vec{Y}_m^{(s2)} = \vec{P}_m \mathbf{A} \mathbf{H}^{(v)} \mathbf{F}_m^{(s2)^H} x_p + \vec{N}_m^{(s2)}, m = 1 \sim MN_{DIR} \qquad (1\text{-}23),$$

where, $\vec{Y}_m^{(s2)}$ is a $1 \times J^{(s2)}$ dimensional pilot vector received on the mth pilot pattern, $\vec{P}_m$ is the m row of **P**, $\mathbf{F}_m^{(s2)}$ is obtained by removing rows in **F** that do not belong to $\mathcal{J}_m^{(s2)}$, and $\vec{N}_m^{(s2)}$ is Gaussian white noise. In consideration of all pilot patterns, the received pilot can be written as the following matrix form

$$\mathbf{Y}^{(s2)} = \mathbf{\Psi} \tilde{\mathbf{H}}^{(p)} x_p + \mathbf{N}^{(s2)} \qquad (1\text{-}24),$$

where, Y(s2) is an $MN_{sub} \times J^{(s2)}$ dimensional matrix,

$$\mathbf{\Psi} = \begin{bmatrix} \vec{\tilde{\Phi}}_1 & & & \mathbf{0} \\ & \vec{\tilde{\Phi}}_2 & & \\ & & \ddots & \\ \mathbf{0} & & & \vec{\tilde{\Phi}}_{MN_{DIR}} \end{bmatrix} \qquad (1\text{-}25),$$

where $\vec{\tilde{\Phi}}_m$ is the m-th row of $\tilde{\Phi}$, and

$$\tilde{\mathbf{H}}^{(p)} = [(\mathbf{H}^{(v)} \mathbf{F}_1^{(s2)^H})^T \ (\mathbf{H}^{(v)} \mathbf{F}_2^{(s2)^H})^T \ \cdots \ (\mathbf{H}^{(v)} \mathbf{F}_{MN_{DIR}}^{(s2)\ H})^T]^T \qquad (1\text{-}26).$$

$\mathbf{Y}^{(s2)}$ is superposition of pilots of all subspaces, but only the pilots in the active subspaces have large power. Therefore, pilots in other subspaces may be processed as additional noise. Because paths having different ToAs may have different active subspaces, it is beneficial to process the paths having different active subspaces separately. Therefore, a filtering technology similar to that in the first stage is used to group the paths, so that paths in the same group have the same active subspace. Paths having the same ToA always have the same active subspace, so that the paths are mapped to the same group.

By using that all paths are grouped into G groups as an example, each group includes paths having the same active subspace. A ToA of paths in the g-th (g=1~G) group is represented as

$$L_g=\{l_g(k)\mid k=1\sim K_g\} \quad (1\text{-}27),$$

where, $l_g(k)$ is the k-th ToA in the g-th group, and K_g is the number of ToAs in the g-th group. A sequential number of the active subspace in the gth group is represented as

$$B_g=\{b_g(1)\ldots b_g(B_g)\} \quad (1\text{-}28),$$

where, B_g is the number of active subspaces in the g-th group.

$\mathbf{F}_m^{(s2)}(g)$ is defined as a sub-matrix of $\mathbf{F}_m^{(s2)}$, and is constructed by rows in $\mathbf{F}_m^{(s2)}$ that have row sequential numbers belonging to L_g; $\overline{\mathbf{F}}_m^{(s2)}(g)$ is defined as a sub-matrix of $\mathbf{F}_m^{(s2)}$, and is constructed by rows in $\mathbf{F}_m^{(s2)}$ that have row sequential numbers belonging to L/L_g, where L/L_g represents a subset after L_g is removed from L. $\overline{\mathbf{F}}_m^{(s2)}(g)$ is a $J^{(s2)}\times(K\text{-}K_g)$ matrix. $J^{(s2)}$ is selected so that $J^{(s2)}>K>K\text{-}K_g$. Therefore, a null space of $\overline{\mathrm{F}}_m^{(s2)^H}(g)$ is calculated through singular value decomposition as follows

$$\overline{\mathbf{F}}_m^{(s2)^H}(g)=\mathbf{U}_m(g)\begin{bmatrix}\sum_m(\mathbf{g}) & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}[\mathbf{V}_m(g)\ \ \overline{\mathbf{V}}_m(g)]^H \quad (1\text{-}29),$$

where, $\overline{\mathbf{V}}_m(g)$ is formed by right singular vectors corresponding to zero singular values. $\overline{\mathbf{V}}_m(g)$ is used as a filtering matrix, and paths in the gth group may be extracted as follows

$$\begin{aligned}\vec{Y}_m^{(s2)}(g)&\equiv\vec{Y}_m^{(s2)}\overline{\mathbf{V}}_m(g)=\vec{\bar{\Phi}}_m\mathbf{H}^{(v)}\mathbf{F}_m^{(s2)^H}\overline{\mathbf{V}}_m(g)x_p+\vec{N}_m^{(s2)}\overline{\mathbf{V}}_m(g)\\&=\vec{\bar{\Phi}}_m\mathbf{H}^{(v)}(g)\mathbf{Z}_m(g)x_p+\vec{N}_m^{(s2)}\overline{\mathbf{V}}_m(g)\\&\overset{(a)}{=}\vec{\bar{\Phi}}_m^{(act)}(g)\mathbf{H}^{(v\_act)}(g)\mathbf{Z}_m(g)x_p+\vec{\bar{\Phi}}_m^{(none)}(g)\mathbf{H}^{(v\_none)}(g)\mathbf{Z}_m(g)x_p+\vec{N}_m^{(s2)}\overline{\mathbf{V}}_m(g)\\&=\vec{\bar{\Phi}}_m^{(act)}(g)\mathbf{H}^{(v\_act)}(g)\mathbf{Z}_m(g)x_p+\vec{N}_m^{(s2)}(g)\end{aligned} \quad (1\text{-}30),$$

where, $\mathbf{H}^{(v)}(g)$ is a sub-matrix formed by columns in $\mathbf{H}^{(v)}$ that have column sequential numbers belonging to L_g, $\mathbf{Z}_m(g)=\mathbf{F}_m^{(s2)}(\mathrm{g})^H\overline{\mathbf{V}}_m(g)$, $\vec{\bar{\Phi}}_m^{(act)}(g)$ and $\vec{\bar{\Phi}}_m^{(none)}(g)$

respectively include elements in $\vec{\tilde{\Phi}}_m$ that belong to B_g and do not belong to B_g, $\mathbf{H}^{(v\_act)}(g)$ includes rows in $\mathbf{H}^{(v)}(g)$ that belong to B_g, $\mathbf{H}^{(v\_none)}(g)$ includes rows in $\mathbf{H}^{(v)}(g)$ that do not belong to B_g, and $\vec{N}_m^{(s2)}(g) = \vec{\tilde{\Phi}}_m^{(none)}(g)\mathbf{H}^{(v\_none)}(g)\mathbf{Z}_m(g)x_p + \vec{N}_m^{(s2)}\overline{\mathbf{V}}_m(g)$. When elements in $\mathbf{H}^{(v\_none)}(g)$ has zero power or very low power, the second item in the above formula may be considered as additional noise processing. In practice, $\{B_g, g=1\sim G\}$ is replaced by an estimation value $\{\hat{\mathcal{B}}_g\}$ thereof in the first stage. In consideration of all the pilot patterns, formula (1-30) can be written as the following matrix

$$\mathbf{Y}^{(s2)}(g) \equiv [\vec{Y}_1^{(s2)^T}(g) \cdots \vec{Y}_{MN_{BF}}^{(s2)\ T}(g)]^T = \mathbf{\Psi}^{(act)}\tilde{\mathbf{H}}^{(p)}(g)x_p + \tilde{\mathbf{N}}^{(s2)}(g) \qquad (1\text{-}31),$$

where,

$$\mathbf{\Psi}^{(act)} = \begin{bmatrix} \vec{\tilde{\Phi}}_1^{(act)} & & & 0 \\ & \vec{\tilde{\Phi}}_2^{(act)} & & \\ & & \ddots & \\ 0 & & & \vec{\tilde{\Phi}}_{MN_{DIR}}^{(act)} \end{bmatrix} \qquad (1\text{-}32),$$

and

$$\tilde{\mathbf{H}}^{(p)}(g) = [(\mathbf{H}^{(v\_act)}(g)\mathbf{Z}_1(g))^T \ \ (\mathbf{H}^{(v\_act)}(g)\mathbf{Z}_2(g))^T \ \cdots \ (\mathbf{H}^{(v\_act)}(g)\mathbf{Z}_{MN_{BF}}(g))^T]^T \qquad (1\text{-}33).$$

It is defined that

$$\tilde{\mathbf{H}}(g) \equiv \mathbf{H}^{(v\_act)}(g)\mathbf{F}^H(g), g = 1 \sim \mathrm{G} \qquad (1\text{-}34).$$

$\mathbf{F}(g)$ is formed by columns in $\mathbf{F}$ that have sequential numbers belonging to L_g. It is assumed that $\{\tilde{\mathbf{H}}(g),\ g = 1 \sim G\}$ is known, a complete channel matrix $\mathbf{H}$ may be constructed as follows

$$\mathbf{H} \approx \sum_{g=1}^{G} \mathbf{A}^{(act)}(g)\tilde{\mathbf{H}}(g) = \sum_{g=1}^{G} \mathbf{A}^{(act)}(g)\mathbf{H}^{(v\_act)}(g)\mathbf{F}^H(g) \qquad (1\text{-}35),$$

where, $\mathbf{A}^{(act)}(g)$ is formed by columns in $\mathbf{A}$ that have sequential numbers belonging to B_g. Therefore, it is expected to estimate $\tilde{\mathbf{H}}(g)$ from formula (1-31).

$\{\tilde{\mathbf{H}}(g)\}$ may be detected from $\{\mathbf{Y}^{(s2)}(g)\}$ by using a minimum mean square error (MMSE) technology. Formula (1-31) is rewritten into a vector form as follows

$$\mathrm{y}^{(s2)}(g) = (\Psi^{(act)} \otimes \mathrm{I})\tilde{\mathrm{h}}^{(p)}(g)x_p + \tilde{\mathrm{n}}^{(s2)}(g) \qquad (1\text{-}36),$$

where, $y^{(s2)}(g) = vec(Y^{(s2)^T}(g))$, $\tilde{h}^{(p)}(g) = vec(\tilde{H}^{(p)^T}(g))$ and $\tilde{n}^{(S2)}(g) = vec(\tilde{N}^{(S2)^T}(g))$. It is defined that

$$\mathbf{R}^{(p)}(g) \equiv \mathrm{E}(\tilde{\mathbf{h}}^{(p)}(g)\tilde{\mathbf{h}}^{(p)^H}(g)) \quad (1\text{-}37),$$

and

$$\mathbf{R}(g) \equiv \mathrm{E}(\tilde{\mathbf{h}}(g)\tilde{\mathbf{h}}^{(p)^H}(g)) \quad (1\text{-}38),$$

where $\tilde{\mathbf{h}}(g) = vec(\tilde{\mathbf{H}}(g))$. It can be seen that

$$R^{(p)}(g) = [R^{(p)}_{(m-1)B_g N_{DIR}+s,(m'-1)B_g N_{DIR}+s'}(g)], m, m' = 1 \sim MN_{DIR} \text{ and } s, s' = 1 \sim B_g N_{DIR} \quad (1\text{-}39),$$

where

$$\begin{aligned}\mathbf{R}^{(p)}_{(m-1)B_g N_{DIR}+s,(m'-1)B_g N_{DIR}+s'}(g) &= \mathrm{E}(\overline{\mathbf{V}}_m^T(g)\mathbf{F}_m^{(s2)}{}'(g)\vec{H}_s^{(v\_act)^T}(g)\vec{H}_{s'}^{(v\_act)}{}'(g)\mathbf{F}_{m'}^{(s2)^T}(g)\overline{\mathbf{V}}_{m'}{}'(g)) \\ &\overset{(a)}{=} \begin{cases}\overline{\mathbf{V}}_m^T(g)\mathbf{F}_m^{(s2)}{}'(g)\mathbf{F}_m^{(s2)^T}(g)\overline{\mathbf{V}}_m{}'(g), & \text{if } s = s' \\ 0, & \text{if } s \neq s'\end{cases} \quad (1\text{-}40),\end{aligned}$$

where **A'** represents transposition of the matrix **A**, and (a) derives from an assumption that elements in $\mathbf{H}^{(v)}$ are zero mean independent random variables. Similarly,

$$R(g) = [R_{s'(m-1)B_g N_{DIR}+s}(g)], m = 1 \sim MN_{DIR} \text{ and } s', \ s = 1 \sim B_g N_{DIR} \quad (1\text{-}41),$$

where,

$$\begin{aligned}\mathbf{R}_{s',(m-1)N_{act}N_{sub}+s}(g) &= \mathbf{F}'(g)\vec{H}_{s'}^{(v\_act)^T}(g)\vec{H}_s^{(v\_act)}{}'(g)\mathbf{F}_m^{(s2)^T}(g)\overline{\mathbf{V}}_m{}'(g) \\ &= \begin{cases}\mathbf{F}'(g)\mathbf{F}_s^{(s2)^T}(g)\overline{\mathbf{V}}_m{}'(g), & \text{if } s' = s \\ 0, & \text{if } s' \neq s\end{cases} \quad (1\text{-}42).\end{aligned}$$

The MMSE standard is used, and $\tilde{\mathbf{H}}(g)$ may be estimated as

$$\hat{\tilde{\mathrm{H}}}(g) = \mathrm{R}(g)(\Psi^{(act)} \otimes \mathrm{I})^H \cdot ((\Psi^{(act)} \otimes \mathrm{I})\mathrm{R}^{(p)}(g)(\Psi^{(act)} \otimes \mathrm{I})^H + \Xi(g))^{-1}\mathrm{y}^{(s2)}(g), g = 1 \sim G \quad (1\text{-}43),$$

where,

$$\Xi(g) = \mathrm{E}(\tilde{\mathbf{n}}^{(s2)}(g)\tilde{\mathbf{n}}^{(s2)^H}(g)) \quad (1\text{-}44).$$

Finally, a complete channel matrix is constructed as the following formula

$$\hat{\mathbf{H}} = \sum_{g=1}^{G} \mathbf{A}^{(act)}(g)\hat{\tilde{\mathbf{H}}}(g) \quad (1\text{-}45).$$

FIG. 1 is a flowchart of a method 110 used in a base station having N transmitting antennas in a MIMO system according to an embodiment of the present invention; FIG. 2 is a flowchart of a method 120 used in a user equipment in a MIMO system according to an embodiment of the present invention. The method 110 is used for sending pilot signals of an N-antenna base station, and the method 120 is used for channel detection corresponding to the pilot signals sent in the method 110. As shown in the drawings, the method 110 includes steps 111, 112 and 113, and the method 120 includes steps 121, 122, 123, 124 and 125.

As shown in formula (1-2), the frequency response **H** of all sub-carriers in the MIMO system may be represented as an $N \times N_{FFT}$ dimensional matrix, where the number of rows N is the number of base station antennas, and the number of columns N_{FFT} is the number of the sub-carriers. By means of matrix transform through uniformly quantized virtual angles and virtual delays, a virtual channel matrix $\mathbf{H}^{(v)}$ is obtained from the actual frequency response **H**, and $\mathbf{H}^{(v)}$ is about an N×(L+1) dimensional matrix, where the number of rows corresponds to the number of time domain samples. $\mathbf{H}^{(v)}$ has sparsity in both the time domain and the spatial domain, and therefore, less pilots are required. In step 111, the base station determines N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns. When the number of antennas N is large, for example but not limited to, N is 30, 50, 80, 100, generally speaking, when N is greater than or equal to 16, the number N_{BF} of pilot patterns may be 10%~15% of N, M may be 15%~50% of N, so as to ensure desirable, at least equivalent channel detection performance. The degree of freedom of channel is not linearly increased along with the number of antennas, and correspondingly, the increase amplitude of the number of required pilot signals is less than the increase amplitude of the number of antennas. When the number of base station antennas is 50, N_{BF} may be 15% of the number of antennas, and M may be 30%~50% of the number of antennas; when the number of base station antennas is 100, N may be approximately 10% of the number of antennas, and M may be 15%~30% of the number of antennas.

In step 112, the base station performs beamforming on N_{BF} subspaces, and sends a pilot signal on each beam, where pilot signals on the beams of the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns. Here, the beamforming uses, for example, a forming matrix shown in formula (1-13). Division of subspaces and selection of the number of subspaces preferably enable each cluster of propagation paths to distribute in as least as possible subspaces, for example, each cluster is distributed in two subspaces.

In step 113, the base station sends the pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas in a manner that sub-directions in each subspace use orthogonal pilot patterns. Here, the signal sending uses, for example, the precoding matrixes shown in formula (1-21) and formula (1-22).

In step 121, a user equipment receives pilot signals on N_{BF} beams from N transmitting antennas of a base station. The received signal is represented by, for example, formula (1-15).

In step 122, the user equipment determines, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, locations of times of arrival of effective elements of a virtual channel matrix. The available recovery algorithm is, for example but not limited to, a Lasso algorithm, for example, formula (1-11) represents estimations of elements in a virtual channel, and formula (1-12) represents decision on the effective elements. The so-called effective elements refer to elements having large amplitudes, and a decision threshold may be determined according to an empirical value of a local channel.

In step 123, the user equipment separates components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determines, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong. Specifically, the received pilot signals are multiplied by a filtering vector shown in, for example, formula (1-16) so as to separate the components having specific times of arrival, and the active subspaces to which the effective elements of the virtual channel matrix belong are determined by using the threshold decision represented by formula (1-20). The active subspace is a subspace including elements having large amplitudes. The decision threshold may be determined according to the empirical value of the local channel.

In step 124, the user equipment receives pilot signals over M pilot patterns from the N transmitting antennas of the base station. Step 124 and steps 122 and 123 do not have a fixed sequence. A received signal is represented by, for example, formula (1-24).

In step 125, the user equipment separates components belonging to the specific active subspaces from the pilot signals received from the M pilot patterns, and recovers, from the separated components, a channel response matrix corresponding to the active subspaces. The received pilot signals are represented as forms shown in, for example, formula (1-23) and formula (1-24). By using the form shown in, for example, formula (1-30), the received pilot signals are multiplied by a filtering vector shown in, for example, formula (1-29), so as to separate the components belonging to the specific active subspaces. Then, by means of the minimum mean square error standard, an estimation of a channel matrix of each active subspace represented by, for example, formula (1-43) may be obtained. Therefore, a complete estimation $\hat{\mathbf{H}}$ of an actual channel matrix can be obtained.

FIG. 5 is a structural diagram of a device 50 used in a base station having N transmitting antennas in a MIMO system according to an embodiment of the present invention; FIG. 6 is a structural diagram of a device 60 used in a user equipment in a MIMO system according to an embodiment of the present invention. The device 50 is used for sending pilot signals of an N-antenna base station, and the device 60 is used for channel detection corresponding to the pilot signals sent by the device 50. As shown in the drawings, the device 50 includes a first device 51, a second device 52, and a third device 53. The device 50 is generally configured in a base station. The device 60 is generally configured in a user equipment, and includes a receiving device 61, a time of arrival detecting device 62, a subspace detecting device 63, and a channel recovering device 64.

As shown in formula (1-2), the frequency response **H** of all sub-carriers in the MIMO system may be represented as an $N \times N_{FFT}$ dimensional matrix, where the number of rows N is the number of base station antennas, and the number of columns N_{FFT} is the number of the sub-carriers. By means of matrix transform through uniformly quantized virtual angles and virtual delays, a virtual channel matrix $\mathbf{H}^{(v)}$ is obtained from the actual frequency response **H**, and $\mathbf{H}^{(v)}$ is an N×(L+1) dimensional matrix, where the number of rows corresponds to the number of time domain samples. $\mathbf{H}^{(v)}$ has sparsity in both the time domain and the spatial domain, and therefore, less pilots are required. The first device 51 is configured to determine N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns. When the number of antennas N is large, for example but not limited to, N is 30, 50, 80, 100, generally speaking, when N is greater than or equal to 16, the number N_{BF} of pilot patterns may be 10%~15% of N, M may be 15%~50% of N, so as to ensure desirable, at least equivalent channel detection performance. The degree of freedom of channel is not linearly increased along with the number of antennas, and correspondingly, the increase amplitude of the number of required pilot signals is less than the increase amplitude of the number of antennas. When the number of base station antennas is 50, N_{BF} may be 15% of the number of antennas, and M may be 30%~50% of the number of antennas; when the number of base station antennas is 100, N may be approximately 10% of the number of antennas, and M may be 15%~30% of the number of antennas.

The second device 52 is configured to perform beamforming on N_{BF} subspaces, and send a pilot signal on each beam, where pilot signals on the beams of the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns. Here, the beamforming uses, for example, a forming matrix shown in formula (1-13). Division of subspaces and selection of the number of subspaces preferably enable each cluster of propagation paths to distribute in as least as possible subspaces, for example, each cluster is distributed in two subspaces.

The third device 53 is configured to send the pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas in a manner that sub-directions in each subspace use orthogonal pilot patterns. Here, the signal sending uses, for example, the precoding matrixes shown in formula (1-21) and formula (1-22).

The receiving device 61 is configured to receive pilot signals on N_{BF} beams from N transmitting antennas of a base station, and receive pilot signals over M pilot patterns from the N transmitting antennas. The received signal is represented by, for example, formula (1-

15).

The time of arrival detecting device 62 is configured to determine, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, locations of times of arrival of effective elements of a virtual channel matrix. The available recovery algorithm is, for example but not limited to, a Lasso algorithm, for example, formula (1-11) represents estimations of elements in a virtual channel, and formula (1-12) represents decision on the effective elements. The so-called effective elements refer to elements having large amplitudes, and a decision threshold may be determined according to an empirical value of a local channel.

The subspace detecting device 63 is configured to separate components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determine, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong. Specifically, the received pilot signals are multiplied by a filtering vector shown in, for example, formula (1-16) so as to separate the components having specific times of arrival, and the active subspaces to which the effective elements of the virtual channel matrix belong are determined by using the threshold decision represented by formula (1-20). The active subspace is a subspace including elements having large amplitudes. The decision threshold may be determined according to the empirical value of the local channel.

The channel recovering device 64 is configured to separate components belonging to the specific active subspaces from the pilot signals received from the M pilot patterns, and recover, from the separated components, a channel response matrix corresponding to the active subspaces. The received pilot signals are represented as forms shown in, for example, formula (1-23) and formula (1-24). By using the form shown in, for example, formula (1-30), the received pilot signals are multiplied by a filtering vector shown in, for example, formula (1-29), so as to separate the components belonging to the specific active subspaces. Then, by means of the minimum mean square error standard, an estimation of a channel matrix of each active subspace represented by, for example, formula (1-43) may be obtained. Therefore, a complete estimation $\hat{\mathbf{H}}$ of an actual channel matrix can be obtained.

A second solution is applicable to a general channel model. One base station is configured with a linear antenna array having N transmitting antennas, and adopts an OFDM system having sub-carriers with the number of N_{FFT}. A wireless multipath channel is formed by K transmission paths, a ToA of each propagation path is τ_k, a DoA thereof is θ_k, a complex amplitude thereof is β_k (k=1~K). A channel model is shown by formula (1-1) to formula (1-7). It is defined that

$$\mathcal{D} = \{(q,l) | \mathcal{S}(q,l) \neq \phi\} \quad (2\text{-}8).$$

$\mathbf{H}^{(v)}$ has major elements (elements having large amplitudes) only at a location of $\mathcal{D}$.

Paths having close times in the multipath channel generally have different directions of arrival (paths having the same ToA and the same DoA may be considered as the same path), and therefore, the transmission paths may be grouped, and each group includes paths having a specific ToA. Such grouping is beneficial to DoA detection. By using grouping all K transmission paths into $K^{(t)}$ time groups as an example, that is, $K^{(t)}$ different quantized TOAs exist in the multipath channel. The number of paths included in the k_t th group is represented as $K_{k_t}^{(s)}$. The following two definitions are used to describe channels after time domain grouping.

$$\mathcal{L} \equiv \{l | \text{there exists any } 1 \leq q \leq \tilde{N} \text{ such that } \mathcal{S}(q,l) \neq \phi\} = \{\ell(k_t) | k_t = 1 \sim K^{(t)}\} \quad (2\text{-}9),$$

and

$$\mathcal{Q}_{k_t} \equiv \{q | \mathcal{S}(q, \ell(k_t)) \neq \phi\} = \{q_{k_t}(k_s) | k_s = 1 \sim K^{(s)}\} \quad (2\text{-}10),$$

where, $\mathcal{L}$ represents $K^{(t)}$ different quantized ToAs, and $\mathcal{Q}_{k_t}$ represents $K_{k_t}^{(s)}$ different quantized DoAs in the k_t th group.

Pilot sending: The base station and the user equipment share an M×N projection matrix S=[$s(m,n)$], where M<<N. M orthogonal pilot patterns are generated randomly in a frequency domain. Each antenna uses a specific column in S to weight the pilot signal, and M weighted pilot sequences are sent over the M pilot patterns. In each pilot pattern, pilots from different antennas superpose spatially. M pilot patterns having the same size is used as an example. $\mathcal{F}_m = \{j_m(1) \cdots j_m(J)\}$ represents a set of sub-carrier sequential numbers in the m-th pilot pattern. Therefore, a signal in each pilot pattern received by a receiver may be represented as

$$\vec{Z}_m = \vec{S}_m \tilde{\mathbf{H}}_m p + \vec{\Xi}_m \quad (2\text{-}11),$$

where, $\vec{Z}_m$ is a 1×J dimensional signal vector received in the mth pilot pattern, $\vec{S}_m$ is the m-th row of **S**, and $\vec{\Xi}_m$ is a 1×J dimensional Gaussian white noise vector. In formula (2-11), $\tilde{\mathbf{H}}_m$ represents a channel coefficient experienced by the signal sent in the *m*th pilot pattern, which is constructed by columns in **H** that have ordinal numbers belonging to $\mathcal{F}_m$, that is

$$\tilde{\mathbf{H}}_m = [\mathbf{h}_{j_m(1)} \cdots \mathbf{h}_{j_m(J)}] \quad (2\text{-}12),$$

each $\vec{Z}_m$ is divided by a pilot signal p, so as to obtain

$$\vec{Y}_m \equiv \vec{Z}_m / p = \vec{S}_m \tilde{\mathbf{H}}_m + \vec{N}_m \quad (2\text{-}13),$$

where, $\vec{N}_m = \vec{\Xi}/p$. Formula (1-5) and formula (2-13) are combined to obtain

$$\vec{Y}_m = \vec{S}_m \mathbf{A}\mathbf{H}^{(v)} \tilde{\mathbf{F}}_m^H + \vec{N}_m \quad (2\text{-}14),$$

where, $\tilde{\mathbf{F}}_m$ is a J×(L+1) dimensional matrix constructed by rows in $\mathbf{F}$ that have ordinal numbers belonging to $\mathcal{F}_m$.

Channel detection: Represent $\overline{\mathbf{h}}^{(v)} = vec(\mathbf{H}^{(v)})$. It can be seen from formula (2-14) that $\vec{Y}_m$ is a linear measurement value of $\overline{\mathbf{h}}^{(v)}$ provided with noise, and

$$\vec{Y}_m^T = (\tilde{\mathbf{F}}_m^* \otimes (\vec{S}_m \mathbf{A}))\overline{\mathbf{h}}^{(v)} + \vec{N}_m^T \quad (2\text{-}15),$$

where, ()* represents conjugation, $()^T$ represents transformation, and ⊗ represents a Kronecker product. Signals received in used pilot patterns are used to form a matrix, so as to obtain

$$\overline{\mathbf{y}} = \mathbf{B}\overline{\mathbf{h}}^{(v)} + \overline{\mathbf{n}} \quad (2\text{-}16),$$

where, $\overline{\mathrm{y}} = [\vec{Y}_1 \cdots \vec{Y}_M]^T$, $\mathrm{B} = [(\tilde{\mathrm{F}}_1^* \otimes (\vec{S}_1 \mathrm{A}))^T \cdots (\tilde{\mathrm{F}}_M^* \otimes (\vec{S}_M \mathrm{A}))^T]^T$, $\overline{\mathrm{n}} = [\vec{N}_1 \cdots \vec{Y}_M]^T$. Various sparse signal recovery algorithms may be used to estimate $\overline{\mathbf{h}}^{(v)}$ from $\overline{\mathbf{y}}$. The length of $\overline{\mathbf{h}}^{(v)}$, that is, $\tilde{N}(L+1)$, is generally large, and complexity of calculation is very high. Detecting ToA and DoA respectively greatly reduces the complexity of calculation.

ToA estimation: The virtual channel matrix $\boldsymbol{H}^{(v)}$ is transformed into time or spatial information including channel only. It is defined that

$$\vec{H}_m^{(t)} \equiv \vec{S}_m \mathbf{A}\mathbf{H}^{(v)} \quad (2\text{-}17).$$

$\vec{H}_m^{(t)}$ is a 1×(L+1) dimensional vector, and only keeps the time information of channel. The vector is approximate to sparse, and major elements having large amplitudes correspond to $K^{(t)}$ different quantized ToAs. Therefore, an effective support (a location of an element having a large amplitude) of $\vec{H}_m^{(t)}$ is $\mathcal{L}$. Formula (2-17) is substituted in formula (2-14), and the received signal may be written as

$$\vec{Y}_m = \vec{H}_m^{(t)} \tilde{\mathbf{F}}_m^H + \vec{N}_m \quad (2\text{-}18).$$

$\vec{Y}_m$ is a linear measurement value of $\vec{H}_m^{(t)}$ provided with noise, and various sparse signal recovery algorithms may be used to recover $\vec{H}_m^{(t)}$ from $\vec{Y}_m$. In addition, $\{\vec{H}_m^{(t)}, m = 1 \sim M\}$ sharing the same support L may be used to further enhance the detection. By using a joint Lasso algorithm as an example, the detection can be executed to solve the following optimization problem.

$$\{\hat{\vec{H}}_m^{(t)}\} = \arg\min_{\{\vec{H}_m^{(t)}\}} \left\{ \sum_{l=1}^{L+1} \sqrt{\sum_m \left|\vec{h}_m^{(t)}(l)\right|^2} + \mu \sum_{m=1}^{M} \left\| \vec{H}_m^{(t)} \tilde{\mathbf{F}}_m^H - \vec{Y}_m \right\|_{l_2} \right\} \quad (2\text{-}19),$$

where, $\{\hat{\vec{H}}_m^{(t)}\}$ represents an estimation of $\{\vec{H}_m^{(t)}\}$, $\vec{h}_m^{(t)}(l)$ is the lth element of $\vec{H}_m^{(t)}$, and μ is a regularization parameter. Random pilot patterns can reduce pilot overhead of precise ToA detection. Therefore, the ToA detection may be achieved through the following threshold decision

$$\{\hat{\ell}(k_t)\} = \left\{ l \left| \frac{1}{M} \sum_{m=1}^{M} \left| \hat{\vec{h}}_m^{(t)}(l) \right|^2 > T_{thred}^{(t)} \right. \right\} \quad (2\text{-}20),$$

where, $\hat{\vec{h}}_m^{(t)}(l)$ is the lth element of $\hat{\vec{H}}_m^{(t)}$, and $T_{thred}^{(t)}$ is a threshold. The size of $\{\hat{\ell}(k_t)\}$ is marked as $\hat{K}^{(t)}$, so as to represent the number of estimations of different ToA $K^{(t)}$.

DoA estimation: Similar to formula (2-17), the virtual channel matrix may be transformed to include spatial information only. Therefore, a J×1 dimensional filtering vector $\mathbf{v}_m$ is introduced, and it is defined that

$$\mathbf{h}^{(s)} \equiv \mathbf{H}^{(v)} \tilde{\mathbf{F}}_m^H \mathbf{v}_m \quad (2\text{-}21).$$

$\mathbf{h}^{(s)}$ only keeps the spatial information of the channel, is approximately sparse, and has major elements corresponding to different quantized DoAs of the multipath channel. Because spatial sparsity of each group after the time domain grouping is increased, a filter $\mathbf{v}_m$ may be designed to enable $\mathbf{h}^{(s)}$ to keep paths corresponding to a certain ToA. Therefore, a filter $\mathbf{v}_{m,k_t}$ of the k_tth group is constructed as follows

$$\mathbf{v}_{m,k_t} = \left[\exp\left\{ -\frac{\iota 2\pi(\ell(k_t)-1)(j_m(1)-1)}{N_{FFT}} \right\}, \cdots, \exp\left\{ -\frac{\iota 2\pi(\ell(k_t)-1)(j_m(J)-1)}{N_{FFT}} \right\} \right]^T \Big/ \sqrt{N_{FFT}},$$

$$k_t = 1 \sim K \quad (2\text{-}22).$$

In actual detection, $\{\ell(k_t)\}$ is replaced by the estimation value in formula (2-20). It can be seen that

$$\tilde{\mathbf{F}}_m^H \mathbf{v}_{m,k_t} = \mathbf{c}_{k_t} + \mathbf{e}_{m,k_t} \quad (2\text{-}23),$$

where, $c_{k_t} = [c_{k_t}(l)]$ and

$$c_{k_t}(l) = \begin{cases} J/N_{FFT}, & l = \ell(k_t) \\ 0, & other \end{cases} \quad (2\text{-}24),$$

$\mathbf{e}_{m,k_t} = [e_{m,k_t}(l)]$ and $e_{m,k_t}(\ell(k_t)) = 0$. For $l \neq \ell(k_t)$, $e_{m,k_t}(l)$ is a zero mean random variable, and a variance thereof depends on the pilot pattern. For example, when the pilot patterns are generated randomly in the frequency domain, if $J \ll N_{FFT}$, a variance of a random element in $\mathbf{e}_{m,k_t}$ is J/N_{FFT}^2. It can be seen that another benefit of the random pilot patterns is random inter-path interference. $\mathbf{v}_{m,k_t}$ is multiplied with $\vec{Y}_m$ rightward, so as to obtain

$$\vec{\mathbf{y}}_{k_t}(m) \equiv \vec{Y}_m \mathbf{v}_{m,k_t} = \vec{S}_m \mathbf{A}\mathbf{H}^{(v)}\tilde{\mathbf{F}}_m^H \mathbf{v}_{m,k_t} + \vec{N}_m \mathbf{v}_{m,k_t} = \vec{S}_m \mathbf{A}\mathbf{H}^{(v)}(\mathbf{c}_{k_t} + \mathbf{e}_{m,k_t}) + \vec{N}_m \mathbf{v}_{m,k_t} = \vec{S}_m \mathbf{A}\mathbf{h}_{k_t}^{(s)} + \eta_{k_t}(m) \quad (2\text{-}25),$$

where

$$\hat{\mathbf{h}}_{k_t}^{(s)} \equiv \mathbf{H}^{(v)}\mathbf{c}_{k_t} \quad (2\text{-}26).$$

$\mathbf{h}_{k_t}^{(s)}$ is an approximately sparse vector, and major elements thereof correspond to quantized DoAs in the ktth group, and

$$\eta_{k_t}(m) = \vec{S}_m \mathbf{A}\mathbf{H}^{(v)}\mathbf{e}_{m,k_t} + \vec{N}_m \mathbf{v}_{m,k_t} \quad (2\text{-}27).$$

$\eta_{k_t}(m)$ can be considered as additional noise. $\{\vec{y}_{k_t}(m), \forall m\}$ is used to form a vector, so as to obtain

$$\vec{\mathbf{y}}_{k_t} \equiv [\vec{y}_{k_t}(1) \cdots \vec{y}_{k_t}(M)]^T = \mathbf{S}\mathbf{A}\mathbf{h}_{k_t}^{(s)} + \boldsymbol{\eta}_{k_t}, k_t = 1 \sim K^{(t)} \quad (2\text{-}28),$$

where, $\boldsymbol{\eta}_{k_t} \equiv [\eta_{k_t}(1) \cdots \eta_{k_t}(M)]^T$. Therefore, various sparse signal recovery algorithms may be used to recover $\mathbf{h}_{k_t}^{(s)}$ from $\vec{\mathbf{y}}_{k_t}$. By using the Lasso algorithm as an example, it is obtained that

$$\hat{\mathbf{h}}_{k_t}^{(s)} = \arg\min_{\mathbf{h}^{(s)}} \{ \| \mathbf{h}^{(s)} \|_{l_1} + \lambda \| \mathbf{S}\mathbf{A}\mathbf{h}^{(s)} - \vec{\mathbf{y}}_{k_t} \|_{l_2} \} \quad (2\text{-}29),$$

where, $\hat{\mathbf{h}}_{k_t}^{(s)}$ represents an estimation of $\mathbf{h}_{k_t}^{(s)}$. Therefore, the estimation of DoA may be obtained through the following threshold decision

$$\{\hat{q}_{k_t}(k_s)\} = \left\{ q \middle| \left| \hat{h}_{k_t}^{(s)}(q) \right|^2 > T_{thred}^{(s)} \right\}, k_t = 1 \sim K^{(t)} \quad (2\text{-}30),$$

where, $\hat{h}_{k_t}^{(s)}(q)$ is the qth element of $\hat{\mathbf{h}}_{k_t}^{(s)}$, and $T_{thred}^{(s)}$ is a threshold. The size of $\{\hat{q}(k_s)\}$ is marked as $\hat{K}_{k_t}^{(s)}$, so as to represent the number of estimations of different DOA $K_{k_t}^{(s)}$ in the k_tth group.

Therefore, based on detection results of ToA and DOA, the minimum mean square error detection is executed on formula (2-16) so as to obtain a complete estimation of the virtual channel matrix. It is defined that

$$\hat{\mathcal{D}} = \{(\hat{q}_1(k_s), \hat{\ell}(1)) \big| k_s = 1 \sim \hat{K}_1^{(s)}\} \cup \cdots \cup \{\hat{q}_{\hat{K}^{(t)}}(k_s), \hat{\ell}(\hat{K}^{(t)})) \big| k_s = 1 \sim \hat{K}_{\hat{K}^{(t)}}^{(s)}\} \quad (2\text{-}31).$$

$\hat{\mathcal{D}}$ is an estimation of $\mathcal{D}$ in formula (8). It is assumed that the virtual channel matrix $\mathbf{H}^{(v)}$ has a non-zero value only at the location in $\hat{\mathcal{D}}$. $\{(\hat{q}_k,\hat{l}_k),k=1\sim\hat{K}\}$ represents elements of $\hat{\mathcal{D}}$, and $\hat{K}=\sum_{k_t=1}^{\hat{K}^{(t)}}\hat{K}^{(s)}_{K_t}$ represents an estimation value of K. therefore, a virtual channel vector $\overline{\mathbf{h}}^{(v)}$ has a non-zero value only at a location in $\{(\hat{l}_k-1)\tilde{N}+\hat{q}_k,k=1\sim\hat{K}\}$. Zero elements in $\overline{\mathbf{h}}^{(v)}$ are removed, and formula (2-16) is transformed to

$$\overline{y}=\mathbf{B}_{\hat{\mathcal{D}}}\overline{\mathbf{h}}^{(v)}_{\hat{\mathcal{D}}}+\overline{\mathbf{n}} \quad (2\text{-}32),$$

where, $\overline{\mathbf{h}}^{(v)}_{\hat{\mathcal{D}}}$ is obtained by removing elements in $\overline{\mathbf{h}}^{(v)}$ that have ordinal numbers not belonging to $\{(\hat{l}_k-1)\tilde{N}+\hat{q}_k,k=1\sim\hat{K}\}$, and $\mathbf{B}_{\hat{\mathcal{D}}}$ is obtained by removing columns in $\mathbf{B}$ that have ordinal numbers not belonging to $\{(\hat{l}_k-1)\tilde{N}+\hat{q}_k,k=1\sim\hat{K}\}$. The minimum mean square error processing is executed for formula (2-32), so as to obtain

$$\hat{\overline{\mathbf{h}}}^{(v)}_{\hat{\mathcal{D}}}=\mathbf{B}^{H}_{\hat{\mathcal{D}}}(\mathbf{B}_{\hat{\mathcal{D}}}\mathbf{B}^{H}_{\hat{\mathcal{D}}}+\sigma^2\mathbf{I})^{-1} \quad (2\text{-}33),$$

where, $\hat{\overline{\mathbf{h}}}^{(v)}_{\hat{\mathcal{D}}}$ is an estimation of $\overline{\mathbf{h}}^{(v)}_{\hat{\mathcal{D}}}$, and σ^2 is noise power. Elements of $\hat{\overline{\mathbf{h}}}^{(v)}_{\hat{\mathcal{D}}}$ are mapped into suitable locations to form the estimation of $\mathbf{H}^{(v)}$ as shown in the following formula, which is marked as $\hat{\mathbf{H}}^{(v)}=[\hat{h}^{(v)}(q,l)]$,

$$\hat{h}^{(v)}(q,l)=\begin{cases}\hat{\overline{h}}^{(v)}_{\hat{\mathcal{D}}}(k) & (q,l)\in\hat{\mathcal{D}}\text{ and }(q,l)=(\hat{q}_k,\hat{l}_k)\\ 0, & (q,l)\notin\hat{\mathcal{D}}\end{cases} \quad (2\text{-}34).$$

Then, an estimation of a(n) (actual) physical channel matrix $\mathbf{H}$ may be obtained through transformation by using formula (1-5).

FIG. 3 is a flowchart of a method 310 used in a base station having N transmitting antennas in a MIMO system according to an embodiment of the present invention; FIG. 4 is a flowchart of a method 320 used in a user equipment in a MIMO system according to an embodiment of the present invention. The method 310 is used for sending pilot signals of an N-antenna base station, and the method 320 is used for channel detection corresponding to the pilot signals sent in the method 310. As shown in the drawings, the method 310 includes steps 311 and 312, and the method 320 includes steps 321, 322 and 323.

As shown in formula (1-2), the frequency response $\mathbf{H}$ of all sub-carriers in the MIMO system may be represented as an $N\times N_{FFT}$ dimensional matrix, where the number of rows N is the number of base station antennas, and the number of columns N_{FFT} is the number of the sub-carriers. By means of matrix transform through uniformly quantized virtual angles and virtual delays, a virtual channel matrix $\mathbf{H}^{(v)}$ is obtained from the actual frequency response $\mathbf{H}$, and $\mathbf{H}^{(v)}$ is an N×(L+1) dimensional matrix, where the number of rows corresponds to the number of time domain samples. $\mathbf{H}^{(v)}$ has sparsity in both the time domain and the spatial domain, and therefore, less pilots are required. In step 311, the base station determines M orthogonal pilot patterns. When the number of antennas N is large, for example but not limited to, N is 30, 50, 80, 100, generally speaking, when N is greater than or equal to 16, the number N_{BF} of pilot patterns may be 10%~15% of N, M may be 15%~50% of N, so as to ensure desirable, at least equivalent channel detection performance. The degree of freedom of channel is not linearly increased along with the number of antennas, and correspondingly, the increase amplitude of the number of required pilot signals is less than the increase amplitude of the number of antennas. When the number of base station antennas is 50, N_{BF} may be 15% of the number of antennas, and M may be 30%~50% of the number of antennas; when the number of base station antennas is 100, N may be approximately 10% of the number of antennas, and M may be 15%~30% of the number of antennas.

In step 312, the base station sends pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas.

In step 321, the user equipment receives pilot signals from the N transmitting antennas of the base station. The received signals are represented by, for example, formula (2-13) and formula (2-14).

In step 322, the user equipment determines, by using a sparse signal recovery algorithm from the received pilot signal, locations of times of arrival of effective elements of a virtual channel matrix. Specifically, for example, by using formula (2-17), the virtual channel matrix is transformed to a form only keeping time information of the channel. Then, a sparse signal recovery algorithm such as a joint Lasso algorithm is used to obtain an estimation of a virtual channel matrix variation only keeping the time information, as represented by formula (2-19). Threshold decision represented by, for example, formula (2-20), is used to determine locations of the times of arrivals of the effective elements in the virtual channel matrix. The so-called effective elements refer to elements having large amplitudes, and a decision threshold may be determined according to an empirical value of a local channel.

In step 323, the user equipment separates components having specific times of arrival from the received pilot signals, and determines, from the separated components, directions of arrivals of the effective elements of the virtual channel matrix. Specifically, a filtering vector in a form represented by, for example, formula (2-22) is used to separate the components having specific times of arrival in a form shown in, for example, formula (2-25). Then, a sparse signal recovery algorithm such as the Lasso algorithm may be used to obtain the estimation of the virtual channel matrix variation only keeping the spatial information as represented by, for example, formula (2-29). The threshold decision represented by, for example, formula (2-30) is used to determine the locations of the directions of arrival of the effective elements in the virtual channel matrix.

Then, the minimum mean square standard shown in, for example, formula (2-16), is used to obtain the estimation of the virtual channel matrix. The estimation of the actual channel matrix may be obtained after the matrix transformation.

FIG. 7 is a structural diagram of a device 70 used in a base station having N transmitting antennas in a MIMO system according to an embodiment of the present invention; FIG. 8 is a structural diagram of a device 80 used in a user equipment in a MIMO system according to an embodiment of the present invention. The device 70 is used for sending pilot signals of an N-antenna base station, and the device 80 is used for channel detection corresponding to the pilot signals sent by the device 70. As shown in the drawings, the device 70 includes a first device 71 and a second device 72. The device 70 is generally configured in a base station. The device 80 is generally configured in a user equipment, and includes a receiving device 81, a time of arrival detecting device 82, and a direction of arrival detecting device 83.

As shown in formula (1-2), the frequency response $\mathbf{H}$ of all sub-carriers in the MIMO system may be represented as an $N \times N_{FFT}$ dimensional matrix, where the number of rows N is the number of base station antennas, and the number of columns N_{FFT} is the number of the sub-carriers. By means of matrix transform through uniformly quantized virtual angles and virtual delays, a virtual channel matrix $\mathbf{H}^{(v)}$ is obtained from the actual frequency response $\mathbf{H}$, and $\mathbf{H}^{(v)}$ is an N×(L+1) dimensional matrix, where the number of rows corresponds to the number of time domain samples. $\mathbf{H}^{(v)}$ has sparsity in both the time domain and the spatial domain, and therefore, less pilots are required. The first device 71 is configured to determine N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns. When the number of antennas N is large, for example but not limited to, N is 30, 50, 80, 100, generally speaking, when N is greater than or equal to 16, the number N_{BF} of pilot patterns may be 10%~15% of N, M may be 15%~50% of N, so as to ensure desirable, at least equivalent channel detection performance. The degree of freedom of channel is not linearly increased along with the number of antennas, and correspondingly, the increase amplitude of the number of required pilot signals is less than the increase amplitude of the number of antennas. When the number of base station antennas is 50, N_{BF} may be 15% of the number of antennas, and M may be 30%~50% of the number of antennas; when the number of base station antennas is 100, N may be approximately 10% of the number of antennas, and M may be 15%~30% of the number of antennas.

The second device 72 is configured to send pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas.

The receiving device 81 is configured to receive pilot signals from the N transmitting antennas of the base station. The received signals are represented by, for example, formula (2-13) and formula (2-14).

The time of arrival detecting device 82 is configured to determine, by using a sparse signal recovery algorithm from the received pilot signal, locations of times of arrival of effective elements of a virtual channel matrix. Specifically, for example, by using formula (2-17), the virtual channel matrix is transformed to a form only keeping time information of the channel. Then, a sparse signal recovery algorithm such as a joint Lasso algorithm is used to obtain an estimation of a virtual channel matrix variation only keeping the time information, as represented by formula (2-19). Threshold decision represented by, for example, formula (2-20), is used to determine locations of the times of arrivals of the effective elements in the virtual channel matrix. The so-called effective elements refer to elements having large amplitudes, and a decision threshold may be determined according to an empirical value of a local channel.

The direction of arrival detecting device 83 is configured to separate components having specific times of arrival from the received pilot signals, and determine, from the separated components, directions of arrivals of the effective elements of the virtual channel matrix. Specifically, a filtering vector in a form represented by, for example, formula (2-22) is used to separate the components having specific times of arrival in a form shown in, for example, formula (2-25). Then, a sparse signal recovery algorithm such as the Lasso algorithm may be used to obtain the estimation of the virtual channel matrix variation only keeping the spatial information as represented by, for example, formula (2-29). The threshold decision represented by, for example, formula (2-30) is used to determine the locations of the directions of arrival of the effective elements in the virtual channel matrix.

Then, the minimum mean square standard shown in, for example, formula (2-16), is used to obtain the estimation of the virtual channel matrix. The estimation of the actual channel matrix may be obtained after the matrix transformation.

Persons skilled in the art should understand that functions of any above module may be executed by multiple physical modules or functional modules, and functions of the multiple above modules may also be integrated into one physical module or functional module for execution.

Although different embodiments of the present invention are illustrated and described, the present invention is not limited to the embodiments, and ordinal numbers such as "first" and "second" involved in claims are only used for distinguishing, instead of meaning that corresponding members have a specific sequence or connection relationship. Technical features only appearing in some claims or embodiments do not mean that the technical features cannot be combined with other features in other claims or embodiments to implement a new beneficial technical solution. Many modifications, variations, deformations, replacements and equivalents are obvious for persons skilled in the art without departing from the spirit and scope of the present invention as described in the claims.

<u>We Claim:</u>

1. A method used in a base station having N transmitting antennas in a multiple input multiple output system, comprising:

determining N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns;

performing beamforming on N_{BF} subspaces, and sending a pilot signal on each beam, wherein pilot signals on the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns; and

sending pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas, in a manner that sub-directions in each subspace use the orthogonal pilot patterns,

wherein a value of N_{BF} is 10%~15% of N, and a value of M is 15%~50% of N.

2. The method according to claim 1, wherein the N_{BF} pilot patterns and the M pilot patterns are randomly distributed in a frequency domain.

3. A method used in a user equipment in a multiple input multiple output system, comprising:

receiving pilot signals from N_{BF} beams of N transmitting antennas of a base station;

determining, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, positions where times of arrival of effective elements of a virtual channel matrix are located;

separating components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determining, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong;

receiving pilot signals from M pilot patterns on the N transmitting antennas of the base station; and

separating components belonging to specific active subspaces from the pilot signals received from the M pilot patterns, and recovering a channel response matrix of corresponding active subspaces from the separated components.

4. A method used in a base stating having N transmitting antennas in a multiple input multiple output system, comprising:

determining M orthogonal pilot patterns; and

sending the pilot signals over at least a part of M pilot patterns through each of the N transmitting antennas,

wherein a value of M is 15%~50% of N.

5. The method according to claim 4, wherein the M pilot patterns are randomly

distributed in a frequency domain.

6. A method used in a user equipment in a multiple input multiple output system, comprising:

receiving pilot signals from N transmitting antennas of a base station;

determining, by using a sparse signal recovery algorithm from the received pilot signals, positions where times of arrival of effective elements of a virtual channel matrix are located; and

separating components having specific directions of arrival from the received pilot signals, and determining, from the separated components, directions of arrival of the effective elements of the virtual channel matrix.

7. A device used in a base station having N transmitting antennas in a multiple input multiple output system, comprising:

a first device, configured to determine N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns;

a second device, configured to perform beamforming on N_{BF} subspaces, and send a pilot signal on each beam, wherein pilot signals on the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns; and

a third device, configured to send pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas, in a manner that sub-directions in each subspace use the orthogonal pilot patterns,

wherein a value of N_{BF} is 10%~15% of N, and a value of M is15%~50% of N.

8. The device according to claim 7, wherein the N_{BF} pilot patterns and the M pilot patterns are randomly distributed in a frequency domain.

9. A device used in a user equipment in a multiple input multiple output (MIMO) system, comprising:

a receiving device, configured to receive pilot signals from N_{BF} beams of N transmitting antennas of a base station and receive pilot signals from M pilot patterns of the N transmitting antennas;

a time of arrival detecting device, configured to determine, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, positions where times of arrival of effective elements of a virtual channel matrix are located;

a subspace detecting device, configured to separate components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determine, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong; and

a channel recovering device, configured to separate components belonging to specific active subspaces from the pilot signals received from the M pilot patterns, and recover a channel response matrix of corresponding active subspaces from the separated components.

10. A device used in a base station having N transmitting antennas in a multiple input multiple output system, comprising:

a first device, configured to determine M orthogonal pilot signals; and

a second device, configured to send the pilot signals over at least a part of M pilot patterns through each of the N transmitting antennas,

wherein a value of M is 15%~50% of N.

11. The device according to claim 10, wherein the M pilot patterns are randomly distributed in a frequency domain.

12. A device used in a user equipment in a multiple input multiple output system, comprising:

a receiving device, configured to receive pilot signals from N transmitting antennas of a base station;

a time of arrival detecting device, configured to determine, by using a sparse signal recovery algorithm from the received pilot signals, positions where times of arrival of effective elements of a virtual channel matrix are located; and

a direction of arrival detecting device, configured to separate components having specific directions of arrival from the received pilot signals, and determine, from the separated components, directions of arrival of the effective elements of the virtual channel matrix.

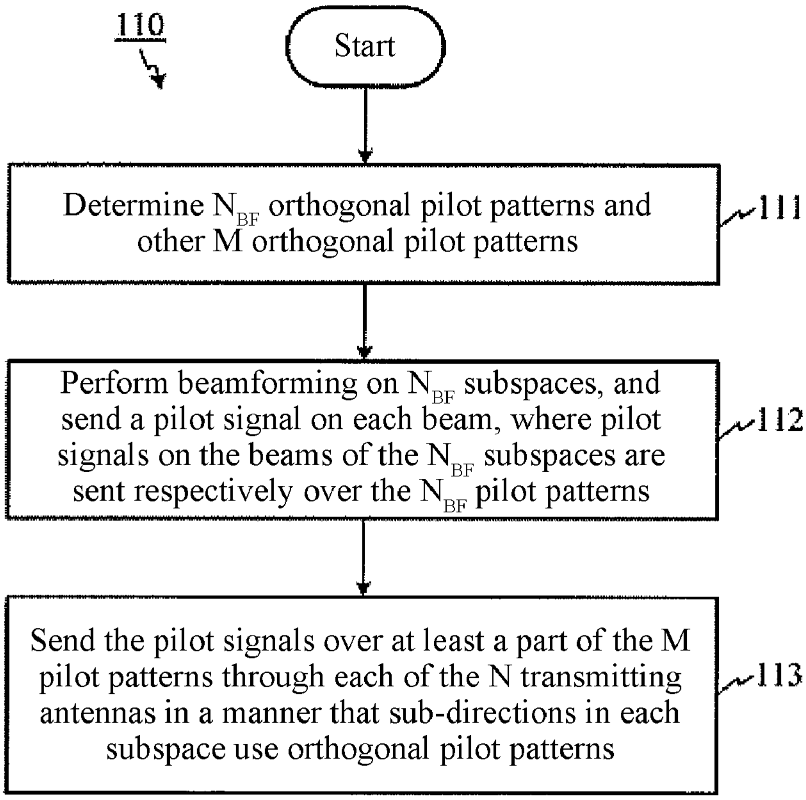
110
Start
Determine N_{BF} orthogonal pilot patterns and other M orthogonal pilot patterns
111
Perform beamforming on N_{BF} subspaces, and send a pilot signal on each beam, where pilot signals on the beams of the N_{BF} subspaces are sent respectively over the N_{BF} pilot patterns
112
Send the pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas in a manner that sub-directions in each subspace use orthogonal pilot patterns
113

FIG. 1

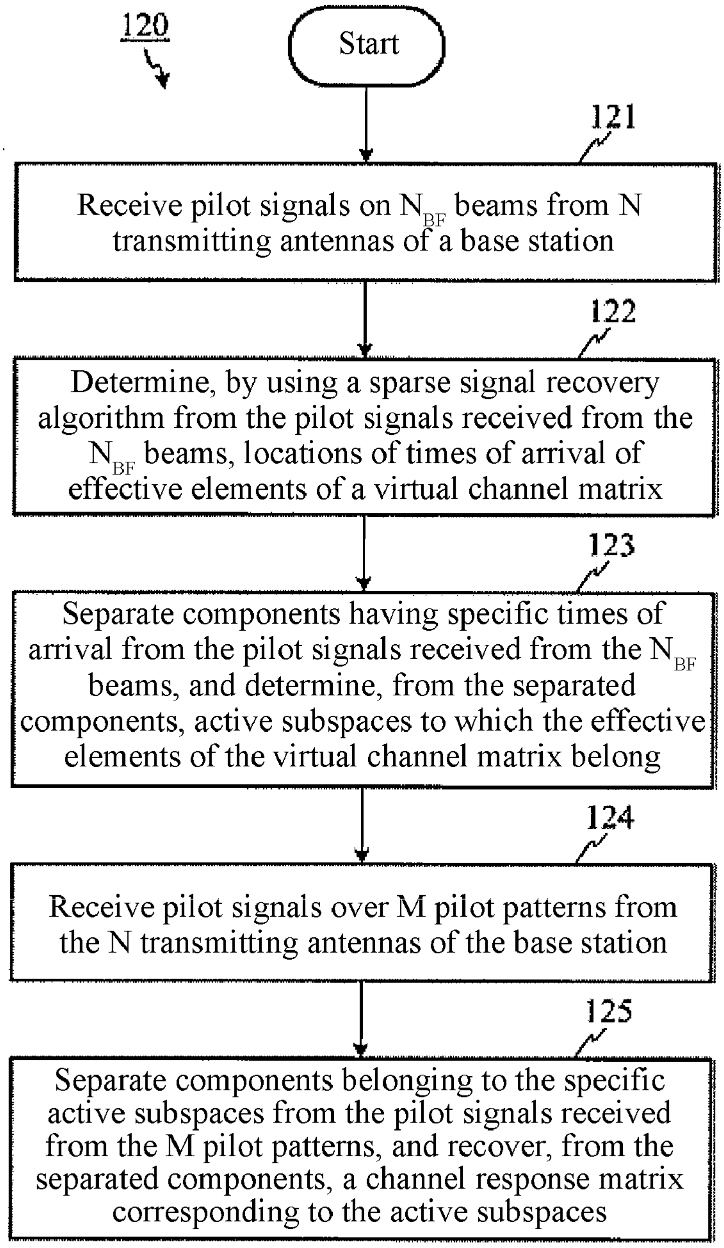
120
Start
121
Receive pilot signals on N_{BF} beams from N transmitting antennas of a base station
122
Determine, by using a sparse signal recovery algorithm from the pilot signals received from the N_{BF} beams, locations of times of arrival of effective elements of a virtual channel matrix
123
Separate components having specific times of arrival from the pilot signals received from the N_{BF} beams, and determine, from the separated components, active subspaces to which the effective elements of the virtual channel matrix belong
124
Receive pilot signals over M pilot patterns from the N transmitting antennas of the base station
125
Separate components belonging to the specific active subspaces from the pilot signals received from the M pilot patterns, and recover, from the separated components, a channel response matrix corresponding to the active subspaces

FIG. 2

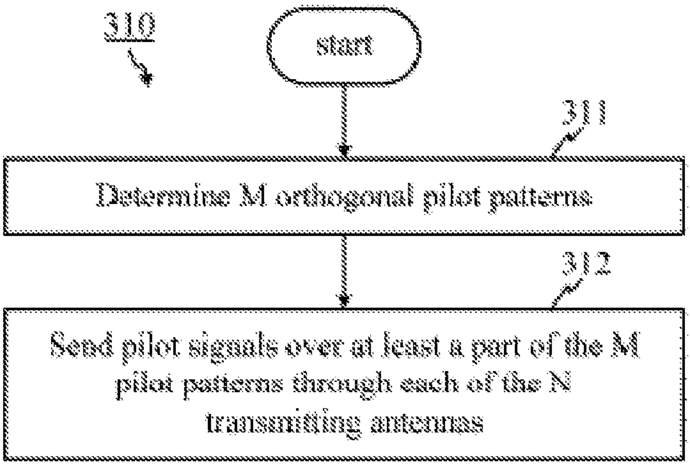
310
start
311
Determine M orthogonal pilot patterns
312
Send pilot signals over at least a part of the M pilot patterns through each of the N transmitting antennas

FIG. 3

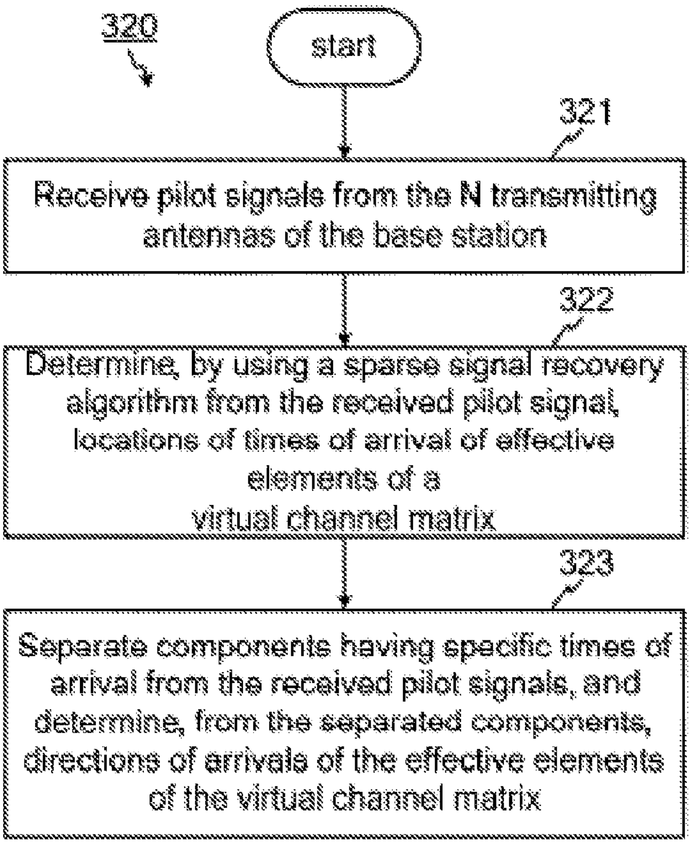
320
start
321
Receive pilot signals from the N transmitting antennas of the base station
322
Determine, by using a sparse signal recovery algorithm from the received pilot signal, locations of times of arrival of effective elements of a virtual channel matrix
323
Separate components having specific times of arrival from the received pilot signals, and determine, from the separated components, directions of arrivals of the effective elements of the virtual channel matrix

FIG. 4

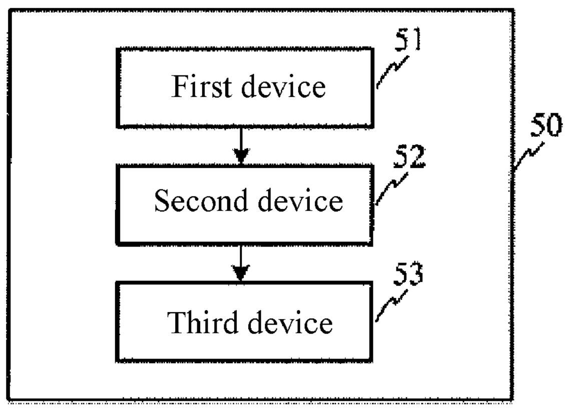
First device
51
Second device
52
Third device
53
50

FIG. 5

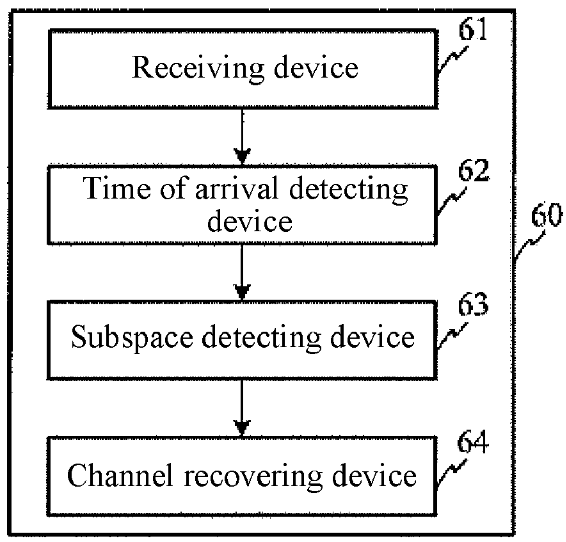
Receiving device
61
Time of arrival detecting device
62
Subspace detecting device
63
Channel recovering device
64
60

FIG. 6

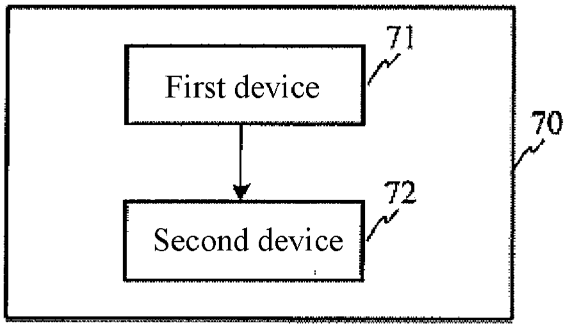
First device
71
70
Second device
72

FIG. 7

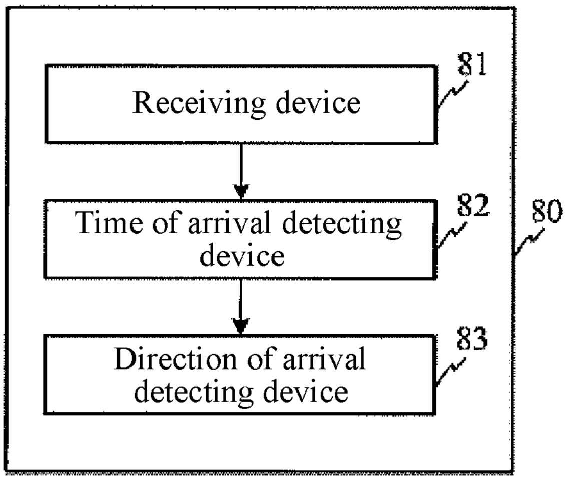
Receiving device
81
Time of arrival detecting device
82
80
Direction of arrival detecting device
83

FIG. 8