

(51) International Patent Classification:
H04B 7/04 (2017.01)(21) International Application Number:
PCT/CN2016/086274(22) International Filing Date:
17 June 2016 (17.06.2016)

(25) Filing Language: English

(26) Publication Language: English

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LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).**Published:**

— with international search report (Art. 21(3))

(54) Title: CHANNEL COEFFICIENT ESTIMATION IN A WIRELESS COMMUNICATION SYSTEM

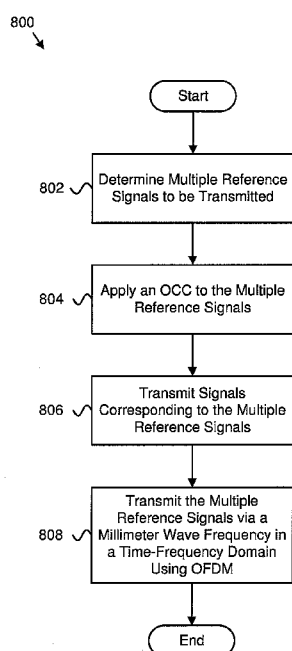


FIG. 8

(57) **Abstract:** Apparatuses, methods, and systems are disclosed for channel coefficient estimation. One apparatus includes an antenna array having multiple antenna elements. The apparatus may include a receiver that receives information via the antenna array. The information may include multiple reference signals and each antenna element of the antenna array receives a version of the information. The apparatus may include a phase shifter that applies a phase shift vector to the version of the information received by each antenna element of the antenna array to produce multiple phase shifted outputs. The apparatus may include a combining device that combines the multiple phase shifted outputs into a digital signal. The apparatus may include a processor that determines an estimated channel coefficient vector for the plurality of antenna elements using the digital signal. The processor may also determine a maximal-ratio combining ("MRC") vector using the estimated channel coefficient vector.

CHANNEL COEFFICIENT ESTIMATION IN A WIRELESS COMMUNICATION SYSTEM

FIELD

5 [0001] The subject matter disclosed herein relates generally to wireless communications and more particularly relates to channel coefficient estimation in a wireless communication system.

BACKGROUND

10 [0002] The following abbreviations are herewith defined, at least some of which are referred to within the following description.

[0003] 3GPP Third Generation Partnership Project

[0004] ACK Positive-Acknowledgment

[0005] ANDSF Access Network Discovery and Selection Function

[0006] AP Access Point

15 [0007] APN Access Point Name

[0008] BLER Block Error Ratio

[0009] BPSK Binary Phase Shift Keying

[0010] CAZAC Constant Amplitude Zero Auto Correction

[0011] CCA Clear Channel Assessment

20 [0012] CCE Control Channel Element

[0013] CP Cyclic Prefix

[0014] CQI Channel Quality Indicator

[0015] CSI Channel State Information

[0016] CSI-RS Channel State Information Reference Signal

25 [0017] CSS Common Search Space

[0018] DCI Downlink Control Information

[0019] DL Downlink

[0020] eNB Evolved Node B

[0021] EPDCCH Enhanced Physical Downlink Control Channel

30 [0022] E-RAB E-UTRAN Radio Access Bearer

[0023] ETSI European Telecommunications Standards Institute

[0024] E-UTRAN Evolved Universal Terrestrial Radio Access Network

[0025] FBE Frame Based Equipment

[0026] FDD Frequency Division Duplex

- [0027] FDMA Frequency Division Multiple Access
- [0028] FEC Forward Error Correction
- [0029] FFT Fast Fourier Transform
- [0030] GPRS General Packet Radio Service
- 5 [0031] GPT GPRS Tunneling Protocol
- [0032] HARQ Hybrid Automatic Repeat Request
- [0033] H-PLMN Home Public Land Mobile Network
- [0034] IFFT Inverse FFT
- [0035] IP Internet Protocol
- 10 [0036] ISRP Inter-System Routing Policy
- [0037] LAA Licensed Assisted Access
- [0038] LBE Load Based Equipment
- [0039] LBT Listen-Before-Talk
- [0040] LTE Long Term Evolution
- 15 [0041] MCL Minimum Coupling Loss
- [0042] MCS Modulation and Coding Scheme
- [0043] MIMO Multiple-Input, Multiple-Output
- [0044] mmW Millimeter Wave
- [0045] MME Mobility Management Entity
- 20 [0046] MMSE Minimum Mean Square Error
- [0047] MRC Maximal-Ratio Combining
- [0048] MU-MIMO Multi-User, Multiple-Input, Multiple-Output
- [0049] NACK or NAK Negative-Acknowledgment
- [0050] NAS Non-Access Stratum
- 25 [0051] NBIFOM Network-Based IP Flow Mobility
- [0052] OCC Orthogonal Cover Code
- [0053] OFDM Orthogonal Frequency Division Multiplexing
- [0054] PCell Primary Cell
- [0055] PBCH Physical Broadcast Channel
- 30 [0056] PCO Protocol Configuration Options
- [0057] PCRF Policy and Charging Rules Function
- [0058] PDCCH Physical Downlink Control Channel
- [0059] PDCP Packet Data Convergence Protocol
- [0060] PDN Packet Data Network

- 5 [0061] PDSCH Physical Downlink Shared Channel
[0062] PDU Protocol Data Unit
[0063] PGW Packet Data Network Gateway
[0064] PHICH Physical Hybrid ARQ Indicator Channel
[0065] PLMN Public Land Mobile Network
[0066] PMI Precoding Matrix Indicator
[0067] PRACH Physical Random Access Channel
[0068] PRB Physical Resource Block
[0069] PTI Procedure Transaction Identity
10 [0070] PUCCH Physical Uplink Control Channel
[0071] PUSCH Physical Uplink Shared Channel
[0072] QoS Quality of Service
[0073] QPSK Quadrature Phase Shift Keying
[0074] RAB Radio Access Bearer
15 [0075] RAN Radio Access Network
[0076] RAR Random Access Response
[0077] RI Rank Indicator
[0078] RRC Radio Resource Control
[0079] RS Reference Signal
20 [0080] RX Receive
[0081] SC-FDMA Single Carrier Frequency Division Multiple Access
[0082] SCell Secondary Cell
[0083] SCH Shared Channel
[0084] SGW Serving Gateway
25 [0085] SIB System Information Block
[0086] SINR Signal-to-Interference-Plus-Noise Ratio
[0087] SNR Signal-to-Noise Ratio
[0088] SR Scheduling Request
[0089] SRS Sounding Reference Signal
30 [0090] TAU Tracking Area Update
[0091] TB Transport Block
[0092] TBS Transport Block Size
[0093] TCP Transmission Control Protocol
[0094] TDD Time-Division Duplex

[0095] TDM Time Division Multiplex

[0096] TEID Tunnel Endpoint Identification ("ID")

[0097] TX Transmit

[0098] UCI Uplink Control Information

5 [0099] UE User Entity/Equipment (Mobile Terminal)

[00100] UL Uplink

[00101] UMTS Universal Mobile Telecommunications System

[00102] V-PLMN Visited Public Land Mobile Network

[00103] WiMAX Worldwide Interoperability for Microwave Access

10 [00104] WLAN Wireless Local Area Network

[00105] ZF Zero Forcing

[00106] In wireless communications networks, higher network capacity may be desired. Accordingly, millimeter wave communications systems may be used. Millimeter wave ("mmW") may have a large amount of available contiguous bandwidth with a shorter wavelength (e.g., 1 mm to 10 mm) than often used in wireless communication networks and may have unique channel properties. Compared with microwave, mmW propagation may exhibit less diffraction and more reflection, resulting in more directional transmission. Moreover, mmW propagation may have larger path loss than microwave thereby making it suitable for use with a small transmission radius (e.g., 100 m to 200 m). In some configurations, mmW propagation may be used as a wireless backhaul technique.

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[00107] Certain mmW communication systems may use large scale antenna arrays and a MIMO technique. For example, because of the shorter wavelength of mmW, a large number of antenna elements may be packed into a small area. In one configuration, an eNB may have 64, 128, 1024, or more antenna elements. In another configuration, a UE may have 16, 32, or more antenna elements. It may be difficult to determine channel coefficients for each antenna element in such a system.

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BRIEF SUMMARY

[00108] Apparatuses for channel coefficient estimation are disclosed. Methods and systems also perform the functions of the apparatus. In one embodiment, the apparatus includes a processor that determines multiple reference signals to be transmitted. In such an embodiment, a number of reference signals of the multiple reference signals is at least equal to a number of antennas configured to receive the reference signals. In various embodiments, the apparatus includes a transmitter that transmits the multiple reference signals via a millimeter

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wave frequency in a time-frequency domain using orthogonal frequency-division multiplexing ("OFDM").

[00109] In certain embodiments, the transmitter includes one antenna port used for transmitting the multiple reference signals. In another embodiment, the transmitter transmits the multiple reference signals using beamforming from multiple antenna elements. In such an embodiment, using beamforming may include using a transmit beamforming vector, and the transmit beamforming vector does not change for a given beamforming configuration. In various embodiments, the transmitter transmits the multiple reference signals in a frequency resource using substantially consecutive OFDM symbols. In some embodiments, the transmitter transmits the multiple reference signals in a downlink as a channel state information reference signal ("CSI-RS").

[00110] In one embodiment, the transmitter transmits the multiple reference signals in an uplink as a sounding reference signal ("SRS"). In certain embodiments, the transmitter transmits the multiple reference signals in substantially adjacent time and frequency resources. In various embodiments, the processor applies an orthogonal cover code ("OCC") to the multiple reference signals, and a length of the OCC matches the number of reference signals. In various embodiments, the transmitter transmits signals corresponding to the multiple reference signals, and the signals include at least one of reference signals within the plurality of reference signals, an OCC used to transmit the plurality of reference signals, and time and frequency resources used to transmit the multiple reference signals.

[00111] A method, in one embodiment, includes determining multiple reference signals to be transmitted. In such an embodiment, a number of reference signals of the multiple reference signals is at least equal to a number of antennas elements configured to receive the multiple reference signals. In certain embodiments, the method may include transmitting the multiple reference signals via a millimeter wave frequency in a time-frequency domain using orthogonal frequency-division multiplexing ("OFDM").

[00112] In one embodiment, an apparatus for channel coefficient estimation includes an antenna array having multiple antenna elements. The apparatus may also include a receiver that receives information via the antenna array. In such an apparatus, the information may include multiple reference signals and each antenna element of the antenna array receives a version of the reference signals based on the antenna element's unique channel coefficient. The apparatus may include a phase shifter that applies a phase shift vector to the version of the information received by each antenna element of the antenna array to produce multiple phase shifted outputs. The apparatus may also include a combining device that combines the multiple

phase shifted outputs into a digital signal. The apparatus may include a processor that determines an estimated channel coefficient vector for the multiple antenna elements using the digital signal. The processor may also determine a maximal-ratio combining ("MRC") vector using the estimated channel coefficient vector.

5 [00113] In some embodiments, the processor that determines the estimated channel coefficient vector further determines a receive beamforming vector using a discrete Fourier transform matrix. In various embodiments, the processor that determines the estimated channel coefficient vector further determines a receive beamforming vector using a Householder transform matrix. In certain embodiments, the processor determines the estimated channel
10 coefficient vector using a zero forcing ("ZF") algorithm. In one embodiment, the processor determines the estimated channel coefficient vector using a minimum mean square error ("MMSE") algorithm.

[00114] Another method for channel coefficient estimation, in one embodiment, includes receiving information via multiple antenna elements. In such an embodiment, the
15 information includes multiple reference signals and each antenna element of the multiple antenna elements receives a version of the information. In various embodiments, the method includes applying a phase shift vector to the version of the information received by each antenna element of the multiple antenna elements to produce multiple phase shifted outputs. In some
20 embodiments, the method includes combining the multiple phase shifted outputs into a digital signal. In certain embodiments, the method includes determining an estimated channel coefficient vector for the multiple antenna elements using the digital signal. In one embodiment, the method includes determining a maximal-ratio combining ("MRC") vector using the estimated channel coefficient vector.

BRIEF DESCRIPTION OF THE DRAWINGS

25 [00115] A more particular description of the embodiments briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. Understanding that these drawings depict only some embodiments and are not therefore to be considered to be limiting of scope, the embodiments will be described and explained with additional specificity and detail through the use of the accompanying drawings, in
30 which:

[00116] Figure 1 is a schematic block diagram illustrating one embodiment of a wireless communication system for channel coefficient estimation;

[00117] Figure 2 is a schematic block diagram illustrating one embodiment of an apparatus that may be used for channel coefficient estimation;

[00118] Figure 3 is a schematic block diagram illustrating another embodiment of an apparatus that may be used for channel coefficient estimation;

[00119] Figure 4 is a schematic block diagram illustrating one embodiment of an antenna array;

5 [00120] Figure 5 is a schematic block diagram illustrating one embodiment of a system for producing a single digital signal;

[00121] Figure 6 is a schematic block diagram illustrating one embodiment of reference signal transmission;

10 [00122] Figure 7 is a schematic block diagram illustrating another embodiment of reference signal transmission;

[00123] Figure 8 is a schematic flow chart diagram illustrating one embodiment of a method for transmitting multiple reference signals; and

[00124] Figure 9 is a schematic flow chart diagram illustrating one embodiment of a method for channel coefficient estimation using information received by a receiver.

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DETAILED DESCRIPTION

[00125] As will be appreciated by one skilled in the art, aspects of the embodiments may be embodied as a system, apparatus, method, or program product. Accordingly, embodiments may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an
20 embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,” “module” or “system.” Furthermore, embodiments may take the form of a program product embodied in one or more computer readable storage devices storing machine readable code, computer readable code, and/or program code, referred hereafter as code. The storage devices may be tangible, non-transitory, and/or non-transmission. The storage devices
25 may not embody signals. In a certain embodiment, the storage devices only employ signals for accessing code.

[00126] Certain of the functional units described in this specification may be labeled as modules, in order to more particularly emphasize their implementation independence. For example, a module may be implemented as a hardware circuit comprising custom very-large-scale integration (“VLSI”) circuits or gate arrays, off-the-shelf semiconductors such as logic
30 chips, transistors, or other discrete components. A module may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices or the like.

[00127] Modules may also be implemented in code and/or software for execution by various types of processors. An identified module of code may, for instance, include one or more physical or logical blocks of executable code which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified module need not be physically located together, but may include disparate instructions stored in different locations which, when joined logically together, include the module and achieve the stated purpose for the module.

[00128] Any combination of one or more computer readable medium may be utilized. The computer readable medium may be a computer readable storage medium. The computer readable storage medium may be a storage device storing the code. The storage device may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, holographic, micromechanical, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing.

[00129] More specific examples (a non-exhaustive list) of the storage device would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory ("RAM"), a read-only memory ("ROM"), an erasable programmable read-only memory ("EPROM" or Flash memory), a portable compact disc read-only memory ("CD-ROM"), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

[00130] Reference throughout this specification to "one embodiment," "an embodiment," or similar language 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," "in an embodiment," and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment, but mean "one or more but not all embodiments" unless expressly specified otherwise. The terms "including," "comprising," "having," and variations thereof mean "including but not limited to," unless expressly specified otherwise. An enumerated listing of items does not imply that any or all of the items are mutually exclusive, unless expressly specified otherwise. The terms "a," "an," and "the" also refer to "one or more" unless expressly specified otherwise.

[00131] Furthermore, the described features, structures, or characteristics of the embodiments may be combined in any suitable manner. In the following description, numerous specific details are provided, such as examples of programming, software modules, user

selections, network transactions, database queries, database structures, hardware modules, hardware circuits, hardware chips, etc., to provide a thorough understanding of embodiments. One skilled in the relevant art will recognize, however, that embodiments may be practiced without one or more of the specific details, or with other methods, components, materials, and so forth. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of an embodiment.

[00132] Aspects of the embodiments are described below with reference to schematic flowchart diagrams and/or schematic block diagrams of methods, apparatuses, systems, and program products according to embodiments. It will be understood that each block of the schematic flowchart diagrams and/or schematic block diagrams, and combinations of blocks in the schematic flowchart diagrams and/or schematic block diagrams, can be implemented by code. These code may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the schematic flowchart diagrams and/or schematic block diagrams block or blocks.

[00133] The code may also be stored in a storage device that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the storage device produce an article of manufacture including instructions which implement the function/act specified in the schematic flowchart diagrams and/or schematic block diagrams block or blocks.

[00134] The code may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the code which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[00135] The schematic flowchart diagrams and/or schematic block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of apparatuses, systems, methods and program products according to various embodiments. In this regard, each block in the schematic flowchart diagrams and/or schematic block diagrams may represent a module, segment, or portion of code, which includes one or more executable instructions of the code for implementing the specified logical function(s).

[00136] It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the Figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved.

5 Other steps and methods may be conceived that are equivalent in function, logic, or effect to one or more blocks, or portions thereof, of the illustrated Figures.

[00137] Although various arrow types and line types may be employed in the flowchart and/or block diagrams, they are understood not to limit the scope of the corresponding embodiments. Indeed, some arrows or other connectors may be used to indicate only the logical
10 flow of the depicted embodiment. For instance, an arrow may indicate a waiting or monitoring period of unspecified duration between enumerated steps of the depicted embodiment. It will also be noted that each block of the block diagrams and/or flowchart diagrams, and combinations of blocks in the block diagrams and/or flowchart diagrams, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of
15 special purpose hardware and code.

[00138] The description of elements in each figure may refer to elements of proceeding figures. Like numbers refer to like elements in all figures, including alternate embodiments of like elements.

[00139] Figure 1 depicts an embodiment of a wireless communication system 100
20 for channel coefficient estimation. In certain embodiments, the wireless communication system 100 may operate using mmW communication. In one embodiment, the wireless communication system 100 includes remote units 102 and base units 104. Even though a specific number of remote units 102 and base units 104 are depicted in Figure 1, one of skill in the art will recognize that any number of remote units 102 and base units 104 may be included in the wireless
25 communication system 100.

[00140] In one embodiment, the remote units 102 may include computing devices, such as desktop computers, laptop computers, personal digital assistants (“PDAs”), tablet computers, smart phones, smart televisions (e.g., televisions connected to the Internet), set-top boxes, game consoles, security systems (including security cameras), vehicle on-board
30 computers, network devices (e.g., routers, switches, modems), or the like. In some embodiments, the remote units 102 include wearable devices, such as smart watches, fitness bands, optical head-mounted displays, or the like. Moreover, the remote units 102 may be referred to as subscriber units, mobiles, mobile stations, users, terminals, mobile terminals, fixed terminals, subscriber stations, UE, user terminals, a device, or by other terminology used in the art. The

remote units 102 may communicate directly with one or more of the base units 104 via UL communication signals.

[00141] The base units 104 may be distributed over a geographic region. In certain embodiments, a base unit 104 may also be referred to as an access point, an access terminal, a base, a base station, a Node-B, an eNB, a Home Node-B, a relay node, a device, or by any other terminology used in the art. The base units 104 are generally part of a radio access network that includes one or more controllers communicably coupled to one or more corresponding base units 104. The radio access network is generally communicably coupled to one or more core networks, which may be coupled to other networks, like the Internet and public switched telephone networks, among other networks. These and other elements of radio access and core networks are not illustrated but are well known generally by those having ordinary skill in the art.

[00142] In one implementation, the wireless communication system 100 is compliant with the LTE of the 3GPP protocol, wherein the base unit 104 transmits using an OFDM modulation scheme on the DL and the remote units 102 transmit on the UL using a SC-FDMA scheme. More generally, however, the wireless communication system 100 may implement some other open or proprietary communication protocol, for example, WiMAX, among other protocols. The present disclosure is not intended to be limited to the implementation of any particular wireless communication system architecture or protocol.

[00143] The base units 104 may serve a number of remote units 102 within a serving area, for example, a cell or a cell sector via a wireless communication link. The base units 104 transmit DL communication signals to serve the remote units 102 in the time, frequency, and/or spatial domain.

[00144] In one embodiment, an apparatus (e.g., UE, remote unit 102, eNB, base unit 104) may determine multiple reference signals to be transmitted in contrast to transmitting only one reference signal. The multiple reference signals may be transmitted at different times (e.g., using different OFDM symbols). In such an embodiment, a number of reference signals of the multiple reference signals is at least equal to a number of antennas elements configured to receive the multiple reference signals. In certain embodiments, the apparatus may transmit the multiple reference signals via a millimeter wave frequency in a time-frequency domain using OFDM. The multiple reference signals may aid in channel coefficient estimation. The set of reference signals used together for channel estimation are transmitted in different OFDM symbols. As may be appreciated, the phase shift vectors (e.g., beamforming vectors) are constant within an OFDM symbol, but may change for different OFDM symbols. Moreover, the same phase shift is applied to all transmission subcarriers. However, a receiver receiving the

transmitted subcarriers applies different phase shifts to received information to use different OFDM reference symbols.

[00145] In another embodiment, an apparatus (e.g., eNB, base unit 104, UE, remote unit 102) may receive information via multiple antenna elements. In such an embodiment, the information may include the multiple reference signals and each antenna element of the multiple antenna elements receives a version of the information. The apparatus may also apply a phase shift vector to the version of the information received by each antenna element of the multiple antenna elements to produce multiple phase shifted outputs. The apparatus may combine the multiple phase shifted outputs into a digital signal. The apparatus may also determine an estimated channel coefficient vector for the plurality of antenna elements using the digital signal. As may be appreciated, the digital signal may include multiple OFDM symbols with different phase shifts. The apparatus may determine an MRC vector using the estimated channel coefficient vector.

[00146] Figure 2 depicts one embodiment of an apparatus 200 that may be used for channel coefficient estimation. The apparatus 200 includes one embodiment of the remote unit 102. Furthermore, the remote unit 102 may include a processor 202, a memory 204, an input device 206, a display 208, a transmitter 210, a receiver 212, an antenna array 214, and circuitry 216. In some embodiments, the input device 206 and the display 208 are combined into a single device, such as a touchscreen. In certain embodiments, the remote unit 102 may not include any input device 206 and/or display 208. In various embodiments, the remote unit 102 may include one or more of the processor 202, the memory 204, the transmitter 210, the receiver 212, the antenna array 214, and the circuitry 216, and may not include the input device 206 and/or the display 208.

[00147] The processor 202, in one embodiment, may include any known controller capable of executing computer-readable instructions and/or capable of performing logical operations. For example, the processor 202 may be a microcontroller, a microprocessor, a central processing unit ("CPU"), a graphics processing unit ("GPU"), an auxiliary processing unit, a field programmable gate array ("FPGA"), or similar programmable controller. In some embodiments, the processor 202 executes instructions stored in the memory 204 to perform the methods and routines described herein. The processor 202 is communicatively coupled to the memory 204, the input device 206, the display 208, the transmitter 210, and the receiver 212. In certain embodiments, the processor 202 may determine multiple reference signals to be transmitted. In such embodiments, a number of reference signals of the multiple reference signals is at least equal to a number of antennas configured to receive the multiple reference

signals. In some embodiments, the processor 202 may determine an estimated channel coefficient for each antenna element using the single digital signal to produce multiple estimated channel coefficients. In various embodiments, the processor 202 may determine an MRC vector using the multiple estimated channel coefficients.

5 [00148] The memory 204, in one embodiment, is a computer readable storage medium. In some embodiments, the memory 204 includes volatile computer storage media. For example, the memory 204 may include a RAM, including dynamic RAM ("DRAM"), synchronous dynamic RAM ("SDRAM"), and/or static RAM ("SRAM"). In some embodiments, the memory 204 includes non-volatile computer storage media. For example, the memory 204
10 may include a hard disk drive, a flash memory, or any other suitable non-volatile computer storage device. In some embodiments, the memory 204 includes both volatile and non-volatile computer storage media. In some embodiments, the memory 204 stores data relating to information to be provided to another device. In some embodiments, the memory 204 also stores program code and related data, such as an operating system or other controller algorithms
15 operating on the remote unit 102.

 [00149] The input device 206, in one embodiment, may include any known computer input device including a touch panel, a button, a keyboard, a stylus, a microphone, or the like. In some embodiments, the input device 206 may be integrated with the display 208, for example, as a touchscreen or similar touch-sensitive display. In some embodiments, the input
20 device 206 includes a touchscreen such that text may be input using a virtual keyboard displayed on the touchscreen and/or by handwriting on the touchscreen. In some embodiments, the input device 206 includes two or more different devices, such as a keyboard and a touch panel.

 [00150] The display 208, in one embodiment, may include any known electronically controllable display or display device. The display 208 may be designed to output
25 visual, audible, and/or haptic signals. In some embodiments, the display 208 includes an electronic display capable of outputting visual data to a user. For example, the display 208 may include, but is not limited to, an LCD display, an LED display, an OLED display, a projector, or similar display device capable of outputting images, text, or the like to a user. As another, non-limiting, example, the display 208 may include a wearable display such as a smart watch, smart
30 glasses, a heads-up display, or the like. Further, the display 208 may be a component of a smart phone, a personal digital assistant, a television, a table computer, a notebook (laptop) computer, a personal computer, a vehicle dashboard, or the like.

 [00151] In certain embodiments, the display 208 includes one or more speakers for producing sound. For example, the display 208 may produce an audible alert or notification (e.g.,

a beep or chime). In some embodiments, the display 208 includes one or more haptic devices for producing vibrations, motion, or other haptic feedback. In some embodiments, all or portions of the display 208 may be integrated with the input device 206. For example, the input device 206 and display 208 may form a touchscreen or similar touch-sensitive display. In other
5 embodiments, the display 208 may be located near the input device 206.

[00152] The transmitter 210 is used to provide UL communication signals to the base unit 104 and the receiver 212 is used to receive DL communication signals from the base unit 104. In one embodiment, the transmitter 210 may transmit multiple reference signals via a millimeter wave frequency in a time-frequency domain using OFDM. In certain embodiments,
10 the receiver 214 may receive information via an antenna array. In such embodiments, the information may include multiple reference signals and each antenna element of the antenna array may receive a version of the information. Although only one transmitter 210 and one receiver 212 are illustrated, the remote unit 102 may have any suitable number of transmitters 210 and receivers 212. The transmitter 210 and the receiver 212 may be any suitable type of
15 transmitters and receivers. In one embodiment, the transmitter 210 and the receiver 212 may be part of a transceiver.

[00153] The antenna array 214 may be used to transmit and/or receive transmissions. In certain embodiments, the antenna array 214 is part of the transmitter 210, while in other embodiments, the antenna array 214 is part of the receiver 212. In some
20 embodiments, the antenna array 214 may be part of a transceiver. The antenna array 214 may include any suitable number of antenna elements. For example, in some embodiments, the antenna array 214 may include less than or greater than 8, 16, 32, 64, or 128 antenna elements. One embodiment of an antenna array 214 is described in Figure 4.

[00154] The circuitry 216 may include any suitable circuitry for the remote unit
25 102. In certain embodiments, the circuitry 216 includes hardware and/or software. In one embodiment, the circuitry 216 includes a phase shifter that applies a phase shift vector to a version of information received by each antenna element of the antenna array 214 to produce multiple phase shifted outputs. In certain embodiments, the circuitry 216 includes a combining device that combines the multiple phase shifted outputs into a digital signal. One embodiment of
30 circuitry 216 is described in Figure 5.

[00155] Figure 3 depicts another embodiment of an apparatus 300 that may be used for channel coefficient estimation. The apparatus 300 includes one embodiment of the base unit 104. Furthermore, the base unit 104 may include a processor 302, a memory 304, an input device 306, a display 308, a transmitter 310, a receiver 312, an antenna array 314, and circuitry

316. As may be appreciated, the processor 302, the memory 304, the input device 306, the display 308, the transmitter 310, the receiver 312, the antenna array 314, and the circuitry 316 may be substantially similar to the processor 202, the memory 204, the input device 206, the display 208, the transmitter 210, the receiver 212, the antenna array 214, and the circuitry 216 of the remote unit 102, respectively. For example, the transmitter 310 is used to provide DL communication signals to the remote unit 102, and the receiver 312 is used to receive UL communication signals from the remote unit 102.

[00156] Figure 4 is a schematic block diagram illustrating one embodiment of an antenna array 400, such as the antenna array 214 and/or the antenna array 314. The antenna array 400 includes 16 antenna columns 402, with each antenna column 402 including 4 antenna elements 404. As may be appreciated, the antenna array 400 may have any suitable number of antenna columns 402. Furthermore, each antenna column 402 may include any suitable number of antenna elements 404. In certain embodiments, the antenna array 400 may be considered a beamforming antenna array.

[00157] Figure 5 is a schematic block diagram illustrating one embodiment of a system 500 for producing a single digital signal. In certain embodiments, the system 500 may be part of the circuitry 216 and/or the circuitry 316. As illustrated, the system 500 may correspond to one antenna column 402. Accordingly, each antenna column 402 in an antenna array 400 may include the system 500.

[00158] During operation, a first antenna element 502 may receive a first signal (e.g., y_0), a second antenna element 504 may receive a second signal (e.g., y_1), a third antenna element 506 may receive a third signal (e.g., y_2), and a fourth antenna element 508 may receive a fourth signal (e.g., y_3). As may be appreciated, in antenna columns 402 with N antenna elements 404 additional signals may be received up to y_{N-1} . As may be appreciated, the signal received Y by all of the antenna elements may be:

$$Y = [y_0, y_1, \dots, y_{N-1}]^T$$

[00159] where T represents time.

[00160] The first signal is provided to a first amplifier 510 (e.g., low noise amplifier "LNA"), the second signal is provided to a second amplifier 512, the third signal is provided to a third amplifier 514, and the fourth signal is provided to a fourth amplifier 516. The amplifiers 510, 512, 514, and 516 are used to amplify the received signals for further processing of the received signals. Moreover, the amplifiers 510, 512, 514, and 516 may be any suitable amplifier, such as LNAs.

[00161] Moreover, the outputs from the amplifiers 510, 512, 514, and 516 are fed into respective first phase shifter 518, second phase shifter 520, third phase shifter 522, and fourth phase shifter 524. The phase shifters 518, 520, 522, and 524 apply a phase shift vector to their respective received signals. In one embodiment, the first phase shifter 518 applies a first phase shift vector, the second phase shifter 520 applies a second phase shift vector, the third phase shifter 522 applies a third phase shift vector, and the fourth phase shifter 524 applies a fourth phase shift vector. Accordingly, the phase shifters 518, 520, 522, and 524 shift the signals and the combining circuit 526 combines the shifted signals.

[00162] The combining circuit 526 directs the combined signals to an RF chain 528. The combined signals are then fed into an analog-to-digital converter ("ADC") 530. The ADC 530 converts the combined analog signals into a digital signal z 532. Thus one set of circuitry is used to produce digital signal z 532 from four antenna elements 502, 504, 506, and 508. After the phase shift and combining, the digital baseband Rx signal z 532 is given by:

$$z = [e^{i\varphi_0}, e^{i\varphi_1}, \dots, e^{i\varphi_{N-1}}][y_0, y_1, \dots, y_{N-1}]^T$$

[00163] where $e^{i\varphi_l}$ is the phase shift angle corresponding to the antenna element l .

[00164] In another example, a channel coefficient vector G from a transmission antenna port to a receiver antenna array may be represented by the following equation:

$$G = [g_0, g_1, \dots, g_{N-1}]^T$$

[00165] where g represents a channel coefficient corresponding to a single antenna element; T represents time; and N represents the number of antenna elements.

[00166] The converted digital signal z on the receiver side for such a channel coefficient vector G may be represented by the following equation:

$$z = \left(\sum_{l=0}^{N-1} e^{i\varphi_l} g_l \right) x + n$$

[00167] where $e^{i\varphi_l}$ is the phase shift corresponding to an antenna element l ; g_l represents a channel coefficient corresponding to an antenna element l ; N represents the number of antenna elements; x represents the transmitted signal; and n represents additive Gaussian white noise. As may be appreciated, like representations may be used in any of the embodiments described herein.

[00168] In one embodiment, an analogue beamforming scheme is achieved using an MRC receiver. For the MRC receiver, a beamforming vector e^{Φ^0} (e.g., phase shift vector Φ^0) may be represented by the following equations:

$$e^{i\phi_l^o} = \frac{g_l^*}{|g_l^*|}, \quad \phi_l^o = i * \ln\left(\frac{g_l}{|g_l|}\right)$$

[00169] where g_l represents a channel coefficient corresponding to an antenna element l .

[00170] In this embodiment, the receiver has a channel coefficient for every antenna element l .

5 [00171] In one embodiment, a receiver with a beamformed antenna array may estimate the entire channel coefficient vector $G = [g_0, g_1, \dots, g_{N-1}]^T$ from the digital output z (e.g., multiple values of z corresponding to multiple beamforming vectors), and use such information to construct an MRC receiver. In one embodiment, the transmitter antenna port transmits a normalized RS signal x_{RS} , $|x_{RS}| = 1$ in $K \geq N$ consecutive symbols in a same
10 frequency resource. As the receiver receives the K RS, it shifts through a set of K different phase shift vectors $\Phi = [\Phi^0, \Phi^1, \dots, \Phi^{K-1}]$. The digital output z_k associated with Φ^k is given by the following equation:

$$z_k = \left(\sum_{l=0}^{N-1} e^{i\phi_l^k} g_l \right) x_{RS} + n_i$$

[00172] In vector form the above equation may be represented by:

$$Z = \begin{bmatrix} e^{i\phi_0^0} & \dots & e^{i\phi_{N-1}^0} \\ \vdots & \ddots & \vdots \\ e^{i\phi_0^{K-1}} & \dots & e^{i\phi_{N-1}^{K-1}} \end{bmatrix} G x_{RS} + \begin{bmatrix} n_0 \\ \vdots \\ n_{K-1} \end{bmatrix} = W G x_{RS} + N$$

[00173] The channel coefficients G may be estimated from Z with different
15 algorithms. For example, a ZF estimator algorithm may be represented by:

$$\hat{G}_{ZF} = (W^* W)^{-1} W^* Z x_{RS}^*.$$

[00174] The channel coefficients G may also be estimated with an MMSE estimator algorithm that may be represented by:

$$\hat{G}_{MMSE} = (W^* W + \frac{1}{\rho} I_N)^{-1} W^* Z x_{RS}^*,$$

20 [00175] where ρ is the receiver SNR before combining.

[00176] In certain embodiments, it may be assumed that the channel coefficients G do not change during the K transmissions. In such embodiments, this may be true if the transmission time $K T_s \ll T_{coh}$, where T_s represents the transmission time of a symbol and T_{coh} represents the coherent time of the channel. If the transmitter applies beamforming (either digital

or analog) to multiple Tx antenna elements to form an antenna port, the beamforming vector does not change during the transmission time KT_s .

[00177] The minimal number of the transmitted RS is N . So is the number of phase shift vectors. As an example, the phase shifter vectors, or equivalently the W matrix, can be generated from FFT (or equivalently IFFT) matrix. In one embodiment,

$$W_{FFT_N} = FFT_N = \left[\left\{ e^{-\frac{i2\pi kl}{N}} \right\}, 0 \leq k, l \leq N-1 \right]$$

$$W_{FFT_N}^* = IFFT_N = \left[\left\{ e^{\frac{i2\pi kl}{N}} \right\}, 0 \leq k, l \leq N-1 \right]$$

[00178] In certain embodiments, the ZF estimator and MMSE estimator may be:

$$\hat{G}_{ZF} = IFFT_N Z x_{RS}^*$$

$$\hat{G}_{MMSE} = \left(1 + \frac{1}{\rho} \right)^{-1} IFFT_N Z x_{RS}^*$$

[00179] In certain embodiments, such as for the case of $K > N$, an oversampled FFT matrix may be used. For example:

$$W_{FFT_{KN}} = \{w_{k,n}\} = \left[\left\{ e^{-\frac{i2\pi kn}{K}} \right\}, 0 \leq k \leq K-1, 0 \leq n \leq N-1 \right]$$

[00180] where:

$$W^k = [1, e^{-j\frac{2\pi k}{K}}, e^{-j\frac{2\pi 2k}{K}}, \dots, e^{-j\frac{2\pi(N-1)k}{K}}]$$

$$W_{FFT_{KN}} = \begin{bmatrix} W^0 \\ \vdots \\ W^{K-1} \end{bmatrix}$$

[00181] Therefore,

$$F = W_{FFT_{KN}}^* W_{FFT_{KN}} = \sum_{k=0}^{K-1} W^k{}^* W^k$$

[00182] where:

$$f_{l,m} = \sum_{k=0}^{K-1} e^{j\frac{2\pi(l-m)k}{K}}$$

[00183] In such embodiments, the ZF estimator and MMSE estimator may be:

$$\hat{G}_{ZF} = F^{-1} W_{FFT_{KN}}^* Z x_{RS}^*$$

$$\hat{G}_{MMSE} = \left(F + \frac{1}{\rho} I_N \right)^{-1} W_{FFT_{KN}}^* Z x_{RS}^*$$

[00184] Besides FFT-based phase shift vectors, other matrices with rank N may also be used. To ease the computation, W may be a unitary matrix. In one embodiment, a Householder transformation matrix of size N may be used, where:

$$W_H = I - 2vv^*$$

[00185] and v is a column unit vector.

$$W_H = W_H^* = W_H^{-1}$$

5 [00186] In such an embodiment, the ZF estimator and MMSE estimator may be:

$$\hat{G}_{ZF} = W_H Z x_{RS}^*$$

$$\hat{G}_{MMSE} = (1 + \frac{1}{\rho})^{-1} W_H Z x_{RS}^*$$

[00187] From the estimated channel coefficient $\hat{G}_{ZF}$ or $\hat{G}_{MMSE}$, the receiver may derive the phase shift vector for the MRC receiver.

[00188] In certain embodiments, a transmitter (e.g., transmitter 210, transmitter 310) transmits the RSs K times for a receiver (e.g., receiver 212, receiver 312) to estimate the
10 entire set of channel coefficients G for receiving beamforming from $K \leq N$ antenna elements. The RSs may be transmitted in the same frequency resources in K consecutive symbols in an OFDM-like system. In certain embodiments, the K consecutive symbols may be physically adjacent, while in other embodiments, the K consecutive symbols may be close (e.g., substantially consecutive, substantially adjacent), but not necessarily physically adjacent. For
15 example, in some embodiments, 1, 2, or 3 OFDM symbols may separate the K consecutive symbols. The adjacent RSs may be transmitted with different (but known to the receiver) symbols or sequences. The densities of the RS in time and frequency dimensions may be determined by the coherent time and frequency of a channel.

[00189] Figure 6 is a schematic block diagram illustrating one embodiment of
20 reference signal transmission 600. In this embodiment, an array of possible resources 602 for transmitting RSs is illustrated. As may be appreciated, the x-axis may correspond to time and the y-axis may correspond to frequency. Pairs of 2 physically adjacent RSs 604 (e.g., $K = 2$) are used in this embodiment to facilitate a receiver estimating the entire set of channel coefficients G for receiving beamforming from $K \leq N$ antenna elements. In certain embodiments, the pairs of 2
25 RSs 604 may be close (e.g., substantially consecutive, substantially adjacent), but not necessarily physically adjacent. For example, in some embodiments, 1, 2, or 3 OFDM symbols may separate each pair of RSs 604.

[00190] Figure 7 is a schematic block diagram illustrating another embodiment of reference signal transmission 700. In this embodiment, an array of possible resources 702 for transmitting RSs is illustrated. As may be appreciated, the x-axis may correspond to time and the y-axis may correspond to frequency. Sets of 4 physically adjacent RSs 704 (e.g., $K = 4$) are used in this embodiment to facilitate a receiver estimating the entire set of channel coefficients G for receiving beamforming from $K \leq N$ antenna elements. In certain embodiments, the pairs of 4 RSs 704 may be close (e.g., substantially consecutive, substantially adjacent), but not necessarily physically adjacent. For example, in some embodiments, 1, 2, or 3 OFDM symbols may separate each RS 704 in the pair of 4 RSs 704.

[00191] In certain embodiments, an OCC of length K may be used when transmitting the RS sequences. For example, for $K = 2$, the following pairs of OCC may be used: $\{[1, 1], [1, -1]\}$. As another example, for $K = 4$, the following sets of OCC may be used: $\{[1, 1, 1, 1], [1, -1, 1, -1], [1, 1, -1, -1], [1, -1, -1, 1]\}$. Thus, different RSs may be multiplexed if necessary.

[00192] Implicit or explicit control signaling, including information of the resources used for the RS, the RS sequences (e.g., including OCC), may be used to coordinate the transmission and reception of the reference signals. The process for the RS transmission and feedback may be considered as a training process for a transmitter-receiver pair. This may be used in either CSI-RS in the downlink or SRS in the uplink.

[00193] Figure 8 is a schematic flow chart diagram illustrating one embodiment of a method 800 for transmitting multiple reference signals. In some embodiments, the method 800 is performed by an apparatus, such as a remote unit 102 or the base unit 104. In certain embodiments, the method 800 may be performed by a processor executing program code, for example, a microcontroller, a microprocessor, a CPU, a GPU, an auxiliary processing unit, a FPGA, or the like.

[00194] The method 800 may include determining 802 multiple reference signals to be transmitted. In one embodiment, a number of reference signals may be at least equal to a number of antenna elements configured to receive the multiple reference signals. The method 800 may include applying 804 an OCC to the multiple reference signals. In some embodiments, a length of the OCC matches the number of reference signals. The method 800 may also include transmitting 806 signals corresponding to the multiple reference signals. In certain embodiments, the signals corresponding to the multiple reference signals include at least one of: reference signals within the multiple reference signals, an OCC used to transmit the multiple reference signals, and time and frequency resources used to transmit the multiple reference signals.

[00195] The method 800 may also include transmitting 808 the multiple reference signals via (e.g., using, by way of) a millimeter wave frequency in a time-frequency domain using OFDM, then the method 800 may end. In one embodiment, transmitting 808 the multiple reference signals may include transmitting the multiple reference signals using one antenna port. In another embodiment, transmitting 808 the multiple reference signals may include transmitting the multiple reference signals using beamforming from multiple antenna elements (e.g., antenna elements 404). In such an embodiment, using beamforming includes using a transmit beamforming vector, and the transmit beamforming vector does not change while beamforming.

[00196] In one embodiment, transmitting 808 the multiple reference signals may include transmitting the number of reference signals in a frequency resource using substantially consecutive OFDM symbols. In another embodiment, transmitting 808 the multiple reference signals includes transmitting the number of reference signals in substantially adjacent time and frequency resources. In certain embodiments, transmitting 808 the multiple reference signals may include transmitting the multiple reference signals in a downlink as a CSI-RS. In various embodiments, transmitting 808 the multiple reference signals may include transmitting the multiple reference signals in an uplink as a SRS.

[00197] Figure 9 is a schematic flow chart diagram illustrating one embodiment of a method 900 for channel coefficient estimation using information received by a receiver. In some embodiments, the method 900 is performed by an apparatus, such as a base unit 104. In certain embodiments, the method 900 may be performed by a processor executing program code, for example, a microcontroller, a microprocessor, a CPU, a GPU, an auxiliary processing unit, a FPGA, or the like.

[00198] The method 900 may include receiving 902 information via (e.g., using, by way of) multiple antenna elements. In one embodiment, the information includes multiple reference signals and each antenna element of the multiple antenna elements receives a version of the information. The method 900 may also include applying 904 a phase shift vector to the version of the information received by each antenna element of the multiple antenna elements to produce multiple phase shifted outputs. The method 900 may include combining 906 the multiple phase shifted outputs into a digital signal. The method 900 may also include determining 908 an estimated channel coefficient vector for the multiple antenna elements using the digital signal.

[00199] In one embodiment, determining 908 the estimated channel coefficient vector includes determining a receive beamforming vector using a discrete Fourier transform matrix. In some embodiments, determining 908 the estimated channel coefficient vector

includes determining a receive beamforming vector using a Householder transform matrix. In certain embodiments, determining 908 the estimated channel coefficient vector includes using a ZF algorithm. In various embodiments, determining 908 the estimated channel coefficient vector includes using an MMSE algorithm. The method 900 may include determining 910 an MRC
5 vector using the estimated channel coefficient vector, then the method 900 may end.

[00200] Embodiments may be practiced in other specific forms. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of
10 the claims are to be embraced within their scope.

CLAIMS

1. An apparatus comprising:
a processor that determines a plurality of reference signals to be transmitted, wherein a
number of reference signals of the plurality of reference signals is at least equal to
5 a number of antennas configured to receive the plurality of reference signals; and
a transmitter that transmits the plurality of reference signals via a millimeter wave
frequency in a time-frequency domain using orthogonal frequency-division
multiplexing ("OFDM").
2. The apparatus of claim 1, wherein the transmitter comprises one antenna port used for
10 transmitting the plurality of reference signals.
3. The apparatus of claim 1, wherein the transmitter transmits the plurality of reference
signals using beamforming from multiple antenna elements.
4. The apparatus of claim 3, wherein using beamforming comprises using a transmit
beamforming vector, and the transmit beamforming vector does not change while
15 beamforming.
5. The apparatus of claim 1, wherein the transmitter transmits the plurality of reference
signals in a frequency resource using substantially consecutive OFDM symbols.
6. The apparatus of claim 1, wherein the transmitter transmits the plurality of reference
signals in a downlink as a channel state information reference signal ("CSI-RS").
- 20 7. The apparatus of claim 1, wherein the transmitter transmits the plurality of reference
signals in an uplink as a sounding reference signal ("SRS").
8. The apparatus of claim 1, wherein the transmitter transmits the plurality of reference
signals in substantially adjacent time and frequency resources.

9. The apparatus of claim 1, wherein the processor applies an orthogonal cover code (“OCC”) to the plurality of reference signals, and wherein a length of the OCC matches the number of reference signals.
10. The apparatus of claim 1, wherein the transmitter transmits signals corresponding to the plurality of reference signals, and wherein the signals comprise at least one of reference signals within the plurality of reference signals, an OCC used to transmit the plurality of reference signals, and time and frequency resources used to transmit the plurality of reference signals.
11. A method comprising:
determining a plurality of reference signals to be transmitted, wherein a number of reference signals of the plurality of reference signals is at least equal to a number of antennas elements configured to receive the plurality of reference signals; and transmitting the plurality of reference signals via a millimeter wave frequency in a time-frequency domain using orthogonal frequency-division multiplexing (“OFDM”).
12. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the plurality of reference signals using one antenna port.
13. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the plurality of reference signals using beamforming from multiple antenna elements.
14. The method of claim 13, wherein using beamforming comprises using a transmit beamforming vector, and the transmit beamforming vector does not change while beamforming.
15. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the number of reference signals in a frequency resource using substantially consecutive OFDM symbols.

16. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the number of reference signals in substantially adjacent time and frequency resources.
- 5 17. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the plurality of reference signals in a downlink as a channel state information reference signal ("CSI-RS").
18. The method of claim 11, wherein transmitting the plurality of reference signals comprises transmitting the plurality of reference signals in an uplink as a sounding reference signal ("SRS").
- 10 19. The method of claim 11, comprising applying an orthogonal cover code ("OCC") to the plurality of reference signals, wherein a length of the OCC matches the number of reference signals.
20. The method of claim 11, comprising transmitting signals corresponding to the plurality of reference signals, wherein the signals comprise at least one of reference signals within the
15 plurality of reference signals, an OCC used to transmit the plurality of reference signals, and time and frequency resources used to transmit the plurality of reference signals.
21. An apparatus comprising:
an antenna array comprising a plurality of antenna elements;
a receiver that receives information via the antenna array, wherein the information
20 comprises a plurality of reference signals and each antenna element of the antenna array receives a version of the information;
a phase shifter that applies a phase shift vector to the version of the information received by each antenna element of the antenna array to produce a plurality of phase shifted outputs;
25 a combining device that combines the plurality of phase shifted outputs into a digital signal; and
a processor that:

determines an estimated channel coefficient vector for the plurality of antenna elements using the digital signal; and
determines a maximal-ratio combining (“MRC”) vector using the estimated channel coefficient vector.

- 5 22. The apparatus of claim 21, wherein the processor that determines the estimated channel coefficient vector further determines a receive beamforming vector using a discrete Fourier transform matrix.
23. The apparatus of claim 21, wherein the processor that determines the estimated channel coefficient vector further determines a receive beamforming vector using a Householder transform matrix.
- 10 24. The apparatus of claim 21, wherein the processor determines the estimated channel coefficient vector using a zero forcing (“ZF”) algorithm.
25. The apparatus of claim 21, wherein the processor determines the estimated channel coefficient vector using a minimum mean square error (“MMSE”) algorithm.
- 15 26. A method comprising:
receiving information via a plurality of antenna elements, wherein the information comprises a plurality of reference signals and each antenna element of the plurality of antenna elements receives a version of the information;
applying a phase shift vector to the version of the information received by each antenna
20 element of the plurality of antenna elements to produce a plurality of phase shifted outputs;
combining the plurality of phase shifted outputs into a digital signal;
determining an estimated channel coefficient vector for the plurality of antenna elements using the digital signal; and
25 determining a maximal-ratio combining (“MRC”) vector using the estimated channel coefficient vector.

27. The method of claim 26, wherein determining the estimated channel coefficient vector comprises determining a receive beamforming vector using a discrete Fourier transform matrix.
28. The method of claim 26, wherein determining the estimated channel coefficient vector
5 comprises determining a receive beamforming vector using a Householder transform matrix.
29. The method of claim 26, wherein determining the estimated channel coefficient vector comprises using a zero forcing (“ZF”) algorithm.
30. The method of claim 26, wherein determining the estimated channel coefficient vector
10 comprises using a minimum mean square error (“MMSE”) algorithm.

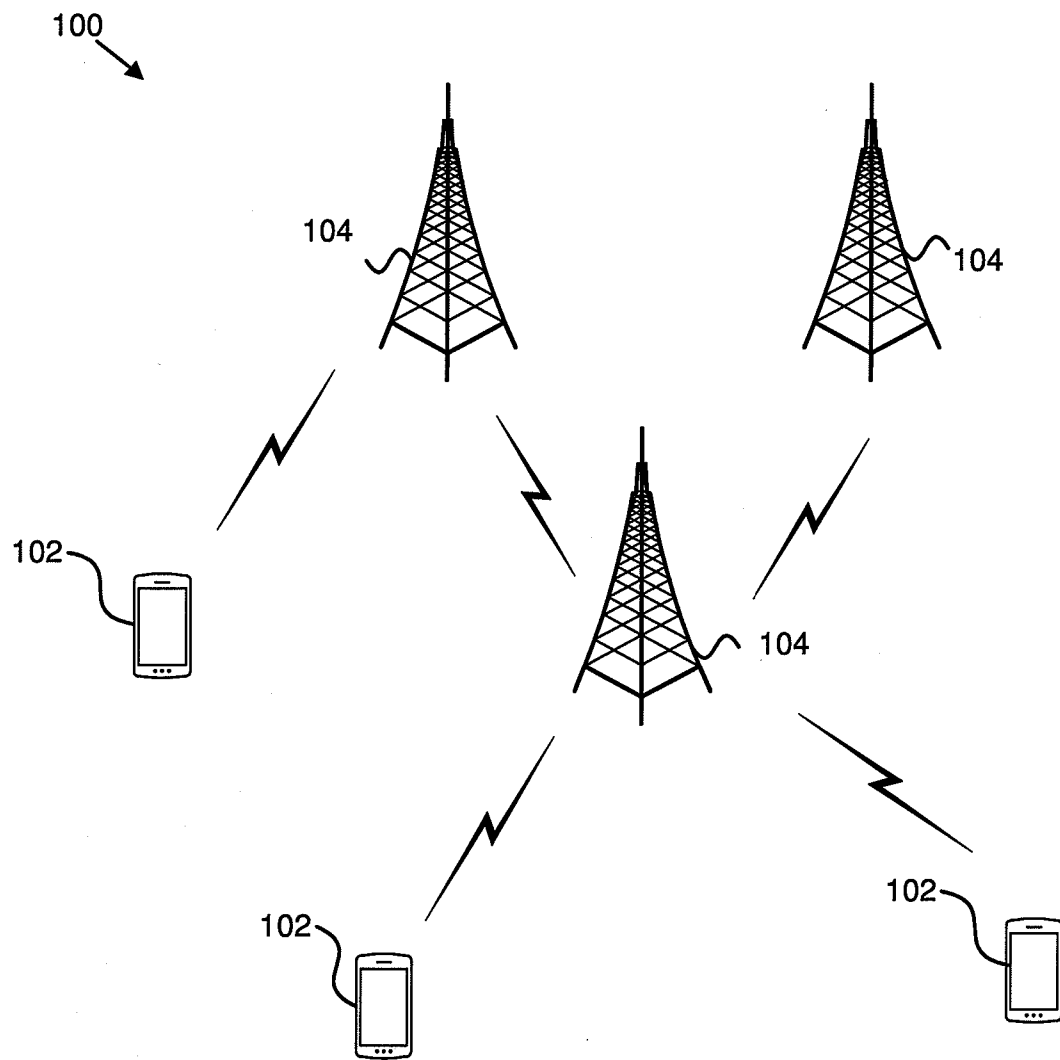


FIG. 1

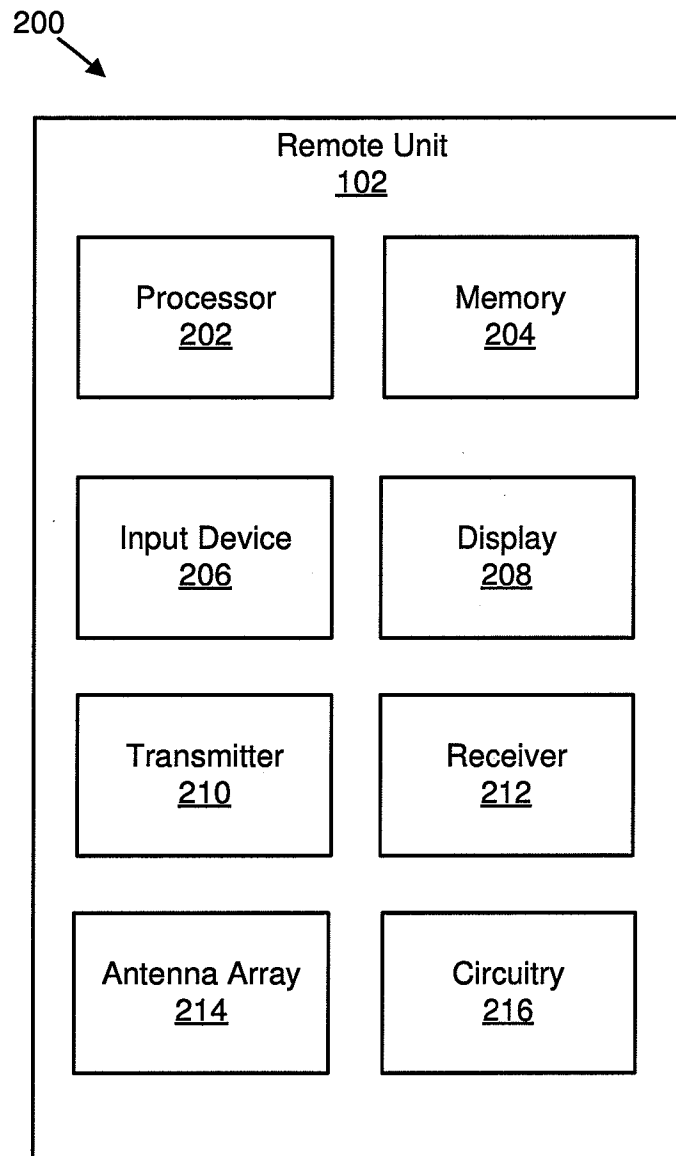


FIG. 2

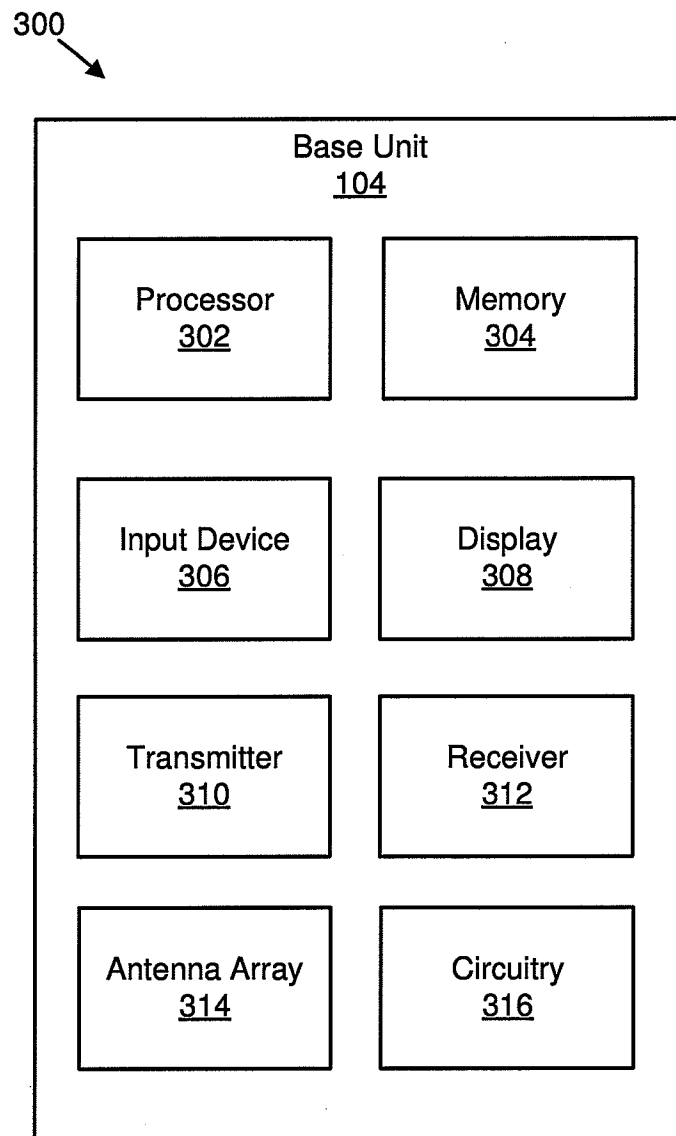


FIG. 3

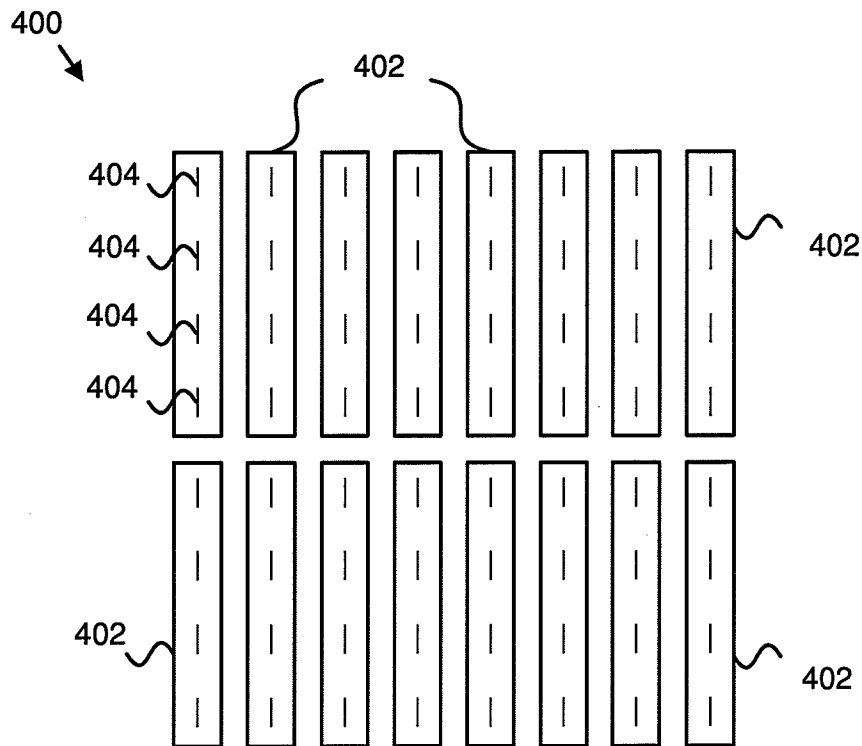


FIG. 4

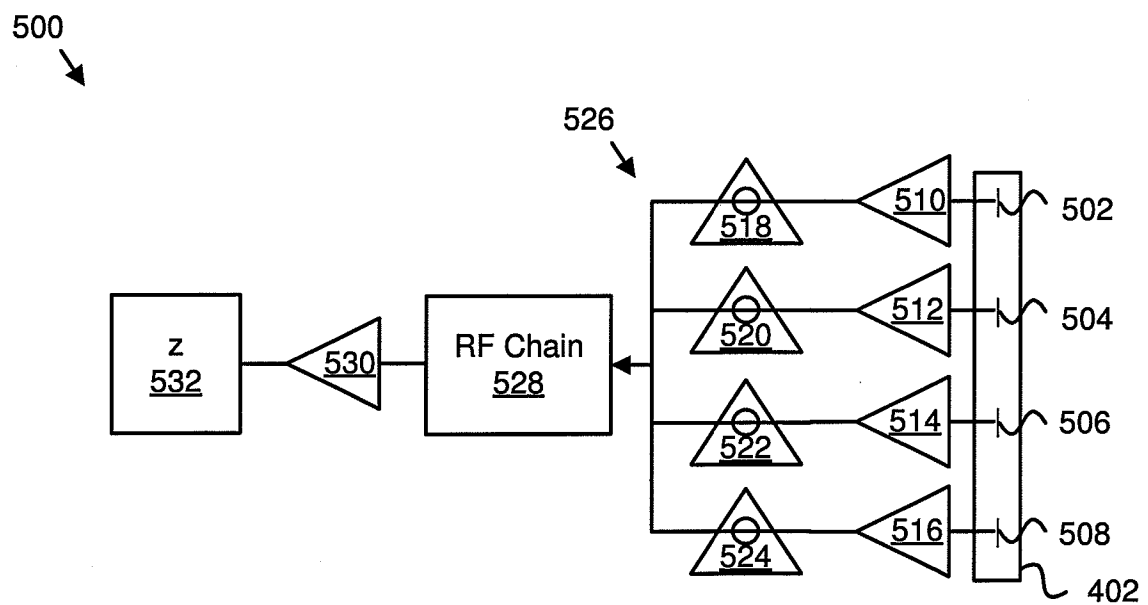


FIG. 5

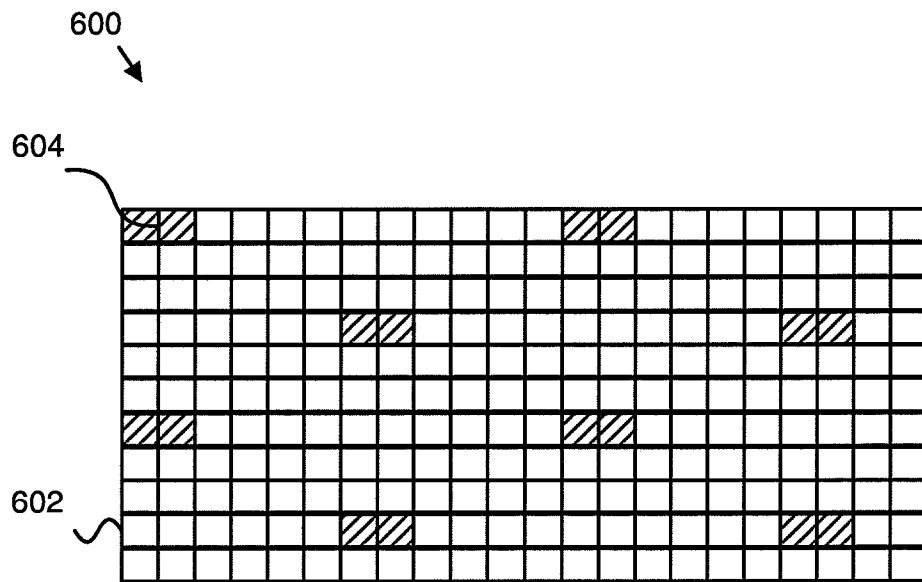


FIG. 6

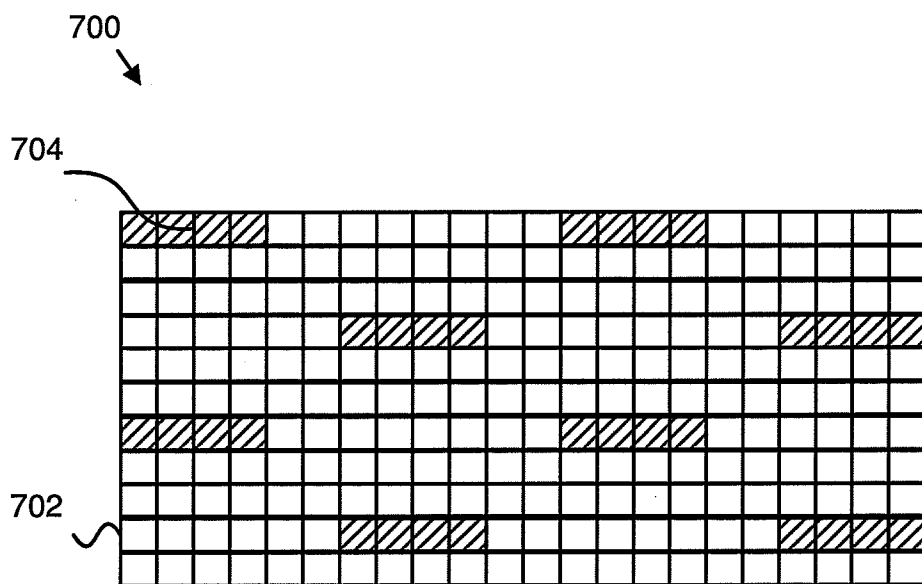


FIG. 7

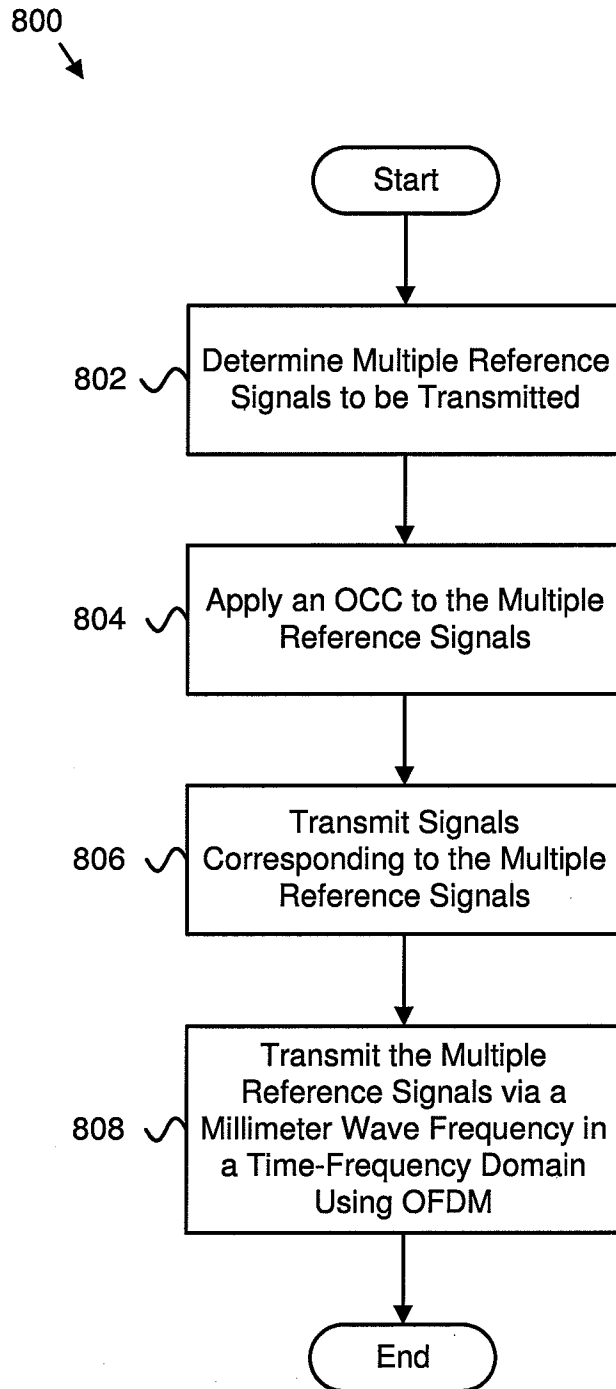


FIG. 8

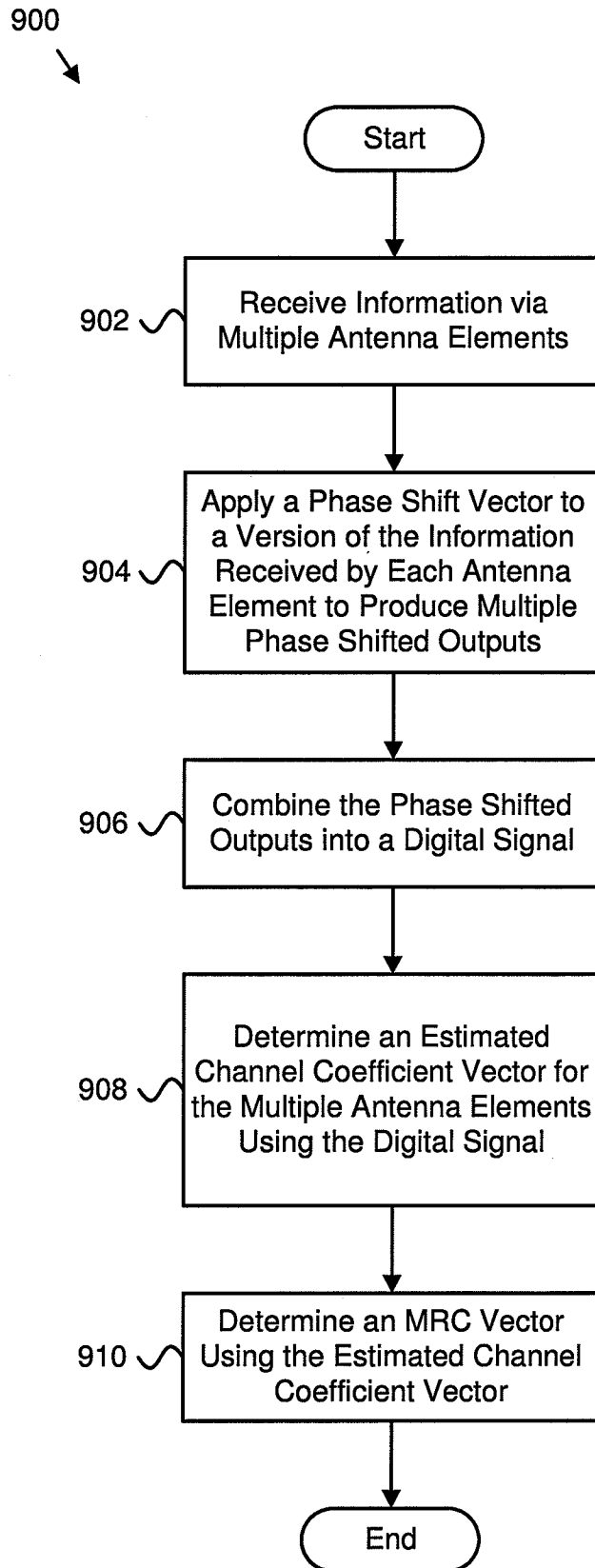


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2016/086274**A. CLASSIFICATION OF SUBJECT MATTER**

H04B 7/04(2017.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04B; H04W; H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNABS;CNTXT;CNKI;SIPOABS;DWPI: millimeter wave, multiple, plurality, reference signal, pilot, antenna, beam w forming, channel, estimat+, phase 2d shift,CPC:H04B7/0413, H04L5/0048

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 105684322 A (ALCATEL LUCENT) 15 June 2016 (2016-06-15) claims 1-15, description, paragraphs 0085 and 0111-0113	1-20
Y	CN 105684322 A (ALCATEL LUCENT) 15 June 2016 (2016-06-15) claims 1-15, description, paragraphs 0085 and 0111-0113	21-30
Y	CN 104303429 A (SAMSUNG ELECTRONICS CO., LTD.) 21 January 2015 (2015-01-21) description, paragraphs 0089-0104 and figure 7	21-30
A	US 2014098912 A1 (SAMSUNG ELECTRONICS CO., LTD.) 10 April 2014 (2014-04-10) the whole document	1-30

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

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“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

20 February 2017

Date of mailing of the international search report

01 March 2017

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2016/086274

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