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Gu et al.

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(54) **METHOD FOR SELECTING ANTENNAS AND BEAMS IN MIMO WIRELESS LANS**

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(51) **Int. Cl.**
H04W 4/00 (2009.01)

(52) **U.S. Cl.** **370/252; 370/311; 370/334; 370/389**

(58) **Field of Classification Search** **370/208, 370/252, 254, 255, 328, 311, 334, 343, 344, 370/389, 431, 437, 465, 480**

See application file for complete search history.

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* cited by examiner

Primary Examiner — Yemane Mesfin

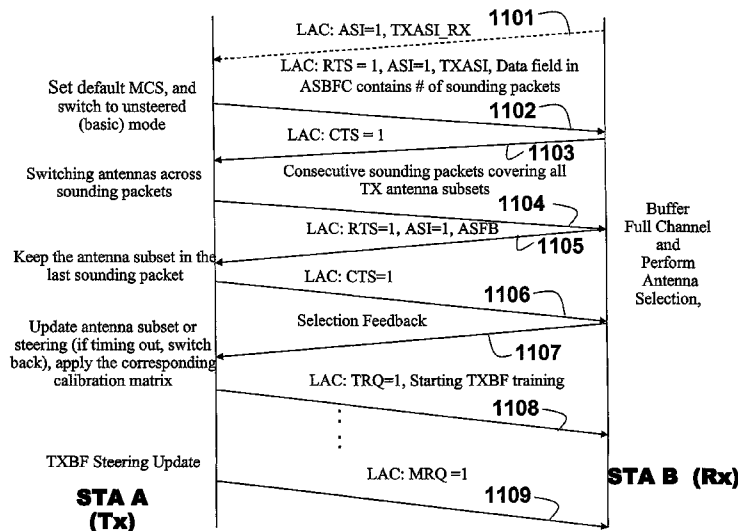
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(57) **ABSTRACT**

A computer implemented method selects antennas in a multiple-input, multiple-output wireless local area network that includes multiple stations, and each station includes a set of antennas. Multiple consecutively transmitted sounding packets are received in a station. Each sounding packet corresponds to a different subset of the set of antennas. A channel matrix is estimated from the multiple consecutively transmitted sounding packets. A frame including a high throughput (HT) control field is sent to initiate a selecting of antennas, and a subset of antennas is selected according to the channel matrix.

20 Claims, 16 Drawing Sheets



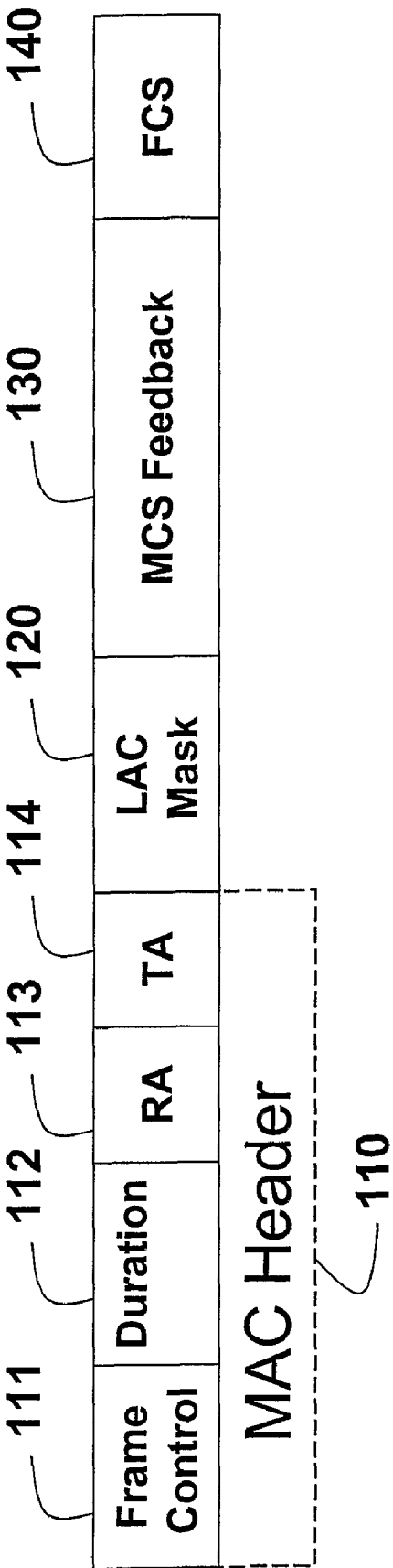


Fig. 1
Prior Art

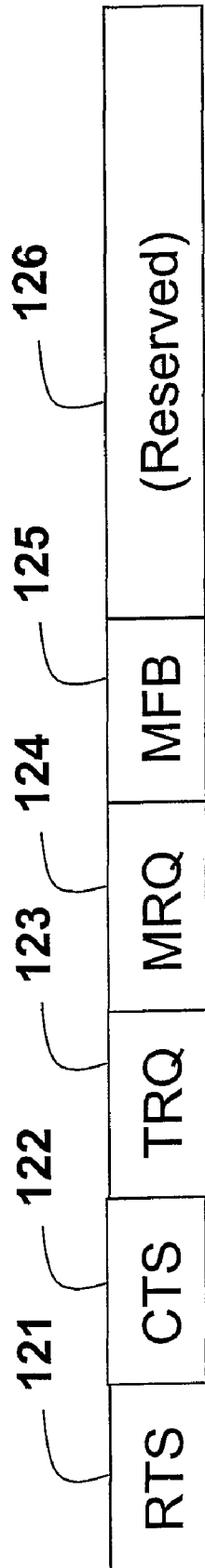


Fig. 2
Prior Art

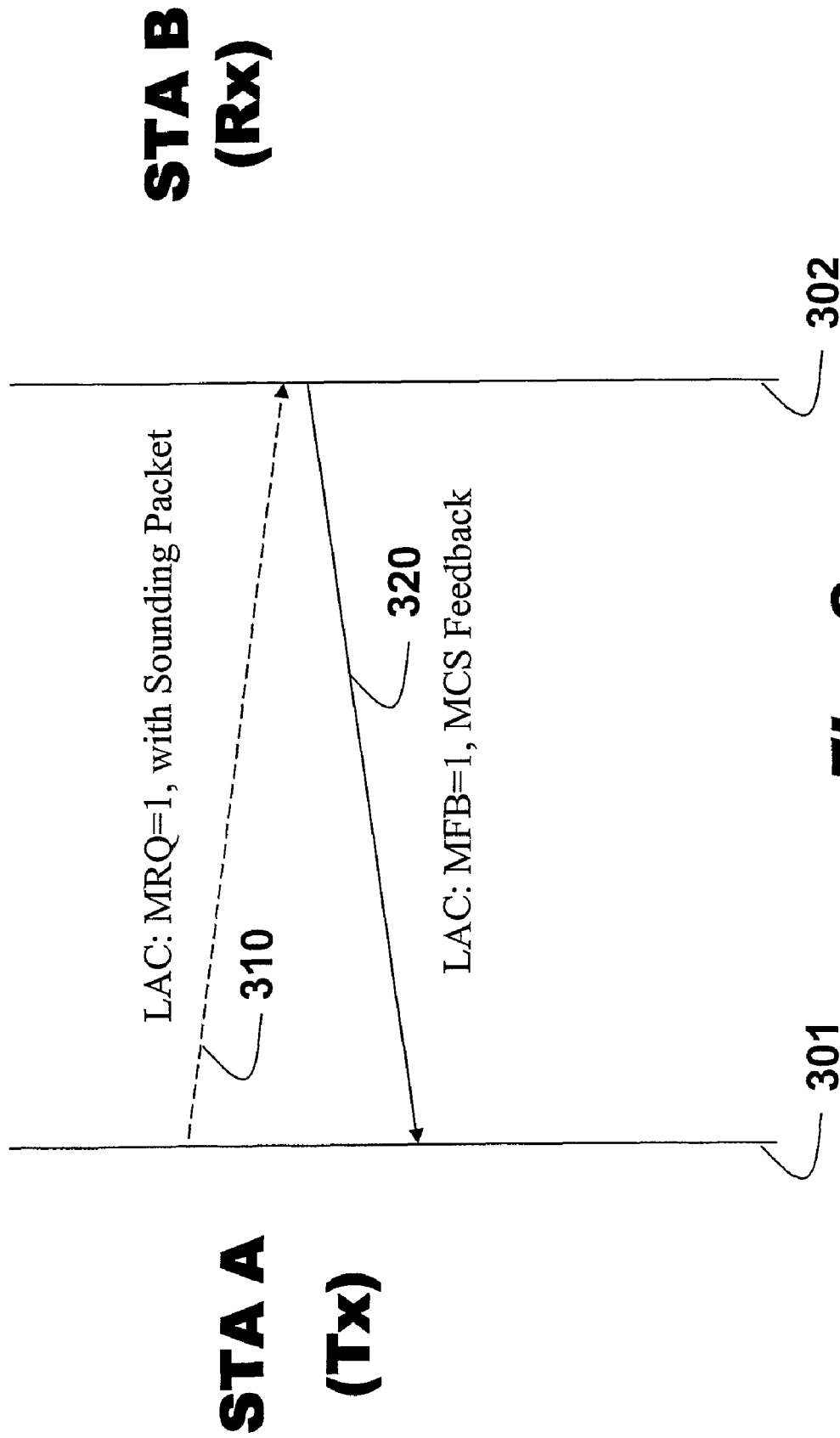


Fig. 3
Prior Art

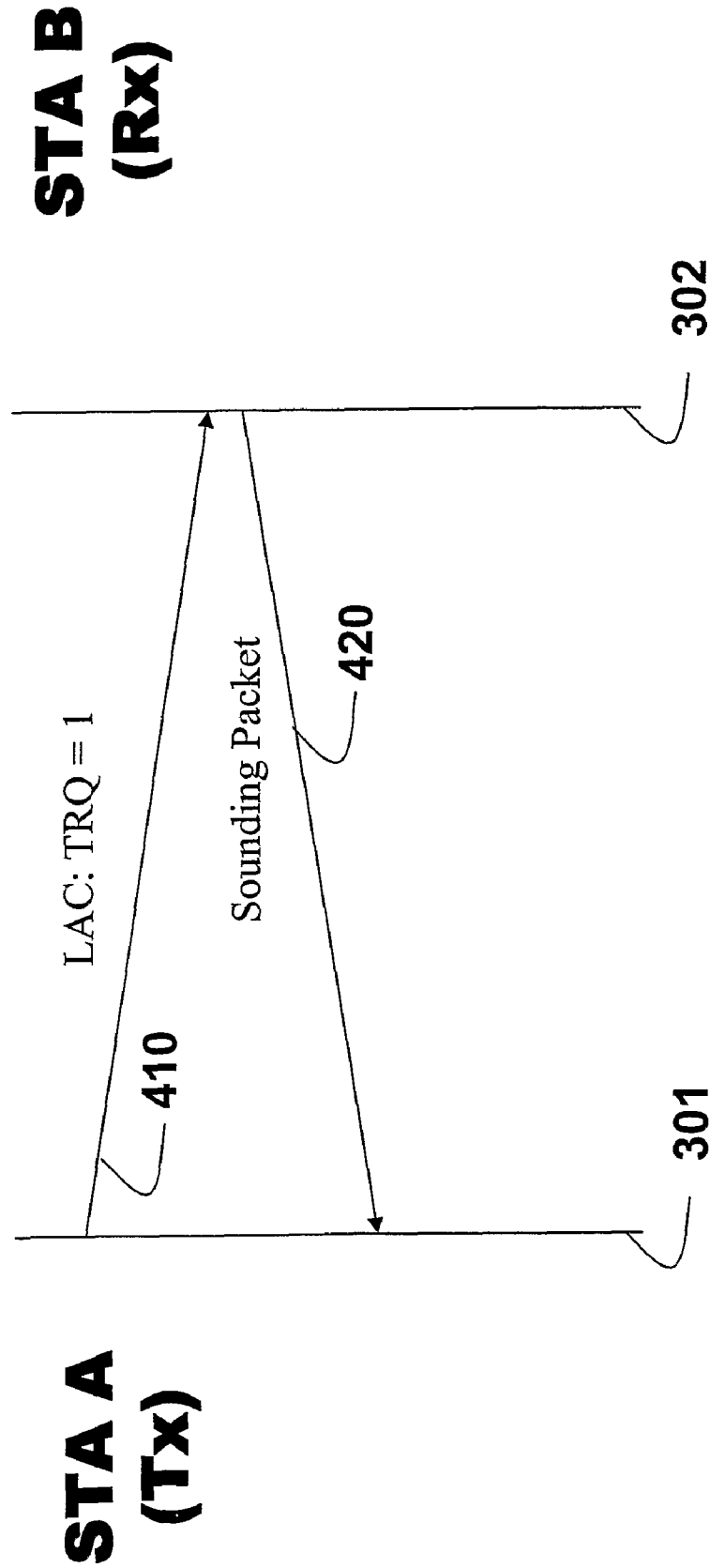


Fig. 4
Prior Art

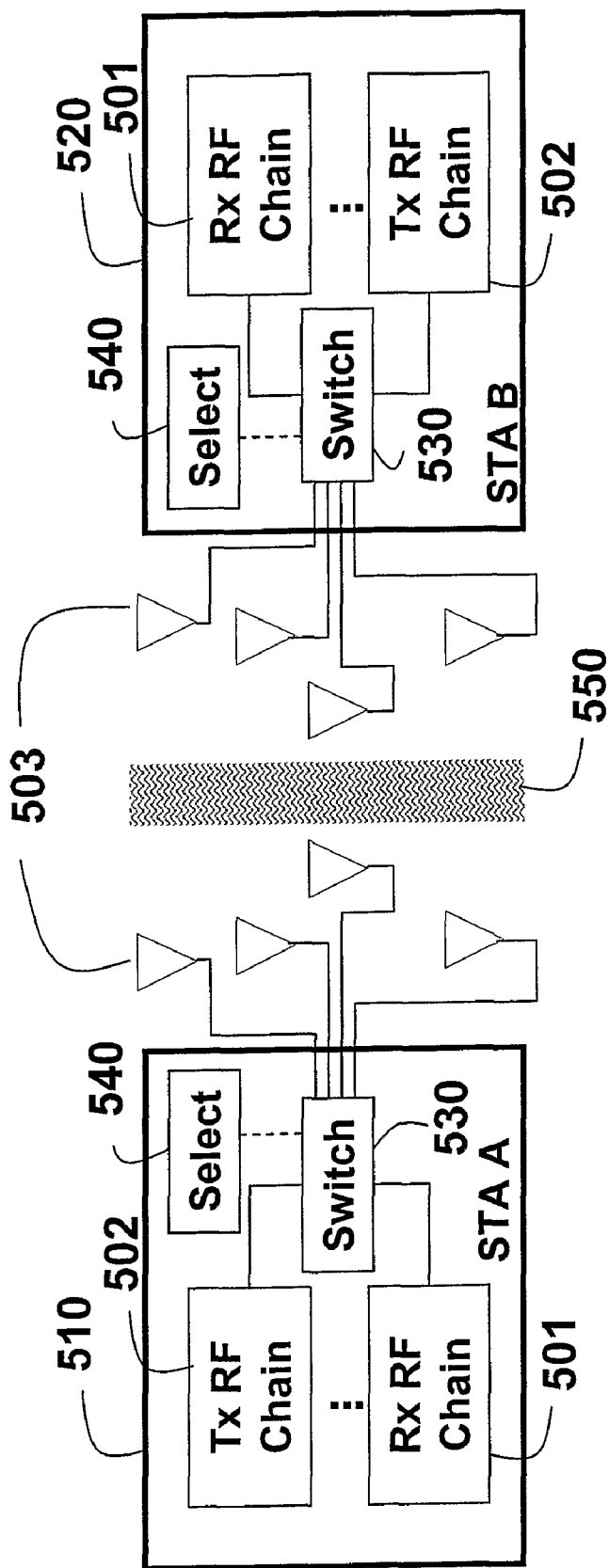
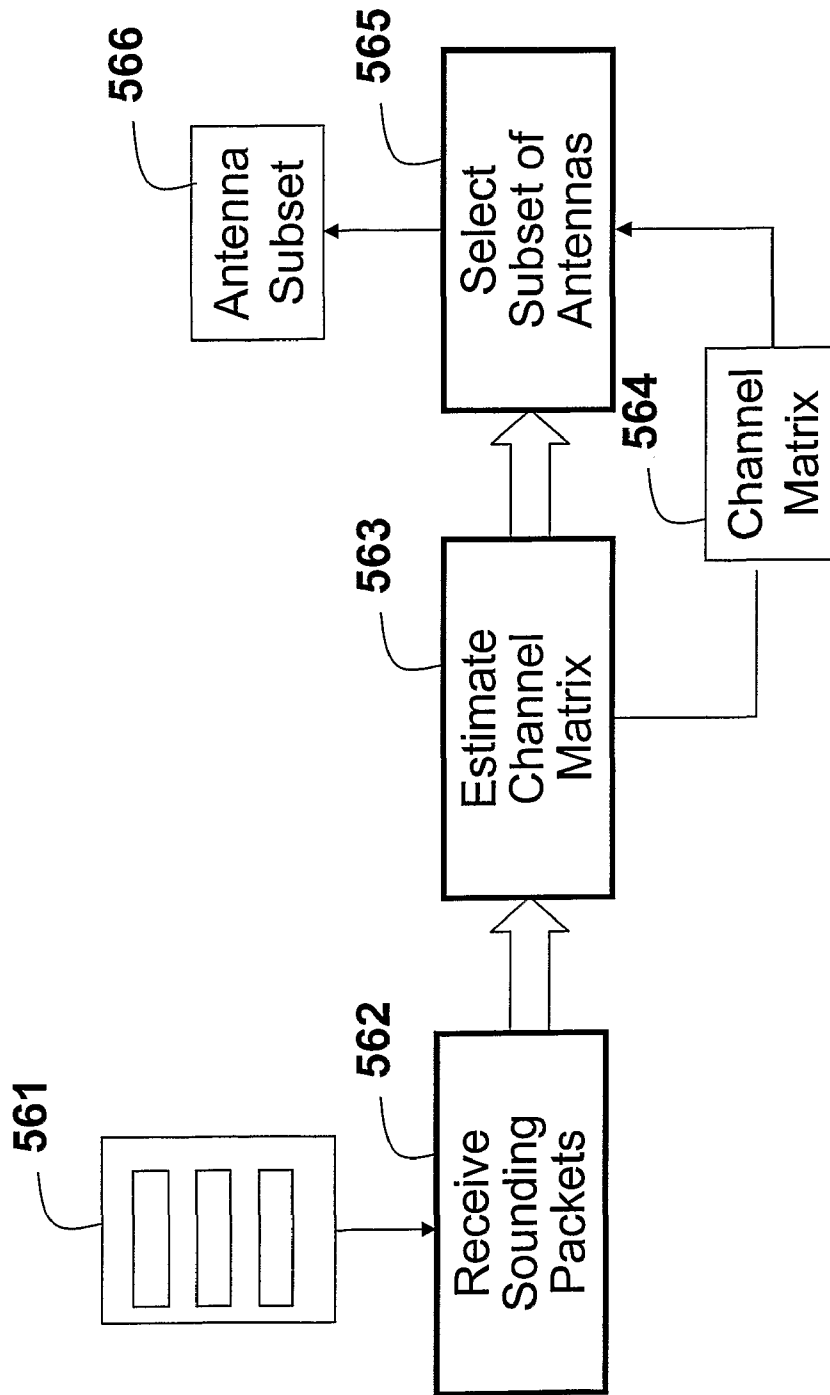


Fig. 5A
100

**Fig. 5B**

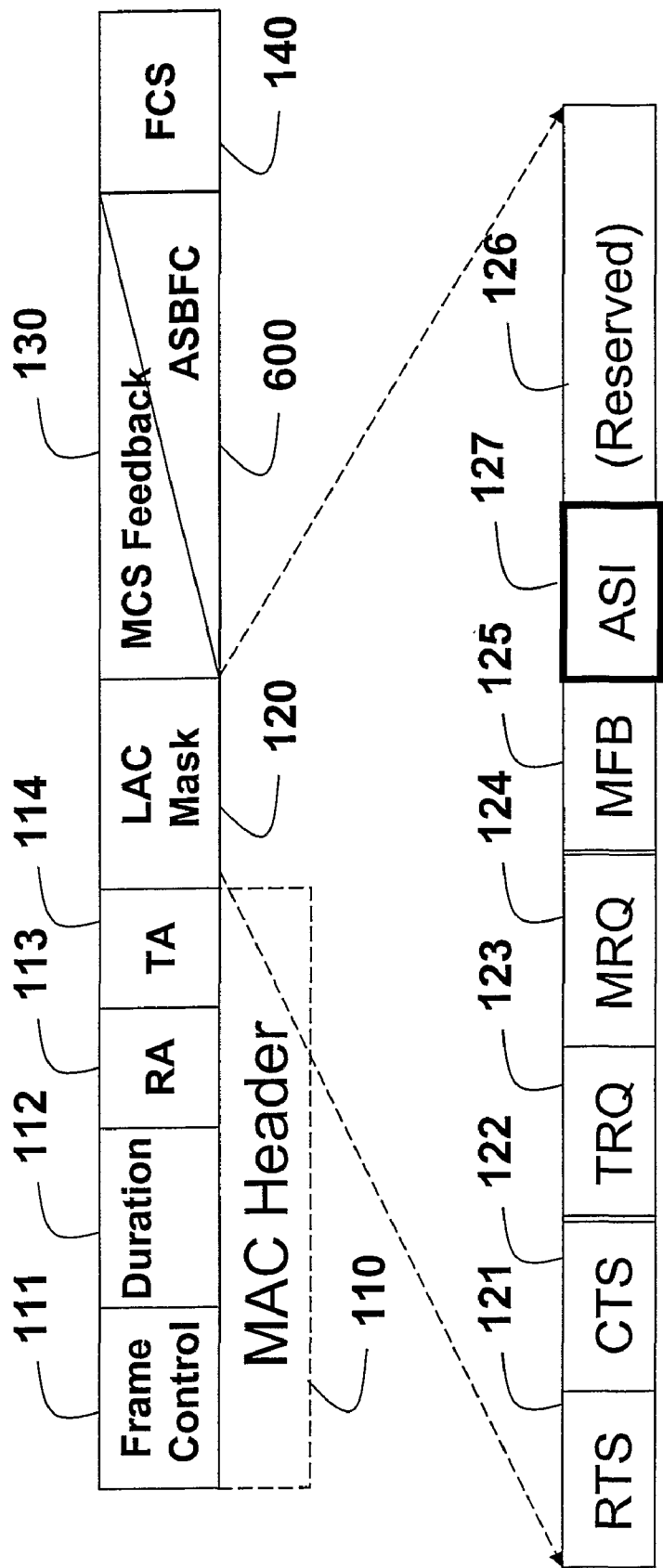


Fig. 5C

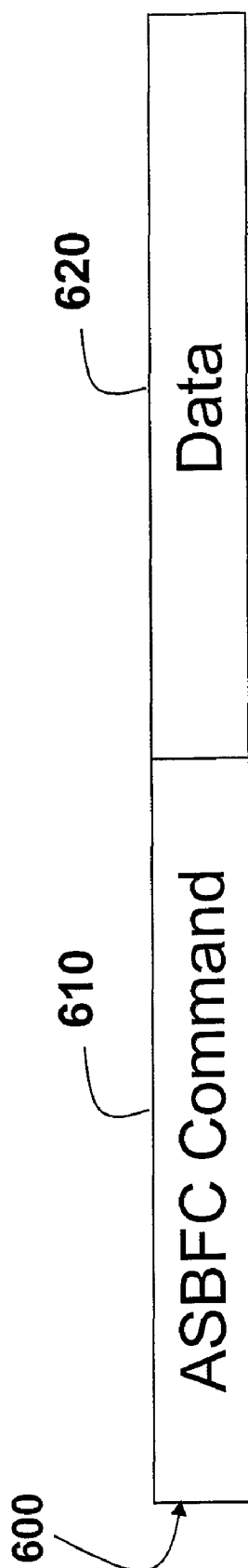
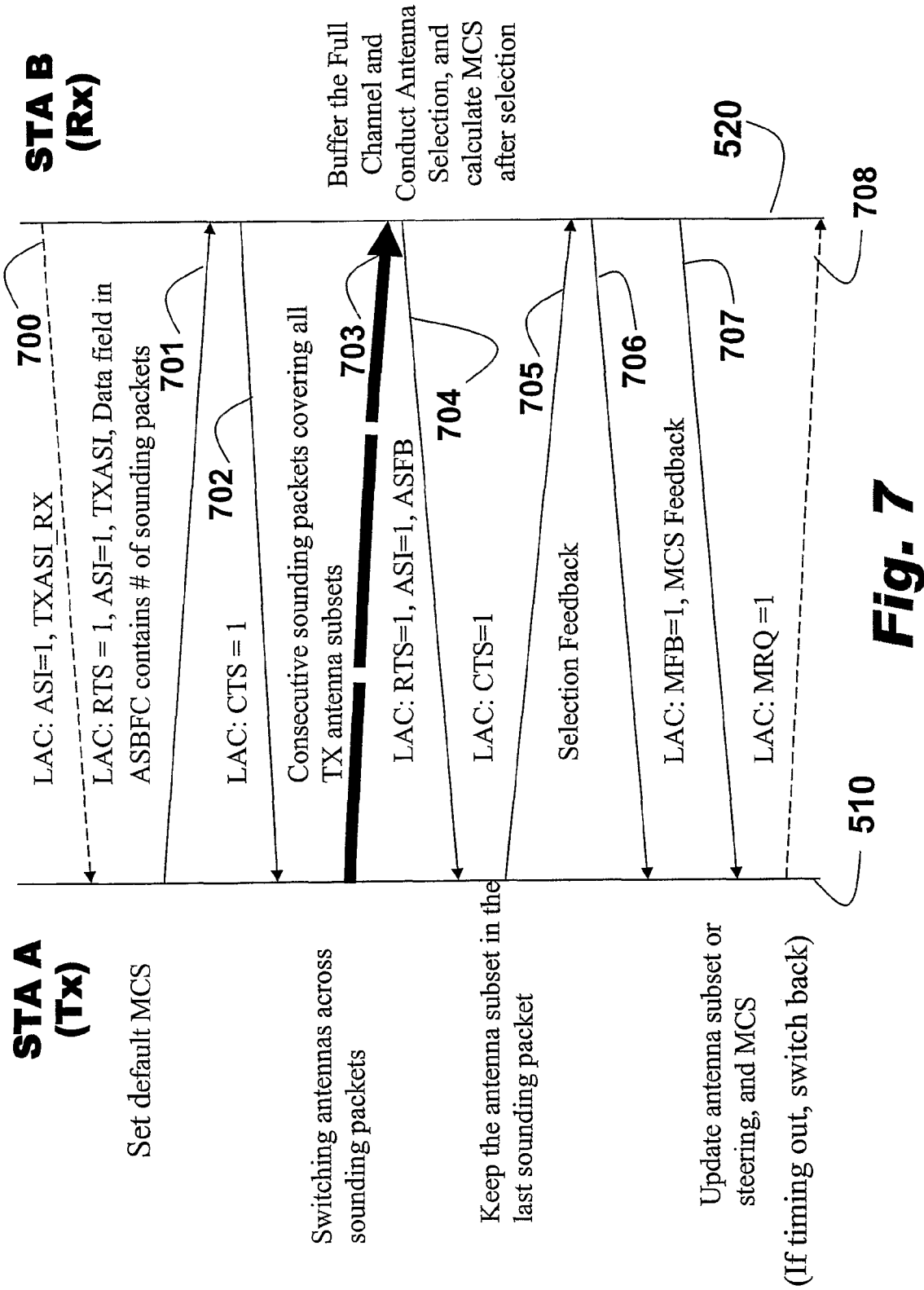


Fig. 6



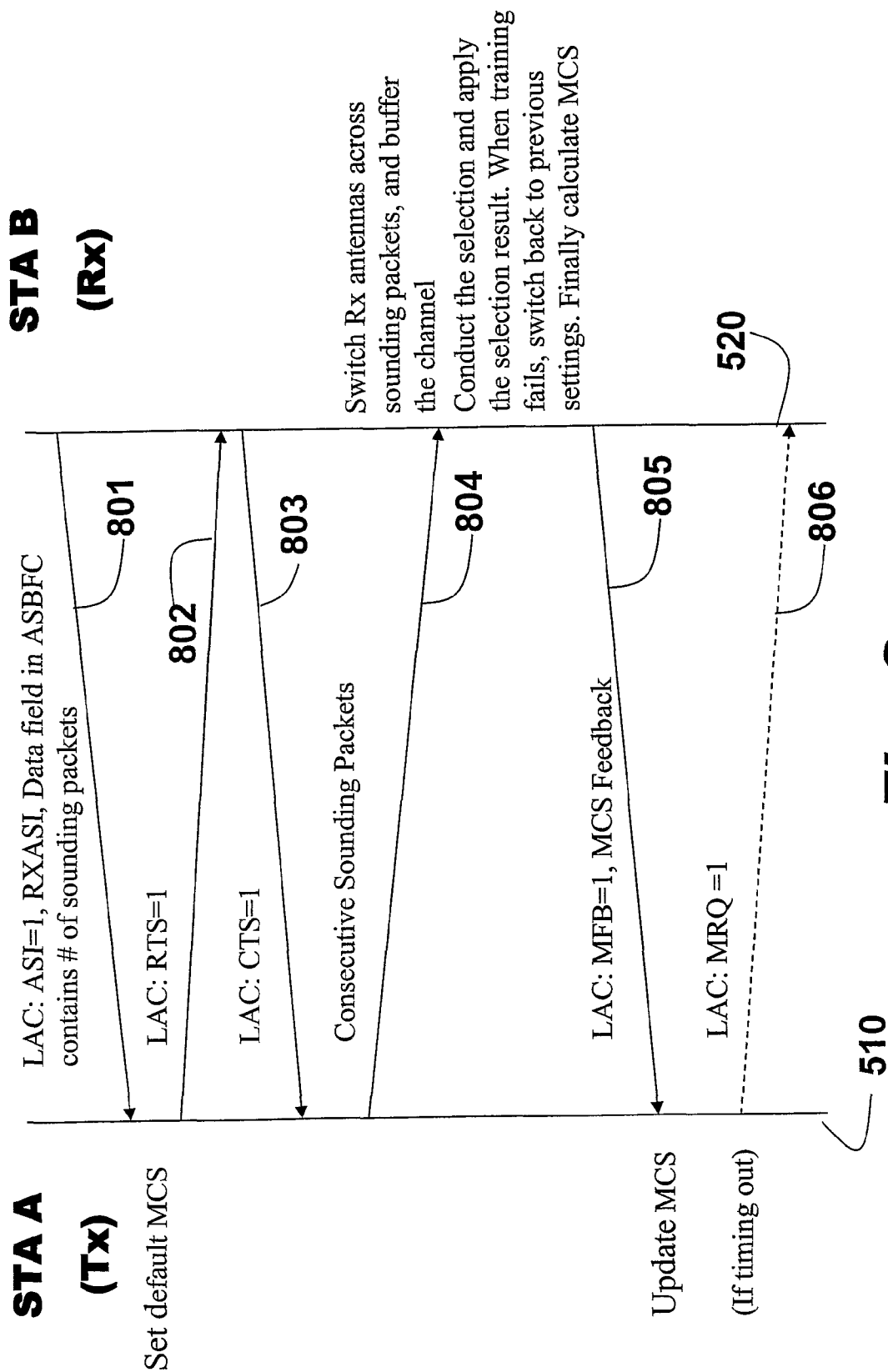


Fig. 8

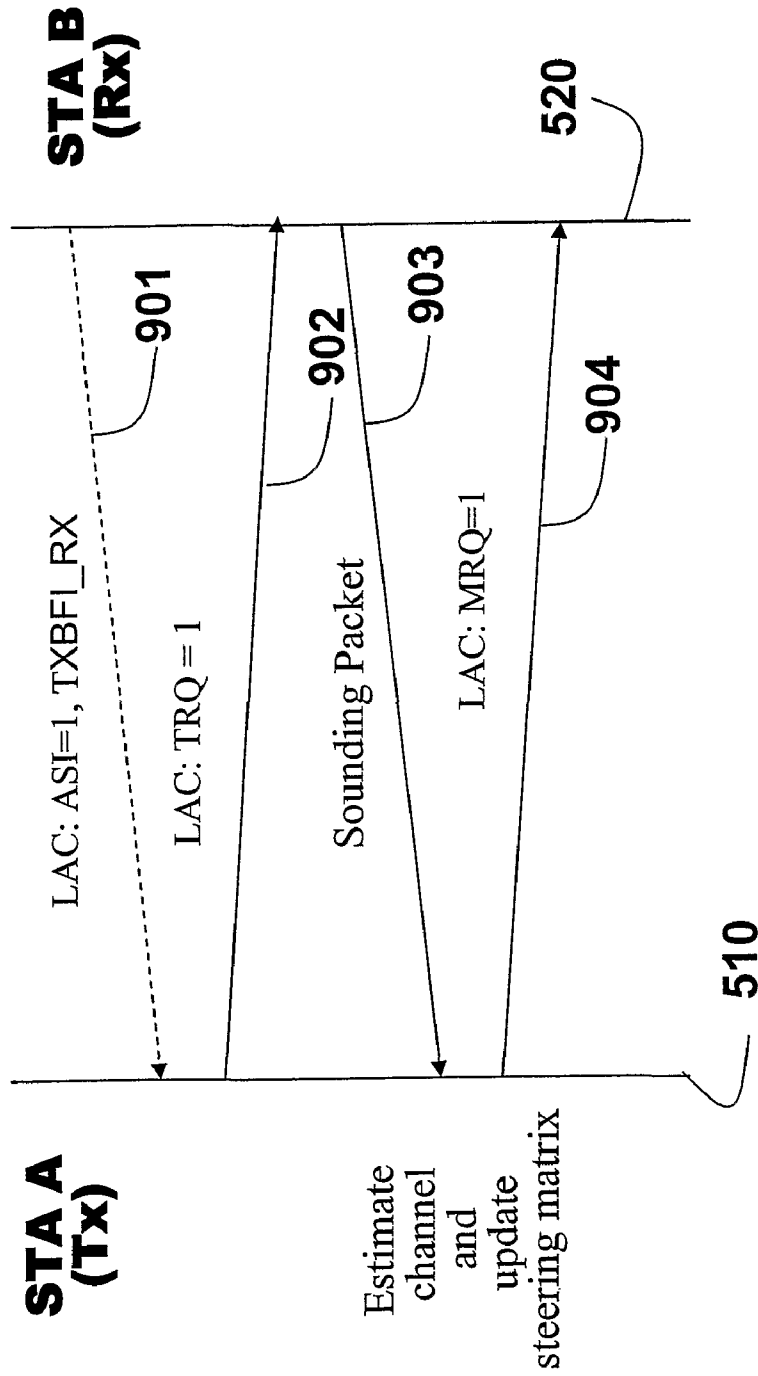


Fig. 9

STA B (Rx)

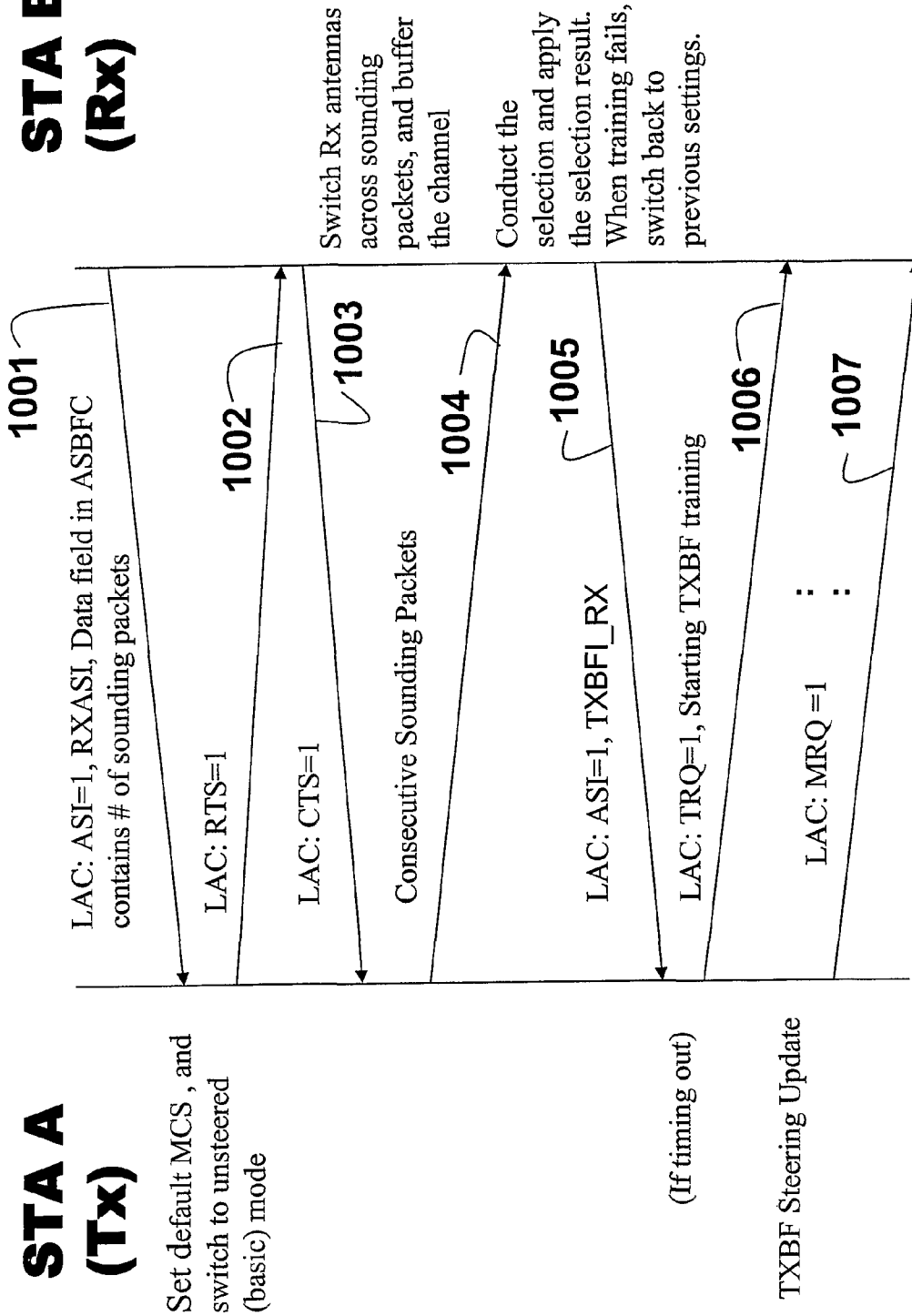


Fig. 10

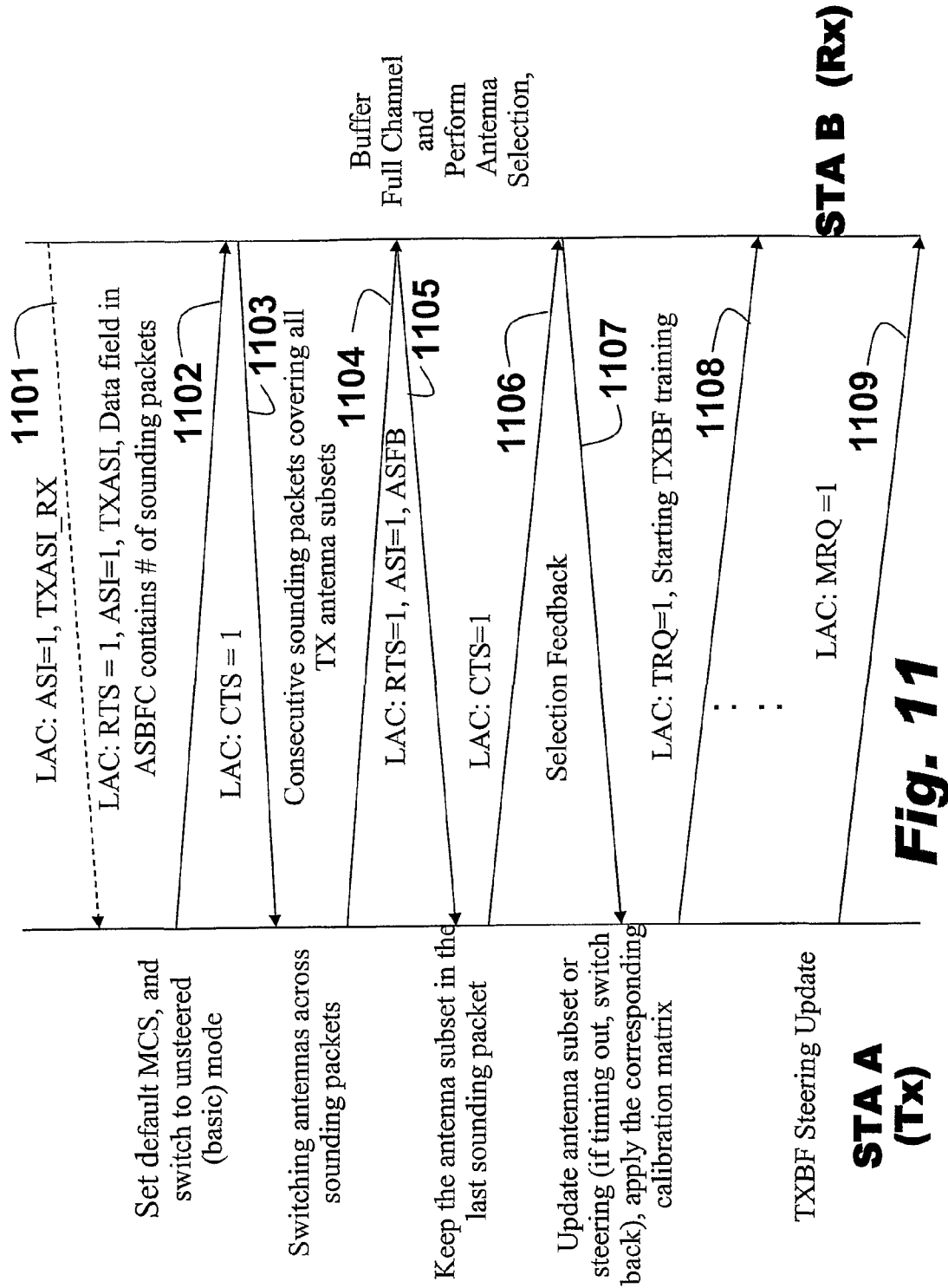


Fig. 11

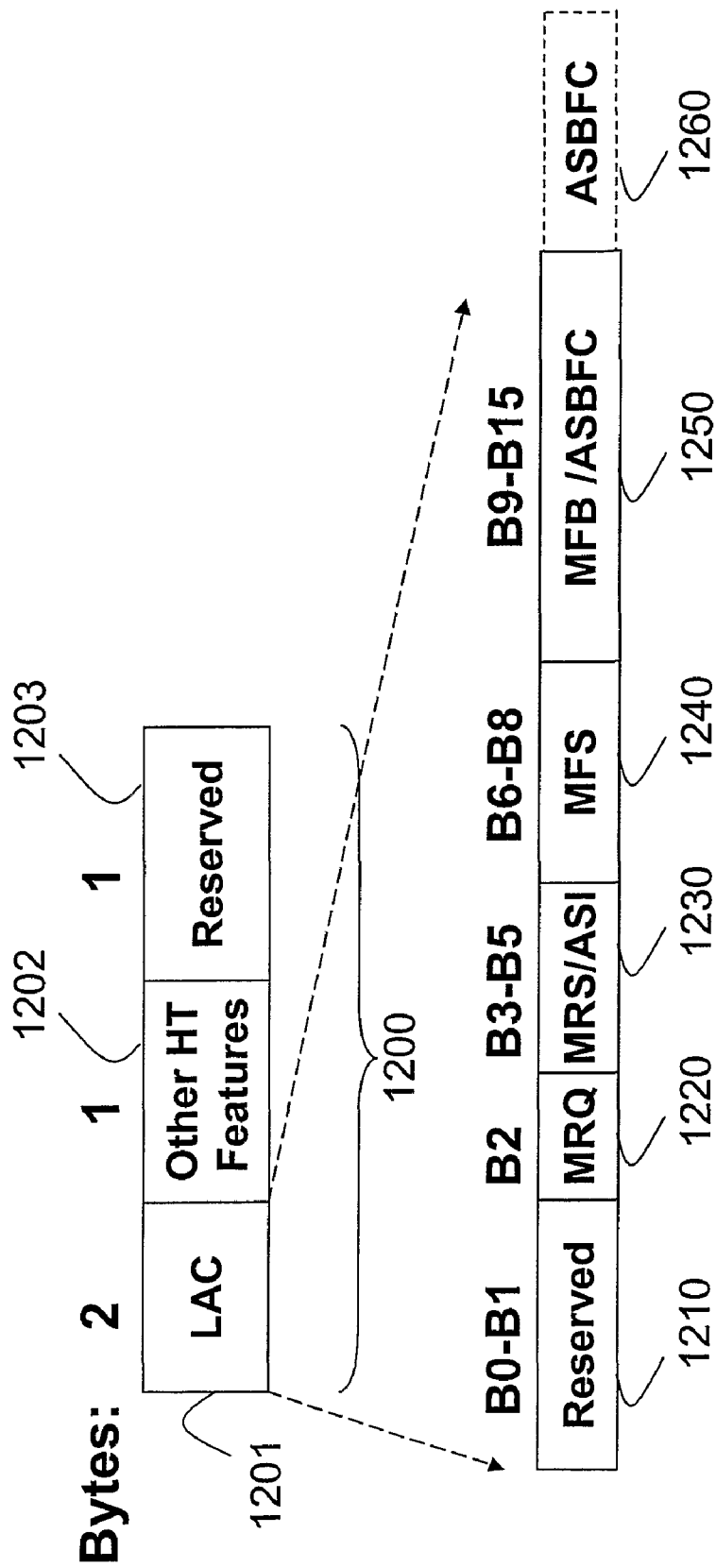
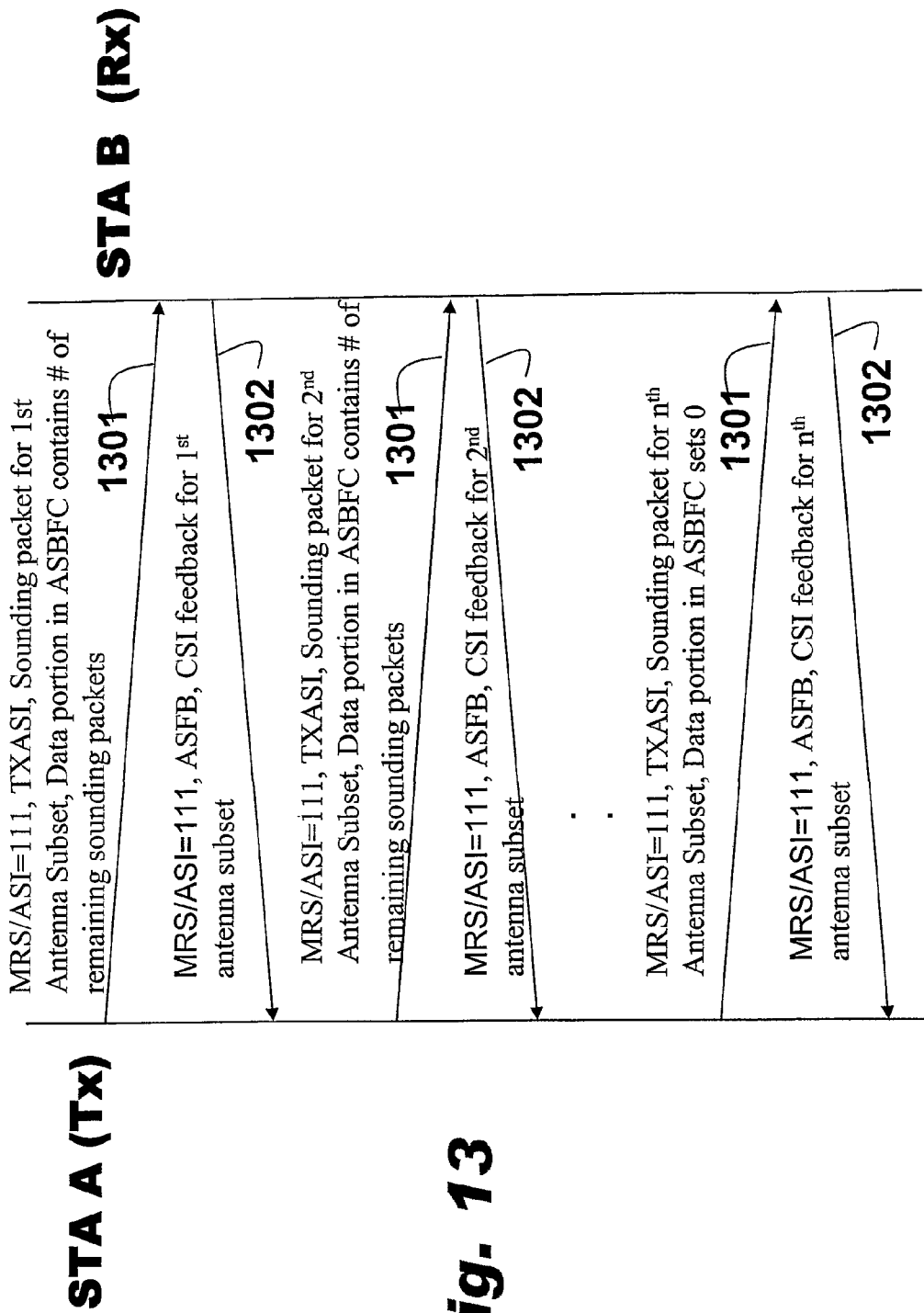


Fig. 12



STA A (Tx) STA B (Rx)

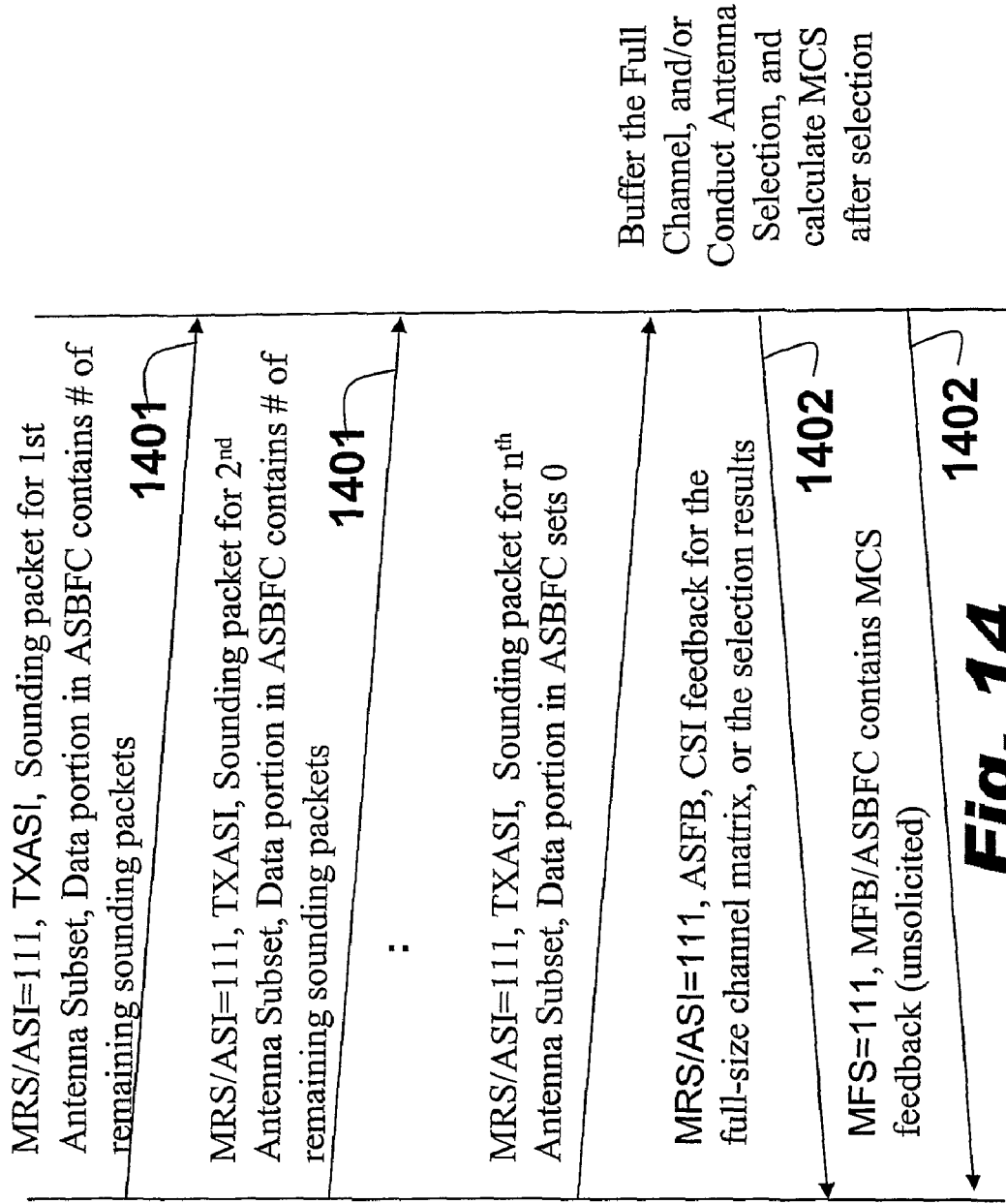


Fig. 14

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METHOD FOR SELECTING ANTENNAS AND BEAMS IN MIMO WIRELESS LANS

RELATED APPLICATION

This application is a Continuation-in-Part of, and claims priority to, PCT Application No. PCT/US2005/039651, "Method for Selecting Antennas and Beams in MIMO Wireless LANS" filed on Nov. 3, 2005, by Gu et al and to PCT Application No. PCT/US2005/035012, "Training Signals for Selecting Antennas and Beams in MIMO Wireless LANS, by Gu et al., filed Sep. 30, 2005.

FIELD OF THE INVENTION

This invention relates generally to multiple-input, multiple-output wireless local area networks, and more particularly to selecting antennas and beams in such networks.

BACKGROUND OF THE INVENTION

Multiple-input, multiple-output (MIMO) techniques can significantly increase system capacity in a scattering environment of a wireless network. However, the use of more antennas increases the hardware complexity and cost because in a typical system, each transmit/receive antenna requires a separate RF chain including a modulator/demodulator, an AD/DA converter, an up/down converter, and a power amplifier. In addition, the processing complexity at the baseband also increases with the number of antennas.

Antenna/beam selection can reduce the number of RF chains while still taking advantage of the capacity/diversity increase provided by multiple antennas. In a wireless local area network (WLAN), stations are typically operated at a high signal to noise ratio (SNR), in which diversity plays a key role in protecting the system from a deep fading channel. Furthermore, it is known that the state of a WLAN channel changes slowly. Therefore, it is advantageous to perform antenna/beam selection in a WLAN.

The idea of antenna/beam selection is to select a submatrix from a complete channel matrix or a transformed channel matrix for beam selection, according to some predetermined criterion. To perform antenna/beam selection, the complete channel matrix is estimated by sending training (sounding) frames that enable the antenna selection station to measure the complete channel state information (CSI). Conventionally, explicit signaling is used in the physical (PHY) or media access (MAC) layer by sending training frame(s) for all the antennas to be selected. However, the additional overheads are undesirable due to practical limitations. On the other hand, the slowly varying WLAN channel environment can advocate a more efficient antenna/beam selection training scheme which requires little or no changes in the MAC and PHY layers.

Structure of IEEE 802.11n WLAN Link Adaptation Control (LAC) Mechanisms in MAC Layer

As shown in FIG. 1 and FIG. 12, the WLAN IEEE 802.11n standard, incorporated herein by reference, also known as WiFi, proposes to specify a fast link adaptation control (LAC) mechanism defined at the MAC layer for supporting MIMO training requests and exchange of link adaptation information. In general, the LAC functionality can be realized either by a single control frame defined as LAC, or the single control frame can be a High Throughput (HT) Control frame, or a HT Control Field can be incorporated into any MAC layer frame. As shown in FIG. 1, LAC frame contains the following fields: a MAC header 110, a LAC mask 120 for indicating the logical

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elements carried in the current control frame, a modulation coding scheme (MCS) feedback field 130 for indicating transmitting parameters, and a frame check sequence (FCS) 140 for error detection. The MAC header 110 applies for any MAC layer packet, which includes a frame control 111, duration 112, receive address (RA) 113, and transmit address (TA) 114. The LAC frame is described in detail in IEEE 802.11-04/0889r7, "TGn Sync Proposal Technical Specification," incorporated herein by reference.

The LAC frame supports control of MIMO training requests and exchange of link adaptation information. The LAC frame can be sent by either an initiator station (transmitter) or a recipient station (receiver).

FIG. 2 shows the LAC mask field 120 in greater detail. Without considering antenna/beam selection, the LAC mask field 120 includes the following: RTS (request to send) 121, CTS (clear to send) 122, TRQ (MIMO training request) 123, MRQ (request for MCS feedback) 124, and MFB (MCS feedback) 125. The three bits 126 are reserved. In the MCS feedback case, i.e., MFB=1, the MCS set is indicated in the 'MCS feedback' field 130 in FIG. 1.

An HT Control Field includes a LAC field which controls the fast link adaptation training process; and two other unused fields which may be dedicated for other HT control features. Without considering antenna/beam selection, the LAC field of an HT control field includes: MRQ, MRS (MRQ sequence number), MFS (MFB sequence number), and MFB with 7 bits functioning as the MCS feedback field in the above LAC frame. Note that the same HT Control Field may also form a single HT Control frame by adding in a MAC header, See FIG. 1, item 110. The HT Control Field is described in detail in IEEE 802.11-20051020 "Link Adaptation Draft Text Alternative 2 r2," incorporated herein by reference.

Closed-Loop MIMO Training Methods for IEEE 802.11n WLAN

The IEEE 802.11n standard requires a throughput of 100 megabits per second (Mbps) at the medium access control (MAC) layer service access point (SAP). Based on the channel property in WLAN environment, closed-loop schemes are preferred for increased throughput, including transmit beam forming (TXBF), MCS adaptation, and antenna/beam selection.

Each PHY layer packet is composed by two portions: preamble and data. The PHY packet preamble includes training information for channel estimation at the receiver. Typically, in a conventional PHY layer packet, the number of antennas or spatial streams indicated in the training field can be less than the maximum number provided by the MIMO channel. A sounding packet is a specific PHY layer packet, which contains the training information for all the available data streams in the MIMO channel, no matter how many data streams are used for transmitting the data portion. When the concept of sounding packet is not applied in the system, an alternative category of PHY layer training packet is the one that enforces a MCS set utilizing all the available data streams in the MIMO channel, so that not only the preamble contains the full training information of the MIMO channel, the data portion is also transmitted using all the available data streams. MCS Training Process

FIG. 3 shows a conventional MIMO training process for MCS adaptation based on LAC frame however, it should be understood that an HT control field can also be used. An initiator (transmit) station STA A 301 sends a LAC frame 310 with MRQ=1, or a frame containing HT Control Field with MRQ=1, and MRS equal to a corresponding sequence number, to a recipient (receive) station STA B 302. The initiator also requests its PHY layer to signal a sounding packet. In

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response to receiving the MRQ and the sounding packet, the recipient **302** estimates the MIMO channel and determines an appropriate MCS set for the current channel. Then, the recipient replies to the initiator a LAC frame **320** with MFB set to 1, and the MCS feedback field **130** contains the selected MCS set, or a frame including a HT Control Field with MFS equal to the MRS in the received frame it is currently responding to, and with MFB including a selected MCS set.

The recipient **302** can also initiate the MCS training process whenever it has the complete MIMO channel knowledge, by determining the MCS and sending an MFB with MCS feedback directly without any matching MRQ element. This is called unsolicited adaptation.

TXBF Training Process

FIG. **4** shows a conventional transmit beam forming (TXBF) training process based on LAC frame. Again, it should be understood that a HT control field can be used, if corresponding TXBF training functionalities are defined in the reserved fields described above. The initiator **301** sends out a LAC frame **410** with TRQ set to 1 to the recipient **302**. In response to receiving the TRQ, the recipient sends back a sounding packet **420** to the initiator. Upon receiving the sounding packet, the initiator estimates the MIMO channel and updates its beam forming steering matrices. Up to now, recipient initiated TXBF training is not defined.

For antenna selection, some prior art training methods use a single PHY layer training frame (e.g., sounding packet) containing the training information for all the antennas to be selected, and different antenna subsets are subsequently connected to the RF chains for this single training frame. This introduces overhead on existing training frame designs.

In another training method, a long sequence of training frames is transmitted from a receive station to a transmit station, and in response the transmit station transmits a short sequence of training frames so that both the transmit and receive station can perform channel estimation and antenna selection, see U.S. patent application Ser. No. 11/127,006 "Training Frames for MIMO Stations," filed by Andreas Molisch, Jianxuan Du and Daqing Gu on May 11, 2005, incorporated herein by reference.

SUMMARY OF THE INVENTION

The invention provides a training method for selecting antennas/beams in a MIMO wireless local area network (WLAN). The method operates at the MAC layer. Compared with prior art antenna/beam selection training methods, the method according to the invention does not require a modification of the PHY layer.

The training method rapidly sends multiple training frames, designated as sounding packets. Each sounding packet conforms to a conventional PHY layer design and is for a different subset of all of the available antennas so that characteristics of the entire channel can be estimated by the receiver of the sounding packets. The receiver of the sounding packets can select either transmit or receive antennas. The entire training method operates at the MAC layer.

The sounding packets, in addition to training the MIMO channel for selecting antennas/beams, can also include data which makes the method extremely efficient because training and data transfer is performed concurrently. Because the method operates at the MAC layer, the method has less overhead than conventional methods that operate at both the MAC and PHY layers.

The sounding and packets can be sequential or alternate?

As an additional advantage, the method can be extended for a general closed-loop MIMO system, such as transmit beam

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forming training processes initiated by the receiver. Also, the antenna/beam selection training method can be combined with transmit beam forming to achieve additional performance improvements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is block diagram of a prior art LAC frame;

FIG. **2** is a block diagram of a prior art LAC mask field;

FIG. **3** is a flow diagram of a prior art MCS training process;

FIG. **4** is a flow diagram of a prior art TXBF training process;

FIG. **5A** is a block diagram of a MIMO system according to an embodiment of the invention;

FIG. **5B** is a flow diagram of a method for selecting antennas according to the invention;

FIG. **5C** is a block diagram of a LAC frame according to an embodiment of the invention;

FIG. **6** is a block diagram of an ASBFC field of the LAC frame according to an embodiment of the invention;

FIG. **7** is a flow diagram of the training for transmit antenna/beam selection according to an embodiment of the invention;

FIG. **8** is a flow diagram of the training for receive antenna/beam selection according to an embodiment of the invention;

FIG. **9** is a flow diagram of receiver initiated beam forming training according to an embodiment of the invention;

FIG. **10** is a flow diagram of combined receive antenna/beam selection and TXBF training according to an embodiment of the invention;

FIG. **11** is a flow diagram of combined transmit antenna/beam selection and TXBF training according to an embodiment of the invention;

FIG. **12** is block diagram of a HT control field having a LAC field according to an embodiment of the invention; and

FIG. **13** is a flow diagram of antenna/beam selection training according to another embodiment of the invention.

FIG. **14** is another flow diagram of antenna/beam selection training according an embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **5A** shows a multiple-input, multiple-output (MIMO) wireless local area network (WLAN) **100** according to an embodiment of the invention. The network includes a first station (STA A) **510** and a second station (STA B) **520**. Either station can operate in receive or transmit mode. Generally, the station that transmits the data is called the transmit station, and the station that receives the data is called the receive station.

A 'set' as defined includes one or more elements; the number of elements in a 'subset' is equal to or less than the number of elements in the corresponding set.

Each station includes a set of receive (Rx) RF chains **501** and a set of transmit (Tx) RF chains **502** connected to a set of antennas **503** by switches **530**. Generally, the number of antennas is larger than the number of RF chains. Therefore, a subset of antennas is selected from the set of total available antennas by a method **540** according to an embodiment of the invention during a training phase as described herein. The selection method can be initiated by either the transmitter or the receiver, and the selection can be conducted either at the transmitter or at the receiver.

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As shown in FIG. 5B, antennas are selected **540** by receiving **562** multiple consecutively transmitted sounding packets **561** in a station. Consecutively transmitting or receiving a predetermined number of packets, as defined herein, means that the packets are transmitted one after the other, without any other intervening packets in either direction, and the number of packets is known to both stations before the sounding packets are sent. Preferably, the sounding packets are transmitted with a relatively short delay. To further decrease the time required for sounding, the size of the sounding packets can be minimized. For example, the sounding packets can be limited to a preamble and header, and exclude any data.

A channel matrix **564** is estimated **563** from the sounding packets, and a subset of antennas **566** is selected **565** according to the channel matrix.

The method can also be used for closed-loop MIMO trainings initiated by a recipient station, e.g., STA B **520**. The training process operates entirely at a media access (MAC) layer and is transparent to the physical (PHY) layer to minimize overhead.

System Model for MIMO Systems with Antenna/Beam Selection

In the MIMO WLAN **100**, the transmitter or initiator station A has a set of N_A antennas, and the receive or recipient station B has a set of N_B antennas. A relationship between a transmitted signal and a received signal in a flat-fading channel **550** can be expressed as:

$$r_B = F_B^H (H_{A \rightarrow B} F_A s_A + n),$$

where r_B is a $N_{B_SS} \times 1$ received signal vector, s_A is a $N_{A_SS} \times 1$ transmitted signal vector, and $H_{A \rightarrow B}$ is a $N_B \times N_A$ channel matrix. A noise vector n has $N_B \times 1$ entries that are independent and identically distributed (i.i.d.) zero-mean circular complex Gaussian random variables with variance N_0 . F_A is a $N_A \times N_{A_SS}$ transmit antenna/beam selection matrix, and F_B is a $N_B \times N_{B_SS}$ receive antenna/beam selection matrix. The matrices used for selection are submatrices of an identity matrix for pure antenna selection. In the case of beam forming, the matrices include orthogonally transformed columns of a unitary matrix. The equivalent channel matrix after antenna/beam selection is a $N_{B_SS} \times N_{A_SS}$ matrix $H_{eq} = F_B^H H_{A \rightarrow B} F_A$, which is a submatrix of the channel matrix $H_{A \rightarrow B}$, or a submatrix of the transformed channel matrix for beam selection. The superscript 'H' means the conjugate transpose, which is used here for selection by the receiver.

The determination of F_A/F_B is typically performed to optimize the capacity of the channel **550** and the signal-to-noise ratio (SNR). Here, only one side antenna/beam selection is considered, i.e., at least one of F_A and F_B equals the identity matrix, and the corresponding number of RF chains equals the number of antennas.

Antenna selection is performed by switching an output signal of a transmit RF chain **502** to a selected transmit antenna, or an input signal of a selected receive antenna to a receive RF chain **501**. For beam selection, if magnitudes of all elements in the selection matrix are either zero or one, the selection **540** can be implemented in the RF domain using phase-shifters, switches, and linear combiners, Sudarshan, P., Mehta, N. B., Molisch, A. F., Zhang, J., "Spatial Multiplexing and Channel Statistics-Based RF Pre-Processing for Antenna Selection," *Globecom*, November 2004, incorporated herein by reference.

In both cases, the required number of RF chains to modulate/demodulate the transmitted/received signals is less than the total number of available transmit/receive antennas. Therefore, the cost of the system is reduced. During the initial association phase, the stations exchange information about

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the number of RF chains, the number of antenna elements, and the type of antenna/beam selection. In particular, the type of information contained in the feedback packet (e.g., whether it is the index of the antennas to be used, and/or the full (instantaneous) channel state information (CSI), and/or the average channel state information) is transmitted during that time or, alternatively, as part of the feedback packet.

MAC Based Training Scheme for MIMO Antenna/Beam Selection

LAC Frame

FIG. 5C shows the structure of a link adaptation control (LAC) frame according to an embodiment of the invention. One of the reserved bits **126** in the LAC mask field **120**, e.g., bit **127**, acts as an antenna/beam selection indicator (ASI). If the ASI field **127** is set to 1, then field **130** is used for antenna/beam selection/transmitter beam forming control, (ASBFC) **600**, as described below, otherwise the use of field **130** is conventional. That is, the field **130** functions as MCS feedback only with MFB=1. Therefore, to use the field **130** for ASBFC **600**, both ASI and MFB cannot be set to 1. Alternatively, a new 1-byte ASBFC field can be included in the LAC frame, which eliminates restriction of simultaneous ASI and MFB.

FIG. 6 shows the structure of field **600**, which includes a command field **610** and a data field **620**. When used for ASBFC, the command field **610** is defined according to Table A.

TABLE A

B0~B3	Command
0	TX Antenna/Beam Selection by TX Initiation (TXASI)
1	TX Antenna/Beam Selection by RX Initiation by RX (TXASI_RX)
2	Antenna/Beam Selection Feedback (ASFB)
3	RX Antenna/Beam Selection Initiation (RXASI)
4	TX Beam forming Initiation by RX (TXBFL_RX)
5~15	Reserved

The five commands are described in greater detail below. The data field **620** carries data for training information, e.g., the number of sounding packets used for antenna/beam selection training.

Thus, only a minor modification to the LAC mask field of the LAC frame is required to perform antenna/beam selection and training as described herein, and the field **130** can be reused whenever an MFB is not necessary.

HT Control Field

As shown in FIG. 12, the HT control field **1200** includes a LAC field **1201** according to an embodiment of the invention, which controls the fast link adaptation training process, and two other unused fields **1202-1203**, which may be dedicated for other HT control features. The LAC field **1201** is also shown in greater detail. Without considering antenna/beam selection, the LAC field includes: MRQ **1220**, MRS **1230**, i.e., MRQ sequence number, MFS **1240**, i.e., MFB sequence number, and MFB **1250** with 7 bits functioning as the MCS feedback field in the above LAC frame. Note that the HT control field can be a single HT control frame, i.e., by adding a MAC header.

The prior art HT control field does not define the bit combination of "111" in MRS. We use the bit combination 111 to reserve the MFB field, i.e. "111" in MRS functions as the ASI in LAC frame.

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Alternatively, we use the MFB field as ASBFC by using one reserved bit as ASI, either in the LAC field, or in one of the reserved portions in HT Control Field. When used for ASBFC, the structure of MFB/ASBFC is similar as in FIG. 6, except for a reduced length (from 4 bits to 3 bits) in the data field. An alternative way is to reduce the command field to 3 bits so that the data field remains 4 bits. In this case, values of 5~7 in Table A act as reserved commands. An alternative solution is to add a new ASBFC field **1260** into the HT Control field, or use one of the unused bytes as ASBFC field. Transmit Antenna/Beam Selection Training Method

The transmit antenna/beam selection can be initiated either by the transmitter **510** or by the receiver **520**. Because the receiver is constantly monitoring the channel during the communication process, it is generally more efficient for the receiver to request the transmitter to start the training process and update the antenna subset or beam steering whenever the receiver measures an unacceptable change in channel quality.

The training process rapidly transmits multiple consecutive sounding packets to the receiver, each packet for a different subset of antennas of all of the available antennas. Thus, the receiver can 'learn' or estimate a full complexity channel matrix, and select the subset of antennas or beam steering from the channel matrix. Due to the slowly changing nature of the WLAN channel **550**, the full channel matrix can be assumed to be substantially unchanged while transmitting the sounding packets.

The inter-packet time interval introduces some distortion on the estimated full channel matrix. Therefore, the interval between the consecutive sounding packets should be relatively short, and the present training scheme is designed based on this requirement.

The receiver performs the antenna/beam selection and feeds back the selected antenna subset or beam steering matrix. This is different for the case when TXBF with explicit feedback is implemented together with transmit antenna/beam selection, as described herein.

FIG. 7 shows the details of the training method with LAC frame according to an embodiment of the invention. In the following Figures, dotted lines indicate optional transfers. In the optional transfer **700**, the receiver (STA B) **520** monitors the channel quality and requests the transmitter (STA A) **510** to initiate the antenna/beam selection training process, by sending a LAC frame with ASI=1 and the command TXASI_RX.

(Receiving TXASI_RX or not) The transmitter sets its MCS selection to a reliable one, e.g., default MCS, and then sends **701** a LAC frame with ASI=1 and the command TXASI. The Data part of the field indicates the number of consecutive sounding packets that will be transmitted for training, with RTS=1 in the LAC mask field **120**.

Upon receiving the LAC frame, the receiver sends **702** a LAC frame with CTS=1. This indicates that the receiver is ready for receive the sounding packets. Also, whenever sounding packet is not applied in the system, in this LAC frame, the receiver can select to set MFB=1 and indicate a suggested MCS set, which utilizes all the available data streams in the MIMO channel, while in each of the streams the most reliable modulation and coding set is deployed.

Upon receiving the LAC frame with CTS=1, the transmitter sends **703** consecutive sounding packets, switching to different subsets of antennas for each sounding packet. Note the "fat" line indicates that the packets are transmitted immediately adjacent in time, without and other packets in either direction. Furthermore, as described above, the number of sounding packets, e.g., three as shown, is predetermined and known to both stations before the packets are transmitted.

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When sounding packet is not applied in the system, the transmitter enforces a MCS set for the same number of consecutive PHY layer training frames, which utilizes all the available data streams in the MIMO channel, while in each of data stream the most reliable modulation and coding set is deployed. Therefore, like in a sounding packet, the training information for all the available streams in the MIMO channel is covered by each of these PHY layer training frames. This MCS set can be applied directly by the transmitter, or based on the one suggested by the receiver and indicated in the previously received LAC frame, if there is any. After consecutively sending out all the training frames, the transmitter then should switch back to the previous MCS set for transmitting LAC frames. Note, the process without applying sounding packets is not depicted in FIG. 7, and in the following text, for the ease of illustration, the term "sounding packet" is used to represent both cases.

The receiver estimates the full channel matrix from the received sounding packets, and performs the antenna/beam selection accordingly. The appropriate MCS set is determined based on the selected antennas result.

After the antenna selection, the receiver sends **704** a LAC frame with RTS=1, ASI=1 and the command ASFB in the field ASBFC **600**.

Using the antenna subset used for sending the last sounding packet, the transmitter sends **705** a LAC frame with CTS=1 when the transmitter is ready to receive the antenna/beam selection feedback.

The receiver sends **706** back a packet containing the selection results.

The receiver sends **707** back a LAC frame with MFB=1, and the ASBFC field **600** contains the selected MCS set number.

The transmitter updates its selected antenna subset or beam steering correspondingly, and applies the new MCS set.

If the transmitter does not receive the ASFB after a predetermined time, the transmitter reverts to the previously selection or the default setting, and sends **708** a LAC frame with MRQ=1 to initiate a new MCS training cycle.

Based on the design of the WLAN PHY layer, the signaling and training preamble of the PHY layer packets are protected much better than a regular data field in which the MCS set is applied. Thus, even if one sounding packet for selection training is erroneously detected, its preamble can still be accurately decoded. Therefore, antenna selection training is not influenced.

For transmitting data packets, the transmitter waits for a short ACK packet, defined at the MAC layer, before transmitting the next data packet. Otherwise, timing out, the transmitter retransmits the previous data packet. While transmitting sounding packets with data for antenna/beam selection training, the transmitter switches to different antenna subsets for each consecutive sounding packet, even though the transmitter may not receive an ACK in response to sending each sounding packet.

The retransmission of 'lost' data in the sounding packets does not increase the number of sounding packets. The lost data retransmitted in the next available packet, no matter whether the packet is a sounding or a conventional packet. In another word, the antenna/beam selection training process is in parallel with the process of transmitting data using the sounding packets. The two processes are independent of each other. In an alternative implementation, it can be required that the data are retransmitted from the same antenna set, but possibly with a different MCS).

If a sounding packet is received erroneously but the preamble is received correctly, then the receiver still buffers the

corresponding channel matrix for antenna/beam selection. However, an ACK is not replied to the erroneously received sounding packet.

If a sounding packet (including its preamble) is erroneously detected or totally lost, the receiver knows that this antenna/beam selection training process has failed, and the receiver terminates the selection process. After a pre-defined time interval, if the transmitter does not receive the ASBF command from the receiver, then the transmitter switches back to the previously selected or default antenna subset or beam steering, and the transmitter sends a LAC frame with MRQ=1 to renew the MCS setting.

To improve the efficiency and reliability of the training process, the time interval between the consecutive sounding packets should be relatively short. Therefore, the amount of data transmitted in the sounding packets should be relatively small. The determination of the length of data packet is beyond the functionality of MAC layer. However, a function block that determines the length of the data to be transmitted, taking into account the required overhead of a sounding packet, as well as the MCS scheme on the different channels, so that the total net throughput is optimized.

If the sounding packets contain no data, which is an alternative option, then the channel estimation is most accurate, and the time required for the whole training process is reduced. Therefore, there is a tradeoff problem between efficiency and performance.

In the case that sounding packets are not allowable and the alternative PHY training frame (packet) with the enforced MCS set is applied for training (as described above), when the number of RF chains at the transmitter is larger than the maximum number of data streams provided by the MIMO channel, i.e., the channel rank, if data are transmitted with the PHY layer training packet, each data stream should contain the independent training sequences with a number equal to the channel rank. If the training packets contain no data, the number should equal to the number of RF chains of the transmitter, so that the required number of training packets is reduced correspondingly. This is another potential advantage of not including data in the training packets.

The transmitter knows the ordering of antennas in the subsets of the different sounding packets, while the receiver simply numbers the antenna indexes by the order of the arriving sounding packets. Therefore, the transmitter can translate the antenna selection feedback, and select the corresponding subset of antennas.

The formatting and queuing of the selection feedback packet can vary based on different antenna/beam selection processes. One example is, when selecting N_{A_SS} antennas/beams from N_A antennas, one $N_A \times N_{A_SS}$ matrix F_A is fed back. For pure antenna selection, F_A contains only 0 and 1 which is a permutation of N_{A_SS} columns of the $N_A \times N_A$ identity matrix; while for RF beam steering, F_A contains phase shift factors.

ASI 127 and MFB 125 bits in LAC Mask field 120 cannot be set to 1 simultaneously. On the forward link (from STA A to STA B in FIG. 7), because the training process does not require any MCS updating before the new selection result is set, there is no influence if the constrain MFB=0 is applied. On the reverse link, because MCS feedback can only be sent from STA A to STA B whenever ASI=0, there is a possibility that an MFB is delayed by the antenna/beam selection training process. On the other hand, if the updated antenna subset or RF steering at STA A is also be applied on the reverse link, there is no necessity to do MCS updating on the reverse link

before finishing the entire training process. Generally speaking, this confliction problem between ASI and MFB does not impact on the system.

The extension to training using the HT control field is straightforward. In FIG. 7 "LAC" should be replaced by "HT Control Field"; "ASI=1" should be replaced by "MRS=111" or "ASI=1" for the case ASI is used to indicate a reuse of the MFB field.

Receive Antenna/Beam Selection Training Process

FIG. 8 shows a receive antenna/beam selection training process with LAC frame initiated by the receiver. The receiver receives multiple sounding packets from the transmitter, and switches its RF chains to different antenna subsets on receiving the different sounding packets. This enables the receiver to estimate the entire channel matrix and perform antenna/beam selection.

The receiver 520 sends a LAC frame 801 with ASI=1, the command RXASI, and the data part in ASBFC field contains the required number of sounding packets.

Similar as in transmit selection training, for protecting LAC frames and the data in the sounding packets (if there are any) from mismatched MCS sets, the transmitter resets MCS upon receiving the RXASI command. Similarly, for the case where sounding packet cannot be applied, the transmitter enforces a MCS set for the consecutive PHY layer training frames, which utilizes all the available data streams in the MIMO channel, while in each data stream, the most reliable modulation and coding set is deployed. This process is not depicted in FIG. 8, and the term "sounding packet" is used to represent both cases.

Upon receiving the first RXASI command, the transmitter 510 sends a LAC frame 802 with RTS=1, and the receiver responds with a LAC frame 803 with CTS=1, and the transmitter sends the sounding packets 804.

At the receiver, when the preamble in the sounding packets is correctly detected, even if the data are not, the receiver continuous to estimate the channel and to conduct antenna/beam selection, but no ACK is sent back if data field is not detected correctly.

If a sounding packet (including its preamble) is lost, the receiver switches back to the previous antenna subset or steering setting, and does the corresponding MCS determination.

Data lost in any sounding packet is retransmitted in a later packet.

Then, the receiver sends a LAC frame 805 with MFB=1, and the MCS feedback indicating the selection.

Upon receiving the first RXASI command, the transmitter starts a clock, if no MCS feedback 805 is received after a time out threshold, which means that the current training process probably failed, the transmitter sends a MRQ to renew the MCS setting.

The other concerns, such as the data length (or no data) in the sounding packets, the number of independent training sequences, and the confliction of MFB and ASI, can be similarly addressed as in the transmitter antenna/beam selection case.

The extension to training using the HT control field is straightforward. In FIG. 7 "LAC" should be replaced by "HT Control Field"; "ASI=1" should be replaced by "MRS=111" or "ASI=1" for the case ASI is used to indicate a reuse of the MFB field.

Receiver Initiated Transmit Beam Forming

As described above, only the transmitter can initiate TXBF training in the prior art. Because the receiver can always monitor the steered channel quality, e.g., the orthogonality among the steered column vectors in MIMO channel matrix in eigen beam forming schemes, it is more efficient for the

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receiver to initiate the TXBF training, whenever the receiver detect an unacceptable steering.

The method as described herein can perform receiver initiated training, by using the command TXBFI_RX.

FIG. 9 shows the TXBF training process initiated by the receiver with LAC frame. The training process assumes that the RTS/CTS exchange has been completed.

The receiver sends a LAC frame **901** with ASI=1, and command TXBFI_RX. The transmitter responds with a LAC frame **902**, with TRQ=1, or directly sends TRQ as the conventional scheme in FIG. 4. The receiver sends one sounding packet **903**. The transmitter estimate the channel, updates the steering matrix, and finally replies with a LAC frame **904** with MRQ=1, to initiate a new MCS training cycle.

The extension to training using the HT control field is straightforward. In FIG. 7 "LAC" should be replaced by "HT Control Field"; "ASI=1" should be replaced by "MRS=11" or "ASI=1" for the case ASI is used to indicate a reuse of the MFB field.

Antenna/Beam Selection Combining with TXBF

As described above, transmit beam forming (TXBF) is another effective close-loop MIMO scheme that increases throughput and reliability of the system. Therefore, it is desired to combine antenna/beam selection with TXBF. Note that the antenna/beam selection training process requires explicit feedback of the selection result, which is usually one matrix, while TXBF can require either explicit feedback of the channel matrices of all the subcarriers in an MIMO-OFDM system applied in high-throughput WLANs, or implicit feedback, where the transmitter can update its beam forming steering matrix based on what the transmitter estimates from the reverse link, assuming the channels on the forward and reverse links are reciprocal. A calibration process, which typically happens only upon associations, is then required for the enforcement of the reciprocity assumption, which needs to be addressed when combining with antenna/beam selections. When explicit feedback is used for TXBF training, it is possible to combine antenna/beam selection with TXBF. Furthermore, because the entire channel matrix can be fed back from the receiver to the transmitter, there is no need for a separate TXBF training. For transmit antenna/beam selection, the transmitter can calculate its selections (instead of at the receiver as in FIG. 7), the beam forming matrices, and the corresponding MCS set, all based on the feedback values. For receiver selections, the selection is determined and applied at the receiver while the beam forming matrices are performed at the transmitter.

As an alternative implementation, it is also possible to perform antenna selection and TXBF as separate operations, where the selection process is performed as described in the previous sections, while the TXBF is done using an implicit feedback scheme (as described, e.g., in the TGnSync draft specifications), possibly at different intervals compared to the antenna selection.

When implicit feedback is used for TXBF training, it is also possible for the receiver to perform antenna/beam selection without any significant modification on the training process, because the transmitter side calibration is sufficient for performing TXBF training.

The training process in FIG. 8 is then correspondingly modified as shown in FIG. 10. The receiver sends a LAC frame **1001** with ASI=1, and command RXASI. The transmitter sets the default MCS, switches to unsteered or basic MIMO mode, and replies with a LAC frame **1002** with RTS=1. The receiver responds with a LAC frame **1003** with CTS=1, which causes the transmitter to send the sounding packets **1004**. The receiver performs channel estimation and

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antenna/beam selection, and responds with a LAC frame **1005** with ASI=1, and command TXBFI_RX, which initiates a TXBF training process. Upon receiving TXBFI_RX or after a predetermined time out threshold, the transmitter sends a LAC frame **1006** with TRQ=1 to start TXBF training. After updating the TXBF steering matrices, the transmitter sends a LAC frame **1007** with MRQ=1 to initiate a new MCS training cycle.

Note, the receiver only selects antennas without determining the corresponding MCS, and after updating the selection result, the transmitter initiates the TXBF and MCS training processes subsequently.

Finally, with implicit feedback used for TXBF training, if the selection is performed at the transmitter, then both the calibration process and antenna/beam selection training process is modified correspondingly.

For example, there are

$$N_S = \begin{pmatrix} N_A \\ N_{A_{SS}} \end{pmatrix}$$

possible antenna subsets at the transmitter STA A, for calibration. The transmitter switches the RF chains to the first subset of antennas and conducts the calibration process. The transmitter then switches the RF chains to the next antenna subset and conducts calibration. This process is repeated until all subsets have been calibrated. The transmitter stores the corresponding calibration correction matrices $K_1 \sim K_{N_S}$ for further use.

During a normal transmission mode, if the antenna subset $\mathbf{I}_e[1, N_S]$ is used for transmission, then the corresponding calibration matrix K_i is applied at the transmitter RF chains. During antenna selection, the transmitter switches to a new calibration matrix whenever the antenna subset is updated.

FIG. 11 shows the corresponding training process. The receiver sends a LAC frame **1101** with ASI=1, and command TXASI_RX (this step is optional as in FIG. 7). The transmitter sets the default MCS, switches to unsteered or basic MIMO mode, and replies with a LAC frame **1102** with ASI=1, and the number of packets in the data part of ASBFC field. The receiver responds with a LAC frame **1103** with CTS=1, which causes the transmitter to send the sounding packets **1104**. The receiver performs channel estimation and antenna/beam selection, and responds with a LAC frame **1105** indicating the completion of selection with RTS=1 as described above. The transmitter retains the antenna subset corresponding to the last sounding packet, and responds with a LAC frame **1106** with CTS=1. The receiver feeds back the selection result **1107**. This causes the transmitter to update the antenna subset or the steering, and apply the corresponding calibration matrix. Then, the transmitter sends a LAC frame **1108** with TRQ=1 to start TXBF training. Lastly, after updating the TXBF beam steering, the transmitter sends a LAC frame **1109** with MRQ=1 to initiate a new MCS training cycle.

The extension to training using the HT control field is straightforward. In FIG. 7 "LAC" should be replaced by "HT Control Field"; "ASI=1" should be replaced by "MRS=111" or "ASI=1" for the case ASI is used to indicate a reuse of the MFB field.

Variations

The above described methods can also be applied to the cases where the system is frequency-selective, such as OFDM systems according to the IEEE 802.11n standard, because both pure antenna selection and beam selection can be imple-

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mented, regardless of frequency. RF-baseband processing has the advantage because the performance gain is independent of frequency-selectivity, while the gain by pure antenna selection tends to be averaged out by frequency-selectivity.

The embodiments described herein use the LAC frame and a HT Control Field. The invention can be used for any similarly defined signaling frame in a MAC layer that allows a fast communication between the transmitter and receiver, in which one bit or bit combination is used to indicating an antenna/beam selection training frame, and any suitable field with a length of at least 7 bits in the control frame can be used for exchanging the selection training information. This field can either be a reused field from the one used for MCS feedback, or a newly defined field dedicated only for antenna/beam selection training. In the latter case, the restriction in simultaneous antenna/beam selection training and MCS feedback is not required.

When both the transmitter and the receiver have antenna/beam selection capability, the training process can alternate on both sides with marginal performance degradation, compared with selecting on both side simultaneously. Yet another alternative would be to increase the number of training packets, making sure that the total number of spatial streams (taken over all training packets) is sufficient for a complete training of the packet.

Yet another alternative is the transmission of dummy data, i.e., data that do not carry useful information, but rather are values that make sure that the transmit signal during the data transmission has the form of a training field, known at the receiver.

Alternating Sounding and Reply Packets

FIG. 13 shows another embodiment of the invention, regarding the transmit antenna/beam selection training using signaling by an HT control field or other MAC signaling. The basic idea is that the transmitter transmits multiple sounding packets 1301, each of which contains an HT control field in the MAC frame as described above.

Information about the antenna selection is included in these HT control field (or similar) that is sent with each of the sounding packets. In the following, we describe one (of many possible) particular implementations.

One sounding packet is transmitted for each of subset of antennas. In each of the sounding packets, MRS/ASI 1230 is set to 111, the command portion 610 in MFB/ASBFC field 1250 is set to TXASI, and data portion 620 of MFB/ASBFC field 1250 of HT Control field 1200 is used to indicate the remaining number of sounding packets to be sent. Alternatively, the control field can also just indicate that a sounding packet is the first (last) of a sequence of sounding packets intended for antenna selection.

The receiver feeds back a packet 1302 containing CSI for each corresponding sounding packet 1301 as each sounding packet is received. In other words, the sounding packets and feedback alternate for each subset of antennas.

Alternatively or additionally, the receiver can feed back the information about which subset of antennas should be used subsequently. This feedback occurs after the last sounding packet has been received.

As shown in FIG. 14, the receiver can also elect to reply 1402 to each of the sounding packets 1401 after all sounding packets are received.

Regarding the feedback structure, if explicit partial CSI, explicit full-size CSI, and antenna selection results are all possible to be applied, additional signaling can be required to differentiate the selection. One possible solution is to utilize

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the reserved commands in the command portion 610 of the MFB/ASBFC field 1250. Another way uses the data portion 620 of MFB/ASBFC field 1250, when the command portion 610 is set to ASFB, so the data portion 610 is not used to indicate the number of sounding packets. Also, feedback structures already defined for other purposes might be used.

Similarly, if different training protocols as shown in FIGS. 7, 13, and 14 coexist, extended command portion 610 may be required to differentiate the protocols. The large number of reserved commands guarantees the possibility of the above extensions.

Although the invention has been described by way of examples of preferred embodiments, it is to be understood that various other adaptations and modifications may be made within the spirit and scope of the invention. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the invention.

We claim:

1. A method for selecting antennas in a multiple-input, multiple-output wireless local area network including a plurality of stations, each station includes a set of antennas, the method comprising the steps of:

receiving multiple transmitted sounding packets in a station, each sounding packet corresponding to a different subset of the set of antennas;

estimating, in the station, a channel matrix for each subset of antennas; and

sending, by the station, a frame including a high throughput (HT) control field to initiate a selecting of antennas after estimating the channel matrix for each subset of antennas, such that a subset of the antennas is selected according to the channel matrices, in which the HT control field includes a MCS selection feedback (MFB) field, and if an ASI field is set to "1" or if an MRS field is set to "111", then the MFB field is used for antenna selection, beam selection, or as a transmitter beam forming control (ASBFC) field, in which ASBFC field includes a command subfield and a data subfield, and in which the data subfield indicates a number of the multiple sounding packets.

2. The method of claim 1, in which the HT control field includes a link adaptation control (LAC) field, and the LAC field includes either an antenna selection or a beam selection indicator (ASI) field.

3. The method of claim 1, in which the data subfield indicates a number of remaining sounding packets to be received.

4. The method of claim 1, in which the data subfield indicates a first of the multiple sounding packets.

5. The method of claim 1, in which the data subfield indicates a last of the multiple sounding packets.

6. The method of claim 1, in which the selected antennas are receive antennas.

7. The method of claim 1, in which the selected antennas are transmit antennas.

8. The method of claim 1, in which all steps operate at a media access control layer of the network.

9. The method of claim 1, in which the multiple sounding packets include data.

10. The method of claim 1, in which a size of a particular sounding packets is minimized by excluding data.

11. The method of claim 1, further comprising: selecting beams according to the channel matrix.

12. The method of claim 1, further comprising: indicating the selected subset of antennas by an index.

13. The method of claim 1, in which the station is a receive station.

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14. The method of claim **1**, in which the station is a transmit station.

15. The method of claim **1**, where the sounding packets are transmitted using each subset of antennas of a transmit station.

16. The method of claim **1**, in which each frame is replied after receiving each corresponding sounding packet.

17. The method of claim **1**, in which each frame is replied after receiving all sounding packets.

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18. The method of claim **1**, in which the ASBFC field specifies a manner in which the subset of antennas is to be selected.

19. The method of claim **18**, in which the selection is according to the channel matrix.

20. The method of claim **18**, in which the selection is according to antenna indices.

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