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**Sutskover et al.**

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(54) **BIDIRECTIONAL ITERATIVE BEAM FORMING**

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(51) **Int. Cl.**

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| ***H04B 1/00*** | (2006.01) |
| ***H04B 15/00*** | (2006.01) |
| ***H04W 72/04*** | (2009.01) |
| ***H01Q 3/26*** | (2006.01) |
| ***H04B 7/06*** | (2006.01) |
| *H04B 7/00* | (2006.01) |

(52) **U.S. Cl.**

CPC ..... ***H04W 72/046*** (2013.01); ***H01Q 3/26*** (2013.01); ***H04B 7/0617*** (2013.01); ***H04B 7/0632*** (2013.01); ***H04B 7/0682*** (2013.01)

(58) **Field of Classification Search**

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USPC ..... 455/25, 69, 524, 525, 561, 562.1; 370/329

See application file for complete search history.

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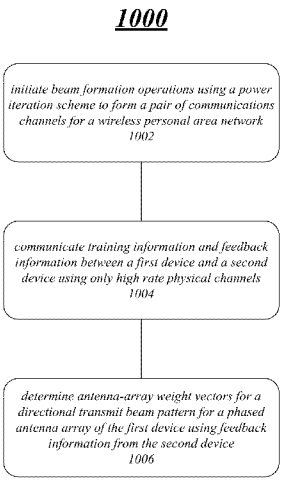
(57) **ABSTRACT**

Bidirectional iterative beam forming techniques are described. An apparatus may include a wireless device having an antenna control module operative to initiate beam formation operations using an iterative training scheme to form a pair of communications channels for a wireless network, the antenna control module to communicate training signals and feedback information with a peer device via the transceiver and phased antenna array using partially or fully formed high rate channels, and iteratively determine antenna-array weight vectors for a directional transmit beam pattern for the phased antenna array using feedback information from the peer device. Other embodiments are described and claimed.

**31 Claims, 12 Drawing Sheets**



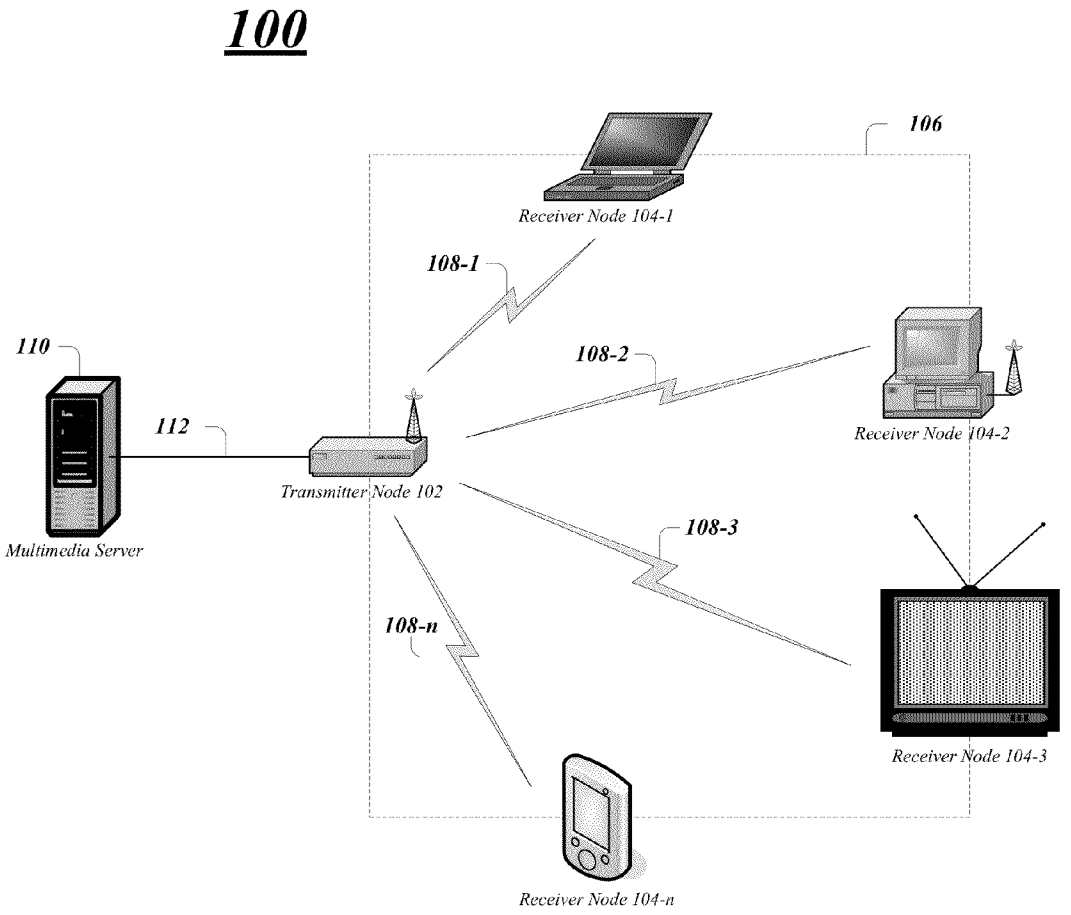

100
106
Receiver Node 104-1
108-1
110
108-2
112
Receiver Node 104-2
Transmitter Node 102
Multimedia Server
108-3
108-n
Receiver Node 104-3
Receiver Node 104-n

FIG. 1

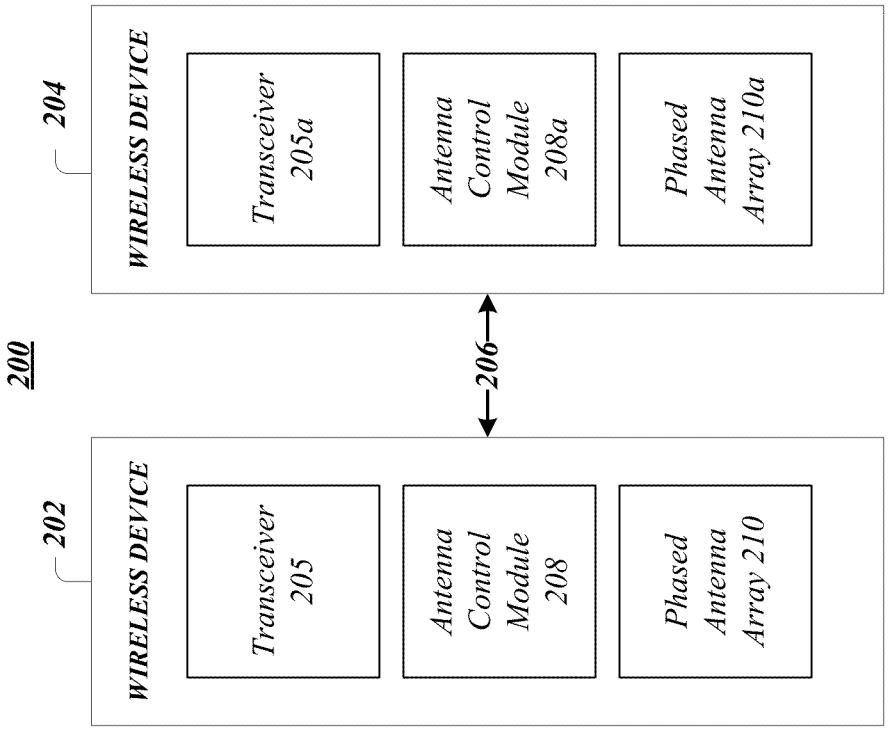

200
202
WIRELESS DEVICE
Transceiver 205
Antenna Control Module 208
Phased Antenna Array 210
206
204
WIRELESS DEVICE
Transceiver 205a
Antenna Control Module 208a
Phased Antenna Array 210a

FIG. 2

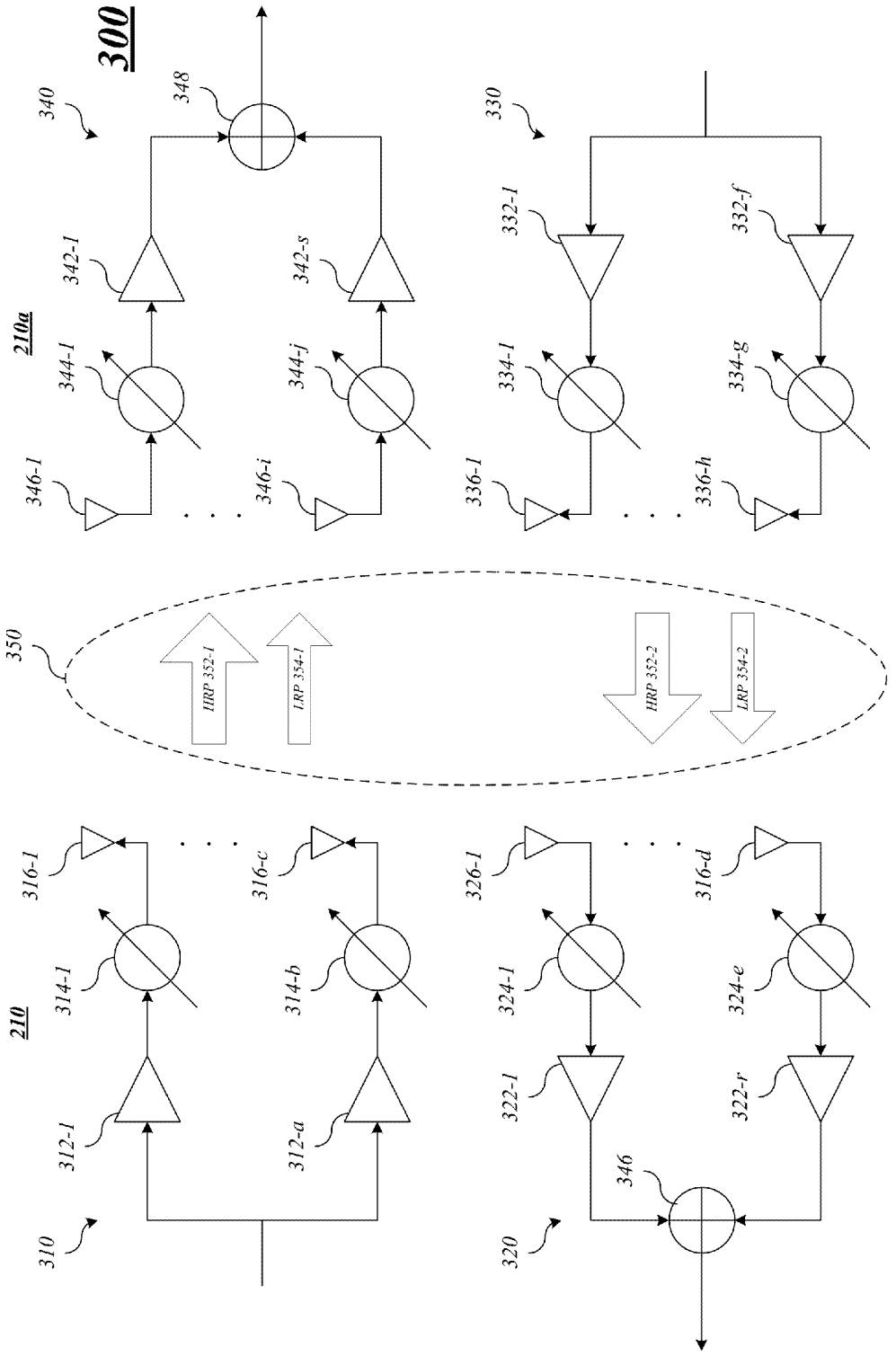

300
340
348
210a
342-1
342-s
344-1
344-j
346-1
346-i
330
332-1
332-f
334-1
334-g
336-1
336-h
350
HRP 352-1
LRP 354-1
HRP 352-2
LRP 354-2
210
316-1
316-c
314-1
314-b
312-1
312-a
310
326-1
316-d
324-1
324-e
322-1
322-r
346
320

FIG. 3

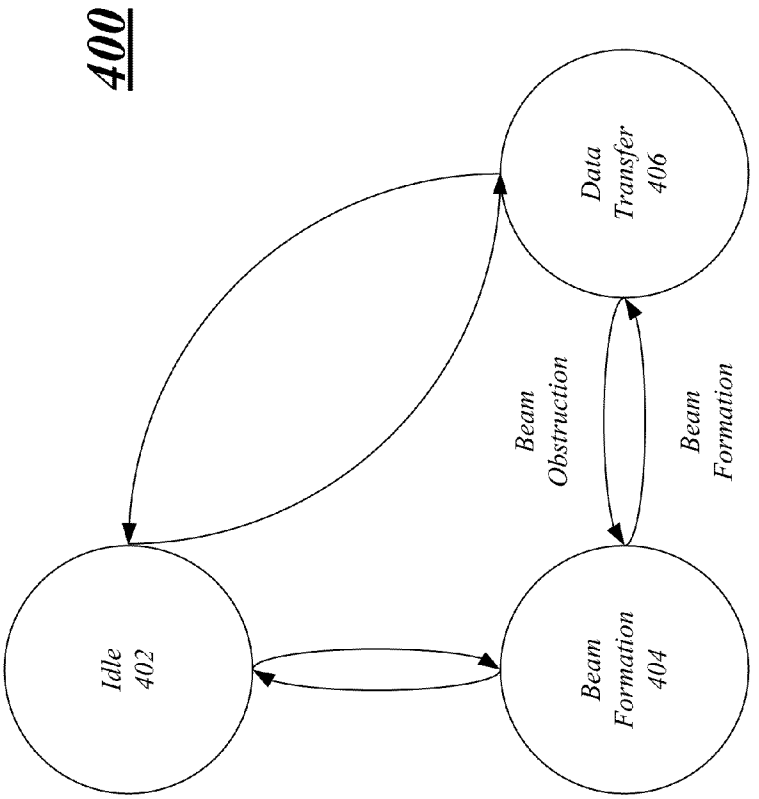

400
Idle
402
Beam
Formation
404
Data
Transfer
406
Beam
Obstruction
Beam
Formation

FIG. 4

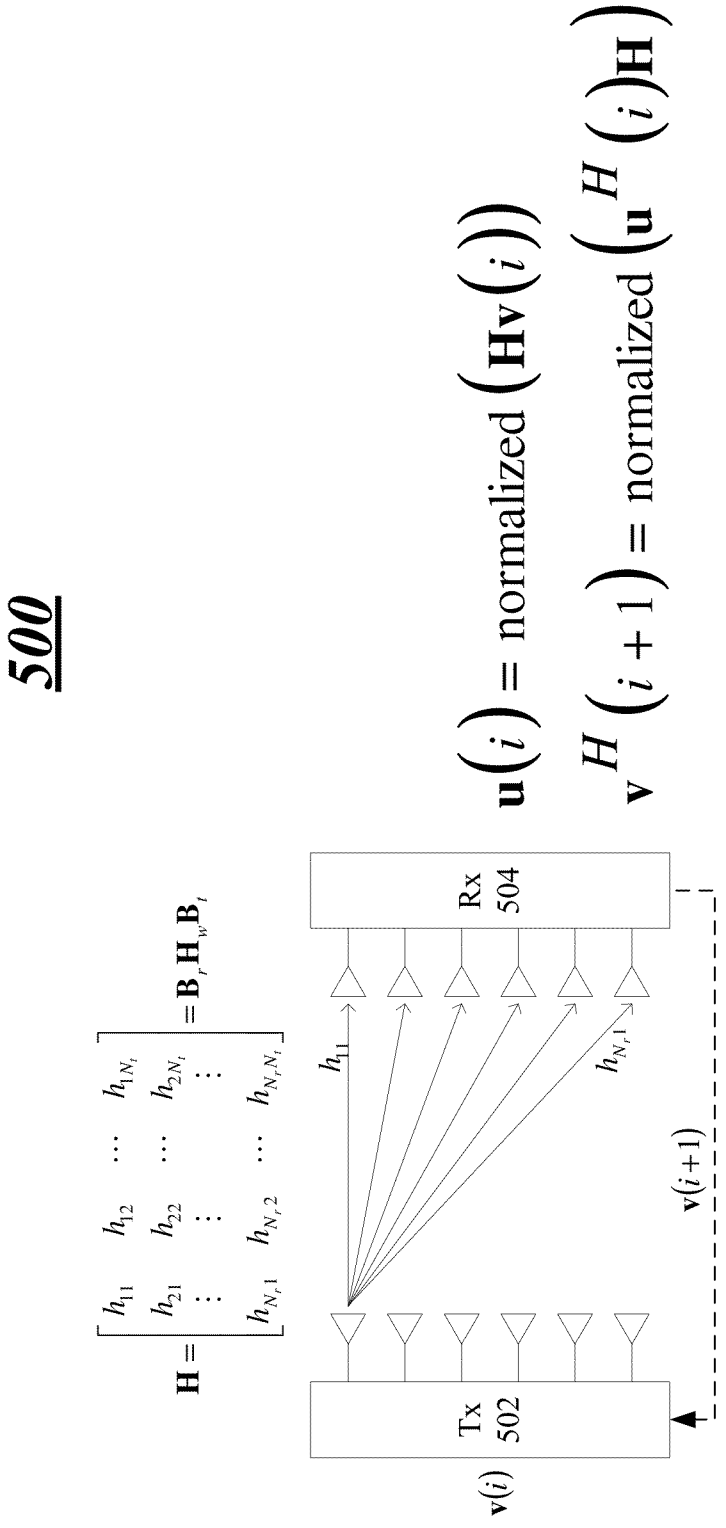

500
$\mathbf{u}(i) = \text{normalized}\left(\mathbf{H}\mathbf{v}(i)\right)$
$\mathbf{v}^H(i+1) = \text{normalized}\left(\mathbf{u}^H(i)\mathbf{H}\right)$
$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{bmatrix} = \mathbf{B}_r\mathbf{H}_w\mathbf{B}_t$
Tx 502
Rx 504
$\mathbf{v}(i)$
$\mathbf{v}(i+1)$
$h_{11}$
$h_{N_r1}$

FIG. 5

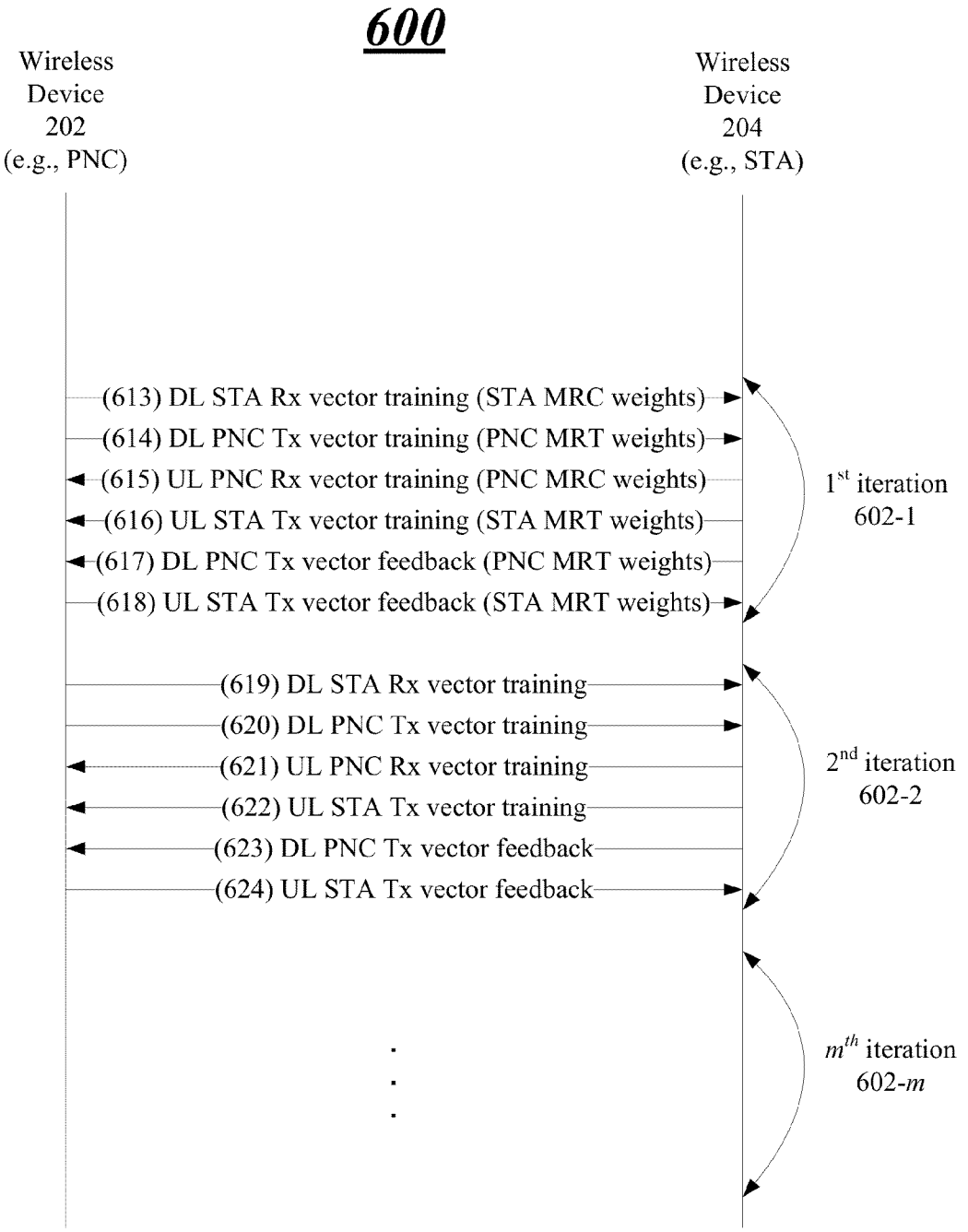

600
Wireless Device 202 (e.g., PNC)
Wireless Device 204 (e.g., STA)
(613) DL STA Rx vector training (STA MRC weights)
(614) DL PNC Tx vector training (PNC MRT weights)
(615) UL PNC Rx vector training (PNC MRC weights)
(616) UL STA Tx vector training (STA MRT weights)
(617) DL PNC Tx vector feedback (PNC MRT weights)
(618) UL STA Tx vector feedback (STA MRT weights)
1st iteration 602-1
(619) DL STA Rx vector training
(620) DL PNC Tx vector training
(621) UL PNC Rx vector training
(622) UL STA Tx vector training
(623) DL PNC Tx vector feedback
(624) UL STA Tx vector feedback
2nd iteration 602-2
mth iteration 602-m

*FIG. 6A*

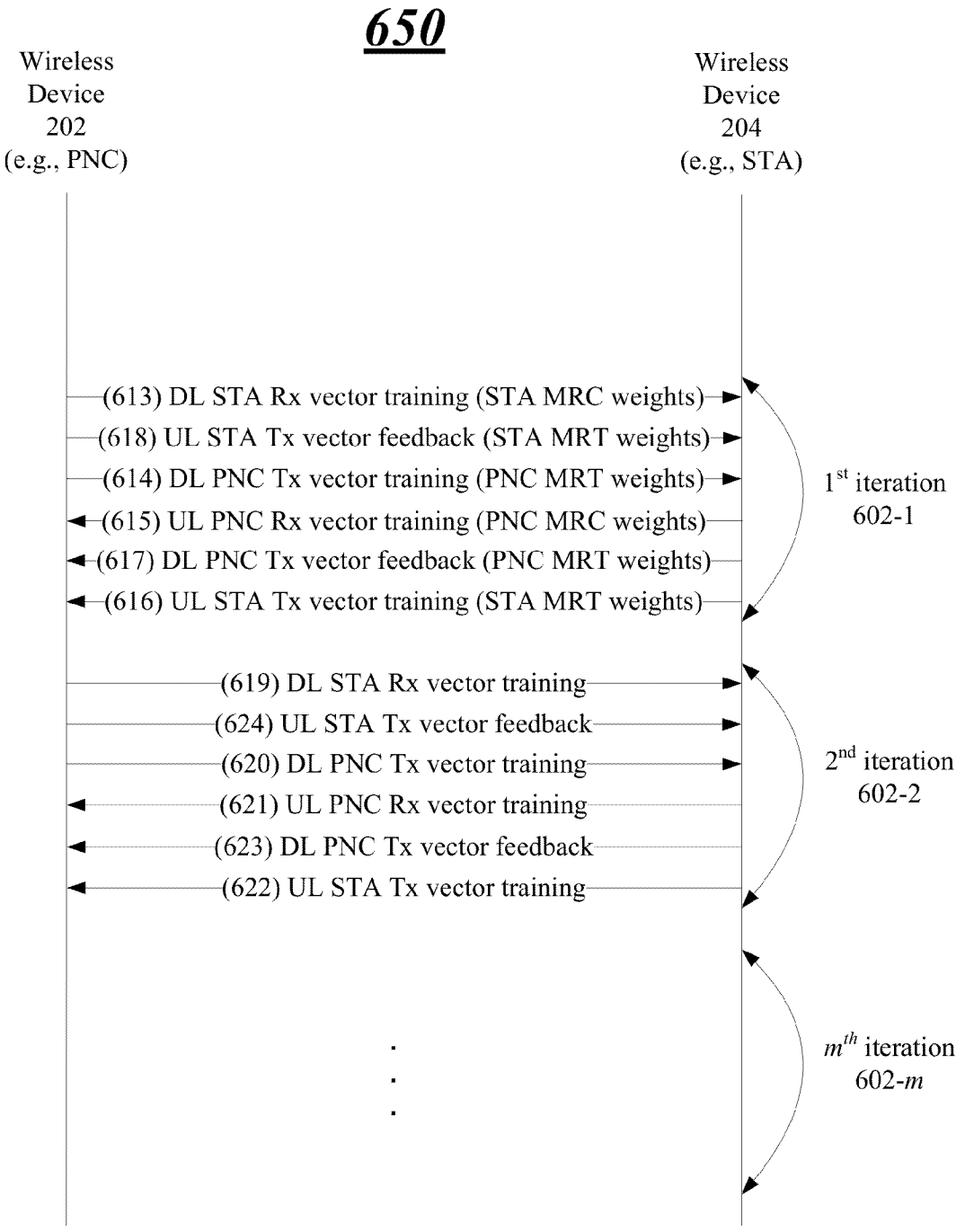

650
Wireless Device 202 (e.g., PNC)
Wireless Device 204 (e.g., STA)
(613) DL STA Rx vector training (STA MRC weights)
(618) UL STA Tx vector feedback (STA MRT weights)
(614) DL PNC Tx vector training (PNC MRT weights)
(615) UL PNC Rx vector training (PNC MRC weights)
(617) DL PNC Tx vector feedback (PNC MRT weights)
(616) UL STA Tx vector training (STA MRT weights)
1st iteration 602-1
(619) DL STA Rx vector training
(624) UL STA Tx vector feedback
(620) DL PNC Tx vector training
(621) UL PNC Rx vector training
(623) DL PNC Tx vector feedback
(622) UL STA Tx vector training
2nd iteration 602-2
mth iteration 602-m

*FIG. 6B*

***700***

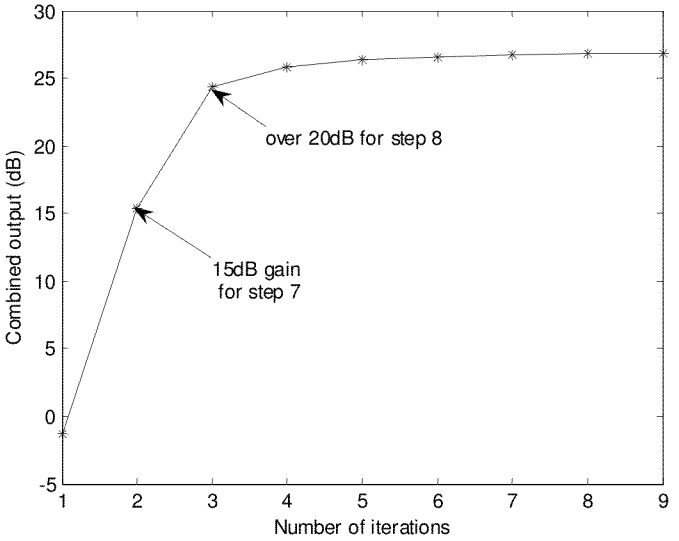

30
25
20
15
10
5
0
-5
1
2
3
4
5
6
7
8
9
Combined output (dB)
Number of iterations
over 20dB for step 8
15dB gain
for step 7

*FIG. 7*

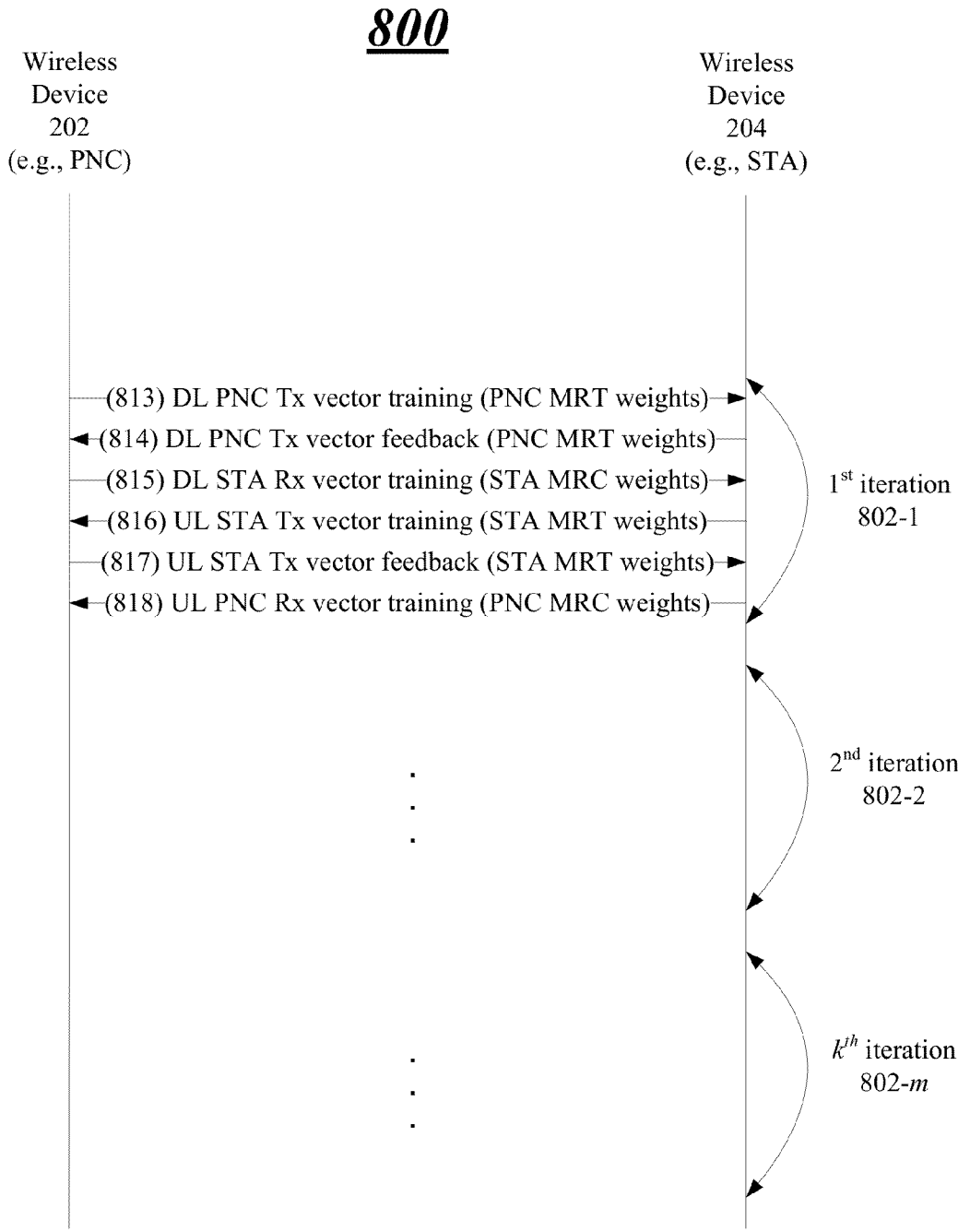

800
Wireless Device 202 (e.g., PNC)
Wireless Device 204 (e.g., STA)
(813) DL PNC Tx vector training (PNC MRT weights)
(814) DL PNC Tx vector feedback (PNC MRT weights)
(815) DL STA Rx vector training (STA MRC weights)
(816) UL STA Tx vector training (STA MRT weights)
(817) UL STA Tx vector feedback (STA MRT weights)
(818) UL PNC Rx vector training (PNC MRC weights)
1st iteration 802-1
2nd iteration 802-2
kth iteration 802-m

*FIG. 8*

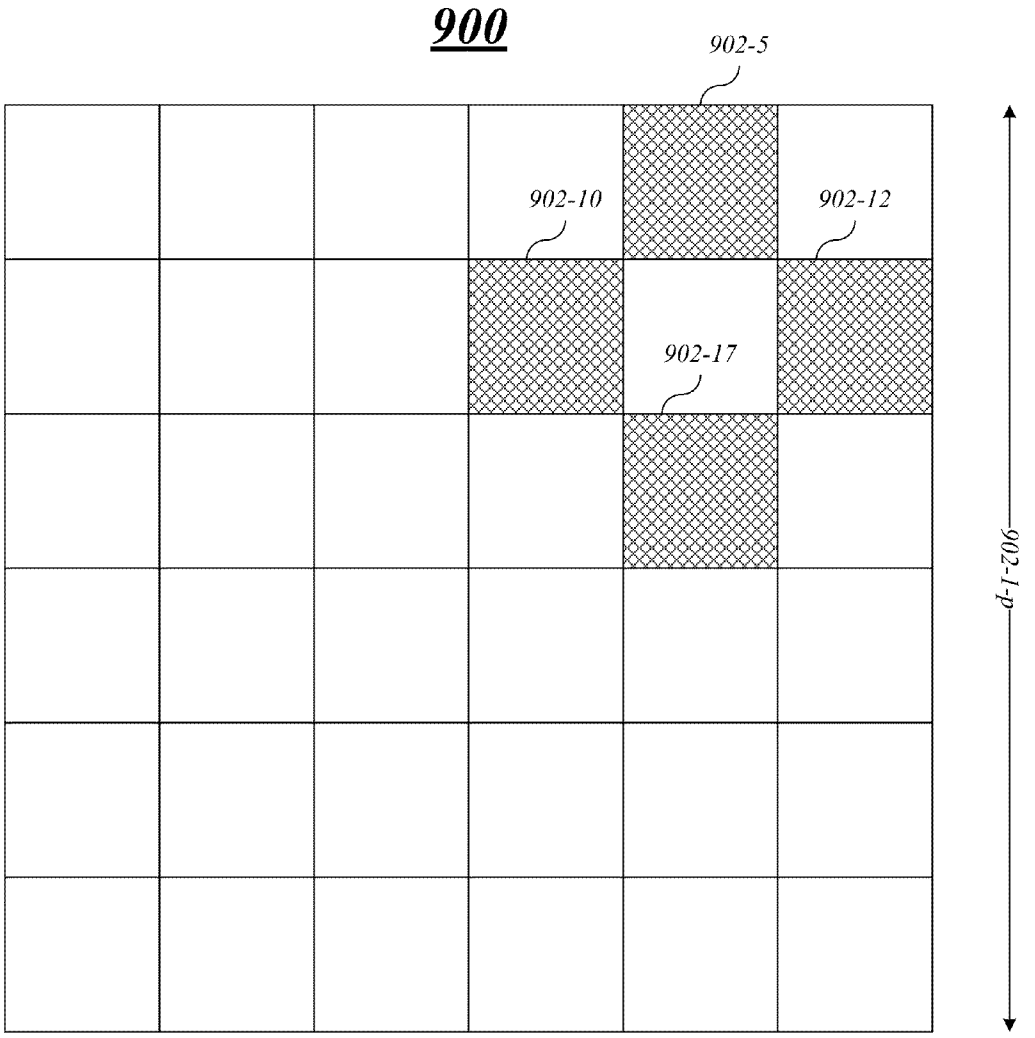



*FIG. 9*

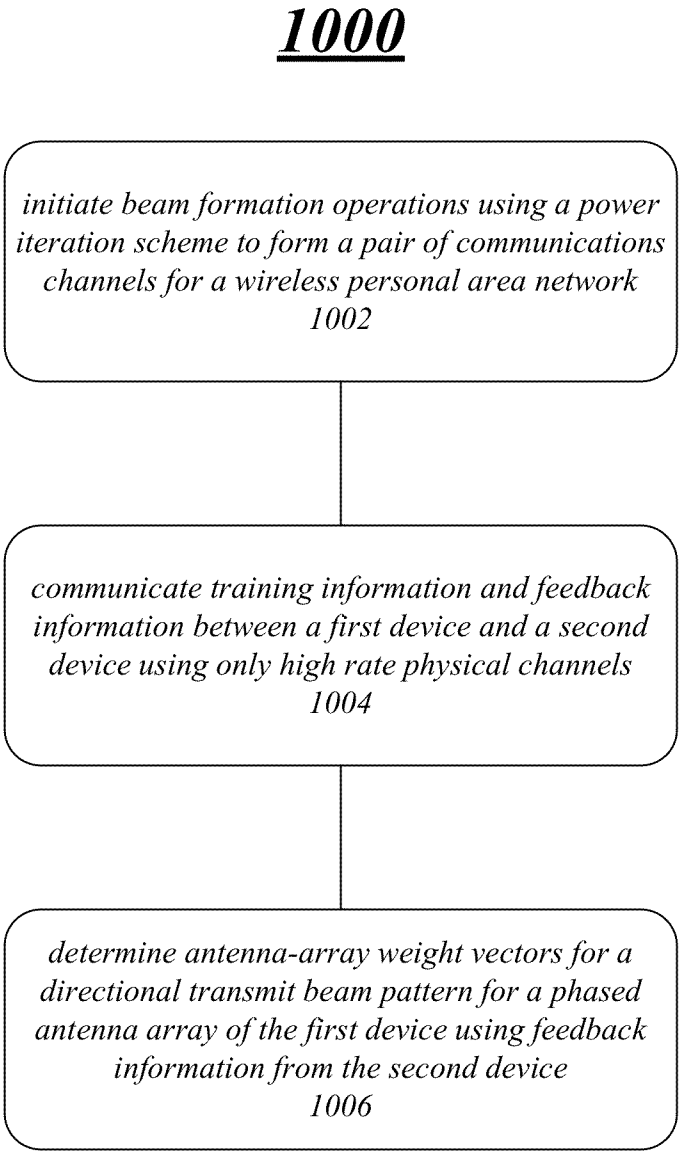

1000
initiate beam formation operations using a power iteration scheme to form a pair of communications channels for a wireless personal area network
1002
communicate training information and feedback information between a first device and a second device using only high rate physical channels
1004
determine antenna-array weight vectors for a directional transmit beam pattern for a phased antenna array of the first device using feedback information from the second device
1006

FIG. 10

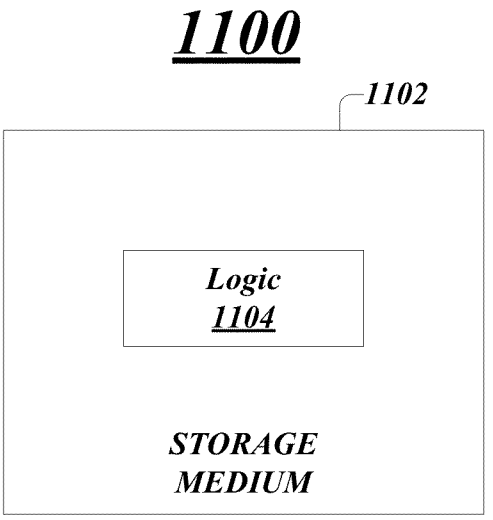



FIG. 11

# BIDIRECTIONAL ITERATIVE BEAM FORMING

## CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of, claims benefit of, and priority to, U.S. patent application Ser. No. 12/262,904, filed Oct. 31, 2008, entitled "BIDIRECTIONAL ITERATIVE BEAM FORMING", and U.S. patent application Ser. No. 12/939,417, filed Nov. 4, 2010, entitled "BIDIRECTIONAL ITERATIVE BEAM FORMING", both of which are incorporated herein by reference in their entirety.

## BACKGROUND

Wireless communication systems communicate information over a shared wireless communication medium such as one or more portions of the radio-frequency (RF) spectrum. Recent innovations in Millimeter-Wave (mmWave) communications operating at the 60 Gigahertz (GHz) frequency band promises several Gigabits-per-second (Gbps) throughput within short ranges of approximately 10 meters. Because of the large signal attenuation and limited transmission power, many 60 GHz devices will rely on antenna arrays with high directivity gain to achieve the 10 meter coverage. These devices use techniques to steer a "beam" from a transmitter antenna array around obstacles to find the best path to a receiver antenna array, thereby directing much of the antenna gain towards the receiver antenna array. Techniques to discover and direct energy between antenna arrays of peer devices is typically referred to as "beam forming" or "beam steering" or "beam searching." Beam forming generally attempts to steer an antenna beam at a transmitter while at the same time focusing a receiver antenna in the direction of incoming power from the transmitter. Conventional beam forming protocols, however, typically take a significant amount of training time before a final high-speed communication channel is established between peer devices. Consequently, techniques designed to reduce overhead associated with training time are desirable.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates one embodiment of a communications system.

FIG. **2** illustrates one embodiment of a wireless network.

FIG. **3** illustrates one embodiment of a phased antenna array.

FIG. **4** illustrates one embodiment of a state diagram.

FIG. **5** illustrates one embodiment of an iterative training scheme.

FIG. **6**A illustrates one embodiment of a first message flow.

FIG. **6**B illustrates one embodiment of a second message flow.

FIG. **7** illustrates one embodiment of a graph for beam forming gain.

FIG. **8** illustrates one embodiment of a third message flow.

FIG. **9** illustrates one embodiment of a phased antenna array.

FIG. **10** illustrates one embodiment of a logic flow.

FIG. **11** illustrates one embodiment of an article of manufacture.

## DETAILED DESCRIPTION

Various embodiments may be generally directed to bidirectional iterative beam forming techniques for wireless communication systems. Some embodiments may be particularly directed to an enhanced bidirectional beam forming protocol designed to concurrently generate bidirectional communication channels between two or more wireless devices over a wireless network, such as a 60 Ghz mmWave wireless video area network (WVAN) or wireless personal area network (WPAN), for example. Such networks are sometimes referred to as "piconets" due to their limited transmission ranges and participating devices. The enhanced bidirectional beam forming protocol generates additional antenna gain for directional antenna transmissions, thereby allowing training and feedback information to be communicated at a higher data rate, resulting in reduced training time and overhead in setting up bidirectional communication channels between two wireless devices.

Since the path loss at 60 GHz band is relatively high and the efficiency of power amplifiers at 60 GHz is relatively low (e.g., CMOS power amplifiers), directional transmission is needed to achieve the desired coverage area (e.g., approximately 10 meters). Namely, the antenna array gain from both transmit and receive beam forming is needed to acquire the signal-to-noise ratio (SNR) for reliable data communications. A beam forming protocol is typically used to find the optimal phase values which maximize receiver SNR, received power or other criterion.

Currently, there are several different types of beam forming protocols for implementing directional transmission techniques. A first directional transmission technique is referred to as a sector scan. It forms several directional beams using predefined weights. Calibration is required, however, in order to form the requisite beams. Another technique is based on singular value decomposition (SVD), which typically does not require calibration. SVD allows transmission over selected singular values by using the singular vectors for antenna patterns. In particular, the singular vector associated with the largest Eigen value typically works well. It is worthy to note, however, that in order to select the singular values and singular vectors, a device typically has to have an estimation of the entire MIMO channel, e.g., the channel from every antenna element at the transmitter to every antenna element at the receiver end. While the SVD technique provides improved performance, it needs feedback information due to lack of channel reciprocity. This potentially introduces channel delay into the SVD directional transmission technique.

A piconet typically implements two general types of communications transmissions, each having different transmission envelopes or characteristics. For example, a first type of transmission may be a directional transmission and a second type of transmission may be an omni-directional transmission. The different types of transmissions may occur at different transmission rates. For example, directional transmissions may be performed using a higher rate channel, and the second type of transmission may be performed using a lower rate channel. In a WirelessHD network, for example, the directional transmissions may be performed using a high rate physical (HRP) channel, and the second type of transmission may be performed using a low rate physical (LRP) channel. The HRP channel may achieve a higher rate than the LRP channel, in part, through the utilization of larger amounts of bandwidth.

Since the location of a pair of devices is unknown during initialization, conventional techniques typically utilize a combination of LRP channels and HRP channels for beam forming operations. For example, one conventional technique utilizes a beam forming protocol for phased array antennas that is based on an iterative training scheme. In one embodiment, for example, the iterative trainings scheme may com-

prise a power iteration scheme. This beam forming protocol designed for one way high rate data transmissions over a HRP channel, where the reverse link suffers from low rate data transmissions over a LRP channel. Feedback information for the iterative search process is transmitted over the LRP channel, which dramatically slows down beam forming operations. This may be acceptable for applications where high rate data transmissions are needed in only one direction, such as for video traffic from a media source to a media sink. For applications where high rate data communications are needed in both directions, such as for computing centric applications, however, this introduces unwarranted delay in beam forming operations.

To solve these and other problems, various embodiments implement an enhanced bidirectional beam forming protocol to perform bidirectional beam forming operations to reduce training overhead and link latency during beam forming operations. Some embodiments delay feedback information until two-way transmit (or receive) beam forming weights are trained, and then send the feedback over a beam formed link with a higher rate (e.g., HRP channel). This may reduce or eliminate the need to use a LRP channel for beam forming operations. Additionally or alternatively, some embodiments interleave transmit and receive beam forming operations to allow use of partially trained links to communicate feedback information at a higher data rate. This reduces the need to use an LRP channel during beam forming operations.

In one embodiment, for example, a wireless device may include a phased antenna array communicatively coupled to a transceiver. The wireless device may further include an antenna control module communicatively coupled to the transceiver and the phased antenna array. The antenna control module may be arranged to perform beam formation operations using an iterative training scheme to form a pair of communications channels between the wireless device and a peer device. For example, the antenna control module may be arranged to communicate training signals and feedback information with the peer device via the transceiver and phased antenna array. The information is communicated using almost exclusively high rate channels, or through partial use of low rate channels to bootstrap setup of the high rate channels. This reduces training time for the devices. The antenna control module iteratively determines antenna-array weight vectors (AWVs) for a directional transmit beam pattern for the phased antenna array using feedback information from the peer device. Once trained the wireless devices may be used for high-speed bidirectional data communications.

Additionally or alternatively, the antenna control module of a wireless device may initiate bidirectional beam formation operations using an iterative training scheme to form a pair of communications channels for a wireless network. The antenna control module may be arranged to interleave transmit and receive beam forming operations for a first wireless device and a second wireless device to allow feedback information received by the first wireless device from the second wireless device to be communicated over a higher data rate channel (e.g., HRP channel).

The wireless devices as described herein may coordinate operations between each other. The coordination may involve the uni-directional or bi-directional exchange of information. In some embodiment, the information can be implemented as signals. For example, training information may comprise training signals or sequences. Further embodiments, however, may alternatively employ data messages. The terms "training information" and "feedback information" are meant to include both signals and data messages, depending on a given implementation. The embodiments are not limited in this context.

Embodiments of the enhanced bidirectional beam forming protocol provide several advantages over conventional beam forming techniques. For example, the enhanced bidirectional beam forming protocol trains both directions of the communications link, allowing for a more structured process prior to a bidirectional operation that is more symmetric, such as in a PC environment. This provides superior performance relative to conventional beam forming protocols that allows the receiver of the high rate transmission to answer (e.g., ACKs etc.) in a low rate dedicated physical layer (PHY) that may not require training of the reverse link. In another example, the enhanced bidirectional beam forming protocol exploits resources more efficiently. The feedback provided during each iteration is based on partially trained antenna arrays. In yet another example, an external listening device can identify transmissions from both ends of the link. This situation is beneficial when an independent station wishes to assess the amount of interference it is going to suffer from the regarded link. If only one side of the link does the transmission, however, then the station has knowledge about interference only about the forward link and not about the reverse link. These are only a few examples of the advantages provided by the enhanced bidirectional beam forming protocol, and it may be appreciated that many other advantages exist as well.

FIG. **1** illustrates a block diagram of one embodiment of a communications system **100**. In various embodiments, the communications system **100** may comprise multiple nodes. A node generally may comprise any physical or logical entity for communicating information in the communications system **100** and may be implemented as hardware, software, or any combination thereof, as desired for a given set of design parameters or performance constraints. Although FIG. **1** may show a limited number of nodes by way of example, it can be appreciated that more or less nodes may be employed for a given implementation.

In various embodiments, the communications system **100** may comprise, or form part of a wired communications system, a wireless communications system, or a combination of both. For example, the communications system **100** may include one or more nodes arranged to communicate information over one or more types of wired communication links. Examples of a wired communication link, may include, without limitation, a wire, cable, bus, printed circuit board (PCB), Ethernet connection, peer-to-peer (P2P) connection, backplane, switch fabric, semiconductor material, twisted-pair wire, co-axial cable, fiber optic connection, and so forth. The communications system **100** also may include one or more nodes arranged to communicate information over one or more types of wireless communication links. Examples of a wireless communication link may include, without limitation, a radio channel, infrared channel, radio-frequency (RF) channel, Wireless Fidelity (WiFi) channel, a portion of the RF spectrum, and/or one or more licensed or license-free frequency bands.

The communications system **100** may communicate information in accordance with one or more standards as promulgated by a standards organization. In one embodiment, for example, various devices comprising part of the communications system **100** may be arranged to operate in accordance with one or more of the WirelessHD™ specifications, standards or variants, such as the WirelessHD Specification, Revision 1.0d7, Dec. 1, 2007, and its progeny as promulgated by WirelessHD, LLC (collectively referred to as the "WirelessHD Specification"). The WirelessHD Specification

defines a next generation wireless digital network interface for consumer electronic products. Specifically, the WirelessHD Specification enables wireless connectivity for streaming high-definition content between various wireless devices, such as a source device and high-definition displays. The WirelessHD Specification defines a wireless protocol that enables the creation of a WVAN. In a current instantiation of the WirelessHD Specification, the MAC and PHY are defined to support the wireless delivery of uncompressed high definition audio and video at formats up to 1080 p at 60 Hertz (Hz) with 24 bit color at a range that is typically at least 10 meters. In addition, the delivery of compressed audio/visual (AV) streams and data is also supported at a similar range. An adaptation sub-layer enables network and service set up by supporting authentication, advanced device and connection control.

Although some embodiments may be described with reference to the WirelessHD Specification by way of example, it may be appreciated that the techniques described herein may also be implemented for other wireless standards as promulgated by other standards organizations as well, such as the International Telecommunications Union (ITU), the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (information IEEE), the Internet Engineering Task Force (IETF), and so forth. In various embodiments, for example, the communications system **100** may communicate information according to one or more IEEE 802.11 standards for wireless local area networks (WLANs) such as the information IEEE 802.11 standard (1999 Edition, Information Technology Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements, Part 11: WLAN Medium Access Control (MAC) and Physical (PHY) Layer Specifications), its progeny and supplements thereto (e.g., 802.11a, b, g/h, j, n, VHT SG, and variants); IEEE 802.15.3 and variants; IEEE 802.16 standards for WMAN including the IEEE 802.16 standard such as 802.16-2004, 802.16.2-2004, 802.16e-2005, 802.16f, and variants; next generation WirelessHD (NGmS) progeny and variants; European Computer Manufacturers Association (ECMA) TG20 progeny and variants; and other wireless networking standards. The embodiments are not limited in this context.

The communications system **100** may communicate, manage, or process information in accordance with one or more protocols. A protocol may comprise a set of predefined rules or instructions for managing communication among nodes. In various embodiments, for example, the communications system **100** may employ one or more protocols such as a beam forming protocol, medium access control (MAC) protocol, Physical Layer Convergence Protocol (PLCP), Simple Network Management Protocol (SNMP), Asynchronous Transfer Mode (ATM) protocol, Frame Relay protocol, Systems Network Architecture (SNA) protocol, Transport Control Protocol (TCP), Internet Protocol (IP), TCP/IP, X.25, Hypertext Transfer Protocol (HTTP), User Datagram Protocol (UDP), and so forth.

The communications system **100** also may be arranged to operate in accordance with standards and/or protocols for media processing. Examples of media processing standards include, without limitation, the High Definition Television (HDTV) standards as defined by the ITU Radiocommunication Sector (ITU-R), such as the Recommendation BT.709-5, Parameter Values for the HDTV Standards For Production and International Programme Exchange, published April 2002, the Digital Video Broadcasting Terrestrial (DVB-T) broadcasting standard, the ITU/IEC H.263 standard, Video Coding for Low Bitrate Communication, ITU-T Recommendation H.263v3, published November 2000 and/or the ITU/IEC H.264 standard, Video Coding for Very Low Bit Rate Communication, ITU-T Recommendation H.264, published May 2003, Motion Picture Experts Group (MPEG) standards (e.g., MPEG-1, MPEG-2, MPEG-4), and/or High performance radio Local Area Network (HiperLAN) standards. Examples of media processing protocols include, without limitation, Session Description Protocol (SDP), Real Time Streaming Protocol (RTSP), Real-time Transport Protocol (RTP), Synchronized Multimedia Integration Language (SMIL) protocol, and/or Internet Streaming Media Alliance (ISMA) protocol. The embodiments are not limited in this context.

As shown in FIG. **1**, the communications system **100** may comprise a transmitter node **102** coupled to a plurality of receiver nodes **104-1-*n***, where n may represent any positive integer value. In various embodiments, the transmitter node **102** and the plurality of receiver nodes **104-1-*n*** may be implemented as various types of wireless devices. Examples of wireless devices may include, without limitation, an IEEE 802.15.3 piconet controller (PNC), a controller, an IEEE 802.11 Private Basic Service Set (PBSS) Control Point (PCP), a coordinator, a station, a subscriber station, a base station, a wireless access point (AP), a wireless client device, a wireless station (STA), a laptop computer, ultra-laptop computer, portable computer, personal computer (PC), notebook PC, handheld computer, personal digital assistant (PDA), cellular telephone, combination cellular telephone/PDA, smartphone, pager, messaging device, media player, digital music player, set-top box (STB), appliance, workstation, user terminal, mobile unit, consumer electronics, television, digital television, high-definition television, television receiver, high-definition television receiver, and so forth. In such embodiments, the transmitter node **102** and the receiver nodes **104-1-*n*** may comprise one more wireless interfaces and/or components for wireless communication such as one or more transmitters, receivers, transceivers, chipsets, amplifiers, filters, control logic, network interface cards (NICs), antennas, antenna arrays, and so forth. Examples of an antenna may include, without limitation, an internal antenna, an omni-directional antenna, a monopole antenna, a dipole antenna, an end fed antenna, a circularly polarized antenna, a micro-strip antenna, a diversity antenna, a dual antenna, an antenna array, and so forth. In one embodiment, certain devices may include antenna arrays of multiple antennas to implement various adaptive antenna techniques and spatial diversity techniques. Some embodiments for an enhanced bidirectional beam forming protocol are discussed in the context of using phased antenna arrays. The enhanced bidirectional beam forming protocol may be used with any type of antenna having a need for feedback information, and the embodiments are not limited in this respect. For example, while some aspects of an enhanced bidirectional beam forming protocol are designed to enable a phased antenna array at both ends of the link, a switched-sector antenna (e.g., an antenna with predefined few directions that can switch from one direction to another) may still use this protocol.

For purposes of illustration and not limitation, examples for an enhanced bidirectional beam forming protocol may be given with reference to WirelessHD networks, protocols and devices. It may be appreciated, however, that an enhanced bidirectional beam forming protocol may be implemented with other types of networks, protocols and devices. For example, an enhanced bidirectional beam forming protocol may be implemented for a NGmS network, protocol or

devices, and still fall within the intended scope of the embodiments. The embodiments are not limited in this context.

In various embodiments, the transmitter node **102** and the receiver nodes **104-1-*n*** may comprise or form part of a wireless network **106**. In one embodiment, for example, the wireless network **106** may comprise a WVAN as defined by the WirelessHD Specification. In the context of a WVAN, both nodes **102**, **104** may be implemented as WirelessHD compliant devices. In a WVAN, the transmitter node **102** may be communicatively coupled to one or more receiver nodes **104-1-*n***. In accordance with the WirelessHD Specification and nomenclature, one or both of the nodes **102**, **104** may be implemented as a coordinator or a station. A coordinator is normally, but not always, a device that is a sink for media information (e.g., audio or video data). The coordinator typically includes a display, and in some cases a media storage device such as a personal video recorder (PVR), media server, or STB. A station may comprise a device that either has media information that it can source or sink, potentially at the same time.

Although some embodiments may be described with the wireless network **106** implemented as a WVAN network for purposes of illustration, and not limitation, it can be appreciated that the embodiments are not limited in this context. For example, the wireless network **106** may comprise or be implemented as various types of wireless networks and associated protocols suitable for a WPAN, a Wireless Local Area Network (WLAN), a Wireless Metropolitan Area Network, a Wireless Wide Area Network (WWAN), a Broadband Wireless Access (BWA) network, a radio network, a television network, a satellite network such as a direct broadcast satellite (DBS) network, and/or any other wireless communications network configured to operate in accordance with the described embodiments.

As shown in the embodiment of FIG. **1**, the transmitter node **102** may be coupled to receiver nodes **104-1-*n*** by wireless communication links **108-*n***. A particular wireless communication link (e.g., wireless communication link **108-1**) may be arranged to establish one or more common or dedicated connections between the transmitter node **102** and a particular receiver node (e.g., receiver node **104-1**). In various embodiments, a particular wireless communication link (e.g., wireless communication link **108-1**) may include multiple virtual channels, with each of the virtual channels comprising a point-to-point logical connection from the transmitter node **102** to a particular receiver node (e.g., receiver node **104-1**). In various implementations, multiple virtual channels may share a physical link, with each virtual channel comprising dedicated resources or bandwidth of the physical link.

In various embodiments, the nodes **102**, **104** may communicate using a physical layer component (PHY), such as a high-rate PHY (HRP). In one embodiment, for example, the HRP supports multi-Gb/s throughput at a distance of approximately 10 meters through adaptive antenna technology. Because of this, the antenna pattern used for the HRP is highly directional. The HRP is optimized for the delivery of uncompressed high-definition video, although other data can be communicated using the HRP. To support multiple video resolutions, the HRP has more than one data rate defined. The HRP carries isochronous data such as audio and video, asynchronous data, MAC commands, antenna beam forming information, and higher layer control data for A/V devices. It may be appreciated that the use of HRP and LRP are for WirelessHD devices, and other types of PHYs may be used for other types of devices. With respect to the NGmS protocol, for example, the high rate PHY may be referred to as the OFDM PHY or the SC PHY depending on the modulation type, while the low rate PHY is called a CONTROL PHY or a MCS of the SC PHY. In the latter case, the low rate transmissions will be based on wide bandwidth with significant processing gain that renders the transmission more robust. Other types of high rate and low rate PHYs may be used for different types of devices, and the embodiments are not limited in this context.

In various embodiments, the nodes **102**, **104** may also communicate using a low-rate PHY (LRP). The LRP is a multi-Mb/s bidirectional link that also provides a relatively short range (e.g., 10 meters). One or more data rates are defined for the LRP, with the lower data rates having near omni-directional coverage while the highest data rates are directional, although this is not necessarily binding. For example, some arrangements may use higher data rates of LRP in almost-omni directional transmissions. Because the LRP has near omni-directional modes, it can be used for both unicast and broadcast connections. Furthermore, because all stations support the LRP, it can be used for station-to-station links for WirelessHD devices, although this may not be possible for NGmS devices. The LRP supports multiple data rates, including directional modes, and is used to carry low-rate isochronous data such as audio, low-rate asynchronous data, MAC commands including the beacon, acknowledgements for HRP packets, antenna beam forming information, capabilities information, and higher layer control data for A/V devices.

In some cases (not all) the HRP and LRP may operate in overlapping frequency bands and so they are coordinated by the MAC. The media access scheme may include a time division multiple access (TDMA) format, a frequency division multiple access (FDMA) format, a TDMA/FDMA format, a code division multiple access (CDMA), a wide-band CDMA (WCDMA) format, an orthogonal frequency division multiple access (OFDMA) format, and so forth. The embodiments are not limited in this context.

The WVAN typically supports two types of devices. In one embodiment, for example, a WVAN may support a coordinator and a station. The coordinator controls the timing in the piconet, keeps track of the members of the WVAN, is able to transmit and receive using the LRP, may be able to transmit data using the HRP, and may be able to receive data using the HRP. A station is able to transmit and receive using the LRP, may initiate stream connections, may be able to transmit data using the HRP, and may be able to receive data using the HRP. A station may be capable of acting as a coordinator in the WVAN. Such a station is referred to as being coordinator capable.

In addition to the two MAC personalities of coordinator and station, each device in a WirelessHD WVAN will have one of four different PHY capabilities as shown in Table 1 as follows:

TABLE 1

| PHY | Description |
|---|---|
| HR0 | A device that is not able to either receive or transmit using the HRP |
| HRRX | A device that is able to receive in the HRP, but is not able to transmit using the HRP |
| HRTX | A device that is able to transmit in the HRP, but is not able to receive using the HRP |
| HRTR | A device that is able to both transmit and receive using the HRP |

All compliant WirelessHD devices are able to transmit and receive using the LRP. Both the HRP and LRP may provide multiple data rates, as specified in the WirelessHD Specification.

In various embodiments, the transmitter node **102** and the receiver nodes **104-1-*n*** may be arranged to communicate various types of media information in multiple communication frames. The various types of media information may include image information, audio information, video information, AV information, and/or other data provided from the media source **108**. In various embodiments, the information may be associated with one or more images, image files, image groups, pictures, digital photographs, music file, sound files, voice information, videos, video clips, video files, video sequences, video feeds, video streams, movies, broadcast programming, television signals, web pages, user interfaces, graphics, textual information (e.g., encryption keys, serial numbers, e-mail messages, text messages, instant messages, contact lists, telephone numbers, task lists, calendar entries, hyperlinks), numerical information, alphanumeric information, character symbols, and so forth. The information also may include command information, control information, routing information, processing information, system file information, system library information, software (e.g., operating system software, file system software, application software, game software), firmware, an application programming interface (API), a program, an applet, a subroutine, an instruction set, an instruction, computing code, logic, words, values, symbols, and so forth.

The transmitter node **102** may be arranged to receive media content from a media source node **110** to be unicast and/or multicast to one or more of the receiver nodes **104-1-*n***. In various embodiments, the transmitter node **102** may be arranged to receive media content from the source node **110**. The media source node **110** generally may comprise any media source capable of delivering static or dynamic media content to the transmitter node **102**. In one embodiment, for example, the media source node **110** may comprise a multimedia server arranged to provide broadcast or streaming media content to the transmitter node **102**. In some implementations, the media source node **110** may form part of a media distribution system (DS) or broadcast system such as an over-the-air (OTA) broadcast system, a radio broadcast system, a television broadcast system, a satellite broadcast system, and so forth. In some implementations, the media source node **110** may be arranged to deliver media content pre-recorded and stored in various formats for use by a device such as a Digital Versatile Disk (DVD) device, a Video Home System (VHS) device, a digital VHS device, a digital camera, video camera, a portable media player, a gaming device, and so forth.

As shown in the embodiment of FIG. **1**, for example, the transmitter node **102** may be coupled to the media source node **110** through a communication medium **112**. The communication medium **112** generally may comprise any medium capable of carrying information signals such as a wired communication link, wireless communication link, or a combination of both, as desired for a given implementation. In various embodiments, the communication medium **112** may comprise a wired communication link implemented as a wired Ethernet and/or P2P connection, for example. In such embodiments, information may be communicated over the communication medium **112** in accordance with the information IEEE 802.3, and the transmitter node **102** may receive media content from the media source node **110** substantially loss-free.

Although some embodiments may be described with the communication medium **112** implemented as a wired Ethernet and/or P2P connection for purposes of illustration, and not limitation, it can be appreciated that the embodiments are not limited in this context. For example, the communication medium **112** between the transmitter node **102** and the source node **110** may comprise various types of wired and/or wireless communication media and, in some cases, may traverse one or more networks between such devices.

The transmitter node **102** may be arranged to buffer media content and to parse or fragment the media content into communication frames for unicast or multicast transmission to the receiver nodes **104-1-*n***. In some implementations, the transmitter node **102** may be arranged to parse or fragment the received media content as it is read into a buffer. In some embodiments, the media content provided to the transmitter node **102** may be delivered as one or more media frames. Each media frame may comprise a discrete data set having a fixed or varying length, and may be represented in terms of bits or bytes such as 16 kilobytes (kB), for example. It can be appreciated that the described embodiments are applicable to various types of communication content or formats, such as frames, packets, fragments, cells, units, and so forth.

In various embodiments, the transmitter node **102** may be arranged to create a sequence of media frames to be broadcast over one or more of the wireless communication links **108-1-*n***. Each media frame may comprise a discrete data set having fixed or varying lengths, and may be represented in terms of bits or bytes. While multicasting, each media frame may contain a destination address comprising a group address corresponding to multiple intended recipients, such as receiver nodes **104-1-*n***. In some embodiments, the destination address may refer to all receiver nodes **104-1-*n*** within the wireless network **106**.

FIG. **2** illustrates a block diagram of one embodiment of a wireless network **200**. For ease of illustration, and not limitation, the wireless network **200** depicts a limited number of nodes by way of example. It can be appreciated that more nodes may be employed for a given implementation.

As shown, the wireless network **200** may comprise a wireless device **202** coupled to a wireless device **204**. In various embodiments, the wireless communications system **200** may comprise or be implemented by one or more elements of the communications system **100** of FIG. **1**, such as wireless network **100**, transmitter node **102**, and receiver nodes **104-1-*n***. The embodiments are not limited in this context.

In one embodiment, for example, the wireless device **202** and the wireless device **204** may be implemented as WirelessHD compliant devices, and the wireless network **200** may be implemented as a WVAN network. In such an embodiment, the wireless network **200** may communicate information in accordance with the WirelessHD Specification and associated techniques, and the wireless device **202** may comprise a WirelessHD compliant device communicatively coupled to the wireless device **204** comprising another WirelessHD compliant device. In various implementations, the wireless network **200** may support a unicast and/or multicast communication environment for distributing media content by unicasting and/or multicasting from the wireless device **202** to the wireless device **204**. Typically, the wireless devices **202**, **204** will utilize unicast or multicast techniques based upon the type of channel being used. For example, the wireless devices **202**, **204** will utilize unicast techniques when using a HRP channel, and multicast techniques when using a LRP channel. The embodiments are not limited in this context.

In one embodiment, for example, the wireless devices **202**, **204** each may include the capability to establish one or more wireless communications channels **206** using respective transceivers **205**, **205***a* coupled to respective antenna control modules **208**, **208***a* coupled to respective phased antenna arrays **210**, **210***a*. In various embodiments, the communications channel **206** may be implemented at the MAC layer of the communication protocol stack within a transceiver and/or wireless communication chipset of a wireless device.

FIG. **3** illustrates one embodiment of wireless system **300** suitable for performing analog beam forming. The wireless system **300** may be implemented for the nodes **102**, **104-1**-*n* as described with reference to FIG. **1**, and/or the wireless nodes **202**, **204** as described with reference to FIG. **2**.

In the illustrated embodiment shown in FIG. **3**, the wireless system **300** may comprise a more detailed diagram for a pair of phased antenna arrays **210**, **210***a* implemented for respective wireless devices **202**, **204**. The phased antenna arrays **210**, **210***a* may be communicatively coupled to the respective antenna control modules **208**, **208***a*. The phased antenna array **210** may comprise a transmitter antenna array **310** and a receiver antenna array **320**. The phased antenna array **210***a* may comprise a transmitter antenna array **330** and a receiver antenna array **340**. Although the antenna arrays **310**, **320** and the antenna arrays **330**, **340** may be illustrated a separate antenna arrays, it may be appreciated that each may be implemented using a single antenna array using different transmit and receive coefficients, vectors or other suitable antenna parameters.

The transmitter antenna arrays **310**, **330** may comprise respective power amplifiers **312-1**-*a* and power amplifiers **332-1**-*f* each coupled to respective phase shifters **314-1**-*b* and phase shifters **334-1**-*g*. The phase shifters **314-1**-*b* and phase shifters **334-1**-*g* may each be coupled to respective antennas **316-1**-*c* and antennas **336-1**-*h*. The receiver antenna arrays **320**, **240** may comprise respective antennas **326-1**-*d* and antennas **346-1**-*i* each coupled to respective phase shifters **324-1**-*e* and phase shifters **344-1**-*j*. The phase shifters **324-1**-*e* and phase shifters **344-1**-*j* may each be coupled to respective low noise amplifiers (LNA) **322-1**-*r* and LNA **342-1**-*s*, which are in turn each coupled to respective combiners **346**, **348**. It may be appreciated that the transmitter and receiver chains can share phase shifters and/or amplifiers as desired for a given implementation. The embodiments are not limited in this context.

The wireless devices **202**, **204** may use the respective phased antenna arrays **210**, **210***a* to communicate control information and media information over a wireless shared media **350**. The transmitter antenna array **310** and the receiver antenna array **340** of the respective wireless devices **202**, **204** may communicate information using an HRP channel **352-1** and/or a LRP channel **354-1**. The transmitter antenna array **330** and the receiver antenna array **320** of the respective wireless devices **204**, **202** may communicate information using an HRP channel **352-2** and/or a LRP channel **354-2**. In one embodiment, the HRP channels **352-1**, **352-2** may be implemented as directional channels operating at higher rate data communication speeds, and the LRP channels **354-1**, **354-2** may be implemented as omni-directional channels operating at lower rate data communications speeds.

The antenna control modules **208**, **208***a* may use the respective transceivers **205**, **205***a* and respective phased antenna arrays **210**, **210***a* to perform beam forming operations. The beam forming operations may include explicit feedback beam forming, which supports all types of WirelessHD compliant devices, such as HR0, HRRX, HRTX and HRTR. There is no requirement that the transmitter and the receiver for a station are the same and no calibration is required. The beam forming operations may also include implicit feedback beam forming, which is typically used when both the source and destination are HRTR capable.

In order to provide data rates on the order of Gbps at approximately 10 meters for 60 GHz mmWave operations, the phased antenna arrays **210**, **210***a* are implemented as high gain antenna networks in the 60 GHz frequency band. The phased antenna arrays **210**, **210***a* can create beams that can be steered around obstacles to find a best path between the wireless devices **202**, **204**. The antenna control modules **208**, **208***a* may cooperate to implement an enhanced bidirectional beam forming protocol suitable for beam search and beam tracking operations. Beam search is a technique of estimating transmitter and receiver antenna-array weight vectors (AWVs) that result in a desired beam with an acceptable level of gain or SNR over the HRP channels **352-1**, **352-2**. Beam tracking is a technique of tracking transmitter and receivers AWVs that correspond to an existing beam over time due to small perturbations of the HRP channels **352-1**, **352-2**. While beam search is typically a stand-alone technique using a dedicated time interval, beam tracking takes place during data transfer and is appended to existing HRP packets and corresponding ACK packets.

FIG. **4** illustrates one embodiment of a state diagram **400**. The state diagram **400** illustrates state transitions for adaptive beam forming using the phased antenna arrays **210**, **210***a*. In the illustrated embodiment shown in FIG. **4**, the wireless device **202** may be in an idle state **402**, and detect a peer device (e.g., wireless device **204**) within communication range of the wireless device **202**. The wireless device **202** may exit the idle state **402**, and enter a beam formation state **404**. The wireless device **202** may initiate beam formation operations using an iterative training scheme to form a pair of communications channels HRP **352-1**, **352-2** between the wireless devices **202**, **204**. For example, the antenna control module **208** for the wireless device **202** may be arranged to communicate training signals and feedback information with the wireless device **204** via the transceiver **205** and phased antenna array **210**. The information is communicated using exclusively the HRP channels **352-1**, **352-2**, while reducing or eliminating the need to use the LRP channels **354-1**, **354-2**. This reduces training time for the devices. The antenna control module **208** iteratively determines AWVs for a directional transmit beam pattern for the phased antenna array **210** using feedback information from the wireless device **204**. Once trained the wireless devices **202**, **204** may exit the beam formation state **404**, and enter a data transfer state **406** to use the HRP channels **352-1**, **352-2** for bidirectional high rate data communications.

FIG. **5** illustrates one embodiment of iterative training scheme for a wireless system **500**. Since the path loss in the 60 GHz frequency band is very high and the efficiency of CMOS power amplifiers at 60 GHz is low, directional transmission is needed to achieve the desired 10 meter coverage. The array gain from transmit and receive beam forming operations is needed to acquire the desired SNR for reliable data communications. Currently, there are several different beam forming protocols to acquire directional transmissions. The first beam forming protocol uses the sectored antenna approach, which switches among several preformed beams. The second beam forming protocol uses phased antenna arrays where transmit and receive beams are formed by changing the phases of the input and output signals of each antenna element, as described with reference to FIG. **3**.

The second beam forming protocol uses an iterative training approach. An iterative training process utilizes training

sequences and feedback in successive iterations in order to train transmitters or receivers. The iterative training approach provides the advantage of distributing transmit power to multiple power amplifiers, and the beam can be adaptively steered. It is worthy to note that this discussion is limited to only a single data stream for purposes of clarity, although some embodiments may be implemented for multiple data streams as well. A brief overview of iterative training is provided below to better illustrate and describe the operations and benefits of the enhanced bidirectional beam forming protocol.

In one embodiment, the desired beam forming weights at the receiver (Rx) **504** and transmitter (Tx) **502**, denoted by vectors u and v, maximize the gain of the beamformed channel as shown in Equation (1) as follows:

$$(u, v) = \underset{\|\hat{u}\|=\|\hat{v}\|=1}{\operatorname{argmax}} |\hat{u}^H H \hat{v}| \quad (1)$$

where H is the effective channel matrix between transmitter **502** and receiver **504**; $\hat{u}^H H \hat{v}$ is the beam formed scalar channel for beam forming weights $\hat{u}$ and $\hat{v}$; and u and v are the normalized beam forming vectors at the receiver **504** and transmitter **502** respectively. The effective channel matrix incorporates the effects of the transmit/receive weighting matrixes and the wireless channel, and it is the product of the transmit weighting matrix $B_t$, wireless channel $H_w$, the receive weighting matrix $B_r$, e.g., $H=B_r H_w B_t$. The weight entries on the i-th row of $B_r$ form the i-th effective receive antenna and similarly the weight entries on the i-th column of $B_t$ form the i-th effective transmit antenna. The entry on the i-th row and j-th column of H is the channel response between the i-th effective receive antenna and the j-th effective transmit antenna. If H is known, then u and v can be computed using the singular value decomposition (SVD) of H. However, H is usually unknown at both transmitter **502** and receiver **504** for 60 GHz systems. Consequently, iterative training is used as an efficient scheme to obtain u and v, and which does not require costly training to learn about the whole H.

Beam forming is needed before the transmission of the data packet. In current protocols and for a P2P scheduled training, and for systems without RF transceiver chain calibration, the beam forming weights of the phased antenna arrays are gradually refined during the beam refinement phase that consumes a significant overhead of about 400 microseconds (μs), for example. It is desirable to reduce the training overhead as much as possible for high network throughput. In the state of the art, iterative training is the scheme employed for the beam refinement because of its superior performance. It is iterative and each iteration has two steps, e.g., the training of maximum ratio combining (MRC) weights and the training of the maximum ratio transmission (MRT) weights, as shown in FIG. **5** and Equation (2) as follows.

$$\text{Step 1: } u(i)=\text{norm}(Hv(i))$$

$$\text{Step 2: } v(i+1)=\text{norm}(H^H u(i)) \quad (2)$$

where

$$norm(x) = \frac{x}{\|x\|}$$

normalizes the magnitude of the beam forming vector. For clarity and simplicity, the noise term is not evaluated. At the i-th iteration, the transmitter **502** has the transmit beam forming vector v(i), which comes from the feedback from the receiver **504**.

In the first step in Equation (2), the transmitter **502** sends training symbols to the receiver **504** using v(i), and the receiver **504** estimates the receive beam forming weights that maximize the received signal strength for the transmit vector v(i) as follows. The receiver measures the response on each effective receive antenna respectively, and the measured responses form the vector Hv(i). The receive beam forming vector maximizing the received signal (e.g., the MRC vector), is shown in Equation (3) as follows:

$$u(i)=\text{norm}(Hv(i)) \quad (3)$$

In the second step in Equation (2), the transmitter **502** sends training symbols through each effective transmit antenna respectively and the receiver **504** estimates the transmit beam forming weights that maximize the received signal strength for the receive vector u(i) as follows. The receiver uses u(i) as the receive vector and measures the beam formed channel response for each effective transmit antenna in H respectively. The measured channel responses form the vector $u^H(i)H$. The transmit beam forming vector maximizing the received signal (e.g., the MRT vector), is shown in Equation (4) as follows:

$$v^H(i+1)=\text{norm}(u^H(i)H) \text{ or } v(i+1)=\text{norm}(H^H u(i)) \quad (4)$$

The value for v(i+1) is fed back to the transmitter **502** for the (i+1)-th iteration. The values for u(i) and v(i) gradually converges to the ideal u and v as each iteration completes.

Iterative training is currently used by certain conventional beam forming protocols, such as those currently implemented by the WirelessHD Specification. The conventional beam forming protocol utilized by the WirelessHD Specification, however, introduces a significant amount of training overhead and link latency. It is also designed for training a link in one direction at a time, which may be suitable to digital television sets that are designed to operate mainly as receivers and less as transmitters. A PC environment is different, however, and focus is placed on both transmitting and receiving operations. The enhanced bidirectional beam forming protocol reduces link latency for training bidirectional links, and is described in further detail with reference to FIG. **6**.

FIG. **6**A illustrates one embodiment of a message flow **600**. The message flow **600** illustrates a message flow for an enhanced bidirectional beam forming protocol that reduces latency introduced by an iterative training scheme by using only HRP channels **352-1**, **352-2**, while reducing or eliminating the need to use the LRP channels **354-1**, **354-2**. For purposes of illustration and not limitation, the wireless device **202** may represent a piconet controller (PNC) or coordinator, and the wireless device **204** may represent a wireless station (STA). In one embodiment, the message flow **600** may be applicable for WirelessHD devices, although the embodiments are not limited in this respect.

In the illustrated embodiments shown in FIG. **6**A, the wireless device **202** exits the idle state **402** and enters the beam forming state **404**. The wireless device **202** may optionally transmit timing acquisition and optimal delay selection sequences to the wireless device **204**. The antenna control module **208** of the wireless device **202** cooperates with the antenna control module **208***a* of the wireless device **204** to implement an iterative training scheme using an enhanced

bidirectional beam forming protocol. The iterative training scheme may use any number of iterations **602-1**-*m* as desired for a given implementation.

During a first iterative training **602-1**, the antenna control module **208** uses the transceiver **205** and the phased antenna array **510** of the wireless device **202** to send training signals, such as training signals **613**, from the wireless device **202** to the wireless device **204** over a downlink (DL) HRP channel **352-1**. In a typical scenario, multiple training signals are transmitted, while the wireless device **202** changes its antenna weights at proper times (e.g., at the beginning of every training signal). For example, the antenna control module **208** sends receiver (Rx) training signals **613** from the wireless device **202** to the wireless device **204** over the DL HRP channel **352-1** to allow the wireless device **204** to deduce the MRC weights and form a directional receive beam pattern for a phased antenna array **210***a* of the wireless device **204**. The antenna control module **208** sends transmitter (Tx) training signals **614** from the wireless device **202** to the wireless device **204** over the DL HRP channel **352-1** to allow the device **204** to measure characteristics of its received signal. These characteristics are later fed back from device **204** to device **202** using message **617** to allow wireless device **202** to deduce its MRT weights so that a directional transmit beam pattern for the phased antenna array **210** of the wireless device **202** can be formed.

In a conventional beam forming protocol, the antenna control module **208** may wait to receive feedback information from the wireless device **204** over the LRP channel **354-1**. In the enhanced bidirectional beam forming protocols, however, the feedback information from the wireless device **204** is delayed until a directional receive beam pattern for the phased antenna array **210** of the wireless device **202** as been formed or partially formed, thereby allowing the wireless device **202** to receive the feedback information from the wireless device **204** over an uplink (UL) HRP channel **352-2**. The UL HRP channel **352-2** operates at a much higher data rate than the LRP channel **354-1**, and therefore using the UL HRP channel **352-2** for the feedback information reduces training overhead and latency.

Referring again to the message flow **600**, the antenna control module **208***a* uses the transceiver **205***a* and the phased antenna array **210***a* of the wireless device **204** to send training signals or sequences to the wireless device **202** over the UL HRP channel **352-2**. For example, the antenna control module **208***a* sends training signals **615** to the wireless device **202** over the UL HRP channel **352-2** to deduce the MRC weights and form a directional receive beam pattern for the phased antenna array **210** of the wireless device **202**. The antenna control module **208***a* also sends training signals **616** to the wireless device **202** over the UL HRP channel **352-2** to allow the wireless device **202** to measure characteristics of its received signal. These characteristics are later fed back from device **202** to device **204** using message **618** to allow wireless device **204** to deduce its MRT weights so that a directional transmit beam pattern for the phased antenna array **210***a* of the wireless device **204** can be formed.

Once the phased antenna array **210** of the wireless device **202** has a fully or partially formed directional receive beam pattern using the weights (e.g., MRC weights) obtained at arrow **615**, the wireless device **204** may send feedback information to the wireless device **202** over the UL HRP channel **352-2**, which is received using the directional receive beam pattern for the phased antenna array **210** of the wireless device **202**, as indicated by the arrow **617**. The phased antenna array **210***a* may use the same transmit beam forming vector as used when previously sending the UL PNC Rx vector training (PNC MRC weights) (arrow **615**). This provides the wireless device **202** with receive gain that may not have been available prior to stage **615** or earlier.

The antenna control module **208** may determine AWVs for the directional transmit beam pattern for the phased antenna array **210** of the wireless device **202** using the feedback information from the wireless device **204**. The first iteration **602-1** may then be completed by having the wireless device **202** send feedback information to the wireless device **204** over the DL HRP channel **352-1** using a directional transmit beam pattern obtained from recently received feedback information (arrow **617**) for the phased antenna array **210** of the wireless device **202**. The phased antenna array **210***a* of the wireless device **204** may use the directional receive beam pattern formed when receiving the DL STA Rx vector training (STA MRC weights) at arrow **613** to receive the feedback information. The antenna control module **208***a* may then use the feedback information in determining AWVs for the directional transmit beam pattern for the phased antenna array **210***a* of the wireless device **204** using the feedback information from the wireless device **202**.

The wireless devices **202**, **204** may continue with the next iterative trainings **602-2**-*m* performing similar beam forming or beam refinement operations as used with the first iterative training **602-1**. For example, for iterative training **602-2** the operations indicated by arrows **619** through **624** are similar to those operations performed as indicated by arrows **613** through **618**. Each iterative training **602-1**-*m* provides successively more accurate AWVs for the HRP channels **352-1**, **352-2**. This process continues until a terminating condition is reached, such as reaching a determined SNR for data communications, reaching a determined number of iterations (e.g., three iterations), or until both ends of the link request termination of the training process. At this point, the HRP channels **352-1**, **352-2** may be used for bidirectional high rate data communications.

It is worthy to note that the feedback information provided at arrow **617** may optionally be moved back and provided during stage **616**. This may add synchronization overhead, however, because of the transmit/receive switching.

FIG. **6**B illustrates one embodiment of a message flow **650**. The message flow **650** illustrates a message flow for an enhanced bidirectional beam forming protocol that reduces latency introduced by an iterative training scheme by using predominantly HRP channels **352-1**, **352-2**, while reducing or eliminating the need to use the LRP channels **354-1**, **354-2**. For purposes of illustration and not limitation, the wireless device **202** may represent a piconet controller (PNC) or coordinator, and the wireless device **204** may represent a wireless station (STA). In one embodiment, the message flow **650** may be applicable for NGmS devices, although the embodiments are not limited in this respect.

In the illustrated embodiments shown in FIG. **6**A, the message flow **650** illustrates a message flow suitable for an enhanced bidirectional beam forming protocol implemented for a NGmS network, protocol or devices. The NGmS protocol, for example, may contain DL RX training, DL feedback and DL TX training, followed by UL RX training, UL feedback and UL TX training, where the DL feedback is feedback sent over a downlink corresponding to UL TX training that was previously transmitted.

The message flow **650** of FIG. **6**B is similar to the message flow **600** described with reference to FIG. **6**A, with a different sequencing for the training signals and messages. As shown in the message flow **650**, signals and/or messages **613** to **618** are reordered in the following sequence: **613**, **618**, **614**, **615**, **617** and **616**. It may be appreciated that this sequencing

provides the following characteristics: (1) all arrows in the same direction may be grouped together to form a single packet; and (2) in a group there is RX training, feedback information and then TX training. Unlike message flow **600**, where the feedback information can correspond to current iteration training, the message flow **650** corresponds to previous iteration training. The embodiments are not limited in this context.

FIG. **7** illustrates one embodiment of a graph **700** for beam forming gain. The graph **700** provides a number of iterations on a x-axis and a combined output (dB) on a y-axis. As a result of the enhanced bidirectional beam forming protocol, the feedback at arrow **618** is sent with approximately 15-25 dB beam forming gain (depending on which iteration) due to performing both transmit and receive beam forming. For example, approximately 15 dB gain may be achieved in the first iteration **602-1**, and 5-6 dB additional gain may be achieved in the second iteration **602-2**. After the second iteration **602-2**, progressively smaller gains are realized by each successive iteration (e.g., **602-3** through **602-9**). These SNR improvements enable much faster feedback for beam forming operations without calibration. These results correspond to 32 or 36 antenna elements on both sides.

FIG. **8** illustrates one embodiment of a message flow **800**. The message flow **800** illustrates an alternative message flow for an enhanced bidirectional beam forming protocol that reduces latency introduced by an iterative training scheme by using the HRP channels **352-1**, **352-2**, while reducing or limiting the need to use the LRP channels **354-1**, **354-2**. For purposes of illustration and not limitation, the wireless device **202** may represent a piconet controller (PNC) or coordinator, and the wireless device **204** may represent a wireless station (STA).

Similar to the message flow **600**, the message flow **800** attempts to coordinate transmit and receive beam forming operations to allow feedback information to be provided over the HRP channels **352-1**, **352-2**. The wireless device **202** exits the idle state **402** and enters the beam forming state **404**. The wireless device **202** utilizes the message flow **800** to initiate bidirectional beam formation operations using an iterative training scheme to form a pair of communications channels for a WPAN or WVAN. The message flow **800** interleaves transmit and receive beam forming operations to allow use of partially trained links to communicate feedback information at a higher data rate. More particularly, the message flow **800** interleaves transmit and receive beam forming operations for the wireless devices **202**, **204** to allow feedback information received by the wireless device **202** from the wireless device **204** to be communicated over the HRP channels **352-1**, **352-2**. This reduces the need to use the LRP channels **354-1**, **354-2** during beam forming operations.

In the illustrated embodiment shown in FIG. **8**, the message flow **800** begins with optional timing acquisition and optimal delay selection operations. During a first iterative training **802-1**, the antenna control module **208** sends transmitter (Tx) training signals **813** from the wireless device **202** to the wireless device **204** over the DL HRP channel **352-1** to allow the device **204** to measure characteristics of its received signal. The wireless device **202** receives feedback information **814** from the wireless device **204** over the UL LRP **354-2** to deduce its MRT weights. The antenna control module **208** of the wireless device **202** determines AWVs for the directional transmit beam pattern for the phased antenna array **210** of the wireless device **202** using the feedback information **814** from the wireless device **204**.

The wireless device **202** then sends Rx training signals (STA MRC weights) to the wireless device **204** over the DL HRP **352-1** to allow the wireless device **204** to deduce and form a directional receive beam pattern for the phased antenna array **210***a* of the wireless device **204**, as indicated by arrow **815**. The wireless device **202** receives Tx training signals (STA MRT weights) from the wireless device **204** over the UL HRP **352-2** to form a directional transmit beam pattern for the phased antenna array **210***a* of the wireless device **204**, as indicated by arrow **816**.

The antenna control module **208** uses the transceiver **205** and the phased antenna array **510** of the wireless device **202** to send training signals **815** from the wireless device **202** to the wireless device **204** over a downlink DL HRP channel **352-1** to allow the wireless device **204** to deduce the MRC weights and form a directional receive beam pattern for a phased antenna array **210***a* of the wireless device **204**. The antenna control module **208***a* also sends training signals **816** to the wireless device **202** over the UL HRP channel **352-2** to allow the wireless device **202** to measure characteristics of its received signal.

The wireless device **202** sends feedback information **817** to the wireless device **204** over the DL HRP **352-1** using a directional transmit beam pattern for the phased antenna array **210** of the wireless device **202**. The feedback information **817** is carried using a partially trained link obtained in the recent half-iteration. As a result, the feedback information **817** is much more robust and efficient than using only the DL LRP channel **354-1**. The wireless device **204** uses the feedback information to determine AWVs for the directional transmit beam pattern for the phased antenna array **210***a* of the wireless device **204** using the feedback information **817** from the wireless device **202**.

To complete the first iterative training **802-1**, the wireless device **202** receives training signals **818** by the wireless device **202** from the wireless device **204** over the UL HRP **352-2** to deduce MRC weights and form a directional receive beam pattern for the phased antenna array **210** of the wireless device **202**.

The wireless devices **202**, **204** may continue with the next iterative trainings **802-2-***k* performing similar beam forming or beam refinement operations as used with the first iterative training **802-1**. For example, the wireless device **202** may receive additional feedback information from the wireless device **204** over the UL HRP **352-2** using the directional receive beam pattern for the phased antenna array **210** of the wireless device **202** during the second iterative training **802-2**. The antenna control module **210** may determine AWVs for the directional transmit beam pattern for the phased antenna array **210** of the wireless device **202** using the additional feedback information from the wireless device **204**. Each iterative training **802-1-***k* provides successively more accurate AWVs for the HRP channels **352-1**, **352-2**. This process continues until a terminating condition is reached, such as reaching a determined SNR for data communications or reaching a determined number of iterations (e.g., three iterations). At this point, the HRP channels **352-1**, **352-2** may be used for bidirectional high rate data communications.

The enhanced bidirectional beam forming protocol utilizes partially trained links to provide a higher data rate for the feedback information during the feedback stages. In the WirelessHD Specification, by way of contrast, feedback stages after the first one are done using "directional" mode, which is a selected antenna pattern. With non-calibrated antennas, a random antenna pattern may yield less than 0 dBi in certain directions. The directional mode is expected to be around 0 dBi as it is the best among few random choices. An additional advantage of the enhanced bidirectional beam forming protocol is that the beamformer need not transfer the selected

antenna pattern for the directional mode to the beamformee, since the next time feedback is already going to be over a beamformed link, which is properly trained.

FIG. **9** illustrates one embodiment of a phased array antenna **900**. The phased array antenna **900** may be representative of, for example, the phased array antennas **210**, **210***a*. In the illustrated embodiment shown in FIG. **9**, the phased array antenna **900** may comprise multiple antenna elements **902-1**-*p*.

In some embodiments, the enhanced bidirectional beam forming protocol may train a subset of antenna elements **902-1**-*p* from the phased array antenna **900**. The first few iterations of beam forming operations may be of reduced time and quality. When the phased antenna array **900** is implemented by the wireless device **202**, and has 36 antenna elements **902-1** through **902-36**, then the antenna control module **208** can couple some of the antenna elements **902-1** through **902-36** together and generate training for fewer overall antenna elements **902-1** through **902-36**. This shortens the time of the training in the first iterative trainings and may still capture some of the expected antenna gain. An example for such coupling is depicted in FIG. **9**, where four (4) antenna elements **902-5**, **902-10**, **902-12** and **902-17** marked in cross-hatchings, for example, are always phase shifted by the same amount, such as 90 degrees, 180 degrees or 270 degrees. This results in essentially eight (8) to nine (9) antenna elements made from the 6×6 phased antenna array **900**.

By way of example, referring again to the exemplary message flows **600**, **800**, the wireless device **202** may send Tx training signals to the wireless device **204** over the DL HRP **352-1** to form a directional transmit beam pattern for a subset of antenna elements **902-1**-*p* of the phased antenna array **210** of the wireless device **202**.

Additionally or alternatively, the wireless devices **202**, **204** may exchange additional information during the enhanced bidirectional beam forming protocol that may accelerate beam forming operations. For example, similar to the way that the WirelessHD Specification uses to identify the proper antenna pattern index for the directional mode, the enhanced bidirectional beam forming protocol can add additional information types to certain stages of beam forming operations, such a needed modulation and coding scheme (MCS) for the wireless devices **202**, **204**. An information field of defined length (e.g., 3 bits) may be used to communicate the MCS information. The MCS information may be communicated, for example, with the transmitter training signals in either link direction in order to assist in generating the feedback information during the feedback stages. Other types of information other than MCS information may be sent during different stages of the enhanced bidirectional beam forming protocol, and the embodiments are not limited in this context.

In embodiments, the feedback information may correspond to measurements done at the receiver and is largely unaware of the antenna patterns applied by the transmitter. An example of feedback information may comprise a channel estimation per given delay, among others. In some embodiments, the amount of feedback information may be uniform. Additionally or alternatively, the wireless devices **202**, **204** may exchange increasing amounts of feedback information during the feedback stages of the enhanced bidirectional beam forming protocol to accelerate beam forming operations. When the HRP channels **352-1**, **352-2** are partially or fully formed, and the feedback overhead becomes cheaper, then one or both of the wireless devices **202**, **204** can increase the amount of feedback information provided over the HRP channels **352-1**, **352-2** at certain stages and/or iterative trainings so that the overall beam forming training time is reduced.

Operations for various embodiments may be further described with reference to the following figures and accompanying examples. Some of the figures may include a logic flow. It can be appreciated that an illustrated logic flow merely provides one example of how the described functionality may be implemented. Further, a given logic flow does not necessarily have to be executed in the order presented unless otherwise indicated. In addition, a logic flow may be implemented by a hardware element, a software element executed by a processor, or any combination thereof. The embodiments are not limited in this context.

FIG. **10** illustrates one embodiment of a logic flow **1000** for selecting a channel pair to form a new wireless network between two or more devices. In various embodiments, the logic flow **1000** may be performed by various systems, nodes, and/or modules and may be implemented as hardware, software, and/or any combination thereof, as desired for a given set of design parameters or performance constraints. For example, the logic flow **1000** may be implemented by a logic device (e.g., transmitter node, receiver node) and/or logic comprising instructions, data, and/or code to be executed by a logic device. For purposes of illustration, and not limitation, the logic flow **1000** is described with reference to FIG. **1**. The embodiments are not limited in this context.

In one embodiment, for example, the logic flow **1000** may initiate beam formation operations using an iterative training scheme to form a pair of communications channels for a wireless network at block **1002**. For example, the wireless device **202** may initiate beam formation operations using an iterative training scheme to form a pair of communications channels (**352-1**, **352-2**) for a 60 GHz mmWave WPAN or WVAN. The embodiments are not limited in this context.

In one embodiment, for example, the logic flow **1000** may communicate training signals and feedback information between a first device and a second device using only high rate channel at block **1004**. For example, may communicate training signals and feedback information between the wireless devices **202**, **204** using only HRP channels **352-1**, **352-2**. The embodiments are not limited in this context.

In one embodiment, for example, the logic flow **1000** may determine antenna-array weight vectors for a directional transmit beam pattern for a phased antenna array of the first device using feedback information from the second device at block **1006**. For example, the antenna control module **208** of the wireless device **202** may determine AWVs for a directional transmit beam pattern for the phased antenna array **210** of the wireless device **202** using feedback information from the wireless device **204**. The embodiments are not limited in this context.

FIG. **11** illustrates one embodiment of an article of manufacture **1100**. As shown, the article **1100** may comprise a storage medium **1102** to store logic **1104** for selecting a channel pair to form a new wireless network between two or more devices. For example, logic **1104** may be used to implement the channel selection module **208**, as well as other aspects of the transmitter node (**102**, **202**) and/or the receiver nodes (**104-1**-*n*, **204**). In various embodiments, the article **1100** may be implemented by various systems, nodes, and/or modules.

The article **1100** and/or machine-readable storage medium **1102** may include one or more types of computer-readable storage media capable of storing data, including volatile memory or, non-volatile memory, removable or non-removable memory, erasable or non-erasable memory, writeable or re-writeable memory, and so forth. Examples of a machine-readable storage medium may include, without limitation, random-access memory (RAM), dynamic RAM (DRAM),

Double-Data-Rate DRAM (DDR-DRAM), synchronous DRAM (SDRAM), static RAM (SRAM), read-only memory (ROM), programmable ROM (PROM), erasable programmable ROM (EPROM), electrically erasable programmable ROM (EEPROM), Compact Disk ROM (CD-ROM), Compact Disk Recordable (CD-R), Compact Disk Rewriteable (CD-RW), flash memory (e.g., NOR or NAND flash memory), content addressable memory (CAM), polymer memory (e.g., ferroelectric polymer memory), phase-change memory (e.g., ovonic memory), ferroelectric memory, silicon-oxide-nitride-oxide-silicon (SONOS) memory, disk (e.g., floppy disk, hard drive, optical disk, magnetic disk, magneto-optical disk), or card (e.g., magnetic card, optical card), tape, cassette, or any other type of computer-readable storage media suitable for storing information. Moreover, any media involved with downloading or transferring a computer program from a remote computer to a requesting computer carried by data signals embodied in a carrier wave or other propagation medium through a communication link (e.g., a modem, radio or network connection) is considered computer-readable storage media.

The article **1100** and/or machine-readable medium **1102** may store logic **1104** comprising instructions, data, and/or code that, if executed by a machine, may cause the machine to perform a method and/or operations in accordance with the described embodiments. Such a machine may include, for example, any suitable processing platform, computing platform, computing device, processing device, computing system, processing system, computer, processor, or the like, and may be implemented using any suitable combination of hardware and/or software.

The logic **1104** may comprise, or be implemented as, software, a software module, an application, a program, a subroutine, instructions, an instruction set, computing code, words, values, symbols or combination thereof. The instructions may include any suitable type of code, such as source code, compiled code, interpreted code, executable code, static code, dynamic code, and the like. The instructions may be implemented according to a predefined computer language, manner or syntax, for instructing a processor to perform a certain function. The instructions may be implemented using any suitable high-level, low-level, object-oriented, visual, compiled and/or interpreted programming language, such as C, C++, Java, BASIC, Perl, Matlab, Pascal, Visual BASIC, assembly language, machine code, and so forth. The embodiments are not limited in this context. When implemented the logic **1104** is implemented as software, the software may be executed by any suitable processor and memory unit.

It is worthy to note that although the terms "downlink" and "uplink" channels are used when describing some embodiments, these terms are used to differentiate between two different channels being used between two different devices. Alternate terms may include a "first" channel and a "second" channel, a "forward" channel and a "reverse" channel, and any other suitable labels. Any two channels between any two devices may be used with an enhanced bidirectional beam forming protocol as described herein, and still fall within the scope of the embodiments. The embodiments are not limited in this context.

It is also worthy to note that the increased gain provided by an enhanced bidirectional beam forming protocol may be realized at any point during iterative training operations due to variations in the iterative training operations for different types of protocols (e.g., WirelessHD, NGmS, and so forth), and flexibility in modifying a particular implementation for interleaving operations in support of bidirectional beamforming operations. For example, the increased gain from communicating feedback information as described with reference FIG. **6**B may be realized during the first iteration or second iteration depending on a particular implementation. The embodiments are not limited in this context.

Numerous specific details have been set forth herein to provide a thorough understanding of the embodiments. It will be understood by those skilled in the art, however, that the embodiments may be practiced without these specific details. In other instances, well-known operations, components and circuits have not been described in detail so as not to obscure the embodiments. It can be appreciated that the specific structural and functional details disclosed herein may be representative and do not necessarily limit the scope of the embodiments.

Unless specifically stated otherwise, it may be appreciated that terms such as "processing," "computing," "calculating," "determining," or the like, refer to the action and/or processes of a computer or computing system, or similar electronic computing device, that manipulates and/or transforms data represented as physical quantities (e.g., electronic) within the computing system's registers and/or memories into other data similarly represented as physical quantities within the computing system's memories, registers or other such information storage, transmission or display devices. The embodiments are not limited in this context.

It is also worthy to note that any reference to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

While certain features of the embodiments have been illustrated as described herein, many modifications, substitutions, changes and equivalents will now occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the embodiments.

The invention claimed is:

**1**. An apparatus, comprising:

a phased antenna array;

a transceiver communicatively coupled to the phased antenna array; and

an antenna control module communicatively coupled to the transceiver and the phased antenna array, the antenna control module to initiate beam formation operations using an iterative training scheme to form a pair of communications channels for a wireless network wherein the pair of communication channels includes a high rate physical (HRP) channel and a low rate physical (LRP) channel, receive and send training signals over the HRP channel, and receive and send feedback information over the HRP channel.

**2**. The apparatus of claim **1**, comprising:

a display;

a processor; and

a memory coupled with the processor.

**3**. The apparatus of claim **1**, the formation of the HRP channel comprising:

sending training signals to a peer device over the HRP channel;

receiving feedback information from the peer device over the LRP channel; and

determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phase antenna array based on the feedback information.

**4**. The apparatus of claim **1**, the antenna control module to send transmitting timing acquisition sequences over the HRP channel.

**5**. The apparatus of claim **1**, the antenna control module to send transmitting delay selection sequences over the HRP channel.

**6**. The apparatus of claim **1**, the antenna control module to send transmitter training signals to a peer device over the HRP channel, the transmitter training signals for use in forming a directional transmit beam pattern for the phased antenna array.

**7**. The apparatus of claim **1**, the antenna control module to receive receiver training signals from a peer device over the HRP to form a directional receive beam pattern for the phased antenna array.

**8**. The apparatus of claim **1**, the antenna control module to receive transmitter training signals from a peer device over the HRP to form a directional transmit beam pattern for a phased antenna array of the peer device.

**9**. The apparatus of claim **1**, the antenna control module to receive feedback information from a peer device over the LRP channel using a directional receive beam pattern for the phased antenna array.

**10**. The apparatus of claim **1**, the antenna control module to send feedback information to a peer device over the LRP channel using a directional transmit beam pattern for the phased antenna array, the feedback information for use in determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phased antenna array of the peer device.

**11**. The apparatus claim **1**, the antenna control module to continue beam forming operations using multiple iterations until a determined signal-to-noise ratio for data communications is reached or a determined number of iterations is reached.

**12**. A method comprising:

initiating beam formation operations using an iterative training scheme to establish a pair of communications channels between a first device and a second device for a wireless network wherein the pair of communication channels includes a high rate physical (HRP) channel and a low rate physical (LRP) channel;

receiving, by the first device, training signals from the second device over the HRP channel; and

sending, by the first device, feedback information to the second device over the HRP channel.

**13**. The method of claim **12**, the establishment of the HRP channel comprising:

sending, by the first device, training signals to the second device over the HRP channel;

receiving, by the first device, feedback information from the second device over the LRP channel; and

determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phase antenna array based on the feedback information.

**14**. The method of claim **12**, the establishment of the HRP channel comprising transmitting timing acquisition sequences.

**15**. The method of claim **12**, the establishment of the HRP channel comprising transmitting delay selection sequences.

**16**. The method of claim **12**, comprising sending transmitter training signals from the first device to the second device over the HRP channel to form a directional transmit beam pattern for a phased antenna array of the first device.

**17**. The method of claim **12**, comprising receiving receiver training signals by the first device from the second device over the HRP channel to form a directional receive beam pattern for a phased antenna array of the first device.

**18**. The method of claim **12**, comprising receiving transmitter training signals by the first device from the second device over the HRP channel to form a directional transmit beam pattern for a phased antenna array of the second device.

**19**. The method of claim **12**, comprising:

receiving feedback information by the first device from the second device over the LRP channel using a directional receive beam pattern for a phased antenna array of the first device; and

determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phased antenna array of the first device using the feedback information from the second device.

**20**. The method of claim **12**, comprising sending feedback information from the first device to the second device over the LRP channel using a directional transmit beam pattern for a phased antenna array of the first device, the feedback information for use in determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phased antenna array of the second device using the feedback information from the first device.

**21**. The method of claim **12**, comprising communicating training signals and feedback information, and determining antenna-array vector weights (AWV) for a directional transmit beam pattern for a phased antenna array of the first device, using multiple iterations until a determined signal-to-noise ratio for data communications is reached or until a determined number of iterations is reached.

**22**. An article comprising a non-transitory computer-readable storage medium containing a plurality of instructions that when executed enable a processor to:

initiate beam formation operations using an iterative training scheme to establish a pair of communications channels for a wireless network wherein the pair of communication channels includes a high rate physical (HRP) channel and a low rate physical (LRP) channel;

receive training signals from a peer device over the HRP channel; and

send feedback information to the peer device over the HRP channel.

**23**. The article of claim **22**, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to:

send training signals to the peer device over the HRP channel;

receive feedback information from the peer device over the LRP channel; and

determine antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phase antenna array based on the feedback information.

**24**. The article of claim **22**, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to transmit timing acquisition sequences to establish the HRP channel.

**25**. The article of claim **22**, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to transmit delay selection sequences to establish the HRP channel.

**26**. The article of claim **22**, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to send transmitter training signals to the peer device over the HRP channel to form a directional transmit beam pattern for a phased antenna array.

27. The article of claim 22, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to receive receiver training signals from the peer device over the HRP channel to form a directional receive beam pattern for a phased antenna array.

28. The article of claim 22, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to receive transmitter training signals from the peer device over the HRP channel to form a directional transmit beam pattern for a phased antenna array of the peer device.

29. The article of claim 22, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to:

receive feedback information from the peer device over the LRP channel using a directional receive beam pattern for a phased antenna array; and

determine antenna-array weight vectors (AWV) for a directional transmit beam pattern for the phased antenna array using the feedback information from the peer device.

30. The article of claim 22, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to send feedback information to the peer device over the LRP channel using a directional transmit beam pattern for a phased antenna array, the feedback information for use in determining antenna-array weight vectors (AWV) for a directional transmit beam pattern for a phased antenna array of the peer device using the feedback information.

31. The article of claim 22, the non-transitory computer-readable storage medium comprising instructions that when executed enable the processor to communicate training signals and feedback information, and determining antenna-array vector weights (AWV) for the directional transmit beam pattern for a phased antenna array using multiple iterations until a determined signal-to-noise ratio for data communications is reached or until a determined number of iterations is reached.

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