



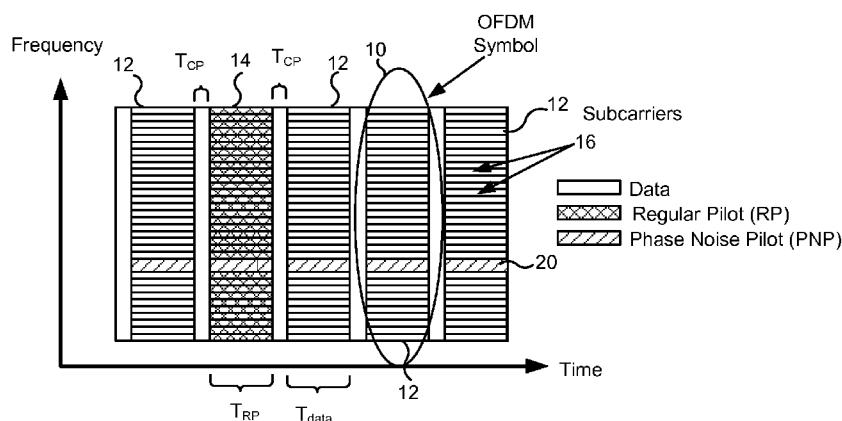
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- (71) **Applicant:** TELEFONAKTIEBOLAGET L M ERICSSON (PUBL) [SE/SE]; Torshamnsgatan 21-23, S-164 83 Stockholm (SE).
- (72) **Inventors:** NING, He; Polhemsvägen 1A, S-191 34 Solentuna (SE). AXNÄS, Johan; Johan Enbergs väg 15, S-171 62 Solna (SE). BALDEMAIR, Robert; Honnörsgatan 16, S-17069 Solna (SE).
- (74) **Agent:** ERICSSON; Patent Development Torshamnsgatan 21-23, S-164 80 Stockholm (SE).
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(54) **Title:** PHASE NOISE ESTIMATION AND COMPENSATION**FIGURE 1**

(57) **Abstract:** Methods of reducing phase noise in a received signal include identifying a pilot component in the received signal and determining an expected pilot component that would have been received in the absence of phase noise. Based on the received pilot component and the expected pilot component, an estimate is generated of the phase noise realization for different parts of an OFDM symbol in the received signal, and based on the estimate of the phase noise realization, the received signal is compensated for the phase noise. Related base stations and user equipment nodes are disclosed.

PHASE NOISE ESTIMATION AND COMPENSATION

TECHNICAL FIELD

[0001] The present disclosure is directed to wireless communication systems, and more particularly, methods, network nodes, user equipment nodes and systems that reduce phase noise in a wireless signal.

BACKGROUND

[0002] Users of mobile broadband communications systems demand increasingly higher data rates. For example, mobile broadband communications systems will be expected to deliver data rates in the range of multiple gigabits per second. One way of increasing data rates is to increase spectral efficiency relative to the existing radio access technologies, for example by applying even higher order modulation, using a larger number of MIMO streams, or both. However, implementing more complex multiplexing schemes may increase the cost of hardware and may also increase energy usage, both of which are undesirable for mobile devices.

[0003] Another way to increase data rates is to simply increase the bandwidth employed by the system. However, many frequency bands are already reserved by law for other types of communications, such as satellite communication, broadcasting, navigation, etc. To find wide frequency bands that are available for use in mobile communications, it may be necessary to consider using frequencies in the millimeter wave bands, i.e. higher than 30 GHz. However, at millimeter wave frequencies, the phase noise contributed by the radio hardware may become an issue, since the oscillator contribution to the phase noise increases quadratically with carrier frequency. To cope with the problem of phase noise, the IEEE 802.11ad standard operating at 60 GHz frequency region with a bandwidth of 2GHz uses a subcarrier spacing of above 5 MHz.

[0004] Orthogonal Frequency Division Multiplexing (OFDM) techniques, which can also include precoded OFDM, such as DFT-spread OFDM or SC-FDMA (Single Carrier Frequency Division Multiple Access), are simple and widely used modulation schemes used in many communications radio access technologies, such as LTE, wifi, DVB etc. OFDM and DFT-spread OFDM are sensitive to phase noise, especially in high frequency bands, which

can cause saturation of the signal to noise ratio (SNR) of the received signal. This limits the data rate that it is possible to achieve. The authors of the paper "A.G. Armada and M. Calvo, *Phase noise and sub-carrier spacing effects on the performance of an OFDM communication system*, IEEE communication letters, vol. 2, No.1 Jan. 1998," provide an analysis of the issue and describe a way to reduce the low frequency part of the phase noise (so called common phase error, or CPE) caused in the reception part. However, reducing CPE may have a limited effect in high frequency systems, since the higher frequency part of phase noise gives a significant performance degradation with systems operating at higher SNR. The IEEE 802.11ad Standard with subcarrier spacing of 5 MHz or above requires a very large overhead in the cyclic prefix and guard period due to the very short OFDM symbol in the time period (the OFDM symbol period is the inverse of the subcarrier spacing). For a system needing a larger cyclic prefix to cover a larger area or/and higher mobility than the systems envisioned by the IEEE 802.11ad standard, the overhead requirements would be even larger.

SUMMARY

[0005] Some embodiments provide methods of reducing phase noise in a received signal. Reducing phase noise can increase the signal to noise ratio of the received signal, which can increase the achievable data rate, especially in systems using OFDM and DFT-spread OFDM.

[0006] Some methods include identifying a pilot component in the received signal and determining an expected pilot component that would have been received in the absence of phase noise. Based on the received pilot component and the expected pilot component, an estimate is generated of the phase noise realization for different parts of an OFDM symbol in the received signal, and based on the estimate of the phase noise realization, the received signal is compensated for the phase noise.

[0007] Phase-noise compensation may be performed sample by sample in the time domain, and phase noise error may be estimated as a per-sample complex angle error. Compensation for phase noise may include de-rotating the time-domain signal.

[0008] The received signal may be received using multiple antenna ports, and the signals received over the multiple antenna ports may be processed separately.

[0009] The received signal may be received using multiple antenna ports, and the phase noise error may be averaged over different multiple antenna ports.

[0010] The pilot component may include a regular OFDM symbol and the data signal may include a DFT-spread OFDM symbol.

[0011] The pilot component may include a DFT-spread OFDM symbol and the data signal may include a regular OFDM symbol. In some embodiments, the pilot component and the data component have the same OFDM type.

[0012] A quantity used to calculate the phase-noise estimate may be smoothened in the time domain before the phase-noise estimate may be calculated. In some embodiments, the quantity used to calculate the phase-noise estimate may include a correlation of actual and expected received pilot signals.

[0013] The phase-noise estimate may be smoothened in the time domain. Further, the phase-noise estimate may be smoothened using a sliding-window averaging. Smoothening the phase-noise estimate using sliding-window averaging may include using sliding-window weights that depend on the value of the quantity being averaged.

[0014] Common Phase Error compensation may be performed before the sample-by-sample compensation. Compensation may be performed for phase noise in the transmitter and/or in the receiver. In particular, compensation may be performed both for phase noise originating from the transmitter and for phase noise originating from the receiver.

[0015] A base station (BS) of a Radio Access Network (RAN) according to some embodiments includes a transceiver configured to provide radio communications with a plurality of wireless terminals, a processor coupled to the transceiver and the network interface, and a memory coupled to the processor.

[0016] The memory includes computer readable program code embodied therein that, when executed by the processor, causes the processor to perform operations including identifying a pilot component in the received signal, determining an expected pilot component that would have been received in the absence of phase noise, based on the received pilot component and the expected pilot component, generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal, and based on the estimate of the phase noise realization, compensating the received signal for the phase noise.

[0017] A user equipment (UE) according to some embodiments includes a transceiver configured to provide radio communications with a base station, a processor coupled to the transceiver and the network interface, and a memory coupled to the processor.

[0018] The memory includes computer readable program code embodied therein that, when executed by the processor, causes the processor to perform operations including identifying a pilot component in the received signal, determining an expected pilot component that would have been received in the absence of phase noise, based on the received pilot component and the expected pilot component, generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal, and based on the estimate of the phase noise realization, compensating the received signal for the phase noise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The accompanying drawings are included to provide a further understanding of the disclosure and are incorporated in and constitute a part of this application. In the drawings:

[0020] Figure 1 illustrates a time and frequency resource map including phase-noise pilots.

[0021] Figure 2 is a block diagram illustrating a communications system in which phase noise reduction according to some embodiments may be implemented.

[0022] Figures 3A and 3B are flowcharts illustrating operations of systems/methods according to some embodiments.

[0023] Figure 4 is a block diagram of a receiver chain including a phase noise compensator in accordance with some embodiments.

[0024] Figure 5 is a graph illustrating simulated results of phase noise reduction in accordance with some embodiments.

[0025] Figure 6 is a block diagram illustrating a Radio Access Network (RAN) in which some embodiments of present inventive concepts may be employed.

[0026] Figure 7 is a flowchart illustrating operations of devices according to some embodiments of the inventive concepts.

[0027] Figures 8 and 9 are block diagrams illustrating elements of a base station BS of Figure 6.

[0028] Figure 10 and 11 are block diagrams illustrating elements of a user equipment UE of Figure 6.

DETAILED DESCRIPTION OF EMBODIMENTS

[0029] Embodiments of the present inventive concepts now will be described more fully hereinafter with reference to the accompanying drawings. The inventive concepts may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the inventive concepts to those skilled in the art. Like numbers refer to like elements throughout.

[0030] It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present inventive concepts. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0031] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes" and/or "including" when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0032] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the

context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0033] Some embodiments estimate phase noise in a received signal (including high frequency phase noise) and compensate for the phase noise before the received signal is processed by the receiver. Because the receiver processes signals having reduced high frequency phase noise, it may be possible to reduce the subcarrier spacing, thereby increasing the OFDM symbol period.

[0034] The disclosure of PCT Application No. PCT/EP2013/056754, filed 28 March 2013, entitled "A Phase Reference Symbol Format For OFDM Phase Synchronization" (the '754 PCT application), which is assigned to the assignee of the present application, is incorporated herein by reference. The '754 PCT application describes a scheme in which a known signal (henceforth referred to as a "phase-noise pilot", or PNP) occupies a small portion of frequency and may be continuously transmitted in the time domain. The scheme described in the '754 PCT application captures the time variation of the phase noise.

[0035] Figure 1 illustrates the use of phase-noise pilots in an OFDM communication system. As shown therein, an OFDM signal is comprised of a series of OFDM symbols 10 that include data symbols 12 interspersed with regular pilot symbols 14. Each of the OFDM symbols includes a plurality of subcarriers 16 that are separated in frequency by a predefined subcarrier spacing. There can, in the general case, also be OFDM symbols containing both data subcarriers and subcarriers with regular pilots (not shown in Figure 1). Although described primarily in the context of OFDM communications, embodiments of the inventive concepts can be applied to various different modulation techniques, such as OFDM based modulation including DFT-spread OFDM, Universal filtered multi-carrier (UFMC) etc., and other multicarrier modulation, such as FBMC (filter band multicarrier).

[0036] The data symbols have a duration of T_{data} , while the regular pilot symbols have a duration of T_{RP} . The OFDM symbols are spaced apart in the time domain by the cyclic prefix T_{CP} . Phase noise pilots (PNP) 20 are inserted at a predefined frequency into one or more OFDM symbols 10, including both the data symbols 12 and the regular pilots 14. It will be appreciated, however, that the PNP 20 can be placed in other sub-carriers and/or may occupy different numbers of sub-carriers than shown in Figure 1. In addition, if an OFDM symbol already contains enough regular pilots, there might not be any need for additional

phase-noise pilots to implement the methods described herein. The PNP is a known signal that can be used by the receiver to measure and quantify distortion in the received signal.

[0037] The pilot component and the data signal may include different types of signals. For example, in some embodiments, the pilot component may be a regular OFDM signal and the data signal may be a DFT-spread OFDM signal. In some embodiments, the pilot component may be a DFT-spread OFDM signal and the data signal may be a regular OFDM signal.

[0038] In other embodiments, the pilot component and the data component may have the same OFDM type.

[0039] Figure 2 illustrates a system that employs a phase noise compensator in accordance with some embodiments. As shown in Figure 2 a transmitting node 30 transmits a signal over a physical channel 32 to a receiving node 34. The physical channel may include a wireless channel, although embodiments described herein are not limited thereto. The receiving node includes a receiver processor 42 and a phase-noise compensator 44 that works together with the receiver processor to process the received signal.

[0040] According to some embodiments, the transmitting node and/or the receiving node may include a radio access network (RAN) base station node or a user equipment node, and the physical channel may be a wireless uplink or downlink physical channel.

[0041] According to some embodiments described herein, a receiver includes a phase noise compensator that estimates and compensates for phase noise, such as phase noise caused by the oscillators in the receiver and/or transmitter. The phase noise compensator can be implemented, for example, using a digital signal processor (DSP), such as the TMS320C5000™ Ultra-Low-Power DSP manufactured by Texas Instruments Incorporated, and/or any signal processing hardware and/or software. Phase noise that originates in both the transmitter side and the receiver side can be compensated according to some embodiments.

[0042] According to some embodiments, the time-domain received signal component associated with the PNP 20 is isolated and compared with what would have been the expected received signal had there been no phase noise. These embodiments perform compensation of the data component of the received signal on a sample by sample basis based on the results of that comparison. That is, phase noise compensation is

performed with different amounts of compensation for different time samples (as opposed to just CPE compensation, which is the same amount for all time samples).

[0043] More precisely, for each time-domain sample in an OFDM symbol, the actual PNP signal component (isolated, e.g., by filtering in the frequency domain) is compared with the PNP signal component that would have been expected in the absence of any phase noise. The phase difference between the two signals is calculated and taken as an estimate of the (actual) phase-noise realization for the respective sample. The sample of the received signal is then compensated for phase noise by phase-shifting the sample in the opposite direction by the amount of estimated phase noise, before normal receiver processing, which may not otherwise include phase-noise compensation. In some embodiments, the phase-noise estimate may be smoothened before being used to adjust the received signal. For example, the phase-noise estimate may be filtered using a sliding window in the time domain.

[0044] Some embodiments may be explained with reference to a single input, single output (SISO) channel that is subject to flat fading and additive white Gaussian noise (AWGN). A SISO channel includes a single transmit antenna and a single receive antenna. However, it will be appreciated that embodiments described herein may be advantageously applied to other types of channels, including MIMO channels, and channels subject to other types of fading and/or noise.

[0045] In the context of a SISO channel, the received signal, after analog-to-digital conversion (ADC), may be expressed as:

$$y(i) = \exp(j\varphi(i)) \cdot h(i) \cdot x(i) + w(i) \quad [1]$$

where i is a time-sample index, $\varphi(i)$ is the (actual) phase noise realization at time instance i , $h(i)$ is the physical channel at time i , $x(i)$ is the transmitted signal, $w(i)$ is the thermal noise realization, and j is the imaginary unit.

[0046] According to some embodiments, phase-noise compensation may be performed as follows. First the received time-domain signal $y(i)$ is converted to a frequency-domain signal $Y(k)$:

$$Y(k) = \text{DFT}(y(i)) \quad [2]$$

where DFT denotes the discrete Fourier transform of its argument function (implemented, e.g., as a fast Fourier transform). Then, the data part of the signal is removed by setting frequency domain samples other than the pilot samples to zero, as follows:

$$Y^{\text{pilot}}(k) = \begin{cases} Y(k) & k \in P_{\text{pilot}} \\ 0 & \text{otherwise} \end{cases} \quad [3]$$

where P_{pilot} is the set of all phase-noise pilot subcarriers. The notation “pilot” in Equation [3] typically refers only to PNP subcarriers, but may also include regular pilot symbols if present. To capture the phase noise sufficiently, the phase-noise pilot subcarriers may preferably span a bandwidth that is comparable to the phase noise bandwidth, or more. The signal component $Y^{\text{pilot}}(k)$ is then converted back to the time domain as follows:

$$y^{\text{pilot}}(i) = \text{IDFT}(Y^{\text{pilot}}(k)) \quad [4]$$

where IDFT denotes the inverse discrete Fourier transform. The signal that would have been expected if there were no phase noise is calculated as:

$$z^{\text{pilot}}(i) = \hat{h}(i) \cdot x^{\text{pilot}}(i) \quad [5]$$

where $\hat{h}(i)$ is the estimated channel (possibly including CPE contribution to the effective channel), for which good enough accuracy is assumed, and $x^{\text{pilot}}(i)$ is the *a priori* known pilot component of the transmitted signal. The known pilot component may be obtained, for example, by applying an IDFT to only the pilot subcarriers of the frequency-domain representation of the transmitted signal. Alternatively, the known pilot component $x^{\text{pilot}}(i)$ may be stored in a lookup table in the receiver.

[0047] Then, the phase angle difference between $y^{\text{pilot}}(i)$ and $z^{\text{pilot}}(i)$ can be obtained as a per-sample complex angle error as follows:

$$\alpha(i) = \arg\left(\frac{y^{\text{pilot}}(i)}{z^{\text{pilot}}(i)}\right) \quad [6]$$

where $\arg()$ denotes the complex angle (the imaginary component of the logarithm). After an optional smoothening step, e.g. using a sliding window over $\alpha(i)$, a smoothened ratio $\overline{\alpha(l)}$ is obtained. If no smoothening is used, $\overline{\alpha(l)}$ may be set equal to $\alpha(i)$. Ideally, $\overline{\alpha(l)}$ may be a good estimate of the actual phase noise realization. Finally, the phase noise in the received signal $y(i)$ is compensated for as

$$y^{\text{compensated}}(i) = \exp(-j\overline{\alpha(i)}) \cdot y(i) \quad [7]$$

[0048] Normal receive processing (equalization, demodulation, decoding, etc) is then performed on $y^{\text{compensated}}(i)$, in the same way as would be performed directly on $y(i)$ in a receiver without phase-noise compensation.

[0049] Alternative Embodiments

[0050] In some embodiments, a power boosting of pilots may be taken into account in the phase noise compensation process. Since detection of pilots is important for good reception and at least indirectly affects all subsequent processing in the receiver, it is not uncommon for radio communication systems to have some means for the receiver to transmit (regular) pilots with a higher power than other resources (such as data or control signaling), thereby facilitating accurate detection. In such systems, an optimal receiver algorithm may be aware of and take into consideration the power difference between pilots and other resources.

[0051] In other embodiments, the phase-angle difference may be formed as follows:

$$\alpha(i) = \arg(y^{\text{pilot}}(i)) - \arg(z^{\text{pilot}}(i)) \quad [8]$$

in which case, however, care needs to be taken to use the appropriate branch of the $\arg$ function.

[0052] In still other embodiments, if the received signal is noisy, it may be useful to remove outliers by placing ceiling ($\alpha_{\max}$) and floor ($\alpha_{\min}$) limits on the raw phase angle differences as follows:

$$\alpha(i) = \begin{cases} \alpha_{\min} & \alpha_{\text{raw}} < \alpha_{\min} \\ \alpha_{\text{raw}} & \alpha_{\min} < \alpha_{\text{raw}} < \alpha_{\max} \\ \alpha_{\max} & \alpha_{\text{raw}} > \alpha_{\max} \end{cases} \quad [9]$$

where

$$\alpha_{\text{raw}}(i) = \arg\left(\frac{y^{\text{pilot}}(i)}{z^{\text{pilot}}(i)}\right) \quad [10]$$

[0053] In further embodiments, the received pilot signal $y^{\text{pilot}}(i)$ may be correlated with the expected pilot signal $z^{\text{pilot}}(i)$, and the phase difference may be taken as the argument of the correlation, as follows:

$$\arg\left(y^{\text{pilot}}(i)(z^{\text{pilot}}(i))^*\right) \quad [11]$$

where * denotes the complex conjugate. An advantage of this method is that more unreliable (weaker) signal components are reduced in weighting. More generally, a weighting function $f_{\text{weight}}(i, \alpha_{\text{raw}}(i))$ may be used in the averaging, e.g.,

$$\frac{\sum_i f_{\text{weight}}(i, \alpha_{\text{raw}}(i)) \cdot \alpha_{\text{raw}}(i)}{\sum_i f_{\text{weight}}(i, \alpha_{\text{raw}}(i))} \quad [12]$$

[0054] The weighting function may be chosen so as to de-emphasize samples with low reliability, e.g. weak samples. Weighting can also be obtained before applying the arg() function, i.e., e.g.,

$$\arg\left(\frac{\sum_i f_{\text{weight}}(i, r_{\text{raw}}(i)) \cdot r_{\text{raw}}(i)}{\sum_i f_{\text{weight}}(i, r_{\text{raw}}(i))}\right) \quad [13]$$

where, e.g.,

$$r_{\text{raw}}(i) = \frac{y^{\text{pilot}}(i)}{z^{\text{pilot}}(i)} \quad [14]$$

or

$$r_{\text{raw}}(i) = y^{\text{pilot}}(i) \left(z^{\text{pilot}}(i) \right)^* \quad [15]$$

[0055] In the latter case, multiplication by $z^{\text{pilot}}(i)$ may already achieve the weighting; in this case, a constant weighting function $f_{\text{weight}}\left(i, r_{\text{raw}}(i)\right) = \text{const}$ could be used.

[0056] MIMO over Flat Fading Channel

[0057] In the case of multiple receive antennas, the processing described above to obtain $y^{\text{compensated}}(i)$ may simply be performed separately for each receive antenna. If it is known that the phase noise is highly correlated between all (or a subset) of the receive antennas, an average may be taken across antennas of the estimated phase error $\alpha(i)$ or $\overline{\alpha(i)}$, for example:

$$\overline{\alpha}_n^{\text{antenna-average}}(i) = \frac{1}{N} \sum_{n=1}^N \overline{\alpha}_n(i) \quad [16]$$

and then the average phase noise estimate $\overline{\alpha}_n^{\text{antenna-average}}(i)$ may be used instead of $\overline{\alpha}(i)$ (or $\alpha(i)$) in subsequent processing.

[0058] In the case of multiple transmit antennas, the case of highly correlated phase noise on different transmit antennas is most easily handled. In that case, processing similar to the case of single transmit antenna may be performed. If the phase noise on different antennas is not fully correlated, it may be preferable to make phase noise pilots transmitted over the different transmit antennas orthogonal to each other, either via orthogonal code/time/frequency resources.

[0059] Non-Flat Fading Channel

[0060] If the channel is not flat fading, i.e. if there is substantial variation in the channel as a function of frequency across the bandwidth, there are in general three cases to

consider: (i) the receiver-side phase noise dominates and (ii) the transmitter phase noise dominates, (iii) the receiver-side and the transmitter-side phase noise is of comparable magnitude. In case (i), the processing techniques described above may be applied directly. In case (ii), it may be desirable to perform equalization of the received signal, e.g. as:

$$\mathbf{Y}^{\text{equalized}}(k) = \mathbf{H}^H(k) \left(\mathbf{H}(k) \mathbf{H}^H(k) + \mathbf{Q}(k) \right)^{-1} \mathbf{Y}(k) \quad [17]$$

where $\mathbf{Y}(k)$ is a vector representing the multi-antenna signal at subcarrier k , $\mathbf{H}(k)$ is the frequency-domain representation of the physical channel (possibly including also transmitter and/or receiver precoder and/or a CPE contribution), and $\mathbf{Q}(k)$ is the noise covariance matrix.

[0061] In case (iii), if time dispersion is not very large, either the method for case (i) or the method for case (ii) may be used. If time dispersion is large, the problem becomes more challenging, but may still be effective.

[0062] Operations 100 according to some embodiments are illustrated in Figure 3A. As shown in Figure 3A, a discrete Fourier transform is performed on the time-domain received signals $y(i)$ to convert the time domain signal into a frequency domain signal $Y(k)$ (block 104). Non-pilot subcarriers in the frequency domain signal $Y(k)$ are then set to zero (block 106).

[0063] An IDFT operation is then performed on the frequency domain pilot signal $Y^{\text{pilot}}(k)$ to obtain a time domain representation $y^{\text{pilot}}(i)$ of the pilot signal (block 110).

[0064] An expected signal $z^{\text{pilot}}(i)$ is then obtained, for example, by applying the channel estimates $\hat{h}(i)$ to the *a priori* known pilot signal $x^{\text{pilot}}(i)$ (block 112). A phase difference $\alpha(i)$ between the received pilot signal $y^{\text{pilot}}(i)$ and the expected pilot signal $z^{\text{pilot}}(i)$ is then determined (block 114).

[0065] The received signal estimates $Y(k)$ are then de-rotated by, for example, shifting the phase of the received signal estimates by an amount opposite to the phase difference estimates $\bar{\alpha}(i)$ to obtain phase-adjusted samples $y^{\text{compensated}}(i)$ (block 120). The phase-adjusted samples $y^{\text{compensated}}(i)$ are then processed according to normal receiver operations (block 122).

[0066] Operations 100' according to further embodiments are illustrated in Figure 3A. In Figure 3B, the operations shown in solid lines are similar to those described above with respect to Figure 3A and a description thereof will not be repeated for brevity. d Optional operations are illustrated in broken lines. However even some operations shown solid lines may be omitted depending on the particular embodiment and/or radio access technology being employed.

[0067] As shown in Figure 3B, the operations 100 may include performing common phase error (CPE) reduction on received signal samples (block 102) before performing a DFT operation on the received signal samples in block 104.

[0068] Furthermore, the signal may optionally be equalized (before or after zeroing out the non-pilot subcarriers) to compensate for channel distortion (block 108) before performing an IDFT operation on the samples in block 110.

[0069] In some embodiments, the phase difference obtained in block 114 may be smoothed, for example, using a moving average filter, a Kalman filter, a weighted average filter, etc., to obtain average phase difference estimates (block 116). Furthermore, in some embodiments, the phase difference may be averaged over a plurality of receive antennas (block 118) before using the phase difference to derotate the received signal in block 120.

[0070] Figure 4 illustrates a simplified OFDM receiver architecture 200 including a phase noise compensator according to some embodiments. The receiver 200 includes an antenna 202 that receives an OFDM signal. The signal is amplified in a low noise amplifier 204 and then mixed in a quadrature mixer 206 that is fed by a local oscillator LO. The resulting complex signal is filtered with a low pass filter 208 and then sampled and converted to digital by an analog to digital converter 210.

[0071] The digital samples are then processed by a phase noise compensator 44 using the techniques described above to obtain phase-adjusted samples.

[0072] The phase-adjusted samples are then processed by a fast Fourier transform processor (FFT) 212, a demodulator 214 and a decoder 216 to recover the original transmitted sequence. It will be appreciated that the phase noise compensator block 44 may internally also include an FFT, demodulator, decoder etc., for example, if data-assisted iterative phase noise compensation is used. Moreover, either hard decision feedback or soft decision feedback may be used.

[0073] Simulation results obtained using systems/methods described herein are illustrated in Figure 5 for an AWGN channel having a 2 GHz bandwidth and employing 5120 OFDM subcarriers. The results (full PN comp.) using various numbers of pilot subcarriers are compared in Figure 5 with performance with a more simple CPE based phase noise compensation approach (ideal CPE comp.). As a reference, performance in the absence of any phase noise disturbance is also shown (in which case a traditional receiver without phase-noise compensation is used). The results shown in Figure 5 were obtained using smoothing of phase noise estimate over 100 samples using a sliding window.

[0074] As can be seen in Figure 5, there is a pronounced error floor if only CPE compensation is used. However, by employing the techniques described herein (referred to in Figure 4 as “full PN comp.”), as little as 128 PNP subcarriers (about 2.5% pilot overhead) is enough to essentially remove the error floor. FOM in the plot of Figure 4 stands for Figure of Merit and is used to describe the local oscillator.

[0075] As can be seen in Figure 5, a simple non-adaptive algorithm for phase noise compensation may degrade performance at low SNR values. Thus, in some embodiments, the phase-noise compensation algorithm may be adaptively modified or completely disabled if it is detected that the signal-to-noise ratio (SNR) is below a certain level. For example, in some embodiments, the phase-noise compensation algorithm may be adaptively modified or disabled if the SNR is 5 dB or lower, and in some embodiments 10 dB or lower.

[0076] In further embodiments, the transmitter may avoid transmitting PN pilots if the receiver reports a low SNR or otherwise indicates that PN pilots are not needed. That is, if the receiver is not benefitting from phase noise compensation, then the subcarriers that would otherwise be used for PNP pilots may be used to carry data instead.

[0077] Figure 6 is a block diagram illustrating a Radio Access Network (RAN) in which some embodiments of present inventive concepts may be employed. As shown, communications between a plurality of base stations BS-A, BS-B, and BS-C may be provided using respective X2 Interfaces, and communications between base stations and one or more core nodes MME/S-GW may be provided using respective S1 interfaces. Each base station BS may communicate over a radio interface (including uplinks and downlinks) with respective wireless terminals UEs in a respective cell or cells supported by the base station. By way of example, base station BS-A is shown in communication with wireless terminals

UE-1 and UE-2, base station BS-B is shown in communication with wireless terminals UE-3 and UE-4, and base station BS-C is shown in communication with wireless terminals UE-5 and UE-6. In embodiments supporting distributed schemes/architectures, each of base stations BS-A, BS-B, and BS-C may be respective peer nodes with respect to distributed scheduling disclosed herein. In embodiments supporting centralized schemes/architectures, one of the base stations (e.g., base station BS-B may serve as a central coordinator node with respect to centralized scheduling disclosed herein.

[0078] It will be appreciated, however, that embodiments of the inventive concepts are not limited to the arrangement shown in Figure 6.

[0079] Figure 7 illustrates operations that may be performed by a network node, such as a base station or a user equipment, in accordance with some embodiments. As shown therein, the operations include identifying a pilot component in the received signal (block 1600), and determining an expected pilot component that would have been received in the absence of phase noise (block 1602).

[0080] An estimate of the phase noise realization for different parts of an OFDM symbol in the received signal is generated based on the received pilot component and the expected pilot component (block 1604), and the received signal is compensated for phase noise based on the estimate of the phase noise realization (block 1606).

[0081] Figure 8 is a block diagram illustrating elements of a base station (BS) 1400 of Figure 6. As shown, a base station 1400 may include a transceiver 1401 configured to provide radio communications with a plurality of wireless terminals, a network interface 1405 configured to provide communications with other base stations of the RAN, and a processor 1403 coupled to the transceiver and the network interface, and a memory (1407) coupled to the processor. The memory 1407 may include computer readable program code that when executed by the processor 1403 causes the processor to perform operations according to embodiments disclosed herein. According to other embodiments, processor 1403 may be defined to include memory so that a memory is not separately provided.

[0082] Figure 9 is a block diagram of a base station 1400 illustrating various functional modules of the base station 1400. As shown therein, the base station 1400 includes a pilot identification module 1420, an expected pilot determining module 1430, a phase noise estimation module 1440 and a signal compensation module 1450. The pilot identification module 1420 identifies a pilot component in a received signal. The expected

pilot determining module 1430 determines an expected pilot component that would have been received in the absence of phase noise. The phase noise estimation module 1440 generates an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component, and the signal compensation module 1450 compensates the received signal for the phase noise based on the estimate of the phase noise realization.

[0083] Figure 10 is a block diagram illustrating elements of a user equipment (UE) 1500 of Figure 6. As shown, a user equipment 1500 may include a transceiver 1501 configured to provide radio communications with a base station, a user interface 1505 configured to enable a user to interact with the UE 1500, a processor 1503 coupled to the transceiver and the user interface, and a memory (1507) coupled to the processor. The memory 1507 may include computer readable program code that when executed by the processor 1503 causes the processor to perform operations according to embodiments disclosed herein. According to other embodiments, processor 1503 may be defined to include memory so that a memory is not separately provided.

[0084] Figure 11 is a block diagram of a UE 1500 illustrating various functional modules of the UE 1500. As shown therein, the UE 1500 includes a pilot identification module 1520, an expected pilot determining module 1530, a phase noise estimation module 1540 and a signal compensation module 1550. The pilot identification module 1520 identifies a pilot component in a received signal. The expected pilot determining module 1530 determines an expected pilot component that would have been received in the absence of phase noise. The phase noise estimation module 1540 generates an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component, and the signal compensation module 1550 compensates the received signal for the phase noise based on the estimate of the phase noise realization.

[0085] ABBREVIATIONS

[0086] Explain all abbreviations and acronyms used in the document.

[0087] Abbreviation Explanation

[0088] ADC Analog-to-digital converter

[0089]	PNP	Phase-noise pilots
[0090]	CPE	Common phase error
[0091]	FOM	Figure of merit
[0092]	QAM	Quadrature amplitude modulation
[0093]	SNR	Signal-to-noise ratio
[0094]	BER	Bit-error rate
[0095]	PN	Phase noise
[0096]	DFT	Discrete Fourier transform
[0097]	IDFT	Inverse discrete Fourier transform
[0098]	arg	Argument (angle of complex number)
[0099]	MIMO	Multiple-input multiple-output
[00100]	SISO	Single-input single-output
[00101]	AWGN	Additive white Gaussian noise
[00102]	OFDM	Orthogonal Frequency Division Multiplexing
[00103]	CPE	Common Phase Error
[00104]	LTE	Long Term Evolution
[00105]	DVB	Digital Video Broadcasting
[00106]	FOM	Figure of Merit
[00107]	DSP	Digital Signal Processor
[00108]	As will be appreciated by one of skill in the art, the present inventive	

concepts may be embodied as a method, data processing system, and/or computer program product. Furthermore, the present inventive concepts may take the form of a computer program product on a tangible computer usable storage medium having computer program code embodied in the medium that can be executed by a computer. Any suitable tangible computer readable medium may be utilized including hard disks, CD ROMs, optical storage devices, or magnetic storage devices.

[00109] Some embodiments are described herein with reference to flowchart illustrations and/or block diagrams of methods, systems and computer program products. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions 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 flowchart and/or block diagram block or blocks.

[00110] These computer program instructions may also be stored in a computer readable memory that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer readable memory produce an article of manufacture including instruction means which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[00111] The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide steps for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[00112] The functions/acts noted in the blocks may occur out of the order noted in the operational illustrations. 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/acts involved. Although some of the diagrams include arrows on communication paths to show a primary direction of communication, it is to be understood that communication may occur in the opposite direction to the depicted arrows.

[00113] Many different embodiments have been disclosed herein, in connection with the above description and the drawings. It will be understood that it would be unduly repetitious and obfuscating to literally describe and illustrate every combination and subcombination of these embodiments. Accordingly, all embodiments can be combined in any way and/or combination, and the present specification, including the drawings, shall be construed to constitute a complete written description of all combinations and subcombinations of the embodiments described herein, and of the manner and process of making and using them, and shall support claims to any such combination or subcombination.

[00114] In the drawings and specification, there have been disclosed typical embodiments and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the inventive concepts being set forth in the following claims.

What is claimed is:

1. A method of reducing phase noise in a received signal, comprising:

identifying (1600) a pilot component in the received signal,

determining (1602) an expected pilot component that would have been received in the absence of phase noise,

based on the received pilot component and the expected pilot component, generating (1604) an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal, and

based on the estimate of the phase noise realization, compensating (1606) the received signal for the phase noise. The phase-noise-compensated signal may then be processed using conventional receiver processing techniques, such as demodulation, decoding, etc.
2. The method of Claim 1, wherein phase-noise compensation is performed sample by sample in the time domain.
3. The method of any preceding Claim, wherein phase noise error is estimated as a per-sample complex angle error.
4. The method of any preceding Claim, wherein compensation for phase noise comprises de-rotating the time-domain signal.
5. The method of any preceding Claim, wherein the received signal is received using multiple antenna ports, and the signals received over the multiple antenna ports are processed separately.
6. The method of any of Claims 1-4, wherein the received signal is received using multiple antenna ports, and wherein the phase noise error is averaged over different multiple antenna ports.

7. The method of any preceding Claim, wherein the pilot component comprises a regular OFDM symbol and the data signal comprises a DFT-spread OFDM symbol.
8. The method of any preceding Claim, wherein the pilot component comprises a DFT-spread OFDM symbol and the data signal comprises a regular OFDM symbol.
9. The method of any of Claims 1-6, wherein the pilot component and the data component have the same OFDM type.
10. The method of any preceding Claim, wherein a quantity used to calculate the phase-noise estimate is smoothened in the time domain before the phase-noise estimate is calculated.
11. The method of Claim 10, wherein the quantity used to calculate the phase-noise estimate comprises a correlation of actual and expected received pilot signals.
12. The method of any preceding Claim, wherein the phase-noise estimate is smoothened in the time domain.
13. The method of any preceding Claim, wherein the phase-noise estimate is smoothened using a sliding-window averaging.
14. The method of Claim 13, wherein smoothening the phase-noise estimate using sliding-window averaging comprises using sliding-window weights that depend on the value of the quantity being averaged.
15. The method of any preceding Claim, wherein Common Phase Error compensation is performed before the sample-by-sample compensation.
16. The method of any preceding Claim, wherein compensation is performed for phase noise in the transmitter.
17. The method of any preceding Claim, wherein compensation is performed for phase noise in the receiver.

18. The method of any preceding Claim, wherein compensation is performed both for phase noise originating from the transmitter and for phase noise originating from the receiver.

19. A base station, BS, of a Radio Access Network, RAN, the base station comprising:

a transceiver (1401) configured to provide radio communications with a plurality of wireless terminals;

a processor (1403) coupled to the transceiver and the network interface; and

a memory (1407) coupled to the processor, the memory comprising computer readable program code embodied therein that, when executed by the processor, causes the processor to perform operations comprising:

identifying a pilot component in the received signal,

determining an expected pilot component that would have been received in the absence of phase noise,

based on the received pilot component and the expected pilot component, generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal, and

based on the estimate of the phase noise realization, compensating the received signal for the phase noise.

20. A user equipment, UE, comprising:

a transceiver (1501) configured to provide radio communications with a plurality of wireless terminals;

a processor (1503) coupled to the transceiver; and

a memory (1507) coupled to the processor, the memory comprising computer readable program code embodied therein that, when executed by the processor, causes the processor to perform operations comprising:

identifying a pilot component in the received signal,

determining an expected pilot component that would have been received in the absence of phase noise,

based on the received pilot component and the expected pilot component, generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal, and

based on the estimate of the phase noise realization, compensating the received signal for the phase noise.

21. A base station, BS, of a Radio Access Network, RAN, the base station comprising:

a pilot identification module (1420) for identifying a pilot component in the received signal,

an expected pilot determining module (1430) for determining an expected pilot component that would have been received in the absence of phase noise,

a phase noise estimation module (1440) for generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component, and

a signal compensation module (1450) for compensating the received signal for the phase noise based on the estimate of the phase noise realization.

22. A user equipment, UE, comprising:

a pilot identification module (1520) for identifying a pilot component in the received signal,

an expected pilot determining module (1530) for determining an expected pilot component that would have been received in the absence of phase noise,

a phase noise estimation module (1540) for generating an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component, and

a signal compensation module (1550) for compensating the received signal for the phase noise based on the estimate of the phase noise realization.

23. A base station of a Radio Access Network, RAN, wherein the base station is adapted to:

identify a pilot component in the received signal (1600),

determine an expected pilot component that would have been received in the absence of phase noise (1602),

generate an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component (1604), and

compensate the received signal for the phase noise based on the estimate of the phase noise realization (1606).

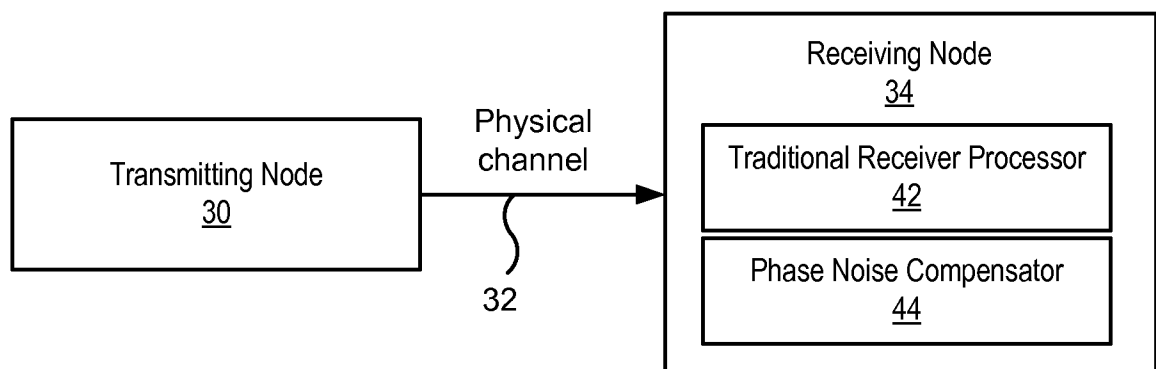
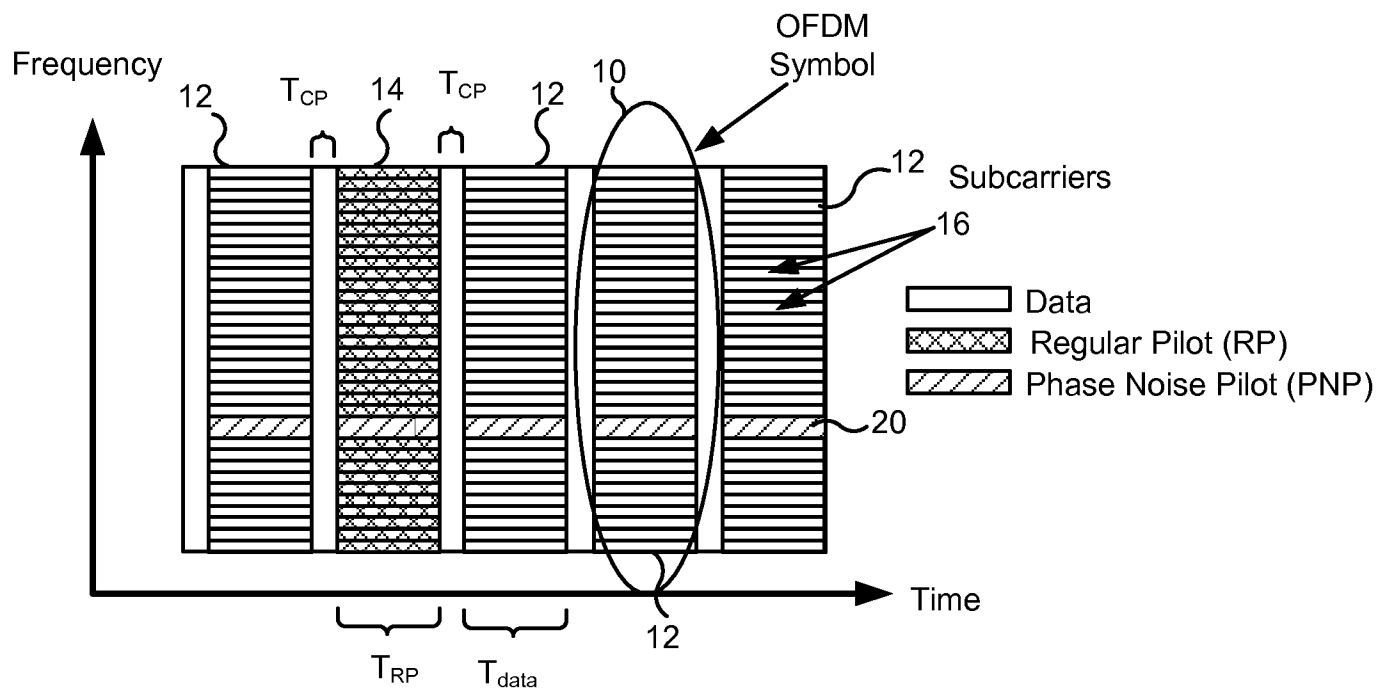
24. A user equipment, wherein the user equipment is adapted to:

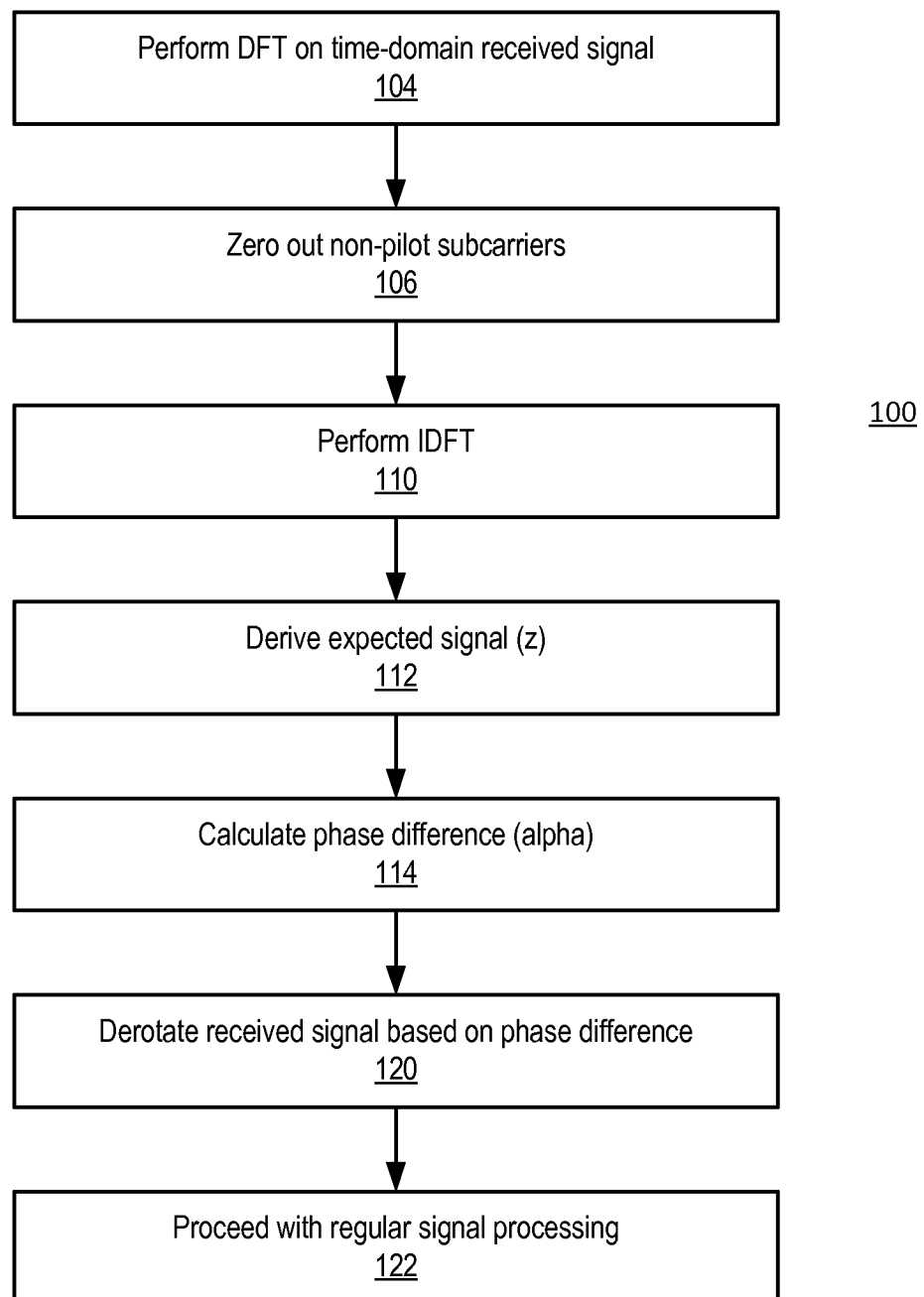
identify a pilot component in the received signal (1600),

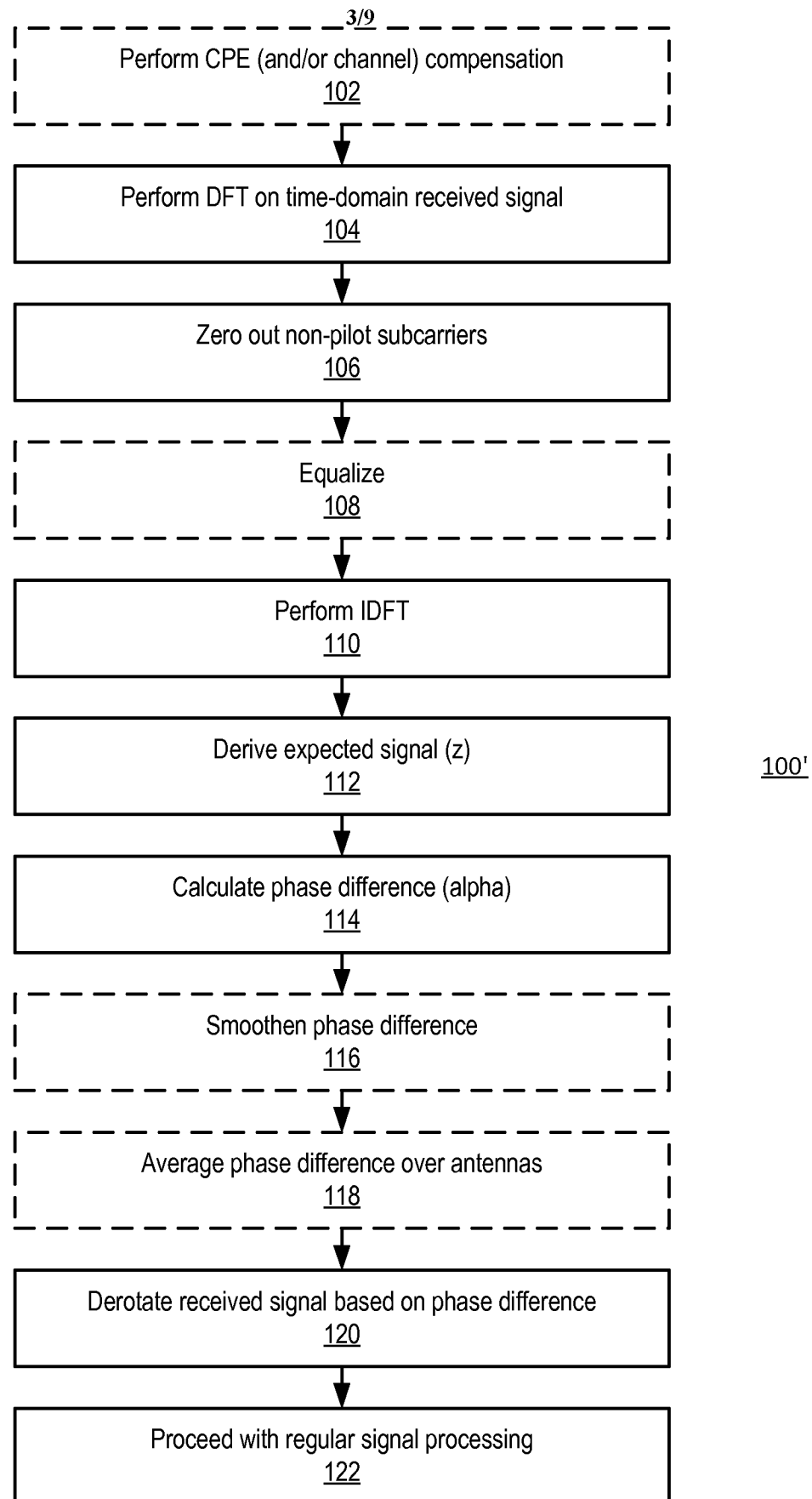
determine an expected pilot component that would have been received in the absence of phase noise (1602),

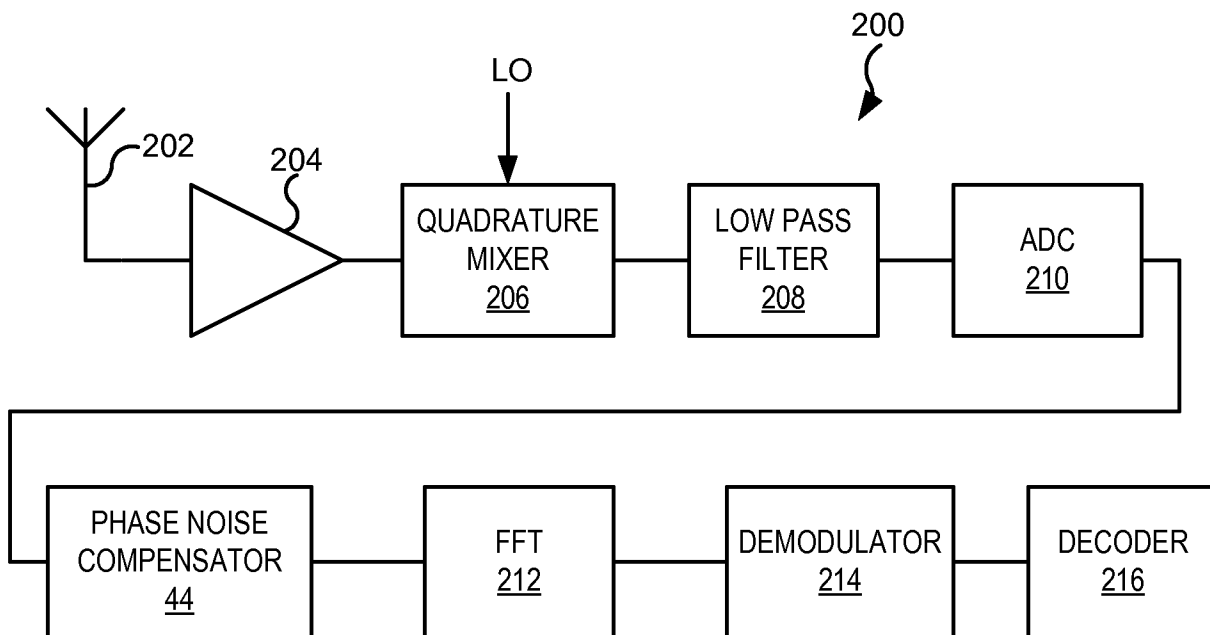
generate an estimate of the phase noise realization for different parts of an OFDM symbol in the received signal based on the received pilot component and the expected pilot component (1604), and

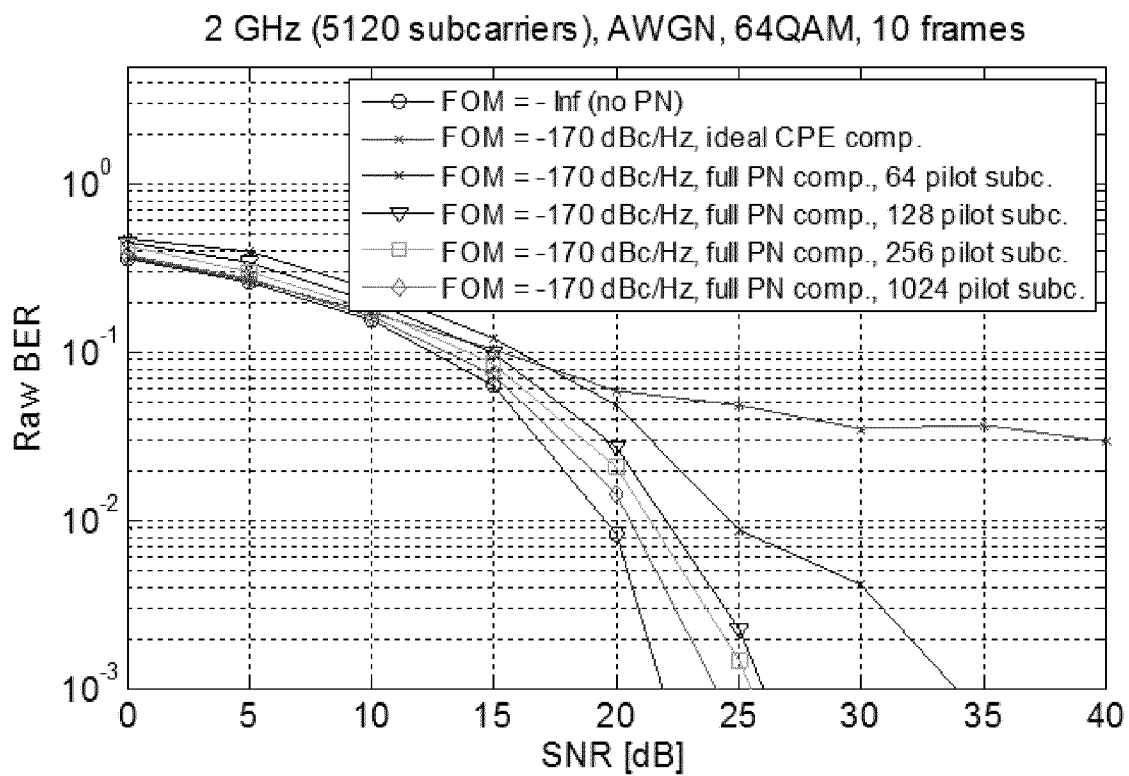
compensate the received signal for the phase noise based on the estimate of the phase noise realization (1606).

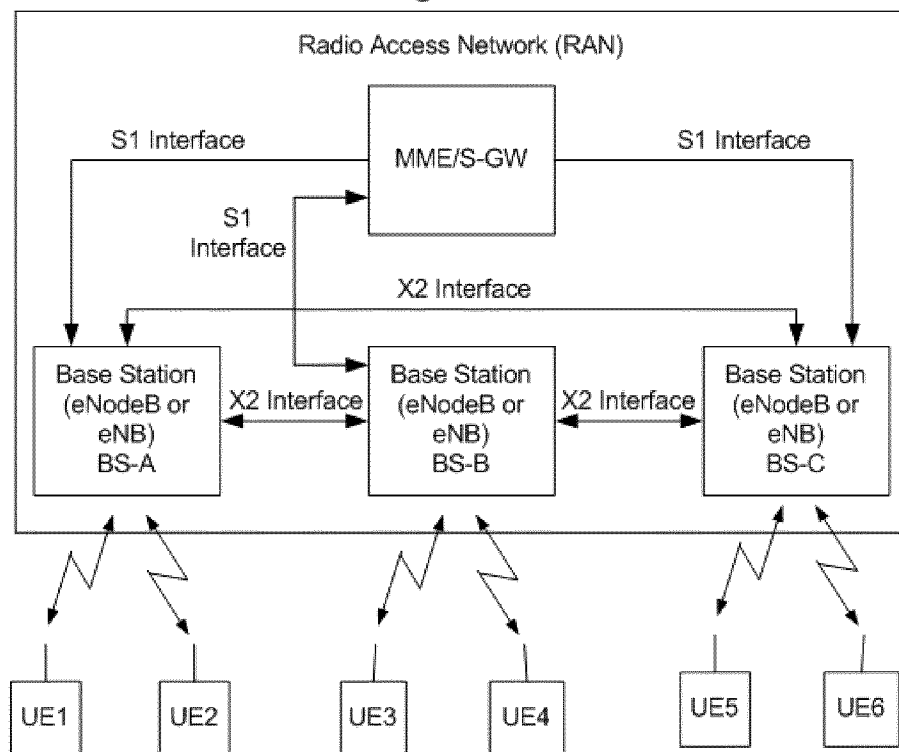


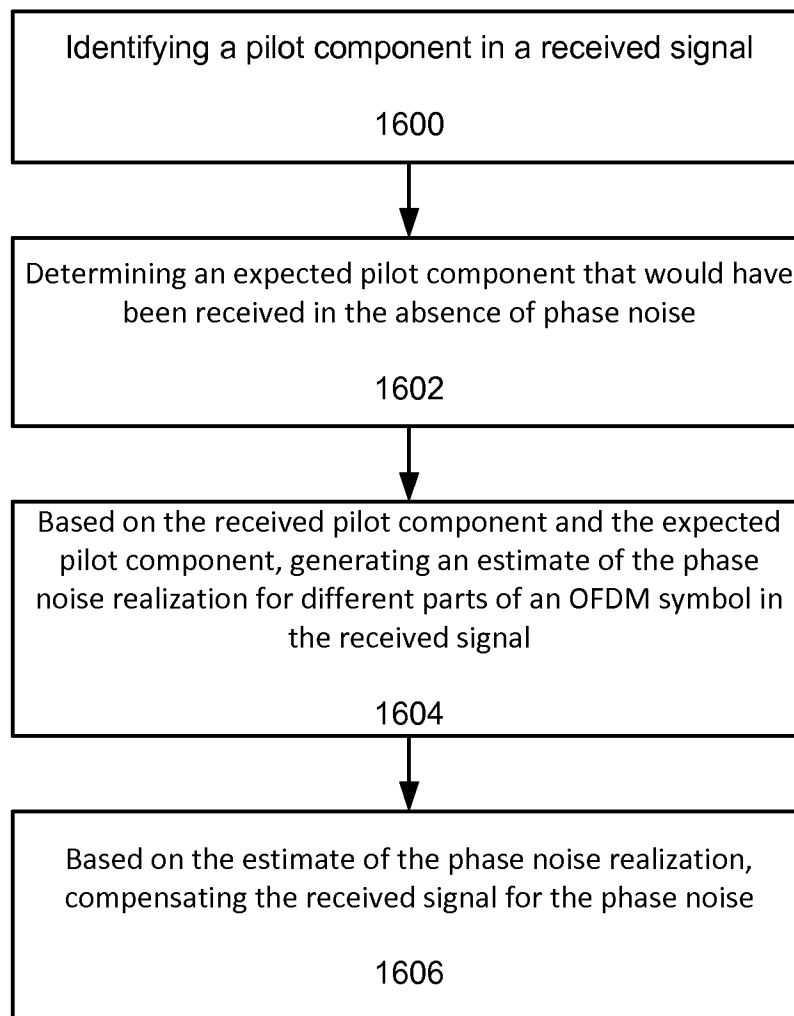
**FIGURE 3A**

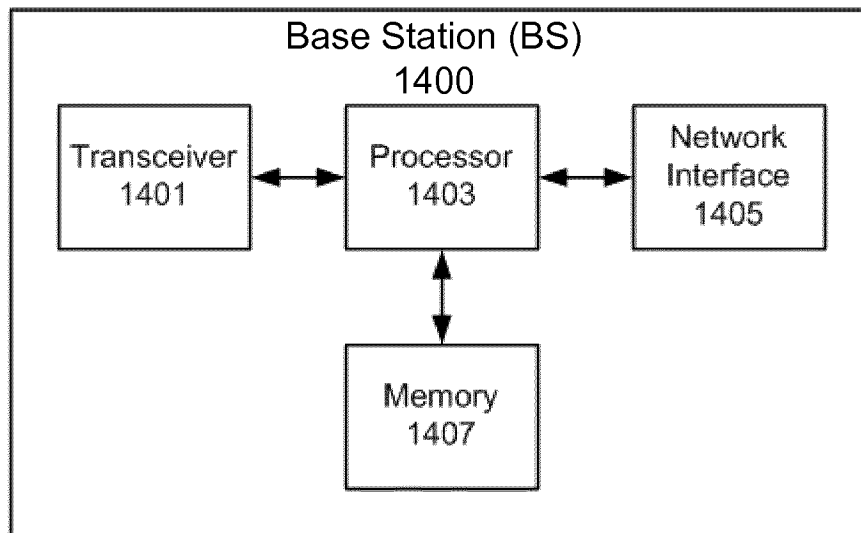
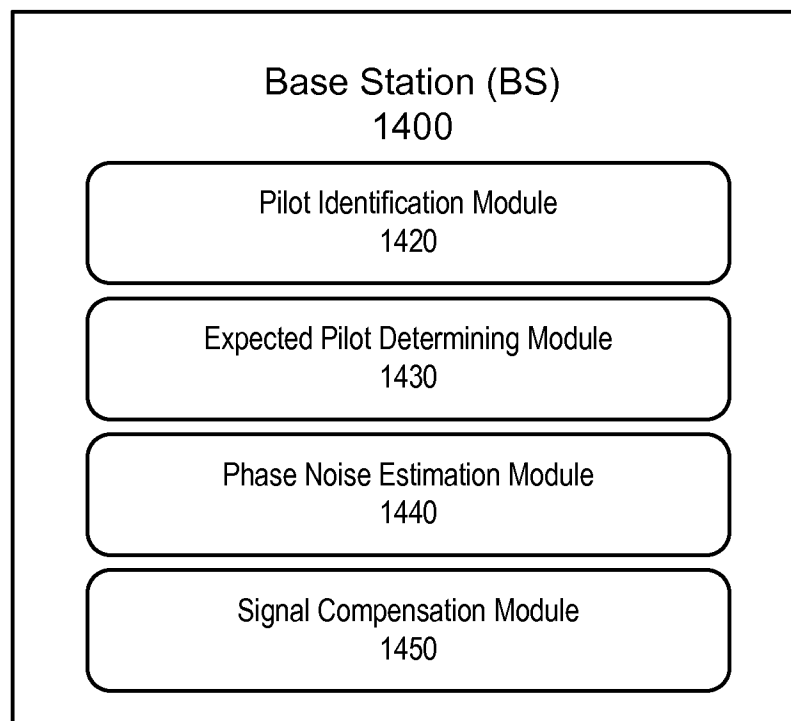
**FIGURE 3B**

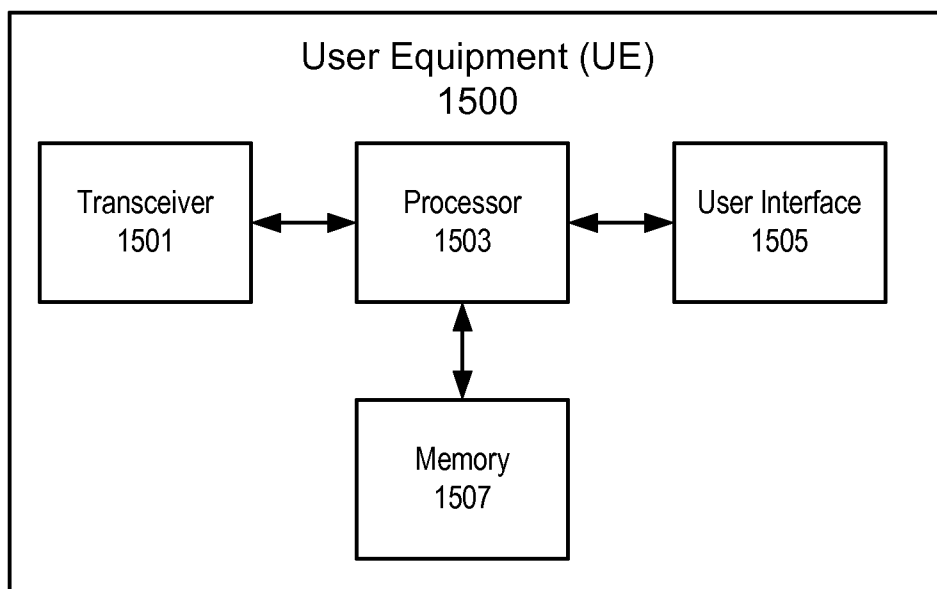
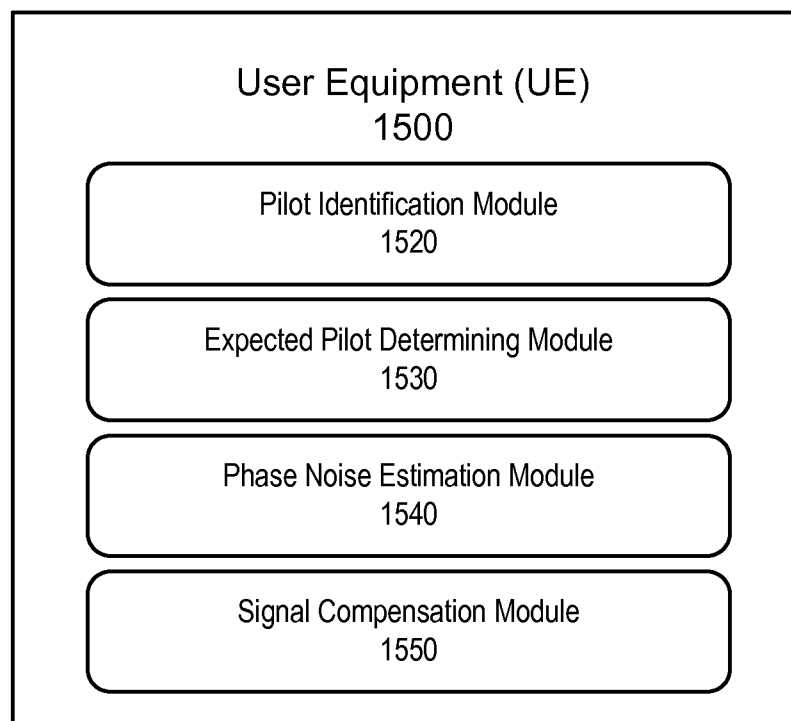
**FIGURE 4**

**FIGURE 5**

**FIGURE 6**

**FIGURE 7**

**FIGURE 8****FIGURE 9**

**FIGURE 10****FIGURE 11**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2015/062783

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-4, 15-24

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/062783

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B15/00 H04L27/26
ADD.

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

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)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SICONG LIU ET AL: "Investigation of pilot-aided phase noise compensation in CO-OFDM system", COMMUNICATIONS AND PHOTONICS CONFERENCE AND EXHIBITION (ACP), 2010 ASIA, IEEE, PISCATAWAY, NJ, USA, 8 December 2010 (2010-12-08), pages 601-602, XP031845205, ISBN: 978-1-4244-7111-9 the whole document	1-4, 16-24
X	US 2013/259174 A1 (QIAN DAYOU [US] ET AL) 3 October 2013 (2013-10-03) the whole document ----- -/-	1-4, 16-24



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

1 September 2015

Date of mailing of the international search report

14/12/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Galli, Paolo

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/062783

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/025461 A1 (PARK WOO-JONG [KR] ET AL) 1 February 2007 (2007-02-01) abstract; figures 1-3 paragraph [0003] - paragraph [0013] paragraph [0025] - paragraph [0049] -----	1-4, 15-24
A	ARMADA A G ET AL: "Phase noise and sub-carrier spacing effects on the performance of an OFDM communication system", IEEE COMMUNICATIONS LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 2, no. 1, 1 January 1998 (1998-01-01) , pages 11-13, XP011429669, ISSN: 1089-7798, DOI: 10.1109/4234.658613 cited in the application the whole document -----	1-4, 15-24

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2015/062783

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013259174	A1	03-10-2013	NONE

US 2007025461	A1	01-02-2007	KR 20070014583 A
			01-02-2007
		US 2007025461	A1
			01-02-2007

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-4, 15-24

Pilot based phase noise compensation for an OFDM system.
Details on where (BS, UE) as well as on how
(sample-by-sample, using complex angle error, derotation,
CPE first) and on for which kind of phase noise (generated
in TX and/or RX) the compensation is made.

2. claims: 5, 6

Pilot based phase noise compensation for an OFDM system.
Details on the application of such compensation to MIMO
systems.

3. claims: 7-9

Pilot based phase noise compensation for an OFDM system.
Details on the OFDM symbols comprised in the pilot and data
components respectively.

4. claims: 10-14

Pilot based phase noise compensation for an OFDM system.
Details on possible performance improvement by applying
different smoothening techniques.
