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(54) **Title:** PHASE COMPENSATION FOR CHANNEL STATE INFORMATION

(57) **Abstract:** Disclosed are example embodiments of devices, methods, apparatuses and computer program products for phase error compensation of channel state information. In an example, a first device may be configured to determine a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device, determine phase error information based on the communication channel estimation, and determine, based on the phase error information, phase compensation information to compensate for phase mismatches of propagation paths associated with the one or more second groups of transmitting antennas relative to propagation paths associated with a first group of transmitting antennas.

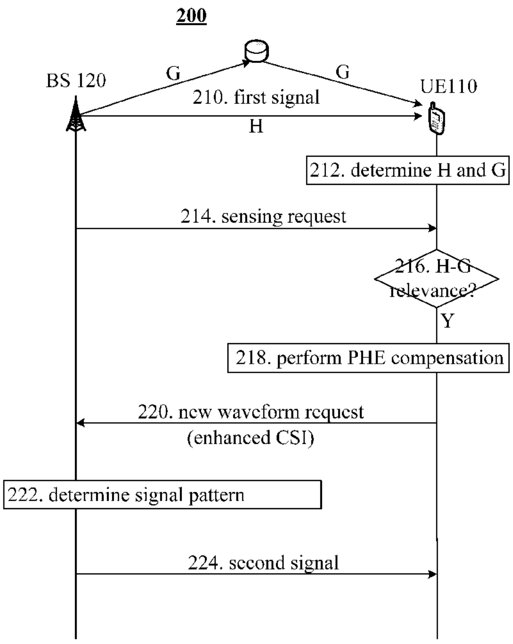

FIG. 5

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PHASE COMPENSATION FOR CHANNEL STATE INFORMATION

TECHNICAL FIELD

[0001] Various example embodiments described herein generally relate to communication technologies, and more particularly, to phase error (PHE) compensation for channel state information (CSI) in a joint communication and sensing (JCAS) system.

BACKGROUND

[0002] Integrated Sensing and Communication (ISAC) refers to technologies that combine sensing and communication functionalities in a joint communication and sensing (JCAS) system, which has been recognized as a promising technology for the next generation wireless networks such as beyond 5G (B5G) and 6G. Compared with dedicated sensing and communication, the JCAS system has advantages in improved wireless resource utilization efficiency, reduced system size, weight and power consumption, and a multitude of application scenarios.

SUMMARY

[0003] A brief summary of example embodiments is provided below to provide basic understanding of some aspects of various example embodiments. It should be noted that this summary is not intended to identify key features of essential elements or define scopes of the example embodiments, and its sole purpose is to introduce some concepts in a simplified form as a preamble for a more detailed description provided below.

[0004] In a first aspect, an example embodiment of a first device is provided. The first device may comprise at least one processor and at least one memory including computer program code. The at least one memory and the computer program code may be configured to, with the at least one processor, cause the first device to determine a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device. The communication channel estimation may contain phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device. The first device is further caused to determine phase error information based on the communication channel estimation. The phase error information may indicate phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas. The first device may determine, based on the phase error information, phase compensation information to compensate for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas.

[0005] In a second aspect, an example embodiment of a second device is provided. The second device may comprise at least one processor and at least one memory including computer program code. The at least one memory and the computer program code may be configured to, with the at least one processor, cause the second device to transmit a sensing request to a first device, and receive a new waveform request and channel state information from the first device. The channel state information may include a communication channel estimation for an integrated sensing and communication channel between the first device and the second device compensated by phase compensation information, and the communication channel estimation may contain phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device. The phase compensation information may be determined based on phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas. The second device may determine new waveform for a signal transmitted to the first device based on the channel state information.

[0006] Example embodiments of methods, apparatus and computer program products are also provided. Such example embodiments generally correspond to the above example embodiments, and a repetitive description thereof is omitted here for convenience.

[0007] Other features and advantages of the example embodiments of the present disclosure will also be apparent from the following description of specific example embodiments when read in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of example embodiments of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Some example embodiments will now be described, by way of non-limiting examples, with reference to the accompanying drawings.

[0009] Fig. 1 is a schematic diagram illustrating a joint communication and sensing (JCAS) system in which example embodiments of the present disclosure can be implemented.

[0010] Fig. 2 is a schematic diagram illustrating transmissions between multiple transmitting antennas and multiple receiving antennas in a multiple input and multiple output (MIMO) system.

[0011] Fig. 3 is a signaling diagram illustrating a 4D channel state information (CSI) tensor including a time series of CSI matrices of MIMO-OFDM (Orthogonal Frequency Division Multiplexing) channels.

[0012] Fig. 4 is a schematic diagram illustrating multiple baseband boards at a base station side in the JCAS system.

[0013] Fig. 5 is a schematic interaction diagram illustrating a process of phase error (PHE) compensation for CSI according to an example embodiment.

[0014] Fig. 6 is a flowchart illustrating a method of PHE compensation for CSI according to an example embodiment.

[0015] Fig. 7 is a schematic diagram illustrating detection of the PHE compensation matrix at user equipment (UE) side according to an example embodiment.

[0016] Figs. 8A, 8B, 8C and 8D are schematic diagrams illustrating performance evaluation for PHE compensation schemes according to some example embodiments.

[0017] Fig. 9 is a simplified block diagram illustrating an example communication system in which example embodiments of the present disclosure can be implemented.

[0018] Throughout the drawings, same or similar reference numbers indicate same or similar elements. A repetitive description on the same elements would be omitted.

DETAILED DESCRIPTION

[0019] Herein below, some example embodiments are described in detail with reference to the accompanying drawings. The following description includes specific details for the purpose of providing a thorough understanding of various concepts. However, it will be apparent to those skilled in the art that these concepts may be practiced without these specific details. In some instances, well known circuits, techniques and components are shown in block diagram form to avoid obscuring the described concepts and features.

[0020] As used herein, the term "network device" refers to any suitable entities or devices that can provide cells or coverage, through which the terminal device can access the network or receive services. The network device may be commonly referred to as a base station. The term "base station" used herein may represent a node B (NodeB or NB), an evolved node B (eNodeB or eNB), or a gNB. The base station may be embodied as a macro base station, a relay node, or a low power node such as a pico base station or a femto base station. The base station may consist of several distributed network units, such as a central unit (CU), one or more distributed units (DUs), one or more remote radio heads (RRHs) or remote radio units (RRUs). The number and functions of these distributed units depend on the selected split RAN architecture.

[0021] As used herein, the term "terminal device" or "user equipment" (UE) refers to any entities or devices that can wirelessly communicate with the network devices or with each other. Examples of the terminal device can include a mobile phone, a mobile terminal (MT), a mobile station (MS), a subscriber station (SS), a portable subscriber station (PSS), an access terminal (AT), a computer, a wearable device, an on-vehicle communication device, a machine type communication (MTC) device, a D2D communication device, a V2X communication device, a sensor and the like. The term "terminal device" can be used interchangeably with a UE, a user terminal, a mobile terminal, a mobile station, or a wireless device.

[0022] Fig. 1 illustrates a joint communication and sensing (JCAS) system 100 in which example embodiments of the present disclosure can be implemented. Referring to Fig. 1, the JCAS system 100 may comprise a plurality of user equipments (UEs) 110-1 to 110-J (each also individually referred to herein as UE 110 or collectively as UEs 110) and a base station 120 serving the UEs 110. The base station 120 may transmit downlink transmissions to the UEs 110 and receive uplink transmissions from the UEs 110. In downlink, the base station 120 is a transmitting (TX) device (also referred to as first device), and the UE 110 is a receiving (RX) device (also referred to as second device). In uplink, the UE 110 is the TX device (the first device), and the base station 120 is the RX device (the second device).

[0023] Depending on the communication technologies, the JCAS system 100 may be implemented in a Code Division Multiple Access (CDMA) network, a Time Division Multiple Address (TDMA) network, a Frequency Division Multiple Access (FDMA) network, an Orthogonal Frequency-Division Multiple Access (OFDMA) network, a Single Carrier-Frequency Division Multiple Access (SC-FDMA) network or any other. Communications discussed in the JCAS system 100 may conform to any suitable standards including, but not limited to, New Radio Access (NR), Long Term Evolution (LTE), LTE-Evolution, LTE-Advanced (LTE-A), Wideband Code Division Multiple Access (WCDMA), Code Division Multiple Access (CDMA), cdma2000, and Global System for Mobile Communications (GSM) and the like. Furthermore, the communications may be performed according to any generation communication protocols either currently known or to be developed in the future. Examples of the communication protocols include, but not limited to, the first generation (1G), the second generation (2G), 2.5G, 2.75G, the third generation (3G), the fourth generation (4G), 4.5G, the fifth generation (5G), the beyond 5G (B5G or 6G) communication protocols. The techniques described herein may be used for the wireless networks and radio technologies mentioned above as well as other wireless networks and radio technologies. For clarity, certain aspects of the techniques are described below for NR and JCAS in the description below.

[0024] There may be one or more objects 130 (only one object is shown) located between the UEs 110 and the base station 120. As shown in Fig. 1, when the base station 120 transmits a downlink signal to the UEs 110, a component of the signal may propagate directly to the UEs 110, while another component of the signal may be reflected by the object 130 and then arrive at the UEs 110. Channel state information (CSI) of the signal received at the UEs 110 can reflect how the wireless signal travels through the objects 130 in time, frequency and spatial domains and therefore can be used for environment sensing. For example, CSI amplitude variations in the time domain have different patterns for different humans, activities, gestures, and so on, which can be used for human presence detection, fall detection, motion detection, activity recognition, gesture recognition, and human identification/authentication. CSI phase shifts in the spatial and frequency domains, i.e., in the transmit/receive antennas and carrier frequencies, are related to signal transmission delay and direction, which can be used for human localization and tracking. CSI phase shifts in the time domain may have different dominant frequency components, which can be used for estimation of breathing rate of human. Therefore, the UEs 110 may measure CSI based on the signal received from the base station 120 to determine parameters and/or characteristics of the objects 130, which may include, but not limited to, locations, speeds, gestures, activities, identities or the like of the objects 130. Here the channel for transmission of the sensing signal component may be referred to as a sensing channel G, the channel for transmission of the communication signal component may be referred to as a communication channel H, and a combination of the sensing channel G and the communication channel H may be referred to as a JCAS channel.

[0025] The JCAS system 110 may be implemented as a multiple input and multiple output (MIMO) system, for example, a JCAS system with mmWave massive MIMO. The base station 120 may include M transmitting (TX) antennas 122-1 to 122-M, and the UE 110 may have N receiving (RX) antennas 112-1 to 112-N. Fig. 2 shows an example of MIMO transmissions between the M TX antennas and the N RX antennas. Referring to Fig. 2, the TX antennas 122-1 to 122-M may transmit signals to the RX antennas 112-1 to 112-N, and each RX antenna 112-1 to 112-N can receive signal components from the TX antennas 122-1 to 122-M. Thus, there are N×M TX-RX antenna pairs (propagation paths) between the base station 120 and the UE 110. The CSI of the multi-path channels may be represented by a N×M matrix which includes N×M matrix elements having complex values to indicate amplitude attenuation and phase shift of the M×N propagation paths from the base station 120 to the UE 110, respectively. Considering that the signal is transmitted on frequency and time resources, a time series of CSI matrices may be represented in a 4D CSI tensor, as shown in Fig. 3. The 4D CSI tensor can capture multipath channel variations, including amplitude attenuation and phase shifts in spatial, frequency and time domains, and it may be used for environment sensing as mentioned above.

[0026] A wide variety of JCAS applications rely on accurate CSI measurements. Due to hardware imperfection of commodity JCAS system, however, there are non-negligible linear and non-linear CSI phase errors (PHEs) in JCAS devices, which makes deriving accurate channel frequency response from CSI measurements a challenging task. Some CSI measurement phase error sources are summarized as follows:

1) power amplifier uncertainty (PAU), which may be due to the resolution limitation of hardware, for example, 0.5 dB for Atheros 9380, the total gain achieved from LNA (Low Noise Amplifier) and PGA (Programmable Gain Amplifier) cannot perfectly compensate the signal amplitude attenuation to the transmitted power level; the measured CSI amplitude equals to the compensated power level, mixed with a power amplifier uncertainty error, which causes a CSI amplitude offset;

2) I/Q (In-phase/ Quadrature) imbalance, which may be caused when the amplitude and phase distortion occurs and the orthogonal baseband signal will be destroyed; once the I/Q is imbalanced, after sampling and FFT (Fast Fourier Transform), the result will be a deformed CSI;

3) carrier frequency offset (CFO): the central frequencies of a transmission pair may not be perfectly synchronized; the carrier frequency offset is compensated by the CFO corrector of the receiver, but due to the hardware imperfection, the compensation may be incomplete, and signal still carries residual CFO, which leads to a time-varying CSI phase offset across subcarriers;

4) sampling frequency offset (SFO): the sampling frequencies of the transmitter and the receiver exhibit an offset due to non-synchronized clocks, which can cause the received signal after ADC (Analog-to-Digital Converter) a time shift with respect to the transmitted signal; after the SFO corrector, residual SFO leads to a rotation error; because clock offsets are relatively stable within a short time (e.g., in the order of minutes), such phase rotation errors are nearly constant;

5) packet detection delay (PDD), which stems from energy detection or correlation detection which occurs in digital processing after down conversion and ADC sampling; packet detection introduces another time shift phase rotation error;

6) PLL (Phase-Locked Loop) phase offset (PPO), which is responsible for generating the center frequency for the transmitter and the receiver, starting at random initial phase; as a result, the CSI phase measurement at the receiver may be corrupted by an additional phase offset;

7) phase ambiguity (PA): when examining the phase difference between two receive antennas, recent work validates a so called four-way phase ambiguity existence when working on 2.4 GHz.

[0027] In general, the JCAS system with OFDM-MIMO is likely to suffer the above-mentioned phase errors (PHEs) because an orthogonal multiple frequency system is more sensitive to synchronization errors than a single-carrier system when a large number of antennas operate at a high frequency band, as well as radio frequency (RF) distortion in a high frequency band is worse than that in traditional low frequency bands. PHE manifests itself as a random, time-varying phase difference between oscillators connected to the antennas at the BS and the UE, resulting in Inter-Carrier Interference (ICI) and rotation of the signal constellation. As a result, PHE gives rise to a Common Phase Error (CPE) and ICI at the receiver, which degrades the performance of the JCAS system.

[0028] In a practical JCAS system with OFDM-MIMO, the base station 120 may include multiple baseband boards (BBs) 121-1 to 121-P, and each baseband board 121-p may connect to M/P TX and RX antennas 122-(p,1) to 122-(p,M/P) where p=1, ..., P, as shown in Fig. 4. By assuming frequency-flat Rayleigh fading between the base station 120 and the UEs 110, the baseband boards 121-1 to 121-P each may be equipped with an independent local oscillator (LO) LO1 to LOP. It means that the local oscillators for the baseband boards 121 may be different from each other, and the PHE for the baseband boards 121 may be different.

[0029] The inaccurate CSI may have great impact on sensing performance of the JCAS system. Thus, it always requires timing offset estimation, PHE estimation, tracking and compensation to improve channel estimation and CSI feedback in the JCAS system. Some phase noise (PHN) compensation schemes have been proposed for mitigating the PHN impact on the system performance. However, these schemes consider theoretical models rather than engineering and thus have a relatively high complexity or execution expense.

[0030] Hereinafter, example embodiments of devices, methods, apparatuses and computer program products for PHE compensation of CSI measurements will be described in detail with reference to Figs. 5-9. In some example embodiments, relative phase mismatch information may be calculated from a propagation channel function during a channel estimation process, which may make every channel element to align with phases of the multipath channels associated with a certain baseband board. By compensating the PHE in the channel estimation process, the scheme can improve the accuracy of CSI phase measurements with a low complexity. To further reduce the complexity and execution expense, a group-average compensation scheme may be used where the phase mismatch may be calculated as average values between the certain baseband board and each another baseband board. Consequently, the PHE compensation scheme would be more flexible and practical to remove PHN and improve the accuracy of CSI measurements. The accurate CSI measurements can be used to optimize the signal pattern for the JCAS system, which would be beneficial for subsequent sensing signals. In this way, the system performance can be improved, and the power consumption of the JCAS devices can be reduced. Furthermore, a new signaling procedure is also proposed to perform sensing efficiently and to balance communication and sensing performance.

[0031] Though Fig. 1 shows downlink sensing where the UEs 110 implement the sensing functionality, it would be appreciated that example embodiments described herein are also applicable to uplink sensing where an uplink signal transmitted from the UE 110 is reflected by the object 130 and then arrives at the base station 120, and the base station 120 implements the sensing functionality.

[0032] Fig. 5 illustrates a PHE compensation procedure 200 according to an example embodiment. The procedure 200 may be performed by the base station 120 and the UEs 110 in the JCAS system 100 discussed above with respect to Fig. 1. In some example embodiments, the base station 120 and the UEs 110 may include or be implemented with a plurality of components, modules, means or elements to perform operations in the procedure 200, and the components, modules, means or elements may be implemented in various manners including but not limited to for example software, hardware, firmware or any combination thereof.

[0033] Referring to Fig. 5, the base station 120 may transmit a first signal on a JCAS channel to the UEs 110 at an operation 210. As described above, the base station 120 has M TX antennas and the UEs 110 has N RX antennas. The first signal transmitted from the base station 120 may be a bi-functional signal that is used for both sensing and communication. A component of the first signal may propagate directly to the UEs 110, while another component of the first signal is reflected by the object 130 and then arrives at and received by the UEs 110.

[0034] The first signal transmitted by the base station 120 may include data payload, together with a pilot signal for synchronization and channel estimation. There may be various forms of pilot signals, including a comb-type pilot, a block-type pilot, a Lattice-type pilot, etc. Without loss of generality, in the context of example embodiments of the present disclosure, a general data structure comprises a sequence of training symbols, denoted by L_t, and data symbols, denoted by L_d, for each spatial stream. Thus, the total length of the first signal may be denoted by $L = L_t + L_d$. By concatenating the symbols from M spatial streams into a matrix X, the signal transmitted from the base station 120 to the UE 110 may be denoted by $X = [X_t, X_d]$, where $X_t = [X_t(1), \cdots X_t(M_t)]^T \in \mathbb{C}^{M_t \times L_t}$ and $X_d = [X_d(1), \cdots X_d(M_t)]^T \in \mathbb{C}^{M_t \times L_d}$, with $X_t(m)$ and $X_d(m)$ denoting the pilot and data symbols transmitted from the m-th antenna, respectively.

[0035] At the operation 210, the first signal received at the j-th UE 110-j, where j∈[1,J], may be described as below:

$$\mathbf{x}_j = K_j^{1/2} \Phi_R \mathbf{H}_j \Phi_T + ICI + v_j \qquad (1)$$

where $K_{jl} = diag\{[\beta_{j1}\beta_{j2} \cdots \beta_{jl}]\}$ denotes a large scale fading factor between the UE 110-j and the base station 120, $\boldsymbol{H_j} \in \mathbb{C}^{N \times M}$denotes a channel function which may be in form of a channel matrix, $\Phi_R \in \mathbb{C}^{N \times N}$ denotes a PHN matrix of the UE 110-j, $\Phi_T \in \mathbb{C}^{M \times M}$ denotes a PHN matrix of the base station 120, ICI denotes the inter-carrier interference, and v_j denotes the additive white Gaussian noise. The expression $\Phi_R H_j \Phi_T$ may indicate common phase error (CPE) caused by the PHN, which exists ubiquitously in practical development, measurement and testing in massive MIMO engineering verification platform if no compensation scheme is adopted.

[0036] Upon receiving the first signal, the UEs 110 may determine a channel estimation of the communication channel H and a channel estimation of the sensing channel G at an operation 212. The UEs 110 may apply signal processing technologies to separate the sensing signal component and the communication signal component based on e.g. channel characteristics, phase and/or time offset, Angle of Arrival (AoA), Angle of Departure (AoD) or the like of the signal components. In an example where beamforming is implemented in the JCAS system 100, the UEs 110 may determine the communication channel estimation and the sensing channel estimation from different beams. For example, the communication channel estimation may be determined from the strongest beam between the base station 120 and the

UEs 110, and the sensing channel estimation may be determined from a side lobe.

[0037] The channel estimation determined at the operation 212 may be a coarse channel estimation corrupted by for example the above mentioned PHN sources at the base station 120 and the UEs 110. According to the formula (1), the communication channel estimation determined at the UE 110-j may be represented by a formula (2):

$$\boldsymbol{H}_j' = \Phi_R \boldsymbol{H}_j \Phi_T$$
$$= \begin{bmatrix} e^{j\phi_r^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\phi_r^N} \end{bmatrix} \cdot \begin{bmatrix} H_{11} & \cdots & H_{1M} \\ \vdots & \ddots & \vdots \\ H_{N1} & \cdots & H_{NM} \end{bmatrix} \cdot \begin{bmatrix} e^{j\phi_t^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\phi_t^M} \end{bmatrix}$$
$$= \begin{bmatrix} H_{11} \cdot e^{j(\phi_r^1+\phi_t^1)} & H_{12} \cdot e^{j(\phi_r^1+\phi_t^2)} & \cdots & H_{1M} \cdot e^{j(\phi_r^1+\phi_t^M)} \\ \vdots & \ddots & & \vdots \\ H_{N1} \cdot e^{j(\phi_r^N+\phi_t^1)} & H_{N2} \cdot e^{j(\phi_r^N+\phi_t^2)} & \cdots & H_{NM} \cdot e^{j(\phi_r^N+\phi_t^M)} \end{bmatrix} \quad (2)$$

where each matrix element indicates amplitude attenuation and phase shift of a propagation path associated with a pair of transmitting and receiving antennas. For example, a matrix element $H_{nm} \cdot e^{j(\phi_r^n+\phi_t^m)}$ indicates phase shift $\phi_{nm} + \phi_r^n + \phi_t^m$ where ϕ_{nm} is the phase offset caused by signal propagation over the air which is contained in the item H_{nm}, ϕ_r^n is the phase offset caused at the UE 110-j, and ϕ_t^m is the phase offset caused at the base station 120. Therefore, the phase information Ψ of the communication channel estimation $\boldsymbol{H}_j'$ may be described as below:

$$\Psi = \begin{bmatrix} e^{j(\phi_{11}+\phi_r^1+\phi_t^1)} & e^{j(\phi_{12}+\phi_r^1+\phi_t^2)} & \cdots & e^{j(\phi_{1M}+\phi_r^1+\phi_t^M)} \\ \vdots & \ddots & \ddots & \vdots \\ e^{j(\phi_{N1}+\phi_r^N+\phi_t^1)} & e^{j(\phi_{N2}+\phi_r^N+\phi_t^2)} & \cdots & e^{j(\phi_{NM}+\phi_r^N+\phi_t^M)} \end{bmatrix} \quad (3).$$

[0038] Because the PHNs are time-varying and change from symbol to symbol, which may be modelled as a Wiener process, $\phi_r^n, n = 1, \cdots, N$ and $\phi_t^m, m = 1, \cdots, M$ also change over symbols as well as subframes in time domain. Thus, the influence of PHN matrices Φ_R and

Φ_T need to be reduced so as to compensate and remove CPE. However, the inherent phase offset between the baseband boards 121 (e.g., due to noisy local oscillators LO1 to LOP equipped for the baseband boards 121) is not considered in the formula (2). Since not only the PHE introduced by I/Q imbalance, SFO, PDD and PPO is a major contributor to the JCAS performance, but also the PHE among baseband boards are also the important impairments affecting the CSI quality in practice. Thus, it is also needed to compensate and remove the common phase error (CPE) among the baseband boards.

[0039] Assuming that the base station 120 has P baseband boards 121 and each baseband board 121 has M/P antennas, the formula (2) may be rewritten from baseband boards' point as below:

$$\begin{aligned}
\boldsymbol{H}_j' &= \boldsymbol{\Phi}_R \boldsymbol{H}_j \boldsymbol{\Phi}_T \\
&= \begin{bmatrix} e^{j\phi_r^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\phi_r^N} \end{bmatrix} \cdot \begin{bmatrix} H_{11} & \cdots & H_{1M} \\ \vdots & \ddots & \vdots \\ H_{N1} & \cdots & H_{NM} \end{bmatrix} \cdot \begin{bmatrix} e^{j\phi_t^1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\phi_t^M} \end{bmatrix} \\
&= \begin{bmatrix} H_{11} \cdot e^{j(\phi_r^1+\phi_t^1)} & H_{12} \cdot e^{j(\phi_r^1+\phi_t^2)} & \cdots & H_{1M} \cdot e^{j(\phi_r^1+\phi_t^M)} \\ \vdots & & \ddots & \vdots \\ H_{N1} \cdot e^{j(\phi_r^N+\phi_t^1)} & H_{N2} \cdot e^{j(\phi_r^N+\phi_t^2)} & \cdots & H_{NM} \cdot e^{j(\phi_r^N+\phi_t^M)} \end{bmatrix} \\
&= \begin{bmatrix} H_{1,BB11} & \cdots & H_{1,BB1\left(\frac{M}{P}\right)}, H_{1,BB21} \cdots H_{1,BB2\left(\frac{M}{P}\right)}, \cdots, H_{1,BBP1} \cdots H_{1,BBP\left(\frac{M}{P}\right)} \\ \vdots & \ddots & \vdots \\ H_{N,BB11} & \cdots & H_{N,BB1\left(\frac{M}{P}\right)}, H_{N,BB21} \cdots H_{N,BB2\left(\frac{M}{P}\right)}, \cdots, H_{N,BBP1} \cdots H_{N,BBP\left(\frac{M}{P}\right)} \end{bmatrix} \\
&= \begin{bmatrix} \boldsymbol{H}'_{1,BB1} & \cdots & \boldsymbol{H}'_{1,BBP} \\ \vdots & \ddots & \vdots \\ \boldsymbol{H}'_{N,BB1} & \cdots & \boldsymbol{H}'_{N,BBP} \end{bmatrix} = \left[\boldsymbol{H}'_{BB1} \cdots \boldsymbol{H}'_{BBP}\right] \qquad (4)
\end{aligned}$$

where

$$\boldsymbol{H}'_{1,BB1} = \left[H_{11} \cdot e^{j(\phi_r^1+\phi_t^1)} \cdots H_{1\left(\frac{M}{P}\right)} \cdot e^{j\left(\phi_r^1+\phi_t^{\frac{M}{P}}\right)} \right]$$

$$= \left[H_{1,BB11} \cdots H_{1,BB1\left(\frac{M}{P}\right)} \right] \tag{5}$$

$$\boldsymbol{H}'_{1,BBP} = \left[H_{1\left(M-\frac{M}{P}+1\right)} \cdot e^{j\left(\phi_r^1+\phi_t^{\left(M-\frac{M}{P}+1\right)}\right)} \cdots H_{1M} \cdot e^{j\left(\phi_r^1+\phi_t^M\right)} \right]$$

$$= \left[H_{1,BBP1} \cdots H_{1,BBP\left(\frac{M}{P}\right)} \right] \tag{6}$$

$$\boldsymbol{H}'_{N,BB1} = \left[H_{N1} \cdot e^{j\left(\phi_r^N+\phi_t^1\right)} \ldots H_{N\left(\frac{M}{P}\right)} \cdot e^{j\left(\phi_r^N+\phi_t^{\frac{M}{P}}\right)} \right]$$

$$= \left[H_{N,BB11} \cdots H_{N,BB1\left(\frac{M}{P}\right)} \right] \tag{7}$$

$$\boldsymbol{H}'_{N,BBP} = \left[H_{N\left(M-\frac{M}{P}+1\right)} \cdot e^{j\left(\phi_r^N+\phi_t^{\left(M-\frac{M}{P}+1\right)}\right)} \cdots H_{NM} \cdot e^{j\left(\phi_r^N+\phi_t^M\right)} \right]$$

$$= \left[H_{N,BBP1} \cdots H_{N,BBP\left(\frac{M}{P}\right)} \right] \tag{8}$$

$$\boldsymbol{H}'_{BB1} = \begin{bmatrix} \boldsymbol{H}'_{1,BB1} \\ \vdots \\ \boldsymbol{H}'_{N,BB1} \end{bmatrix} \tag{9}$$

$$\boldsymbol{H}'_{BBP} = \begin{bmatrix} \boldsymbol{H}'_{1,BBP} \\ \vdots \\ \boldsymbol{H}'_{N,BBP} \end{bmatrix} \tag{10}.$$

[0040] Similarly, the phase information Ψ of the communication channel estimation $\boldsymbol{H}_j'$ may be rewritten as below:

$$\Psi = \begin{bmatrix} e_{1,BB11} \cdots e_{1,BB1(M/P)}, & e_{1,BB21} \cdots e_{1,BB2(M/P)}, & \cdots, & e_{1,BBP1} \cdots e_{1,BBP(M/P)} \\ \vdots & \ddots & \ddots & \vdots \\ e_{N,BB11} \cdots e_{N,BB1(M/P)}, & e_{N,BB21} \cdots e_{N,BB2(M/P)}, & \cdots & e_{N,BBP1} \cdots e_{N,BBP(M/P)}, \end{bmatrix}$$

$$= \begin{bmatrix} e'_{1,BB1} & \cdots & e'_{1,BBP} \\ \vdots & \ddots & \vdots \\ e'_{N,BB1} & \cdots & e'_{N,BBP} \end{bmatrix}$$

$$= \left[e'_{BB1} \cdots e'_{BBP} \right] \tag{11}$$

where

$$\begin{aligned} e'_{1,BB1} &= \left[e_{1,BB11} \quad \cdots \quad e_{1,BB1(M/P)} \right] \\ &= \left[e^{j(\phi_{11}+\phi_r^1+\phi_t^1)} \quad \dots \quad e^{j\left(\phi_{1(M/P)}+\phi_r^1+\phi_t^{M/P}\right)} \right] \end{aligned} \tag{12}$$

$$\begin{aligned} e'_{1,BBP} &= \left[e_{1,BBP1} \quad \cdots \quad e_{1,BBP(M/P)} \right] \\ &= \left[e^{j\left(\phi_{1(M-M/P+1)}+\phi_r^1+\phi_t^{(M-M/P+1)}\right)} \quad \dots \quad e^{j(\phi_{1M}+\phi_r^1+\phi_t^M)} \right] \end{aligned} \tag{13}$$

$$\begin{aligned} e'_{N,BB1} &= \left[e_{N,BB11} \quad \cdots \quad e_{N,BB1(M/P)} \right] \\ &= \left[e^{j(\phi_{N1}+\phi_r^N+\phi_t^1)} \quad \dots \quad e^{j\left(\phi_{N(M/P)}+\phi_r^N+\phi_t^{M/P}\right)} \right] \end{aligned} \tag{14}$$

$$\begin{aligned} e'_{N,BBP} &= \left[e_{N,BBP1} \quad \cdots \quad e_{N,BBP(M/P)} \right] \\ &= \left[e^{j\left(\phi_{N(M-M/P+1)}+\phi_r^N+\phi_t^{(M-M/P+1)}\right)} \quad \dots \quad e^{j(\phi_{NM}+\phi_r^N+\phi_t^M)} \right] \end{aligned} \tag{15}$$

$$e'_{BB1} = \begin{bmatrix} e'_{1,BB1} \\ \vdots \\ e'_{N,BB1} \end{bmatrix} \tag{16}$$

$$e'_{BBP} = \begin{bmatrix} e'_{1,BBP} \\ \vdots \\ e'_{N,BBP} \end{bmatrix} \tag{17}.$$

[0041] At an operation 214, the UEs 110 may receive a sensing request from the base station 120. For example, when a sensing application is executed at the base station 120, the base station 120 may transmit the sensing request to the UEs 110 (including the j-th UE 110-j) and instruct the UEs 110 to calculate and analyze the reflected signals for sensing. In an example embodiment, the sensing request may be embedded in the first signal transmitted at the operation 210, and the operation 214 may be omitted. In some example embodiments, the UEs 110 may determine the sending channel estimation when they receive the sensing request.

[0042] Upon receiving the sensing request, the UEs 110 may calculate relevance between the communication channel estimation H (e.g., $H_j^{'}$ at the UE 110-j) and the sensing channel estimation G at an operation 216. In an example, the relevance may be calculated as an Euclidean distance between the channel estimations H and G as below:

$$Relevance(H, G) = min\|H - G\|_F^2 \tag{18}$$.

[0043] If the communication channel estimation H and the sensing channel estimation G are obtained based on the same signal (e.g., the bi-functional signal transmitted at the operation 210), the communication channel estimation H and the sensing channel estimation G would usually have a high relevance, e.g., higher than or equal to a predetermined threshold. Then the UEs 110 may compensate the phase error (PHE) of the communication channel estimation to obtain accurate channel state information for the sensing application.

[0044] Fig. 6 illustrates an example method 300 for PHE compensation according to an example embodiment. The method 300 may be performed at the UEs 110 to compensate for common phase error in the channel estimation and obtain accurate CSI measurements. In some example embodiments, the UEs 110 may include or be implemented with a plurality of components, modules, means or elements to perform operations in the method 300, and the components, modules, means or elements may be implemented in various manners including but not limited to for example software, hardware, firmware or any combination thereof.

[0045] Referring to Fig. 6, at an operation 310, the UEs 110 may determine phase error information based on the communication channel estimation. Considering the inherent phase offset between the baseband boards 121 as discussed above, the phase error information may be determined as phase mismatches between propagation paths associated with a certain baseband board 121 (or exactly, associated with a group of transmitting antennas of the baseband board 121) and propagation paths associated with other baseband boards 121. For convenience of description, here the first baseband board 121-1 having antennas 122-(1,1) to

122-(1,M/P) is taken as a reference baseband board, and the phase error information is determined as phase mismatches of the propagation paths associated with each of the baseband board 121-2 to 121-P relative to the propagation paths associated with the reference baseband board 121-1, but it would be appreciated that any one of the baseband boards 121-1 to 121-P may be regarded as the reference baseband board. According to the formula (11), the phase error information Ψ' may be determined as below:

$$\begin{aligned}\Psi' &= \left[1 \quad \left(\frac{\boldsymbol{e}^{\,j\phi'_{BB2}}}{\boldsymbol{e}^{\,j\phi'_{BB1}}}\right) \quad \cdots \quad \left(\frac{\boldsymbol{e}^{\,j\phi'_{BBP}}}{\boldsymbol{e}^{\,j\phi'_{BB1}}}\right)\right] \\ &= \left[1 \quad e^{\,j(\phi'_{BB2}-\phi'_{BB1})} \quad \cdots \quad e^{\,j(\phi_{BBP}-\phi'_{BB1})}\right] \\ &= \left[1 \quad e^{\,j(\Delta\phi'_{BB2})} \quad \ldots \quad e^{\,j(\Delta\phi'_{BBP})}\right] \qquad (19)\end{aligned}$$

where $\boldsymbol{e}^{\,j\phi'_{BB1}}$ represents the phase information of $\boldsymbol{H}'_{BB1}$ on a baseband board's level, and $\Delta\phi'_{BBp} = \phi'_{BBp} - \phi'_{BB1}$ represent the phase mismatch (difference) of $\boldsymbol{H}'_{BBp}$ relative to $\boldsymbol{H}'_{BB1}$. With reference to formulas (11) to (17), it would be appreciated that each item in the matrix Ψ' represents a block matrix with a dimension of N rows and (M/P) columns. Since the first baseband board 121-1 is taken as the phase reference baseband board, all (N×M/P) elements in the first block matrix is "1".

[0046] To further reduce complexity and execution expense, an average phase of one or more elements in $\boldsymbol{H}'_{BBp}, p = 1,\cdots,P$ may be used in some example embodiments. When the average phase is taken into account, $\boldsymbol{e}^{j\phi'_{BBp}}, p = 2,\cdots,P$ may be rewritten as $\boldsymbol{e}^{j\bar{\phi}_{BBp}}, p = 2,\cdots,P$ for representing the baseband board 121-p, and the formula (19) may be rewritten as below:

$$\Psi' = \left[1 \quad e^{\,j(\Delta\bar{\phi}_{BB2})} \quad \ldots \quad e^{\,j(\Delta\bar{\phi}_{BBP})}\right] \qquad (20)$$

where $\{\Delta\bar{\phi}_{BBp}, p = 2,\cdots,P\}$ on subframe i may be written as $\left\{\Delta\bar{\phi}_{BS_{i,p}}, p = 2,\cdots,P\right\}$ which represents a phase value obtained by averaging phase differences between the p-th baseband board 121-p and the first baseband board 121-1 (again, the other baseband boards could be taken as the reference) on subframe *i*. Here the average phase differences between two groups of phase vectors associated with two baseband boards are used.

[0047] There are flexible algorithms to obtain the average phase differences $e^{j(\Delta\bar{\Phi}_{BBp})}$ between the p-th baseband board 121-p and the first baseband board 121-1. For example, $e^{j(\Delta\bar{\Phi}_{BBp})}$ could be calculated by selectively averaging one or more phase differences associated with different receiving antennas (matrix rows). In other words, one or more matrix elements in a column of the block matrix $e^{j(\Delta\Phi'_{BBp})}, p = 2, \cdots, P$ may be selected and averaged to obtain an average value, which may be used for all matrix elements in said column. The following formulas (21-23) give some examples to calculate the average phase differences:

$$e^{j(\Delta\bar{\Phi}_{BB2})} = average\ of \left\{\mathbf{e}_{1,BB2} \ \cdots \ \mathbf{e}_{N,BB2}\right\} \tag{21}$$

$$e^{j(\Delta\bar{\Phi}_{BB2})} = average\ of \left\{\mathbf{e}_{1,BB2} \ \mathbf{e}_{3,BB2} \cdots \mathbf{e}_{N-2,BB2} \ \mathbf{e}_{N,BB2}\right\} or$$

$$\left\{\mathbf{e}_{1,BB2} \ \mathbf{e}_{5,BB2} \cdots \mathbf{e}_{N-4,BB2} \ \mathbf{e}_{N,BB2}\right\} \tag{22}$$

$$e^{j(\Delta\bar{\Phi}_{BB2})} = any\ one\ of\ \mathbf{e}_{q,BB2}\ where\ q = 1, \ldots, N \tag{23}$$

[0048] In an example embodiment, the UEs 110 may run a smoothing algorithm to smooth the phase error information Ψ’. As mentioned above, the channel estimation may be performed for subframes k in the time domain, and a series of phase error information Ψ'_k may be obtained with respect to the subframes k where k=0, ..., *i*. The UEs 110 may use a sliding window which includes a plurality of subframes to smooth the phase error information Ψ'_k within the sliding window and mitigate sharp changes of the phase error information Ψ'_k.

[0049] When the phase error information Ψ’ is determined for the communication channel estimation H (e.g., H_j' at the UE 110-j), the UEs 110 may determine at an operation 312 phase compensation information to compensate for the phase mismatches of the propagation paths associated with the respective baseband boards 121-2 to 121-P (or exactly, the propagation paths associated with the respective groups of transmitting antennas of the respective baseband boards 121-2 to 121-P) relative to the propagation paths associated with the first baseband board 121-1 (or exactly, the propagation paths associated with the first group of transmitting antennas of the first baseband board 121-1). The phase compensation information may be determined to compensate the phase mismatches of the respective baseband boards 121-2 to 121-P relative to the first baseband board 121-1 so that the phases of the respective baseband boards 121-2 to 121-P are aligned to the phase of the first baseband board 121-1. In an example embodiment, the phase compensation information Ψ" may be determined as a conjugate matrix of the phase error matrix Ψ' as shown below:

$$\Psi'' = \left[1 \quad e^{j(-\Delta\bar{\phi}_{BB2})} \quad \dots \quad e^{j(-\Delta\bar{\phi}_{BBP})}\right] \tag{24}$$

where each item in the formula (24) represents a block matrix having a dimension of N rows and M/P columns, and all elements in the first block matrix is "1".

[0050] Once the phase compensation information Ψ" is determined, the UEs 110 may compensate the communication channel estimation H to obtain accurate CSI. For example, the UE 110-j may compensate the communication channel estimation $H_j^{'}$ as below:

$$\begin{aligned}
\boldsymbol{H}_{i,j}^{''} &= \left(\Phi_R \boldsymbol{H}_j \Phi_T\right) \circ \Psi^{''} \\
&= [\boldsymbol{H}^{'}_{BB1} \cdots \boldsymbol{H}^{'}_{BBP}] \circ \left[1 \quad e^{j(-\Delta\bar{\phi}_{BB2})} \quad \dots \quad e^{j(-\Delta\bar{\phi}_{BBP})}\right] \\
&= \left[\boldsymbol{H}^{'}_{BB1} \quad \boldsymbol{H}^{'}_{BB2} e^{j(-\Delta\bar{\phi}_{BB2})} \dots \quad \boldsymbol{H}^{'}_{BBP} e^{j(-\Delta\bar{\phi}_{BBP})}\right] \\
&= \left[\left|\boldsymbol{H}^{'}_{BB1}\right| \quad \left|\boldsymbol{H}^{'}_{BB2}\right| \cdots \quad \left|\boldsymbol{H}^{'}_{BBP}\right|\right] \boldsymbol{e}^{j\phi^{'}_{BB1}}
\end{aligned} \tag{25}$$

where $\boldsymbol{e}^{j\phi^{'}_{BB1}}$ represents the phase information of $\boldsymbol{H}^{'}_{BB1}$. When an average phase is used for $\boldsymbol{H}^{'}_{BB1}$, $\boldsymbol{e}^{j\phi^{'}_{BB1}}$can be written as $\boldsymbol{e}^{j\bar{\phi}_{BB1}}$. It can be seen from the formula (25) that all the baseband boards 121-1 to 121-P are aligned to the phase of the first (reference) baseband board 121-1. Therefore, the phase noise represented by Φ_R and Φ_R can be cancelled out, and the phase differences among the baseband boards at the base station 120 can be eliminated. By the PHE compensation, the UEs 110 obtains refined/enhanced channel state information $\boldsymbol{H}_{i,j}^{''}$.

[0051] Referring back to Fig. 5, when the phase error is compensated, the UEs 110 may send a new waveform request together with the enhanced channel state information $\boldsymbol{H}_{i,j}^{''}$ to the base station 120 at an operation 220. In an example embodiment, the new waveform request and the enhanced channel state information $\boldsymbol{H}''_{i,j}$ may be transmitted via separate messages.

[0052] In response to the new waveform request, the base station 120 may design a new waveform for signals in several subsequent frames by adjusting a signal pattern based on the enhanced CSI, at an operation 222. The base station 120 may adjust the signal pattern to achieve balance between good communication and sending and maximize the mutual information (MI) associated with the JCAS channel. In an example embodiment, the base station 120 may determine the transmit signal pattern X_d in space-time domain in matrix form as follows:

$$\begin{cases} X_d = (\Theta \Xi^{1/2} U^H_{\mathbf{H}''_{i,j}})^T \\ \Theta^H \Theta = I_N \\ \sum_{\mathbf{H}''_{i,j}} = \frac{1}{N} E\{\mathbf{H}''_{i,j} \mathbf{H}''^{H}_{i,j}\} = U_{\mathbf{H}''_{i,j}} \Lambda U^H_{\mathbf{H}''_{i,j}} \end{cases} \quad (26)$$

where Ξ is calculated based on the compensated communication channel estimation $\mathbf{H}''_{i,j}$, Θ is the preconfigured matrix that satisfy $\Theta^H \Theta = I_N$, $U^H_{\boldsymbol{H}''_{i,j}}$ is the right unitary matrix after singular value decomposition (SVD) of the communication channel covariance matrix $\boldsymbol{H}''_{i,j} \boldsymbol{H}''^{H}_{i,j}$, and $\Lambda = diag([\lambda_{1,1}, \ldots, \lambda_{i,i}, \ldots, \lambda_{N,N})$ is a diagonal matrix with $\lambda_{i,i}$ being the singular values.

[0053] The base station 120 may transmit a second signal based on the adjusted signal pattern to the UEs 110 at an operation 224. With the enhanced CSI, the second signal may better meet the requirements of signal processing techniques and classification/estimation algorithms employed in the sensing applications.

[0054] The PHE compensation scheme proposed above may be performed time to time to maintain accurate CSI measurements. For example, when one or more objects 130 moves and consequently the state of the JCAS channel changes, the base station 120 and the UEs 110 may perform the proposed PHE compensation scheme again. In an example, the base station 120 and the UEs 110 may perform the proposed PHE compensation scheme periodically, e.g., with a periodicity of one or plural frames.

[0055] The phase compensation information Ψ" used in the transmit signal is detectable at the UEs 110 due to the unique data structure of the phase compensation information Ψ". Fig. 7 illustrates an example of detecting the PHE compensation matrix used in the downlink transmit signal at the UE side according to an example embodiment. The UEs 110 may extract the phase compensation information Ψ" in form of compensation matrix 410 from the signal blocks received from the base station 120 through reference signal estimation. As described above, the compensation matrix 410 (Ψ") comprises a block matrix with a dimension of N×M/P in which all elements is a unit value “1”, combined in the row direction with a block matrix with a dimension of N×(M-M/P) in which the elements is not the unit value. A N×M/P detection matrix 420 with all elements “1” may be used to calculate sliding correlation with respect to the phase compensation matrices 410 extracted from the receiving data blocks. If the calculated sliding correlation appears like an impulse-shaped peak with a certain periodicity in the time domain, it can be determined that the phase compensation matrix Ψ" proposed in the present disclosure is adopted in the system.

[0056] The example embodiments have been described in the context of the JCAS system. It would be appreciated that the example embodiments are also applicable to other scenarios where accurate CSI measurement is needed.

[0057] Figs. 8A, 8B, 8C and 8D illustrate performance evaluation for PHE compensation schemes according to some example embodiments. The performance evaluation is simulated in an environment shown in Table 1 below, the field measurement scenarios include LOS (line of sight)/NLOS (non-line of sight) indoor for 30m at TX power 24dBm. The evaluation metric for JCAS communication is mainly the spectral efficiency (the total throughput is spectral efficiency multiplied by bandwidth). In each of Figs. 8A-8D, five PHE compensation schemes are compared: a first scheme denoted by “with PHN” where no PHE compensation is applied, a second scheme denoted by “Scheme 1” where PHE compensation is applied without considering phase mismatch among the baseband boards, a third scheme denoted by “Scheme 2.1” where the proposed PHE compensation is applied with the average phase mismatch calculated from the formula (21), a fourth scheme denoted by “Scheme 2.2” where the proposed PHE compensation is applied with the average phase mismatch calculated from the formula (22), and a fifth scheme denoted by “Scheme 2.3” where the proposed PHE compensation is applied with the average phase mismatch calculated from the formula (23).

Table 1: Simulation Parameters

Parameter	**Value**
Baseband board number at gNB	8
UEs per gNB	30
Used Symbol Per Subband	24720/24800
IMCS	3
Tx power	24dBm
Noise figure	-174dBm/Hz
Receive figure	9dB
CodeRate	0.67
CBSize/CBS with CRC	4072/4096
@28GHz CSI-RS 16 Ports Channel Bandwidth	1008MHz
Total PRB/Subcarrier Spacing	200/270KHz
Sampling Frequency(SF)	$2^{n} \times \Delta f^{MMW}$ =2048 x 270KHz=552.96MHz.
Total BS antenna number	64
Single UE’s antenna number	16/4

[0058] Fig. 8A illustrates performance comparison of the five compensation schemes at a sampling frequency SF1=552.96 MHz with 64 TX antennas and 4 RX antennas (64T4R). Fig. 8B illustrates performance comparison of the five compensation schemes at the sampling frequency SF=552.96 MHz with 64 TX antennas and 16 RX antennas (64T16R). Fig. 8A indicates that Scheme1 provides a better gain than other schemes, but Scheme 1 also has higher complexity and execution expense. Scheme 2.1 seems to be the optimal among these schemes in Fig. 8A. If 64T16R is utilized, as shown in Fig. 8B, the performance of Scheme 1 is not superior than the proposed Schemes 2.1, 2.2 and 2.3. Fig. 8C and Fig. 8D show similar cases to Fig. 8A and Fig. 8B, respectively, except that double sampling at SF2=1.10592 Ghz is utilized. It can be seen that the performance of Schemes 2.1, 2.2 and 2.3 is almost equivalent with Scheme 1.

[0059] The above evaluation results indicate that the proposed inter-baseband board (inter-BB) PHE cancellation scheme plays a larger role when more receiving antennas are used or when double sampling frequency is used. Overall, the algorithm design for PHE compensation in the JCAS system is a trade-off according to system antenna configurations and system sampling frequency configuration. The proposed PHE compensation scheme exhibits good performance in practice while maintaining low complexity and execution expense.

[0060] Fig. 9 is a simplified block diagram illustrating an example communication system 500 in which example embodiments of the present disclosure can be implemented. As shown in Fig. 9, the communication system 500 may include a terminal device 510 which may be implemented as one of the UEs 110 discussed above, and a network device 520 which may be implemented as the base station 120 discussed above. Although Fig. 9 shows only one terminal device 510, it would be appreciated that the communication system 500 may comprise a plurality of terminal devices 510 that wirelessly connect to the network device 520.

[0061] Referring to Fig. 9, the terminal device 510 may comprise one or more processors 511, one or more memories 512 and one or more transceivers 513 interconnected through one or more buses 514. The one or more buses 514 may be address, data, or control buses, and may include any interconnection mechanism such as series of lines on a motherboard or integrated circuit, fiber, optics or other optical communication equipment, and the like. Each of the one or more transceivers 513 may comprise a receiver and a transmitter, which are connected to a plurality of antenna elements 516. The terminal device 510 may wirelessly communicate with the network device 520 through the antenna elements 516. The one or more memories 512 may include computer program code 515. The one or more memories 512 and the computer program code 515 may be configured to, when executed by the one or more processors 511, cause the terminal device 510 to perform processes and operations relating to the UEs 110 as described above.

[0062] The network device 520 may comprise one or more processors 521, one or more memories 522, one or more transceivers 523 and one or more network interfaces 527 interconnected through one or more buses 524. The one or more buses 524 may be address, data, or control buses, and may include any interconnection mechanism such as a series of lines on a motherboard or integrated circuit, fiber, optics or other optical communication equipment, and the like. Each of the one or more transceivers 523 may comprise a receiver and a transmitter, which are connected to a number of antenna elements 526. In an example, the network device 520 may include multiple transceivers 526 for multiple baseband boards, and each transceiver 526 is connected to a group of antenna elements 526 for transmitting and receiving radio signals. The network device 520 may operate as a base station for the terminal device 510 and wirelessly communicate with the terminal device 510 through the antenna elements 526. With the plurality of antenna elements 526, the network device 520 can support MIMO technologies including for example beam-forming. The one or more network interfaces 527 may provide wired or wireless communication links through which the network device 520 may communicate with other network devices, entities or functions. The one or more memories 522 may include computer program code 525. The one or more memories 522 and the computer program code 525 may be configured to, when executed by the one or more processors 521, cause the network device 520 to perform processes and operations relating to the base station 120 as described above.

[0063] The one or more processors 511, 521 discussed above may be of any appropriate type that is suitable for the local technical network, and may include one or more of general purpose processors, special purpose processor, microprocessors, a digital signal processor (DSP), one or more processors in a processor based multi-core processor architecture, as well as dedicated processors such as those developed based on Field Programmable Gate Array (FPGA) and Application Specific Integrated Circuit (ASIC). The one or more processors 511, 521 may be configured to control other elements of the terminal/network device and operate in cooperation with them to implement the procedures discussed above.

[0064] The one or more memories 512, 522 may include at least one storage medium in various forms, such as a volatile memory and/or a non-volatile memory. The volatile memory may include but not limited to for example a random access memory (RAM) or a cache. The non-volatile memory may include but not limited to for example a read only memory (ROM), a hard disk, a flash memory, and the like. Further, the one or more memories 512, 522 may include but not limited to an electric, a magnetic, an optical, an electromagnetic, an infrared, or a semiconductor system, apparatus, or device or any combination of the above.

[0065] The network device 520 can be implemented as a single network node, or disaggregated/distributed over two or more network nodes, such as a central unit (CU), a distributed unit (DU), a remote radio head-end (RRH), using different functional-split architectures and different interfaces.

[0066] It would be understood that blocks in the drawings may be implemented in various manners, including software, hardware, firmware, or any combination thereof. In some example embodiments, one or more blocks may be implemented using software and/or firmware, for example, machine-executable instructions stored in the storage medium. In addition to or instead of machine-executable instructions, parts or all of the blocks in the drawings may be implemented, at least in part, by one or more hardware logic components. For example, and without limitation, illustrative types of hardware logic components that can be used include Field-Programmable Gate Arrays (FPGAs), Application-Specific Integrated Circuits (ASICs), Application-Specific Standard Products (ASSPs), System-on-Chip systems (SOCs), Complex Programmable Logic Devices (CPLDs), etc.

[0067] Some example embodiments further provide computer program code or instructions which, when executed by one or more processors, may cause a device or apparatus to perform the procedures described above. The computer program code for carrying out procedures of the example embodiments may be written in any combination of one or more programming languages. The computer program code may be provided to one or more processors or controllers of a general purpose computer, special purpose computer, or other programmable data processing apparatus, such that the program code, when executed by the processor or controller, cause the functions/operations specified in the flowcharts and/or block diagrams to be implemented. The program code may execute entirely on a machine, partly on the machine, as a stand-alone software package, partly on the machine and partly on a remote machine or entirely on the remote machine or server.

[0068] Some example embodiments further provide a computer program product or a computer readable medium having the computer program code or instructions stored therein. The computer readable medium may be any tangible medium that may contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device. The machine readable medium may be a machine readable signal medium or a machine readable storage medium. A machine readable medium may include but is not limited to an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples of the machine readable storage medium would include 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), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing.

[0069] Further, while operations are depicted in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Likewise, while several specific implementation details are contained in the above discussions, these should not be construed as limitations on the scope of the present disclosure, but rather as descriptions of features that may be specific to particular example embodiments. Certain features that are described in the context of separate example embodiments may also be implemented in combination in a single example embodiment. Conversely, various features that are described in the context of a single example embodiment may also be implemented in multiple example embodiments separately or in any suitable sub-combination.

[0070] Although the subject matter has been described in a language that is specific to structural features and/or method actions, it is to be understood the subject matter defined in the appended claims is not limited to the specific features or actions described above. On the contrary, the above-described specific features and actions are disclosed as an example of implementing the claims.

[0071] Abbreviations used in the description and/or in the figures are defined as follows:

CFO	Carrier Frequency Offset
CPE	Common Phase Error
CSI	Channel State Information
gNB	next Generation Node-B
ICI	Inter Carrier Interference
ISAC	Integrated Sensing and Communication
JCAS	Joint Communication and Sensing
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing

PHE	Phase Error
PHN	Phase Noise
UE	User Equipment

WHAT IS CLAIMED IS:

1. A first device comprising:

at least one processor; and

at least one memory including computer program code, the at least one memory and the computer program code being configured to, with the at least one processor, cause the first device to:

determine a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device;

determine phase error information based on the communication channel estimation, the phase error information indicating phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determine, based on the phase error information, phase compensation information to compensate for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas.

2. The first device of Claim 1 wherein the phase information of respective propagation paths comprises phase offset caused by the first device, phase offset caused by the second device, and phase offset caused by signal propagation over the air.

3. The first device of Claim 1 wherein the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas are selectively averaged with respect to one or more receiving antennas to obtain an averaged phase mismatch, and the averaged phase mismatch is used as the phase mismatch of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with the first group of transmitting antennas.

4. The first device of Claim 1 wherein the phase error information comprises a phase error matrix including a first block matrix and one or more second block matrices, the first block matrix including matrix elements with a value of one, the one or more second block matrices including matrix elements indicating the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas.

5. The first device of Claim 4 wherein one or more of the matrix elements in a column of the one or more second block matrices are selectively averaged to obtain an average phase mismatch, and the obtained average phase mismatch is used for the matrix elements in the column.

6. The first device of Claim 4 wherein the phase compensation information comprises a conjugate matrix of the phase error matrix.

7. The first device of Claim 1 wherein the at least one memory and the computer program code are further configured to, with the at least one processor, cause the first device to:

determine a sensing channel estimation based on the first signal received on the integrated sensing and communication channel from the second device;

receive a sensing request from the second device, the phase compensation information being determined in response to the sensing request;

determine relevance between the communication channel estimation and the sensing channel estimation;

compensate the communication channel estimation using the phase compensation information when the relevance between the communication channel estimation and the sensing channel estimation is higher than or equal to a threshold; and

transmit a new waveform request and the compensated communication channel estimation to the second device.

8. The first device of Claim 7 wherein the sensing request is embedded in the first signal.

9. The first device of Claim 1 wherein the first device is a terminal device, and the second device is a network device.

10. A second device comprising:

at least one processor; and

at least one memory including computer program code, the at least one memory and the computer program code being configured to, with the at least one processor, cause the second device to:

transmit a sensing request to a first device;

receive a new waveform request and channel state information from the first device, the channel state information including a communication channel estimation for an integrated sensing and communication channel between the first device and the second device compensated by phase compensation information, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device, the phase compensation information being determined based on phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determine new waveform for a signal transmitted to the first device, based on the channel state information.

11. The second device of Claim 10 wherein the sensing request is embedded in a first signal transmitted on the integrated sensing and communication channel to the first device, and the channel state information is determined from the first signal.

12. The second device of Claim 10 wherein the phase compensation information compensates for the phase mismatches of the propagation paths associated with the one or

more second groups of transmitting antennas relative to the propagation paths associated with the first group of transmitting antennas to align phases of the propagation paths associated with the one or more second groups of transmitting antennas to phase of the propagation paths associated with the first group of transmitting antennas.

13. The second device of Claim 10 wherein the phase compensation information comprises a phase compensation matrix including a first block matrix and one or more second block matrices, the first block matrix including matrix elements with a value of one, the one or more second block matrices including matrix elements indicating the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas.

14. The second device of Claim 10 wherein the respective groups of transmitting antennas, including the first group and the one or more second groups, are associated with respective baseband boards at the second device.

15. The second device of Claim 10 wherein the first device is a terminal device, and the second device is a network device.

16. A method comprising:

determining at a first device a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device;

determining phase error information based on the communication channel estimation, the phase error information indicating phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determining, based on the phase error information, phase compensation information to compensate for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas.

17. The method of Claim 16 wherein the phase information of respective propagation paths comprises phase offset caused by the first device, phase offset caused by the second device, and phase offset caused by signal propagation over the air.

18. The method of Claim 16 wherein the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas are selectively averaged with respect to one or more receiving antennas to obtain an averaged phase mismatch, and the averaged phase mismatch is used as the phase mismatch of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with the first group of transmitting antennas.

19. The method of Claim 16 wherein the phase error information comprises a phase error matrix including a first block matrix and one or more second block matrices, the first block matrix including matrix elements with a value of one, the one or more second block matrices including matrix elements indicating the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas.

20. The method of Claim 19 wherein one or more of the matrix elements in a column of the one or more second block matrices are selectively averaged to obtain an average phase mismatch, and the obtained average phase mismatch is used for the matrix elements in the column.

21. The method of Claim 19 wherein the phase compensation information comprises a conjugate matrix of the phase error matrix.

22. The method of Claim 16 further comprising:

determining a sensing channel estimation based on the first signal received on the integrated sensing and communication channel from the second device;

receiving a sensing request from the second device, the phase compensation information being determined in response to the sensing request;

determining relevance between the communication channel estimation and the sensing channel estimation;

compensating the communication channel estimation using the phase compensation information when the relevance between the communication channel estimation and the sensing channel estimationis higher than or equal to a threshold; and

transmitting a new waveform request and the compensated communication channel estimation from the first device to the second device.

23. The method of Claim 22 wherein the sensing request is embedded in the first signal.

24. The method of Claim 16 wherein the first device is a terminal device, and the second device is a network device.

25. A method comprising:

transmitting a sensing request from a second device to a first device;

receiving a new waveform request and channel state information from the first device, the channel state information including a communication channel estimation for an integrated sensing and communication channel between the first device and the second device compensated by phase compensation information, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device, the phase compensation information being determined based on phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determining new waveform for a signal transmitted to the first device, based on the channel state information.

26. The method of Claim 25 wherein the sensing request is embedded in a first signal transmitted on the integrated sensing and communication channel to the first device, and the channel state information is determined from the first signal.

27. The method of Claim 25 wherein the phase compensation information compensates for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with the first group of transmitting antennas to align phases of the propagation paths associated with the one or more second groups of transmitting antennas to phase of the propagation paths associated with the first group of transmitting antennas.

28. The method of Claim 25 wherein the phase compensation information comprises a phase compensation matrix including a first block matrix and one or more second block matrices, the first block matrix including matrix elements with a value of one, the one or more second block matrices including matrix elements indicating the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas.

29. The method of Claim 25 wherein the respective groups of transmitting antennas, including the first group and the one or more second groups, are associated with respective baseband boards at the second device.

30. The method of Claim 25 wherein the first device is a terminal device, and the second device is a network device.

31. An apparatus comprising:

means for determining at a first device a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device;

means for determining phase error information based on the communication channel estimation, the phase error information indicating phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

means for determining, based on the phase error information, phase compensation information to compensate for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas.

32. An apparatus comprising:

means for transmitting a sensing request from a second device to a first device;

means for receiving a new waveform request and channel state information from the first device, the channel state information including a communication channel estimation for an integrated sensing and communication channel between the first device and the second device compensated by phase compensation information, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device, the phase compensation information being determined based on phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

means for determining new waveform for a signal transmitted to the first device, based on the channel state information.

33. A computer program product embodied in at least one computer readable medium and comprising instructions, when executed by at least one processor of a first device, causing the first device at least to:

determine a communication channel estimation based on a first signal received on an integrated sensing and communication channel from a second device, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device;

determine phase error information based on the communication channel estimation, the phase error information indicating phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determine, based on the phase error information, phase compensation information to compensate for the phase mismatches of the propagation paths associated with the one or more second groups of transmitting antennas.

34. A computer program product embodied in at least one computer readable medium and comprising instructions, when executed by at least one processor of a second device, causing the second device at least to:

transmit a sensing request to a first device;

receive a new waveform request and channel state information from the first device, the channel state information including a communication channel estimation for an integrated sensing and communication channel between the first device and the second device compensated by phase compensation information, the communication channel estimation containing phase information of respective propagation paths between a plurality of receiving antennas at the first device and a plurality of transmitting antennas at the second device, the phase compensation information being determined based on phase mismatches of the propagation paths associated with one or more second groups of transmitting antennas relative to the propagation paths associated with a first group of transmitting antennas; and

determine new waveform for a signal transmitted to the first device, based on the channel state information.

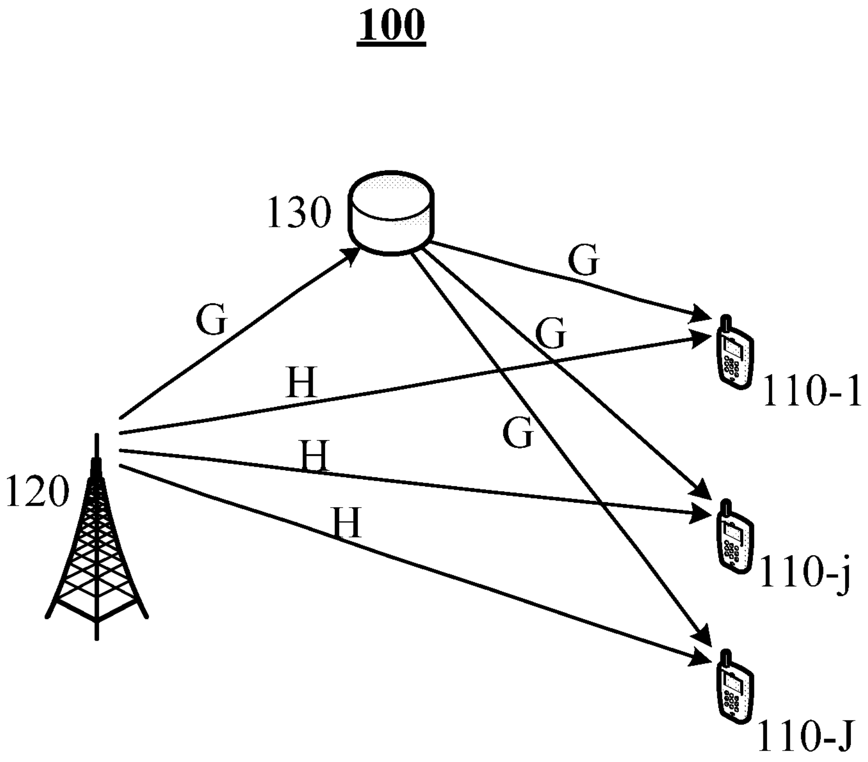

FIG. 1

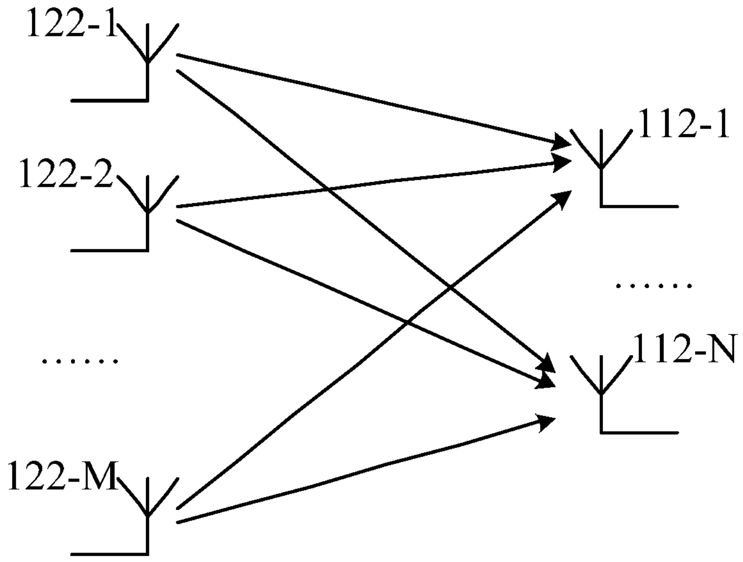

FIG. 2

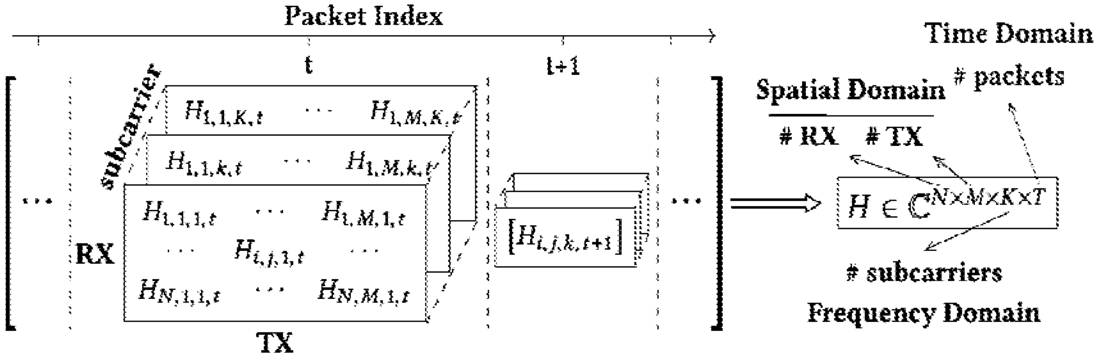
Packet Index
t
t+1
subcarrier
$H_{1,1,K,t}$ ··· $H_{1,M,K,t}$
$H_{1,1,k,t}$ ··· $H_{1,M,k,t}$
$H_{1,1,1,t}$ ··· $H_{1,M,1,t}$
··· $H_{i,j,1,t}$ ···
$H_{N,1,1,t}$ ··· $H_{N,M,1,t}$
RX
TX
$[H_{i,j,k,t+1}]$
Spatial Domain
RX
TX
Time Domain
packets
$H \in \mathbb{C}^{N \times M \times K \times T}$
subcarriers
Frequency Domain

FIG. 3

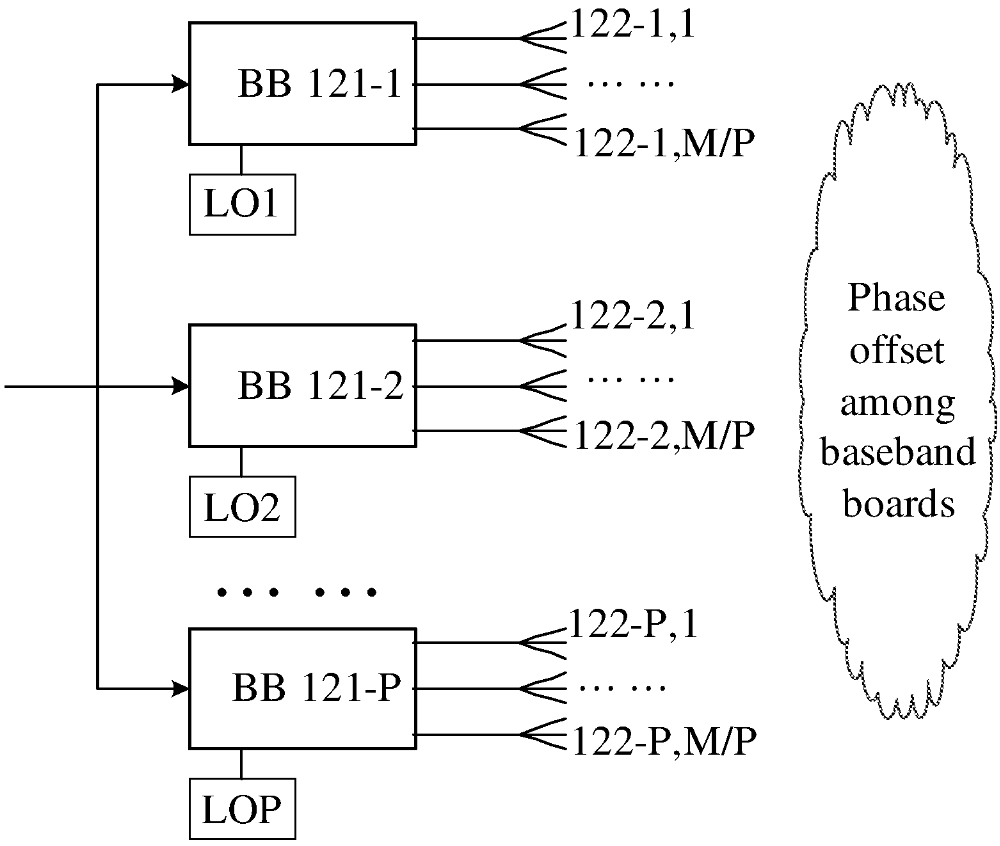
BB 121-1
LO1
122-1,1
…… …
122-1,M/P
BB 121-2
LO2
122-2,1
…… …
122-2,M/P
• • • • • •
BB 121-P
LOP
122-P,1
…… …
122-P,M/P
Phase offset among baseband boards

FIG. 4

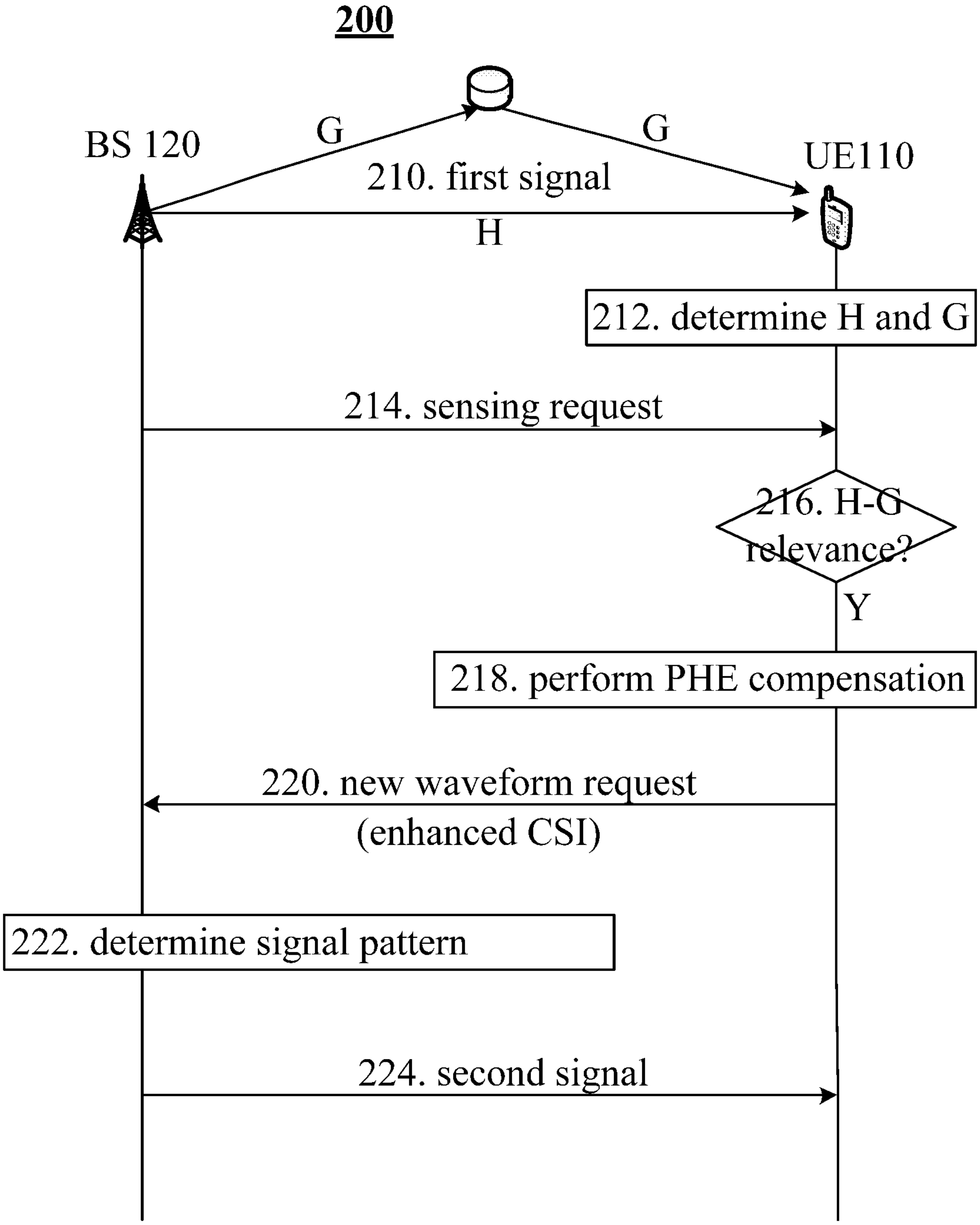
200
G
G
BS 120
UE110
210. first signal
H
212. determine H and G
214. sensing request
216. H-G relevance?
Y
218. perform PHE compensation
220. new waveform request
(enhanced CSI)
222. determine signal pattern
224. second signal

FIG. 5

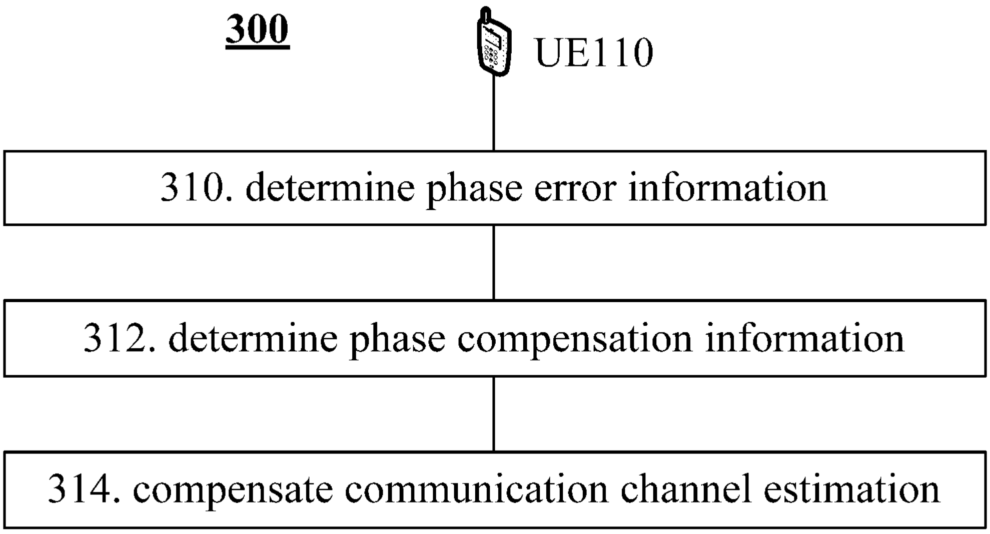
300
UE110
310. determine phase error information
312. determine phase compensation information
314. compensate communication channel estimation

FIG. 6

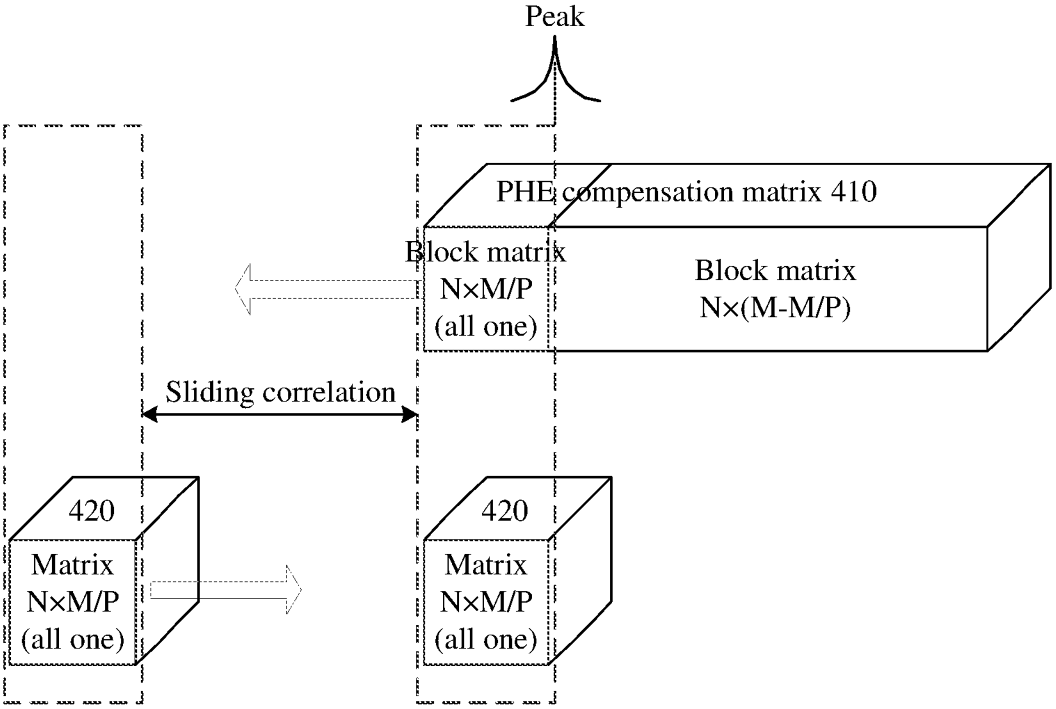
Peak
PHE compensation matrix 410
Block matrix
N×M/P
(all one)
Block matrix
N×(M-M/P)
Sliding correlation
420
Matrix
N×M/P
(all one)
420
Matrix
N×M/P
(all one)

FIG. 7

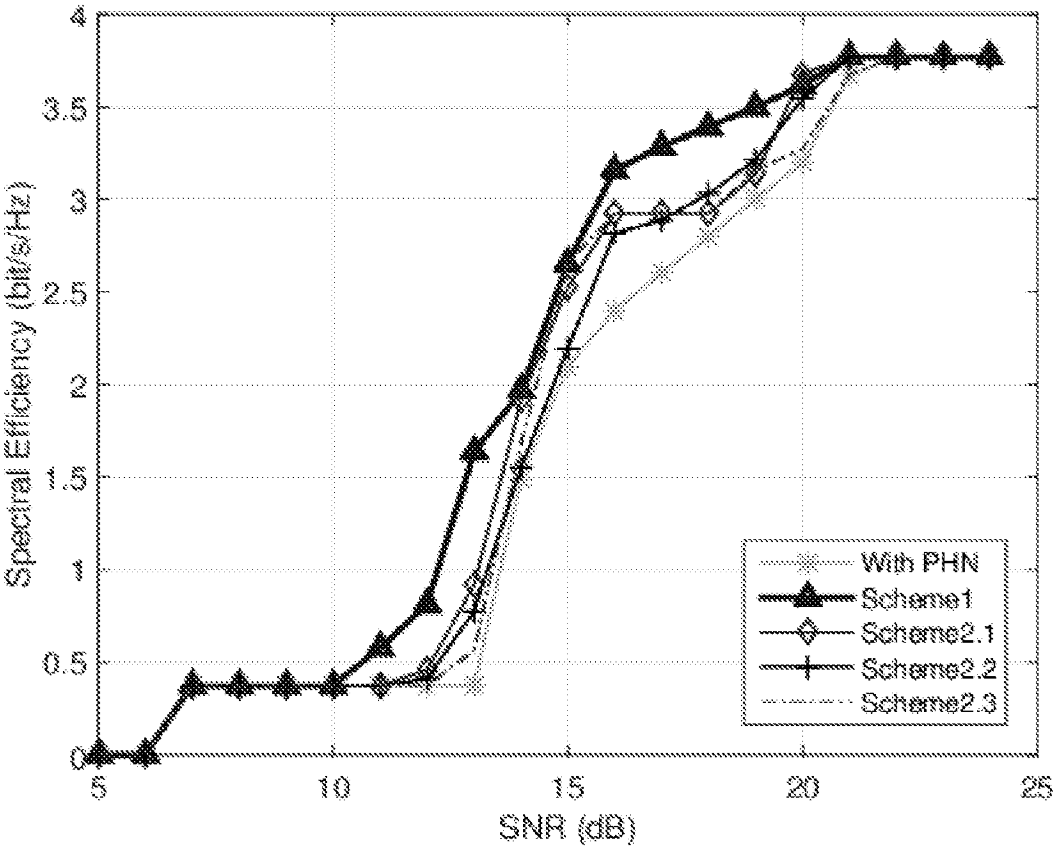
Spectral Efficiency (bit/s/Hz)
SNR (dB)
0
0.5
1
1.5
2
2.5
3
3.5
4
5
10
15
20
25
With PHN
Scheme1
Scheme2.1
Scheme2.2
Scheme2.3

FIG. 8A

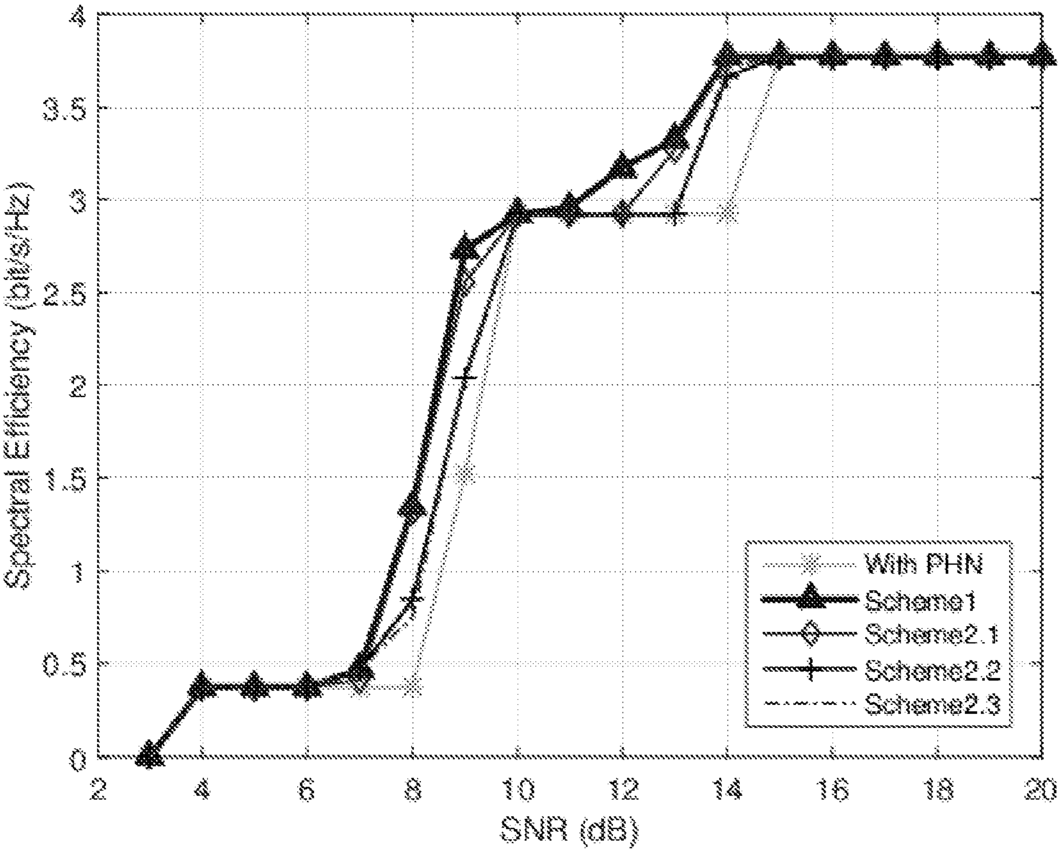
Spectral Efficiency (bit/s/Hz)
0
0.5
1
1.5
2
2.5
3
3.5
4
SNR (dB)
2
4
6
8
10
12
14
16
18
20
With PHN
Scheme1
Scheme2.1
Scheme2.2
Scheme2.3

FIG. 8B

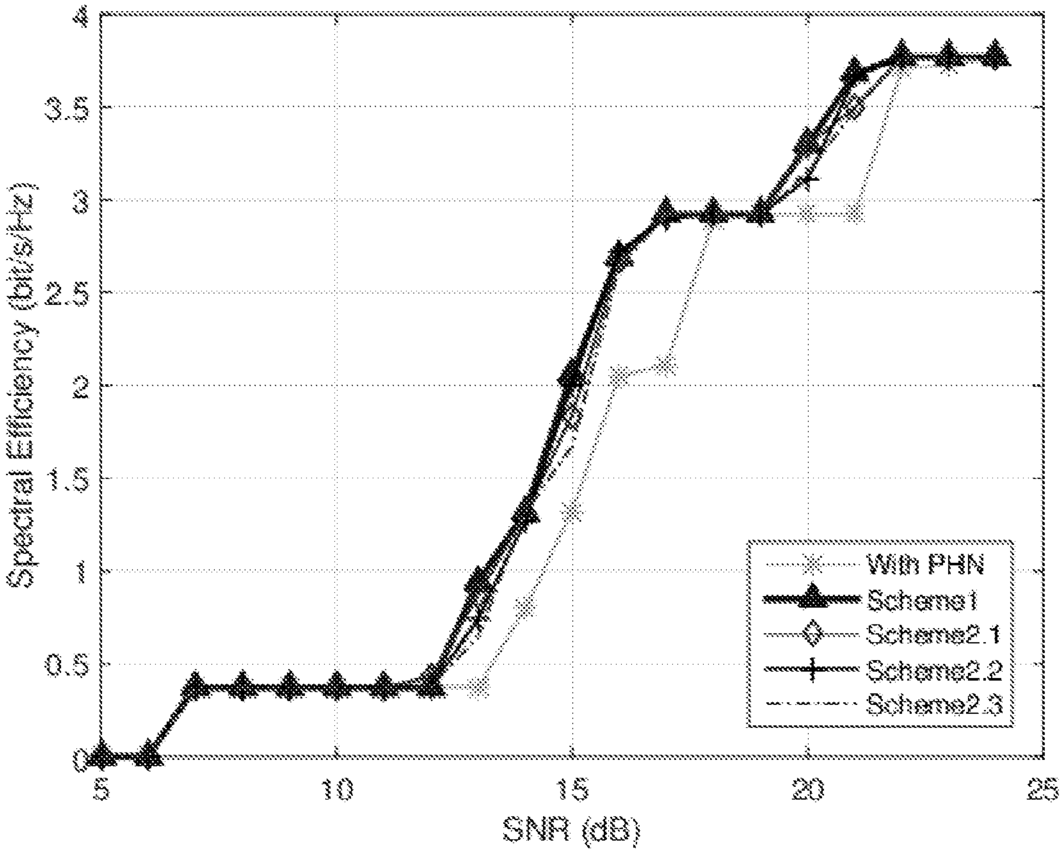
Spectral Efficiency (bit/s/Hz)
0
0.5
1
1.5
2
2.5
3
3.5
4
SNR (dB)
5
10
15
20
25
With PHN
Scheme1
Scheme2.1
Scheme2.2
Scheme2.3

FIG. 8C

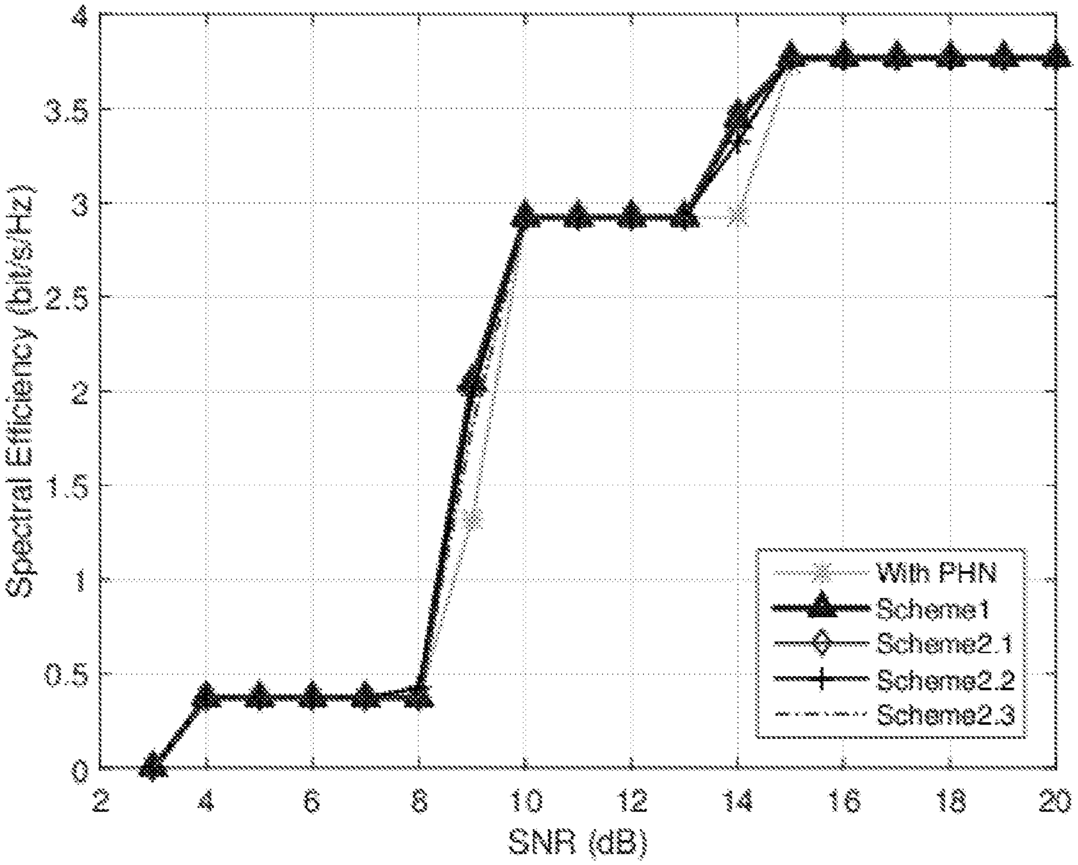
Spectral Efficiency (bits/s/Hz)
SNR (dB)
0
0.5
1
1.5
2
2.5
3
3.5
4
2
4
6
8
10
12
14
16
18
20
With PHN
Scheme1
Scheme2.1
Scheme2.2
Scheme2.3

FIG. 8D

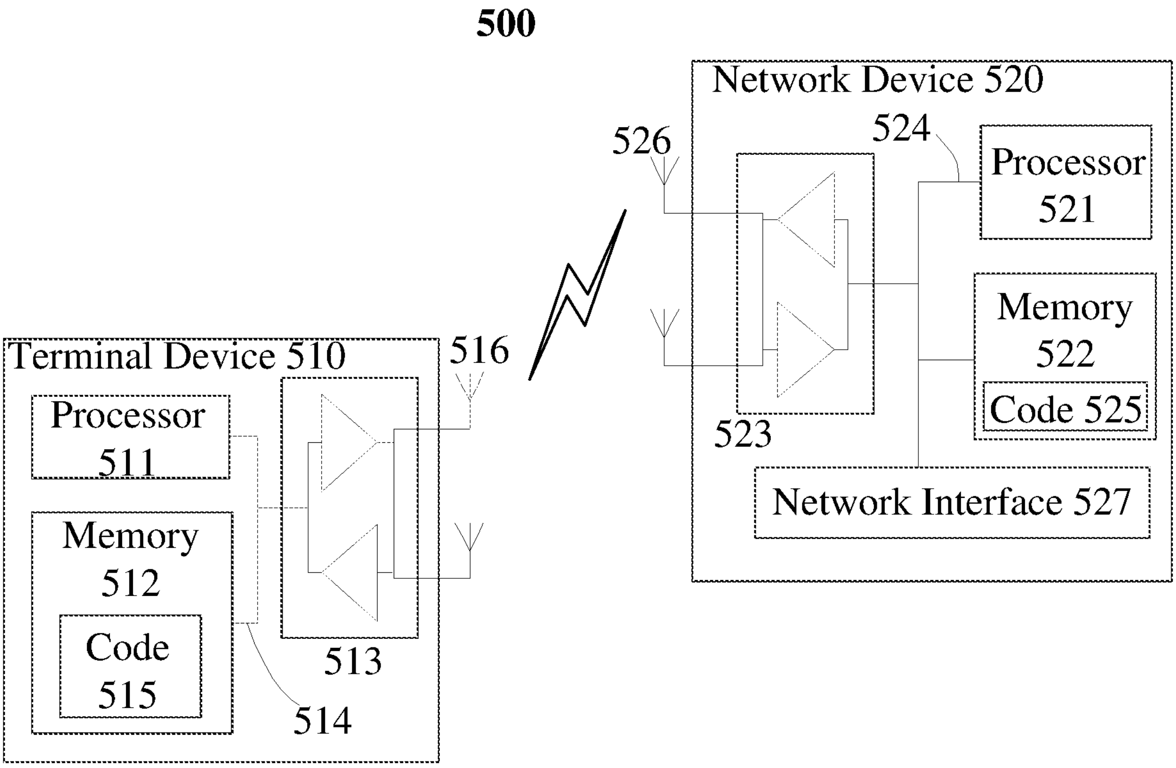
500
Network Device 520
526
524
Processor 521
Memory 522
Code 525
523
Network Interface 527
Terminal Device 510
516
Processor 511
Memory 512
Code 515
513
514

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CN2022/091821

A. CLASSIFICATION OF SUBJECT MATTER

H04B 7/06(2006.01)i

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04B; H04L; H04W

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)

CNPAT,WPI,EPODOC,IEEE,CNKI,3GPP: sensing, propagation path, error, CSI, phase compensation, CPE, PHE, antenna, JCAS, ISAC, mismatch

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2018006700 A1 (TELEFONAKTIEBOLAGET LM ERICSSON PUBL) 04 January 2018 (2018-01-04) description，paragraphs 0017-0300	1-34
A	US 2007098092 A1 (MITRAN，Patrick) 03 May 2007 (2007-05-03) the whole document	1-34
A	CN 113366790 A (APPLE INC.) 07 September 2021 (2021-09-07) the whole document	1-34
A	CN 111801917 A (TELEFONAKTIEBOLAGET LM ERICSSON PUBL) 20 October 2020 (2020-10-20) the whole document	1-34
A	MEDIATEK INC. "Full Tx power UL transmission" *3GPP TSG RAN WG1 #96bis，R1-1904477,* 12 April 2019 (2019-04-12), the whole document	1-34

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"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 **11 November 2022**	Date of mailing of the international search report **29 November 2022**
Name and mailing address of the ISA/CN **National Intellectual Property Administration, PRC** **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing 100088, China** Facsimile No. **(86-10)62019451**	Authorized officer **CHEN,Jing** Telephone No. **86-(10)-53961688**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2022/091821

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US 2018006700 A1	04 January 2018	WO 2016122387 A1	04 August 2016
US 2007098092 A1	03 May 2007	None	
CN 113366790 A	07 September 2021	US 2022094496 A1	24 March 2022
		WO 2020146275 A1	16 July 2020
		JP 2022517936 A	11 March 2022
CN 111801917 A	20 October 2020	WO 2019135103 A1	11 July 2019
		EP 3735766 A1	11 November 2020
		US 2021083816 A1	18 March 2021