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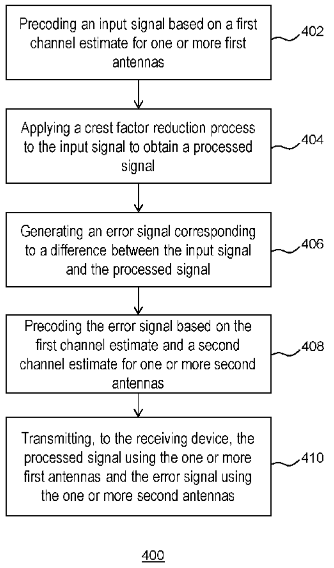

Figure 4

(57) **Abstract:** In a first aspect, a transmitting device is provided. The transmitting device comprises a plurality of antennas, processing circuitry, and a machine-readable medium storing instructions which, when executed by the processing circuitry, cause the transmitting device to: apply a crest factor reduction process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network. The processing circuitry further causes the transmitting device to generate an error signal corresponding to a difference between the input signal and the processed signal, and transmit, to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

REDUCING SIGNAL DISTORTION

Technical Field

Embodiments of the present disclosure relate to wireless communications networks and in particular to transmitting devices and methods for transmitting signals using a plurality of antennas.

Background

In active array systems (AASs), radio frequency components such as power amplifiers and transceivers are integrated with an array of antenna elements. These systems, which can also be referred to as advanced antenna systems, offer several benefits compared to more traditional deployments in which passive antennas are connected to transceivers through feeder cables. Antennas in an AAS can be closely integrated with radio equipment, which boosts coverage area while reducing power consumption and system size. AASs can also be cheaper to construct than other (non-integrated) antennas. AASs can be particularly advantageous for higher frequency deployments since feeder cables exhibit more significant losses at these frequencies. As Fifth Generation (5G) networks use these higher frequencies, AASs are increasingly being incorporated into next generation mobile communication systems to mitigate the impact of increased feeder loss and propagation loss, as well as the degradation of the receiver sensitivity by an inferior noise figure.

There are many applications of AAS such as, for example, cell-specific beamforming, user-specific beamforming, vertical sectorization, massive multiple-input multiple-output (MIMO), elevation beamforming and hybrid beamforming. AASs can also be used to implement further advanced antenna concepts such as deploying a large number of MIMO antenna elements at a base station. For example, an AAS can be used to deploy, 32, 64, 128, 192, 256 or 384 antenna elements at a base station.

In 5G networks, orthogonal frequency division multiplexing (OFDM) is used to multiplex signals for multiple subcarriers using digital signal processing to form a single time-domain signal. Summing many subcarrier components in this manner can create large amplitude fluctuations (high peak values) in the time-domain signal. As a result of this, OFDM signals typically have a higher peak-to-peak average power ratio (PAPR) than single carrier signals.

Before transmission, OFDM signals are amplified using a power amplifier. However, amplifying a signal with a high PAPR can cause in-band distortion such as error vector magnitude (EVM), as well as out-of-band emissions. These distortions can degrade system performance for both the cell in which the transmission is performed and any neighbouring cells. Signals with a high PAPR also suffer from a decreased signal-to-quantisation noise ratio (SQNR) when converted between the digital and analogue domains using an analogue-to-digital converter (ADC) or a digital-to-analogue converter (DAC), whilst also degrading the efficiency of the power amplifier.

One way to mitigate the impact of a high PAPR is to apply a power back-off to prevent a signal from being amplified beyond the saturation point of the amplifier. However, applying the required power back-off can make it difficult to achieve the same cell coverage.

Modulation	**%EVM Limit**
QPSK	17.5
16-QAM	12.5
64-QAM	8
256-QAM	3.5
1024-QAM (LTE)	2.5

Table 1

Alternatively, a signal can be pre-processed before it is amplified to reduce the PAPR. For example, clipping and filtering algorithms can be used to clip the peaks of a baseband signal after application of an inverse fast Fourier transform (IFFT). Whilst filtering eliminates some of the out-of-band emissions generated by this clipping, heavy clipping still increases the EVM and generates out-of-band emissions.

This is demonstrated by **Figure 1**, which shows the EVM measured at the receiver versus PAPR after a clipping and filtering process has been applied. The EVM is measured at the receiver with ideal tap equalization. Since signals are clipped to reduce PAPR, lower PAPR values indicate that heavier clipping has been applied. As shown in Figure 1, EVM increases from approximately 0% of receiver EVM to 20% of receiver

EVM as the PAPR is reduced from 10 dB to just above 2dB. Applying increasingly heavy clipping thus increases the EVM.

The arrows in Figure 1 indicate the maximum EVM permitted for various modulation schemes according to the 3GPP technical specification TS 38.104 V17.1.0. These EVM limits are also presented in Table 1. As illustrated, lower order modulation schemes such as Quadrature Phase Shift Keying (QPSK) and 16-Quadrature Amplitude Modulation (QAM) are subject to less restrictive upper EVM limits than higher order modulation schemes such as 64-QAM and 256-QAM. In order to satisfy 3GPP regulations, signals cannot be clipped beyond these limits, which means that conventional clipping and filtering can only be used to reduce the PAPR to a certain level. For 256-QAM, for example, the PAPR cannot be reduced to less than 7dB using clipping and filtering without breaching the 3GPP EVM limit.

Summary

Embodiments of the present disclosure seek to address these and other problems.

In a first aspect, a transmitting device is provided. The transmitting device comprises a plurality of antennas, processing circuitry and a machine-readable medium storing instructions which, when executed by the processing circuitry, cause the transmitting device to: apply a crest factor reduction process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network. The processing circuitry further causes the transmitting device to generate an error signal corresponding to a difference between the input signal and the processed signal, and transmit, to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

In a further aspect, a method performed by a transmitting device in a wireless communications network is provided. The transmitting device comprises a plurality of antennas. The method comprises applying a crest factor reduction process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network. The method further comprises generating an error signal corresponding to a difference between the input signal and the processed signal, and transmitting, to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

A still further aspect provides a transmitting device configured to perform the aforementioned method. In another aspect, a computer program is provided. The computer program comprises instructions which, when executed on at least one processor of a transmitting device, cause the transmitting device to carry out the aforementioned method. In a further aspect, a carrier containing the computer program is provided, in which the carrier is one of an electronic signal, optical signal, radio signal, or non-transitory machine-readable storage medium.

By applying a crest factor reduction process to an input signal, aspects of the present disclosure reduce the peak-to-peak average power ratio of the input signal which reduces the risk of distortion when the input signal is amplified for transmission. Since the error signal is generated to correspond to the difference between the input signal and the signal after it has been processed with a crest factor reduction process, transmitting the error signal cancels out any errors or distortions that may otherwise arise due to the crest factor reduction process and thus reduces the error vector magnitude at the receiving device. Aspects of the present disclosure thus reduce signal distortion at the receiving device, thereby improving system performance.

Brief description of the drawings

For a better understanding of examples of the present disclosure, and to show more clearly how the examples may be carried into effect, reference will now be made, by way of example only, to the following drawings in which:

Figure 1 shows the transmitter EVM for signals that have been clipped and filtered;

Figure 2 shows an illustration of a wireless communications network according to embodiments of the disclosure;

Figure 3 shows an illustration of a base station according to embodiments of the disclosure;

Figure 4 shows a flowchart of a method according to embodiments of the disclosure;

Figures 5-9 show peak-to-peak average power ratio (PAPR) values and constellation diagrams for simulations of a wireless communication network;

Figures 10 and 11 show examples of a transmitting device according to embodiments of the disclosure.

Detailed description

Figure 2 shows a wireless communications network 200 according to embodiments of the disclosure. The wireless communications network 200 may implement any suitable wireless communications protocol or technology, such as Global System for Mobile communication (GSM), Wide Code-Division Multiple Access (WCDMA), Long Term Evolution (LTE), New Radio (NR), WiFi, WiMAX, or Bluetooth wireless technologies. In one particular example, the wireless communications network 200 forms part of a cellular telecommunications network, such as the type developed by the 3rd Generation Partnership Project (3GPP). The wireless communications network 200 may thus, for example, form part of a Fifth Generation (5G) communications network. Those skilled in the art will appreciate that various components of the wireless communications network 200 are omitted from Figure 2 for the purposes of clarity.

The network 200 comprises a base station 202 configured to provide radio service to one or more wireless devices in its coverage area. The base station 202 may be, for example, a Node B, evolved Node B (eNB), a next generation Node B (gNB) or any other suitable base station.

The base station 202 couples the wireless devices to a core network 206 in the communications network 200 (e.g. via a backhaul network 208). In the illustration, only one wireless device 204 is shown. However, the skilled person will appreciate that the network 200 may comprise any number of wireless devices and may comprise many more wireless devices than shown.

The base station 202 comprises one or more amplifiers which boost signals for transmission. However, amplifiers have saturation limits, which means that signals that are boosted beyond this limit can be distorted during amplification. As a result, signals with large amplitude fluctuations, reflected in their high peak-to-average power ratio (PAPR) values, are likely to experience distortion when they are amplified. The PAPR of a signal can be reduced to some extent by applying a crest factor reduction (CFR) process, such as clipping and/or filtering, to the signal. However, these CFR processes can also distort the signal, which can increase the error vector magnitude (EVM) and degrade system performance.

Embodiments of the disclosure seek to address these and other problems by providing a transmitting device having a plurality of antennas. In operation, the transmitting device applies a CFR process to an input signal to obtain a processed signal. The transmitting device generates an error signal which corresponds to the difference between the input signal and the processed signal, thereby capturing the effect of the CFR process. The transmitting device transmits both the error signal and the processed signal, using a first set of the antennas for the processed signal and a second set of the antennas for the error signal.

Thus, according to embodiments of the disclosure, the base station 202 is configured to apply a CFR process to an input signal to generate a processed signal for transmission to the wireless device 204. The CFR process may comprise one or more of a clipping and filtering process, and a peak cancellation process, for example.

As a result of the crest reduction process, the processed signal will have a smaller PAPR than the input signal. However, CFR processes can create out-of-band emissions and increase EVM at the receiver. To account for this, the base station 202 generates an error signal corresponding to the difference between the processed signal and the input signal. The base station 202 may generate the error signal by subtracting the processed signal from the input signal, for example.

The base station 202 transmits the processed signal and the error signal to the wireless device 204. The base station 202 comprises a plurality of antennas (e.g. forming an antenna array) and uses one or more first antennas to transmit the processed signal and one or more second antennas to transmit the error signal. The base station 202 may thus, for example, use different antennas to transmit the processed signal and the error signal.

The base station 202 may transmit the processed signal and the error signal synchronously such that they superpose at the wireless device 204. The processed signal and the error signal may thus superpose at the receiver to cancel out any distortions or errors caused by the crest reduction process.

By applying a CFR process to an input signal, embodiments of the disclosure reduce the PAPR of the input signal, which reduces the risk of distortion when the signal is amplified for transmission. Transmitting the additional error signal, generated to correspond to the difference between the input signal and the signal after it has been processed with the CFR process, cancels out errors or distortions that may otherwise arise due to the CFR process and thus reduces the EVM at the wireless device 204 (at the receiver).

As higher order modulation schemes may be subject to stricter EVM limits, in some embodiments, the methods disclosed herein may be selectively used for higher order modulation schemes. Thus, for example, the methods disclosed herein (e.g. the generation of and transmission of an error signal) may be initiated in response to determining that an input signal (e.g. a baseband signal) is being modulated with a Quadrature Amplitude Modulation (QAM) scheme. In particular examples, the methods disclosed herein may be initiated based on a determination that the signal is being modulated using a QAM scheme having a constellation size above a threshold value (e.g. of 64 or higher). Selective application of the methods disclosed herein for signals modulated with higher order modulation schemes can ensure that the additional processing required by these methods is only employed when they are needed to comply with EVM limits.

Figure 3 shows an illustration of a base station 300 according to embodiments of the disclosure. The base station 300 is configured to operate in a wireless communications network, such as the network 200 described above in respect of Figure 2. The base station 300 may be the base station 202 described above in respect of Figure 2, for example.

The base station 300 comprises a baseband unit 302, a first modulator 304, a crest factor reduction (CFR) unit 306, one or more first radio units 308, a difference unit 310, a demodulator 312, a precoder 314, a second modulator 316 and one or more second radio units 318.

The base station 300 further comprises a plurality of antennas (not illustrated) associated with the radio units 308, 318. For example, each of the antennas in the base station 300 may be provided with a respective radio unit. In particular examples, the radio units 308, 318 are integrated with their respective antennas to form an AAS.

The operation of the base station 300 is discussed in detail with respect to **Figure 4**, which shows a flowchart of a method 400 performed by the base station 300 according to embodiments of the disclosure. The base station 300 is configured to implement the method 400 in order to perform a transmission to a receiving device in the wireless communications network 200. The receiving device may be the wireless device 204, for example.

The method 400 begins in step 402, in which the baseband unit 302 precodes an input signal based on a channel estimate for a channel, $\boldsymbol{H}_d$, between one or more first antennas at the base station 300 and the receiving device. Precoding may be referred to as spatial or multiple input multiple output (MIMO) precoding, for example. As precoding techniques are well-known in the art, they will not be discussed in detail here. After precoding the signal may comprise M baseband signals, in which M is the number of antennas in the base station 300. The precoded signal may thus be a vector having one element per antenna (branch) at the base station 300. Although not illustrated in Figure 3, any subsequent processing of the precoded signal may performed per element (e.g. per branch).

The channel estimate itself may be determined based on one or more measurements performed by the base station 300 and/or the receiving device. Thus, the channel estimate may be determined based on reference signal measurements performed by the base station 300 and/or the receiving device. For example, the channel estimate may be determined based on one or more Sounding Reference Signal (SRS) measurements.

The baseband unit 302 provides the precoded input signal x to the first modulator 304. The first modulator 304 modulates the signal x according to an orthogonal frequency division multiplexing (OFDM) modulation process to form an input signal, y, comprising a time domain sequence. The first modulator 304 may thus, for example, modulate subcarriers in the input signal with a modulation scheme before applying an inverse Discrete Fourier Transform (iDFT) to the input signal. The first modulator 304 may then apply a cyclic prefix (CP) to the transformed signal in order to generate the time domain sequence y. There are various modulation schemes which may be used, including, for example, Quadrature Phase Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM, such as 16-QAM, 64-QAM, 256-QAM and 1024-QAM).

In step 404, the CFR unit 306 applies a CFR process to the input signal to obtain a processed signal y_c. CFR processes are known in the art and the skilled person will appreciate that there are many suitable CFR processes that may be used. One exemplary CFR process that may be used is clipping and filtering, which can comprise hard clipping the input signal and passing the clipped signal through a low-pass filter. The hard clipping reduces the PAPR of the input signal and the filtering reduces the incidence of any out-of-band emissions created by clipping the signal.

Another exemplary CFR process that may be used is peak cancellation, in which peaks in the input signal that exceed a particular threshold amplitude are identified. For each of the identified peaks, a cancellation pulse is determined and subtracted from the input signal to reduce the PAPR.

A further CFR process that may be used is peak windowing, in which the input signal is multiplied with an attenuating window function to reduce the height of peaks in the signal. Attenuating the input signal in this manner can reduce the PAPR without creating sharp corners (e.g. steep changes in amplitude) in the signal.

Thus, there are various CFR processes that may be applied in step 404. In general, one or more of these CFR processes may be applied in step 404. Regardless of the particular process or algorithm used, the CFR process reduces the height of peaks in the input signal relative to the average signal amplitude, thus reducing the PAPR of the input signal y.

The processed signal y_c is input to the one or more first radio units 308 for transmission. The first radio units 308 are associated with one or more first antennas (not illustrated) in the base station 300 and thus comprise any necessary circuitry and/or software for facilitating transmission of the processed signal by the first antennas. The first radio units 308 may thus be configured to apply one or more of the following to the processed signal: power amplifier linearisation (e.g. digital pre-distortion, DPD), digital-to-analogue conversion (DAC), amplification at one or more power amplifiers and analogue radio frequency filtering.

The transmission of the processed signal is discussed in more detail below.

In step 406, the difference unit 310 generates an error signal e corresponding to a difference between the input signal y and the processed signal y_c. Thus, for example, the difference unit 310 may subtract the processed signal from the input signal to form an error signal $e=y-y_c$. Alternatively, the difference unit 310 may subtract the input signal from the processed signal to form an error signal $e=y_c-y$. The error signal e thus indicates the changes (e.g. errors) to the input signal *y* caused by the application of the CFR process.

The error signal *e* is input to a demodulator 312, which demodulates the error signal *e* to generate a frequency domain signal, ε. The demodulator 312 may effectively perform the inverse of the operation of the first modulator 304. The demodulator 312 may thus, for example, demodulate the error signal by removing the cyclic prefix applied by the modulator 304 from the error signal and applying a Fourier Transform (e.g. a discrete Fourier transform).

The demodulated error signal ε is input to a precoder 314. As discussed in more detail below, the error signal is to be transmitted by one or more second antennas at the base station 300.

The precoder 314 precodes the error signal according to a precoding matrix, ***W***, determined based on channel estimates for the base station 300. The channel estimates may be determined based on one or more measurements performed by the base station 300 and/or the receiving device. Thus, for example, the channel estimates may be determined based on reference signal measurements (e.g. Sounding Reference Signal measurements) performed by the base station 300 and/or the receiving device. The skilled person will be aware that there are various ways of estimating a channel that may be suitable, and thus they are not discussed in detail here.

The precoding matrix ***W*** is determined by seeking to minimise the relationship

$$\boldsymbol{H_d} - \boldsymbol{H_e}\boldsymbol{W} = 0,$$

in which $\boldsymbol{H_d}$ is the channel between the first antennas (for transmitting the processed signal) and the receiving device, and $\boldsymbol{H_e}$ is the channel between the second antennas (for transmitting the error signal) and the receiving device. As, in general, the matrices $\boldsymbol{H_d}, \boldsymbol{H_e}$ and $\boldsymbol{W}$ may not be square matrices, it may not be possible to invert them directly to determine ***W***. Instead, a generalised inverse, such as a Moore-Penrose pseudo-inverse, may be used. Using a generalised inverse (denoted by the superscript †), the precoder matrix may be determined according to the relationship $\boldsymbol{W} = \boldsymbol{H_e^\dagger H_d}$.

However, the skilled person will appreciate that this is just one approach for precoding the demodulated error signal. In general, the precoder 314 precodes the demodulated error signal based on the channel estimate for the channel $\boldsymbol{H_e}$ between the one or more second antennas and the receiving device.

The precoded error signal is input to the second modulator 316 which modulates the error signal $\boldsymbol{W\varepsilon}$ to form a time domain sequence for transmission. The second modulator 316 may modulate the error signal in substantially the same manner that the first modulator 304 modulated the input signal. The second modulator 316 may thus, for example, modulate subcarriers in the error signal with a modulation scheme before applying an iDFT to the input signal. The second modulator 316 may then apply a CP to the transformed signal in order to generate the time domain sequence for transmission.

The modulated error signal is input to the one or more second radio units 318 for transmission. The second radio units 318 are associated with the one or more second antennas (not illustrated) in the base station 300 and thus comprise any necessary circuitry and/or software for facilitating transmission of the error signal by the second antennas. The second radio units 318 may thus be configured to apply one or more of the following to the error signal: power amplifier linearisation (e.g. digital pre-distortion, DPD), digital-to-analogue conversion (DAC), amplification at one or more power amplifiers and analogue radio frequency filtering.

The operation of the first and second radio units is discussed in more detail below.

In step 410, the base station 300 transmits, to the receiving device, the processed signal using the one or more first antennas and the error signal using the one or more second antennas. The first and second antennas may be different such that, for example, a first subset of antennas in the base station 300 are used to transmit the processed signal and a different second subset of antennas is used to transmit the error signal. The second subset of antennas may be reserved exclusively for transmitting error signals.

The processed signal and the error signal may be transmitted synchronously (e.g. simultaneously) such that they superpose at the receiving device to cancel any errors that occurred in the processed signal due to the CFR processes. The transmission of the signal by the first and second antennas may be coordinated to mitigate the impact of the CFR process whilst still minimising the PAPR of the processed signal. In order to achieve this, the processed signal path and the error signal path in the base station 300 may be tightly synchronised. The base station 300 may coordinate the first and second radio units to ensure that the processed signal and the error signal arrive at the receiving device at the same time. For example, the base station 300 may delay transmission of the processed signal until the error signal is also ready for transmission.

The processed signal and the error signal are thus transmitted to the receiving device by the first and second antennas respectively. The receiving device receives a combined signal from the base station 300 comprising the error signal and the processed signal. After demodulation, this combined signal may be expressed as

$$r = \boldsymbol{H_d} x_c + \boldsymbol{H_e W}(x - x_c) + n,$$

in which x is the precoded input signal, x_c is the processed signal and $x - x_c$ is the error signal. $\boldsymbol{H_d}$ is the channel for the first antennas (used to transmit the processed signal), $\boldsymbol{H_e}$ is the channel between for second antennas (used to transmit the error signal, $x - x_c$), and *n* accounts for noise.

Since the precoding matrix may be written as $\boldsymbol{W} = \boldsymbol{H_e^{\dagger} H_d}$, the received signal may be expressed as

$$r = \boldsymbol{H_e W} x + n = \boldsymbol{H_e H_e^{\dagger} H_d} x + n = \boldsymbol{H_d} x + n.$$

The error signal and the processed signal thus superpose at the receiving device to form the original precoded input signal x sent through the channel $\boldsymbol{H_d}$, plus any additional noise contamination n. The method 400 thus removes distortions or errors in the received signal that are caused by the CFR process.

The skilled person will appreciate that there is a trade-off between transmitting the processed signal with a sufficient number of antennas to minimise performance loss whilst also reserving enough antennas to transmit the error signal. The optimal solution may vary depending on a number of factors, including the modulation and coding scheme (MCS) applied to the input signal, the location of the base station 300 and signal-to-noise ratio (SNR) and channel correlation. To account for this, the base station 300 may dynamically determine which antennas to use for transmission of the error signal based on one or more of these factors.

The base station 300 may thus, for example, select the one or more second antennas for transmitting the error signal based on a modulation and coding scheme (MCS) applied to the input signal. Different MCSs have differing data rates and may thus be subject to different EVM limits. In particular, MCSs having a higher data rate may be subject to more stringent EVM limits, which means that applying an aggressive CFR process risks increasing the EVM above these limits. One way of addressing this issue is to apply CFR less aggressively. This reduces the increase in EVM, but also means the PAPR remains high. In contrast, according to some aspects of the present disclosure, EVM and the PAPR can be reduced by configuring more branches for the error signal. This can reduce the EVM below the stringent limits needed to demodulate high data rate signals. The base station 300 may thus be configured to use a larger number of antennas to transmit the error signal for MCSs having a higher data rate.

The base station 300 may be configured to use a same number of antennas to transmit the error signal for MCSs having a same data rate, even if the modulation scheme differs. Thus, for example, the base station may be configured to use the same number of antennas to transmit the error signal for a first input signal modulated with 64QAM having 6 bits per symbol and CR=1/2 as for a second input signal modulated with 16QAM having 4 bits per symbol with CR=3/4, since both of these MCSs correspond to a data rate of 3 data bits per symbol.

The one or more second antennas may be selected based on the path loss between the base station 300 and the receiving device. As high pathloss between the base station 300 and the receiving device can cause lower receiver power and thus lower SNR at the receiving device, lower order modulation schemes, such as QPSK, are typically used when pathloss is high. In contrast, higher order modulation schemes, such as 256-QAM, tend to be used when pathloss is low. As lower order MCSs can tolerate more EVM, fewer antenna branches can be allocated for transmitting the error signal when the path loss is high. Thus, in some examples, fewer antennas may be selected for transmitting the error signal when the path loss between the base station 300 and the receiving device is high (e.g. above a threshold value) compared to when it is low.

The skilled person will appreciate that pathloss can depend on the location of the receiving device. For example, devices at cell edges, particularly those with a poor line-of-sight to the base station 300, can experience more pathloss than devices at or towards the centre of the cell. Thus, in particular examples, the second antennas may be selected based on the location of the receiving device in a cell served by the base station 300. Thus, in some examples, fewer antennas may be selected for a receiving device at the cell edge than for a receiving device that is at or towards the centre of the cell.

The base station 300 may select the one or more second antennas for transmitting the error signal based on the SNR of a channel between the base station 300 and the receiving device (e.g. an SNR for signals transmitted by the base station 300). Lower quality channels, as indicated by a low SNR, typically have lower data rates and use lower order modulation schemes, such as QPSK. Therefore, fewer antennas may be used to transmit the error signal for channels having a low SNR.

Any suitable parameter may be used to quantify the SNR. The base station 300 may, for example, select the second antennas based on a channel quality indicator (CQI) report received from the receiving device. For example, the base station 300 may select more second antennas for a channel having higher CQI indices than for a channel with lower CQI indices. In particular examples, the base station 300 may select no second antennas for a channel having low CQI indices (e.g. CQI indices below a particular threshold). Thus, the base station 300 may determine not to transmit the error signal in response to determining that the channel has a low SNR.

The base station 300 may select the one or more second antennas for transmitting the error signal based on the channel correlation of the base station 300. Thus, for example, the base station 300 may select more second antennas for a channel that is strongly (or highly) correlated compared to a weakly correlated channel.

The skilled person will appreciate that the SNR and the channel correlation are both indicative of channel conditions. In general, the base station 300 may select the antennas to be used to transmit the error signal based on channel conditions between the base station 300 and the receiving device. For example, the base station 300 may select a larger proportion of base station antennas for transmitting the processed signal in response to determining that channel conditions are poor. The skilled person will thus appreciate that there are various other parameters which are indicative of channel conditions that may be suitable for this purpose.

There are various ways in which the antennas may be selected based on one or more of the factors discussed above. For example, simulations may be employed to determine the optimum number of antennas to use for transmitting error signals for a particular base station or type of base station.

Thus, the base station 300 may dynamically select the second antennas for transmitting the error signal based on one or more factors. Alternatively, the base station 300 may be preconfigured to use particular antennas, or a particular number of antennas, for transmitting the error signal.

The base station 300 may be configured to use fewer antennas for transmitting the error signal than the processed signal. Since the error signal is effectively a correction to the processed signal, this correction may typically be smaller than the processed signal itself. The base station 300 may thus use fewer antennas for transmitting the error signal than the processed signal. Maximising the number of antennas that are available for transmitting the processed signal in this manner improves system performance.

As discussed above, OFDM modulation is used to transmit the input signal and the error signal using multiple subcarriers. The embodiments described herein may be particularly advantageous for transmissions over multiple subcarriers (such as OFDM transmissions), which can be particularly prone to high PAPR values. In general, the method 400 and the base station 300 may be adapted for transmissions over multiple subcarriers (e.g. other than OFDM). More generally, embodiments described herein may be advantageous for any signals to be transmitted in a wireless communication network that suffer from a large PAPR, and thus are not limited to either transmissions over multiple subcarriers or, in particular, OFDM.

It is further noted that, although the method 400 is described above as being performed by the base station 300, the skilled person will appreciate that the method may be performed by any base station, such as the base station 202 described above in respect of Figure 2. More generally, the method 400 may be implemented by any transmitting device, such as those discussed below in respect of Figures 10 and 11.

The present disclosure thus provides a method 400 for reducing the PAPR of a signal to be transmitted by a transmitting device, such as a base station, to a receiver whilst also minimising the EVM at the receiver. The method 400 achieves this, at least in part, by transmitting an error signal, in addition to the processed signal, which accounts for the any errors induced by using a CFR process. Reducing the PAPR and the EVM can reduce signal distortion at the receiver and thus improve system performance.

However, in some embodiments, the error signal itself may still have a high PAPR and may thus suffer from distortion when it is amplified by a power amplifier (e.g. in the one or more second radio units 318) for transmission.

To address these and other problems, the present disclosure provides the following further developments of the method 400.

As described above in respect of Figure 3, the first and second antennas in the base station 300 are associated with the first and second radio units 308, 318 respectively. These radio units 308, 318 may be configured to apply one or more of the following to the processed signal and the error signal respectively: power amplifier linearisation (e.g. digital pre-distortion, DPD), digital-to-analogue conversion (DAC), amplification at one or more power amplifiers and analogue radio frequency filtering.

In a first approach, the second radio units 318 may apply a power back off to the second antennas. Thus, a power back-off may be applied only to the antennas used to transmit the error signal, with no power back-off being applied to the processed signal by the first radio units 308. Alternatively, a power back-off may be applied to both the first and second antennas, but the back-off applied to the first antennas (for transmitting the processed signal) may be smaller than the back-off applied to the second antennas. This can prevent saturation from occurring when the error signal is amplified for transmission, thereby limiting signal distortion and out-of-band emissions. As the back-off applied to the antennas used to transmit the processed signal is smaller (or no back-off at all is applied), the impact on the coverage of the base station 300 is minimised.

In a second approach, any increase in the PAPR caused by the error signal may also be mitigated by amplifying the error signal, at the second radio unit 308, using one or more amplifiers having a higher dynamic range than one or more amplifiers used to amplify the processed signal at the first radio unit 318. Using amplifiers that have a higher dynamic range reduces the distortion that would otherwise result from amplifying an error signal having a high PAPR. As amplifiers with a high dynamic range can be costly, selectively using these amplifiers for the error signal (e.g. rather than for the error signal and the processed signal) achieves these benefits whilst reducing implementation costs.

In a third approach, this issue may be mitigated by applying a more complex DPD to the error signal than to the processed signal. The skilled person will appreciate that DPD is often used to improve power amplifier linearisation, allowing power amplifiers to run closer to saturation whilst minimising signal distortion. However, this can be computationally expensive. According to the present disclosure therefore, a more complex (e.g. more computationally intensive) DPD may be selectively applied to the error signal. As the error signal may be likely to have a higher PAPR than the processed signal, this mitigates the impact of that high PAPR whilst minimising processing overhead.

The skilled person will appreciate that, in general, a combination of these approaches may be used. The present disclosure thus provides methods for further reducing the risk of signal distortion at a receiving device.

Figure 5 shows the complementary cumulative probability distribution (CCDF) of the PAPR for simulations of an AAS in a wireless communications network. In the simulations, 48 antennas were used for transmitting the processed signal and the remaining 16 antennas were used for transmitting the error signal in accordance with the method 400 described above in respect of Figure 4. These simulations assume that there is no error in the channel estimates used to determine the precoding matrix $\boldsymbol{W}$.

The dashed, left-most line shows the PAPR when no CFR is applied and the solid, right-most line, labelled SAR (Selective Antenna Reservation), shows the PAPR when the method 400 is applied. As shown in Figure 5, applying the method 400 reduces the PAPR by around 6dB.

However, Figure 5 only shows the PAPR of the processed signal (e.g. the PAPR of the error signal is omitted). The dotted, left-most line in **Figure 6** shows the CCDF of the PAPR of the signals transmitted from all antennas (e.g. the sum of the PAPR of the error signal and the PAPR of the processed signal). The solid, right-most line in Figure 6 is the same as in Figure 5. Comparing the left-most lines in Figures 5 and 6 shows that the error signal adds a small contribution to the PAPR. However, there is still an overall net decrease in the PAPR compared to simulations in which no CFR was applied.

Figure 7 is a constellation diagram of the transmitted and received symbols for these simulations. As shown in the figure, the EVM is zero even when the method 400 is applied, showing that the method 400 reduces the PAPR without increasing the EVM.

Figures 8 and 9 show the CCDF of the PAPR and the constellation diagram for simulations of an AAS in a wireless communications network. As above, 48 antennas were used for transmitting the processed signal and the remaining 16 antennas were used for transmitting the error signal in accordance with the method 400 described above in respect of Figure 4. However, these simulations also model inaccuracies in channel estimation, assuming the SNR of the link is -5dB.

The dot-dashed, left-most line in Figure 8 shows the PAPR when no CFR is applied and the solid, right-most line shows the PAPR when the method 400 is applied. As shown in Figure 8, the PAPR is still reduced by around 6dB compared to simulations in which no CFR is applied. However, Figure 9 shows that there is an EVM component due to errors in channel estimation. In these simulations, the receiver EVM is 0.79% for 256-QAM modulation, which is significantly below the upper EVM limit specified in TS 38.104 V17.1.0. Thus, even despite the channel estimation error, the method 400 still reduces the PAPR whilst keeping the EVM within the limits specified by the standard.

Figure 10 is a schematic diagram of a transmitting device 1000 for a wireless communications network according to embodiments of the disclosure. The transmitting device 1000 may be a base station such as, for example, the base station 202 described in respect of Figure 2 or the base station 300 described in respect of Figure 3. The transmitting device 1000 may be operable to carry out the example method 400 described with reference to Figure 4 and possibly any other processes or methods disclosed herein. It is also to be understood that the method of Figure 4 may not necessarily be carried out solely by the transmitting device 1000. At least some operations of the method can be performed by one or more other entities.

The transmitting device 1000 comprises a plurality of antennas. The antennas may form an antenna array, for example. In particular examples, the antennas may form part of an advanced antenna system (AAS), also referred to herein as an active antenna array system.

The transmitting device 1000 comprises processing circuitry 1002 (such as one or more processors, digital signal processors, general purpose processing units, etc), a machine-readable medium 1004 (e.g., memory such as read-only memory (ROM), random-access memory, cache memory, flash memory devices, optical storage devices, etc) and one or more interfaces 1006.

In one embodiment, the machine-readable medium 1004 stores instructions which, when executed by the processing circuitry 1002, cause the transmitting device 1000 to apply a CFR process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network. The transmitting device is further caused to generate an error signal corresponding to a difference between the input signal and the processed signal, and transmit, to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

In other embodiments, the processing circuitry 1002 may be configured to directly perform the method, or to cause the transmitting device 1000 to perform the method, without executing instructions stored in the non-transitory machine-readable medium 1004, e.g., through suitably configured dedicated circuitry.

The one or more interfaces 1006 may comprise hardware and/or software suitable for communicating with other nodes of the communication network using any suitable communication medium. For example, the interfaces 1006 may comprise one or more wired interfaces, using optical or electrical transmission media. Such interfaces may therefore utilize optical or electrical transmitters and receivers, as well as the necessary software to encode and decode signals transmitted via the interface. In a further example, the interfaces 1006 may comprise one or more wireless interfaces. Such interfaces may therefore utilize one or more antennas, baseband circuitry, etc. The components are illustrated coupled together in series; however, those skilled in the art will appreciate that the components may be coupled together in any suitable manner (e.g., via a system bus or suchlike).

In further embodiments of the disclosure, the transmitting device 1000 may comprise power circuitry (not illustrated). The power circuitry may comprise, or be coupled to, power management circuitry and is configured to supply the components of transmitting device 1000 with power for performing the functionality described herein. Power circuitry may receive power from a power source. The power source and/or power circuitry may be configured to provide power to the various components of transmitting device 1000 in a form suitable for the respective components (e.g., at a voltage and current level needed for each respective component). The power source may either be included in, or external to, the power circuitry and/or the transmitting device 1000. For example, the transmitting device 1000 may be connectable to an external power source (e.g., an electricity outlet) via an input circuitry or interface such as an electrical cable, whereby the external power source supplies power to the power circuitry. As a further example, the power source may comprise a source of power in the form of a battery or battery pack which is connected to, or integrated in, the power circuitry. The battery may provide backup power should the external power source fail. Other types of power sources, such as photovoltaic devices, may also be used.

In particular embodiments of the disclosure, the transmitting device 1000 may comprise a plurality of separate units over which the functionality of the transmitting device 1000 is distributed. The transmitting device 1000 may be a distributed (e.g. modular) base station such as, for example, an Open Radio Access Network (O-RAN) node.

In these embodiments, the transmitting device 1000 may comprise a radio equipment controller (e.g. a baseband processing unit) and one or more remote radio equipment nodes (e.g. radio frequency transceivers). The radio equipment nodes are not co-located with the radio equipment controller and, in particular, the radio equipment nodes may be positioned at a significant distance from the radio equipment controller such that the radio equipment controller can centrally serve a large number of remote radio equipment nodes.

The radio equipment controller may be directly or indirectly connected to the remote radio equipment nodes. The radio equipment nodes may be connected to the radio equipment controller via one or more fibre links (e.g. lossless fibre links). The interface between the units may be defined by the Common Public Radio Interface (CPRI), which standardizes the protocol interface between a radio equipment controller and radio equipment nodes in wireless distributed base stations to enable interoperability of equipment from different vendors. In order to reduce the number of connections (e.g. fibre links) needed, the radio equipment nodes may be connected to a common CPRI concentrator, for example.

Thus, in embodiments in which the transmitting device 1000 comprises a distributed base station, the processing circuitry 1002 and the machine-readable medium 1004 may be comprised in, for example, a radio equipment controller which is configured to control one or more radio equipment nodes forming part of the transmitting device 1000. Thus, the methods described herein (e.g. the method 400) may be performed by a radio equipment controller in the transmitting device 1000. Alternatively, the processing circuitry 1002 and the machine-readable medium 1004 may be comprised in one of the radio equipment nodes (e.g. at a transceiver).

Figure 11 is a schematic diagram of a transmitting device 1100 for a wireless communications network according to embodiments of the disclosure. The transmitting device 1100 may be a base station such as, for example, the base station 202 described in respect of Figure 2 or the base station 300 described in respect of Figure 3. The transmitting device 1100 may be operable to carry out the example method 400 described with reference to Figure 4 and possibly any other processes or methods disclosed herein. It is also to be understood that the method of Figure 4 may not necessarily be carried out solely by the transmitting device 1100. At least some operations of the method can be performed by one or more other entities.

The transmitting device 1100 comprises a CFR (crest factor reduction) unit 1102, which is configured to apply a CFR process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network. The transmitting device 1100 further comprises a generation unit 1104, which is configured to generate an error signal corresponding to a difference between the input signal and the processed signal. The transmitting device 1100 further comprises a transmission unit 1106, which is configured to transmit, to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas. Thus, for example, the CFR unit 1102, the generation unit 1104 and the transmission unit 1106 may be configured to perform steps 404, 406 and 408 (described above in respect of Figure 4) respectively.

The transmitting device 1100 may comprise processing circuitry, which may include one or more microprocessor or microcontrollers, as well as other digital hardware, which may include digital signal processors (DSPs), special-purpose digital logic, and the like. The processing circuitry may be configured to execute program code stored in memory, which may include one or several types of memory such as read-only memory (ROM), random-access memory, cache memory, flash memory devices, optical storage devices, etc. Program code stored in memory includes program instructions for executing one or more telecommunications and/or data communications protocols as well as instructions for carrying out one or more of the techniques described herein, in several embodiments. In some implementations, the processing circuitry may be used to cause the CFR unit 1102, the generation unit 1104 and the transmission unit 1106, and any other suitable units of transmitting device 1100 to perform corresponding functions according one or more embodiments of the present disclosure.

The transmitting device 1100 may additionally comprise power-supply circuitry (not illustrated) configured to supply the transmitting device 1100 with power.

It should be noted that the above-mentioned examples illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative examples without departing from the scope of the appended statements. The word “comprising” does not exclude the presence of elements or steps other than those listed in a claim, “a” or “an” does not exclude a plurality, and a single processor or other unit may fulfil the functions of several units recited in the statements below. Where the terms, “first”, “second” etc. are used they are to be understood merely as labels for the convenient identification of a particular feature. In particular, they are not to be interpreted as describing the first or the second feature of a plurality of such features (i.e. the first or second of such features to occur in time or space) unless explicitly stated otherwise. Steps in the methods disclosed herein may be carried out in any order unless expressly otherwise stated. Any reference signs in the statements shall not be construed so as to limit their scope.

CLAIMS

1. A transmitting device (202; 300; 1000; 1100) for a wireless communications network (200), the transmitting device comprising a plurality of antennas, processing circuitry (1002), and a machine-readable medium (1004) storing instructions which, when executed by the processing circuitry, cause the transmitting device to:

apply (404) a crest factor reduction process to an input signal to obtain a processed signal to be transmitted to a receiving device (204) in the wireless communications network;

generate (406) an error signal corresponding to a difference between the input signal and the processed signal; and

transmit (410), to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

2. The transmitting device of claim 1, wherein the processing circuitry further causes the transmitting device to:

precode (408) the error signal based on a first channel estimate for the one or more first antennas and a second channel estimate for the one or more second antennas.

3. The transmitting device of claim 2, wherein the processing circuitry further causes the transmitting device to:

precode (402) the input signal based on the first channel estimate.

4. The transmitting device of any of the preceding claims, wherein the one or more first antennas are different to the one or more second antennas.

5. The transmitting device of any of the preceding claims, wherein the error signal is transmitted using fewer antennas than the processed signal.

6. The transmitting device of any of the preceding claims, wherein the processing circuitry further causes the transmitting device to select the one or more second antennas for transmission of the error signal based on one or more of the following:

a modulation and coding scheme applied to the input signal;

a path loss between the transmitting device and the receiving device;

a signal-to-noise ratio of a channel between the transmitting device and the receiving device; and

a channel correlation of the transmitting device.

7. The transmitting device of claim 6, wherein selecting the one or more second antennas for transmission of the error signal based on the modulation and coding scheme applied to the input signal comprises selecting a larger number of antennas for a modulation and coding scheme having a higher data rate.

8. The transmitting device of any of the preceding claims, wherein the input signal is modulated using orthogonal frequency division multiplexing, OFDM.

9. The transmitting device of any of the preceding claims, wherein the input signal is modulated using Quadrature Amplitude Modulation, QAM.

10. The transmitting device of any of the preceding claims, wherein the processing circuitry further causes the transmitting device to:

apply a first digital pre-distortion, DPD, to the error signal; and

apply a second DPD to the processed signal, wherein the first DPD has a higher complexity than the second DPD.

11. The transmitting device of any of the preceding claims, further comprising one or more first amplifiers for amplifying the processed signal and one or more second amplifiers for amplifying the error signal, wherein the one or more second amplifiers have a higher dynamic range than the one or more first amplifiers.

12. The transmitting device of any of the preceding claims, wherein the processing circuitry further causes the transmitting device to apply a power back off to one or more second amplifiers used to amplify the error signal.

13. The transmitting device of any of the preceding claims, wherein the crest factor reduction process comprises one or more of: a peak cancellation process and a clipping and filtering process.

14. The transmitting device of any of the preceding claims wherein the transmitting device is a base station (202; 300) and/or the receiving device is a wireless device (204).

15. A method performed by a transmitting device (202; 300; 1000; 1100) in a wireless communications network (200), the transmitting device comprising a plurality of antennas, the method (400) comprising:

applying (404) a crest factor reduction process to an input signal to obtain a processed signal to be transmitted to a receiving device in the wireless communications network;

generating (406) an error signal corresponding to a difference between the input signal and the processed signal; and

transmitting (410), to the receiving device, the processed signal using one or more first antennas of the plurality of antennas and the error signal using one or more second antennas of the plurality of antennas.

16. The method of claim 15, further comprising:

precoding (408) the error signal based on a first channel estimate for the one or more first antennas and a second channel estimate for the one or more second antennas.

17. The method of claim 16, further comprising:

precoding (402) the input signal based on the first channel estimate.

18. The method of any of claims 15-17, wherein the one or more first antennas are different to the one or more second antennas.

19. The method of any of claims 15-18, wherein the error signal is transmitted using fewer antennas than the processed signal.

20. The method of any of preceding claims 15-19, further comprising selecting the one or more second antennas for transmission of the error signal based on one or more of the following:

a modulation and coding scheme applied to the input signal;

a path loss between the transmitting device and the receiving device;

a signal-to-noise ratio of a channel between the transmitting device and the receiving device; and

a channel correlation of the transmitting device.

21. The method of claim 20, wherein selecting the one or more second antennas for transmission of the error signal based on the modulation and coding scheme applied to the input signal comprises selecting a larger number of antennas for a modulation and coding scheme having a higher data rate.

22. The method of any of claims 15-21, wherein the input signal is modulated using orthogonal frequency division multiplexing, OFDM.

23. The method of any of claims 15-22, wherein the input signal is modulated using Quadrature Amplitude Modulation, QAM.

24. The method of any of claims 15-23, further comprising:

applying a first digital pre-distortion, DPD, to the error signal; and

applying a second DPD to the processed signal, wherein the first DPD has a higher complexity than the second DPD.

25. The method of any of claims 15-24, wherein one or more first amplifiers used to amplify the processed signal have a lower dynamic range than one or more second amplifiers used to amplify the error signal.

26. The method of any of claims 15-25, further comprising applying a power back off to one or more second amplifiers used to amplify the error signal.

27. The method of any of claims 15-26, wherein the crest factor reduction process comprises one or more of: a peak cancellation process and a clipping and filtering process.

28. The method of any of claims 15-27, wherein the transmitting device is a base station and/or the receiving device is a wireless device.

29. A base station (202; 300) configured to perform the method of any of claims 15-28.

30. A computer program comprising instructions which, when executed on at least one processor of a transmitting device, cause the transmitting device to carry out the method according to any one of claims 15-28.

31. A carrier containing the computer program of claim 30, wherein the carrier is one of an electronic signal, optical signal, radio signal, or non-transitory machine-readable storage medium.

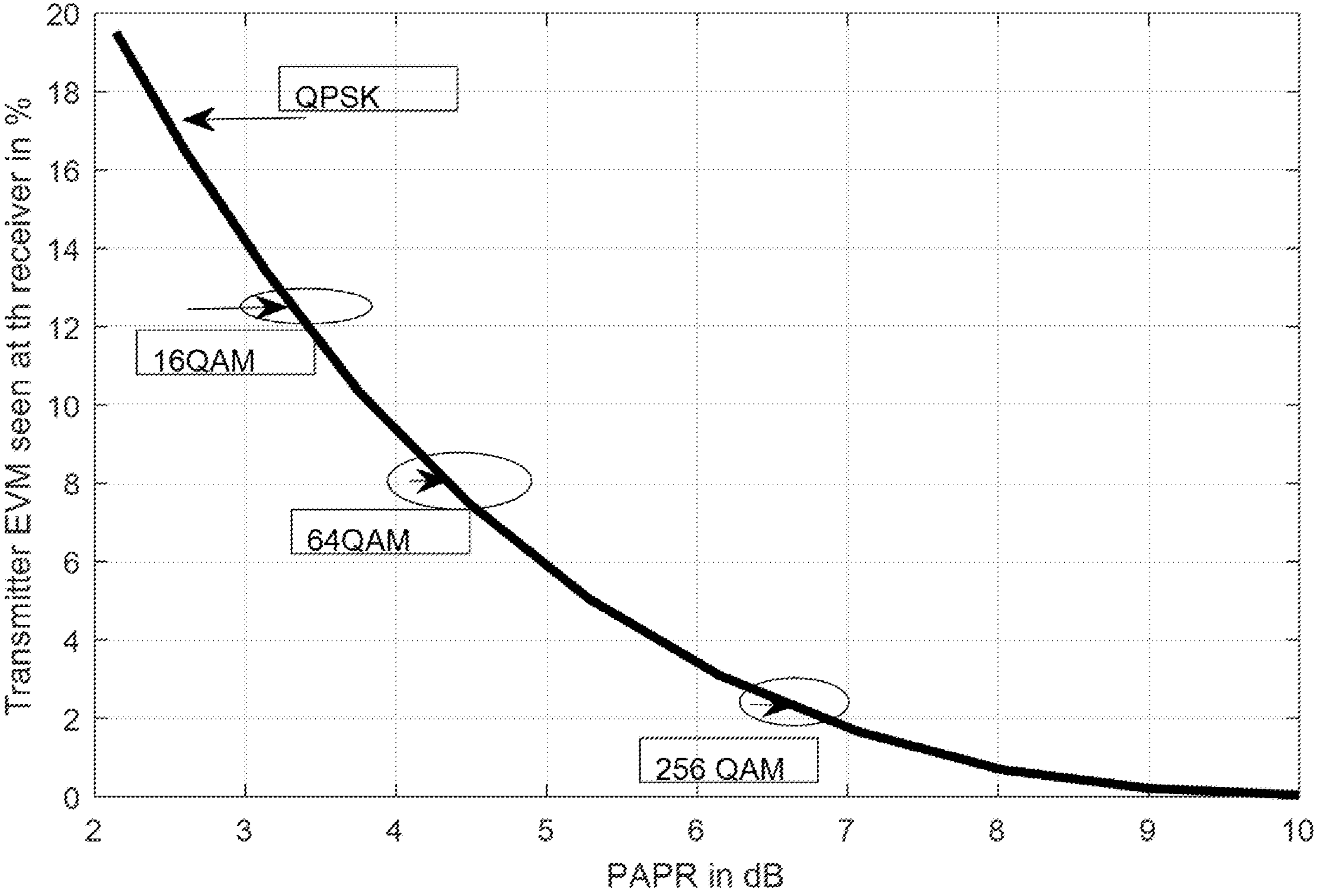
20
18
16
14
12
10
8
6
4
2
0
Transmitter EVM seen at th receiver in %
QPSK
16QAM
64QAM
256 QAM
2
3
4
5
6
7
8
9
10
PAPR in dB

Figure 1

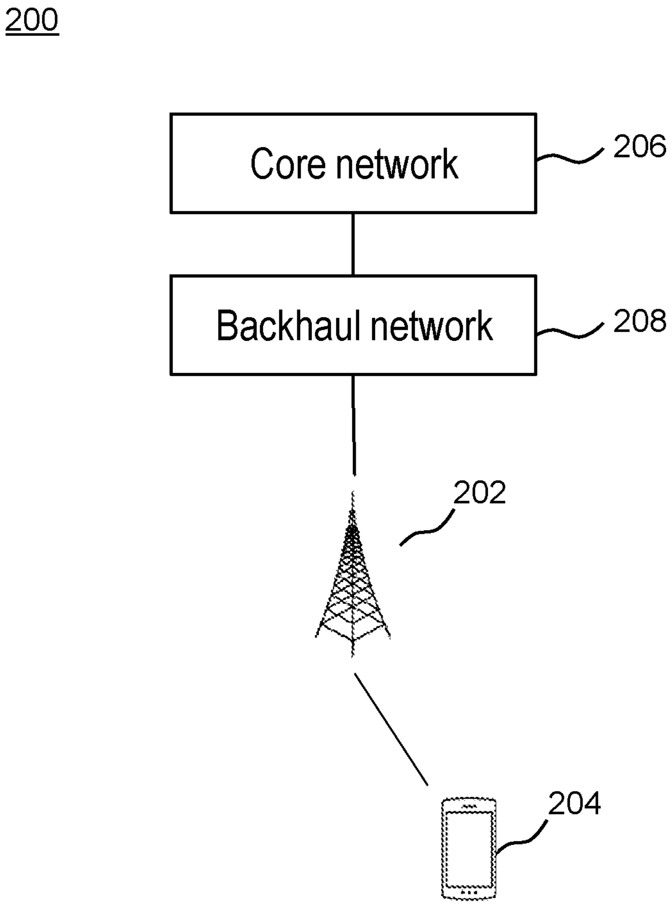

Figure 2

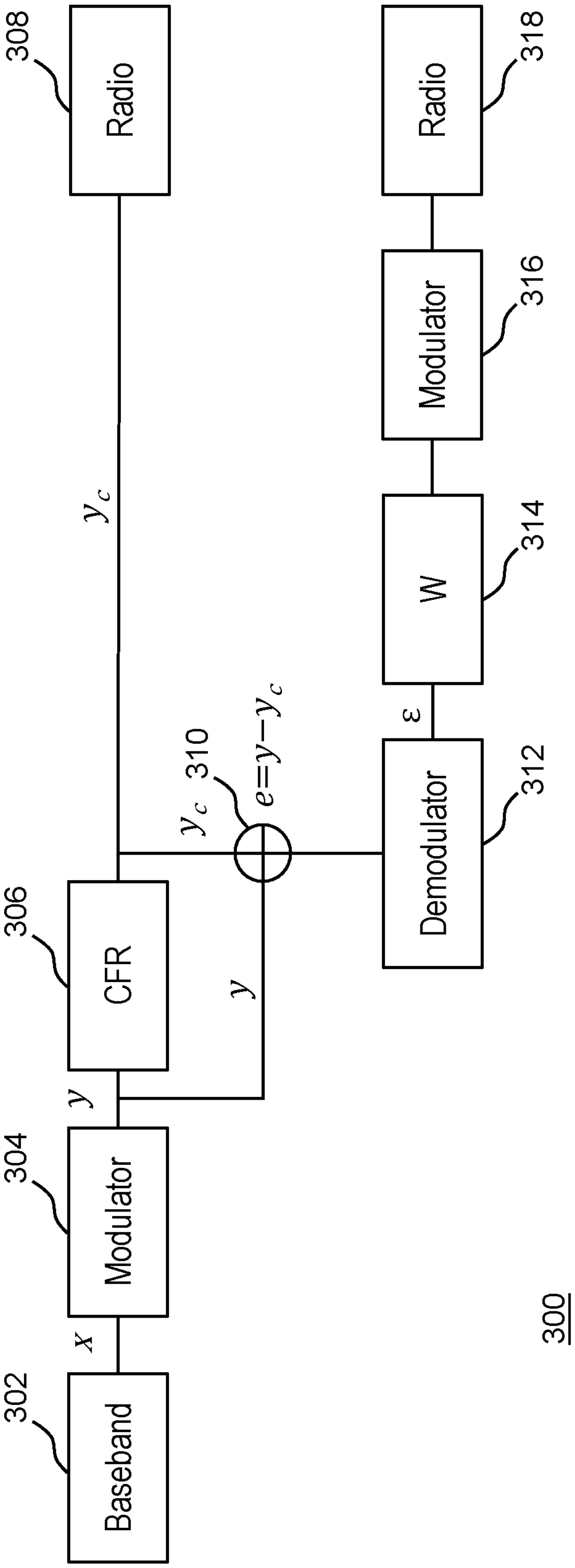
Baseband
302
x
Modulator
304
y
CFR
306
y
y_c
$e=y-y_c$
310
y_c
Radio
308
Demodulator
312
ε
W
314
Modulator
316
Radio
318
300

Figure 3

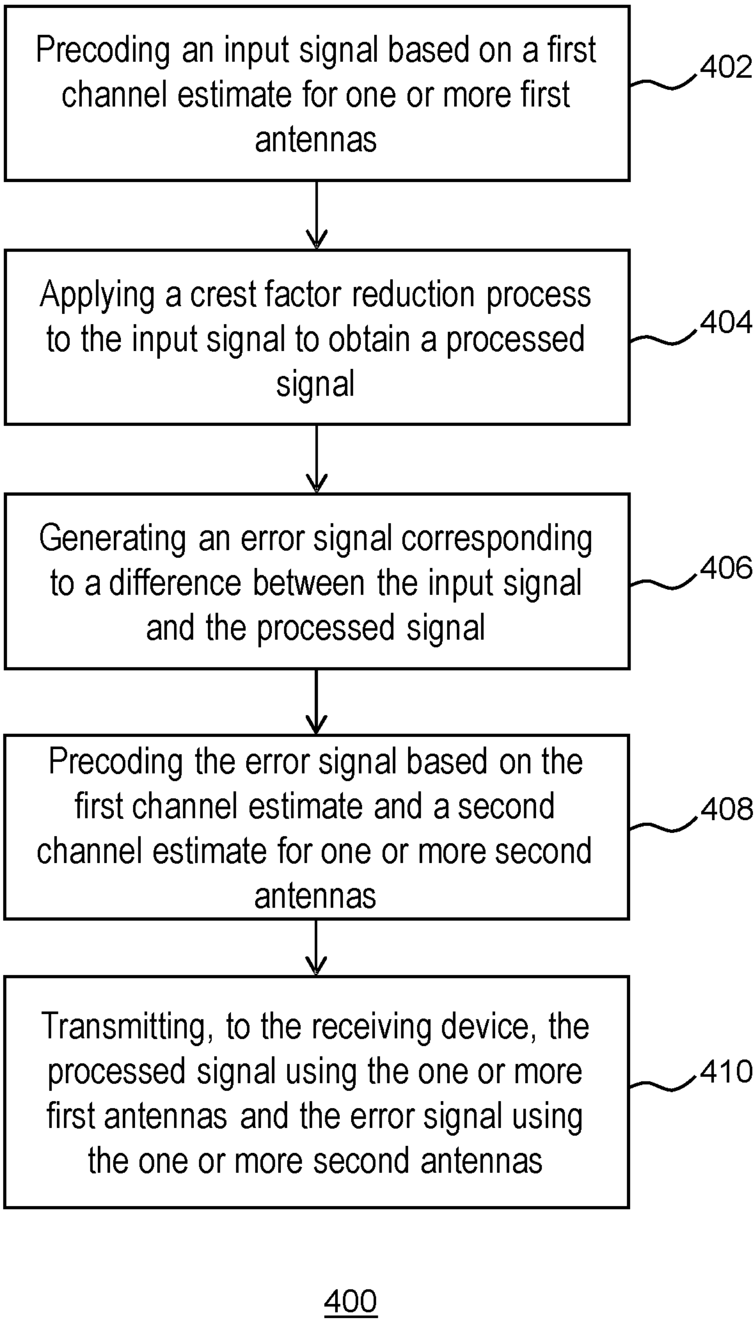
Precoding an input signal based on a first channel estimate for one or more first antennas
402
Applying a crest factor reduction process to the input signal to obtain a processed signal
404
Generating an error signal corresponding to a difference between the input signal and the processed signal
406
Precoding the error signal based on the first channel estimate and a second channel estimate for one or more second antennas
408
Transmitting, to the receiving device, the processed signal using the one or more first antennas and the error signal using the one or more second antennas
410
400

Figure 4

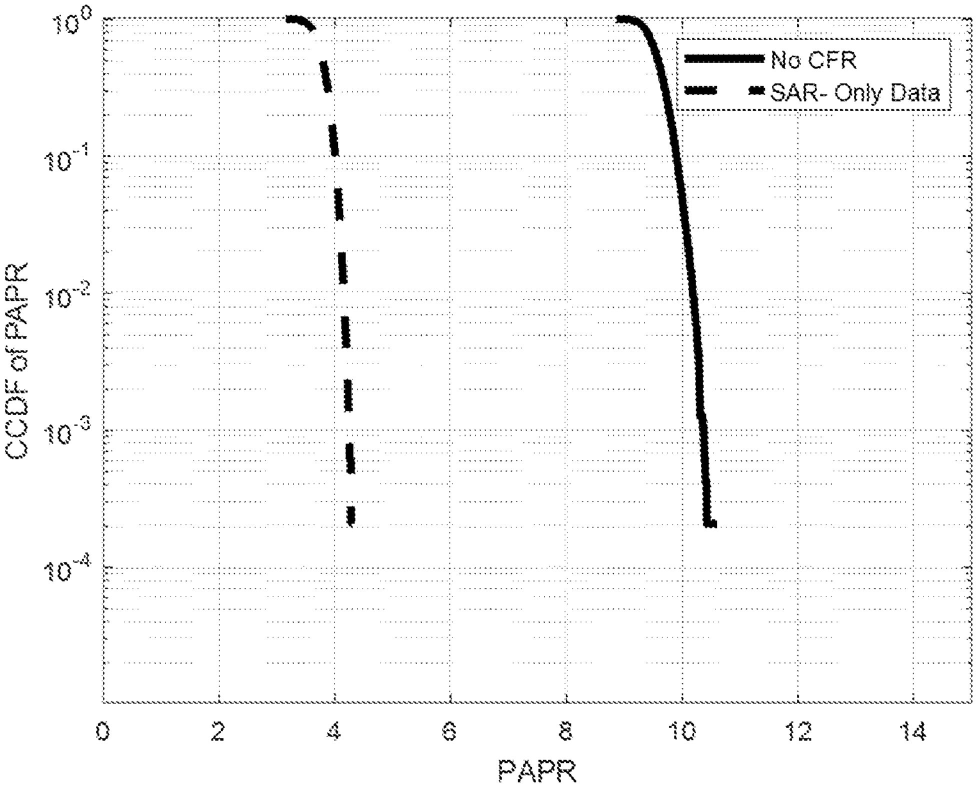

Figure 5

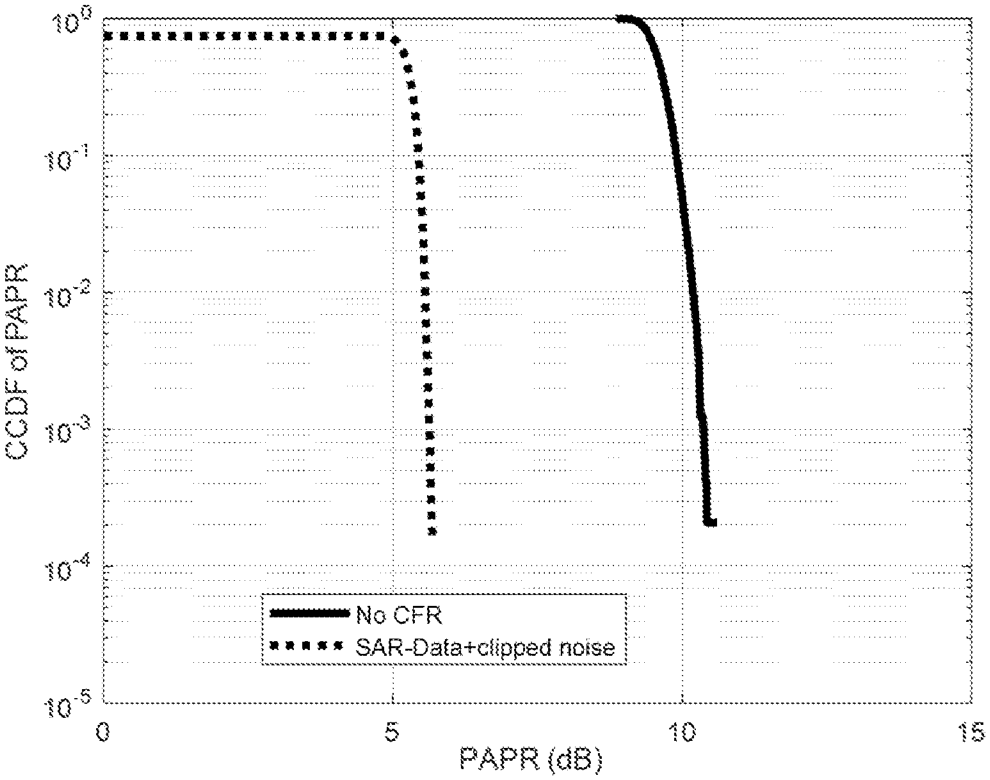

Figure 6

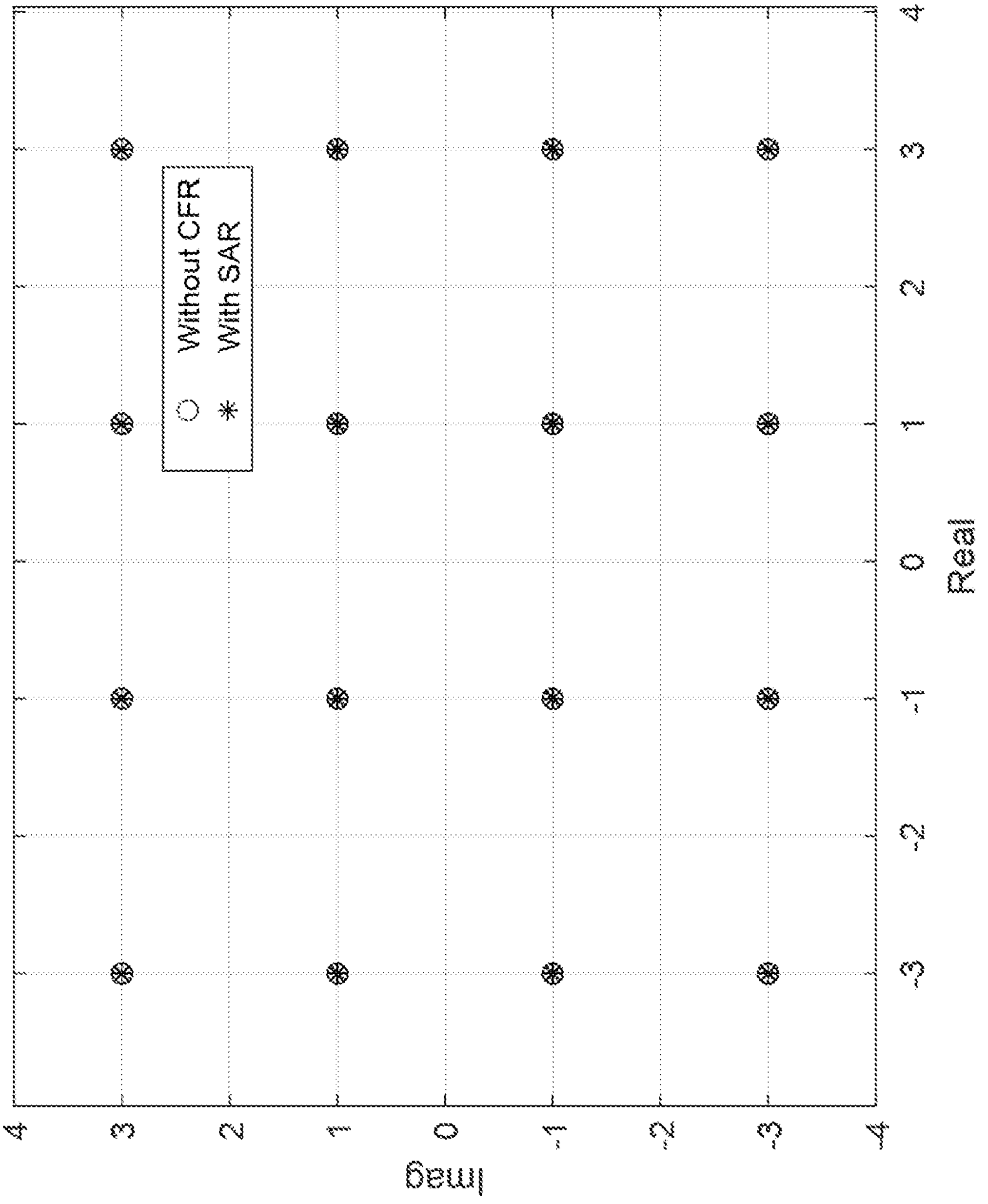

Figure 7

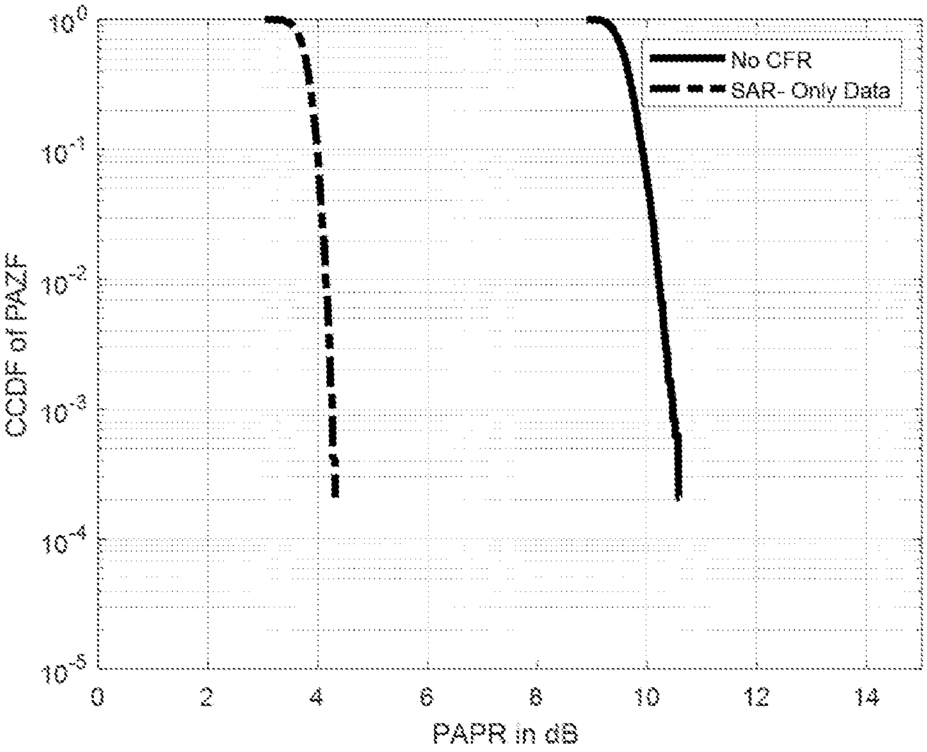

Figure 8

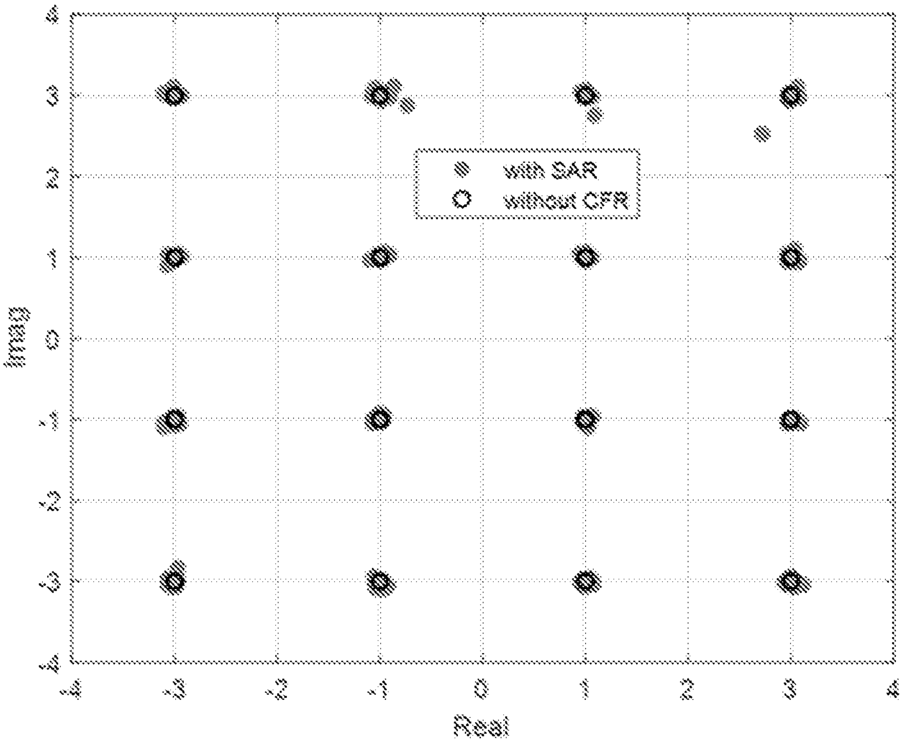

Figure 9

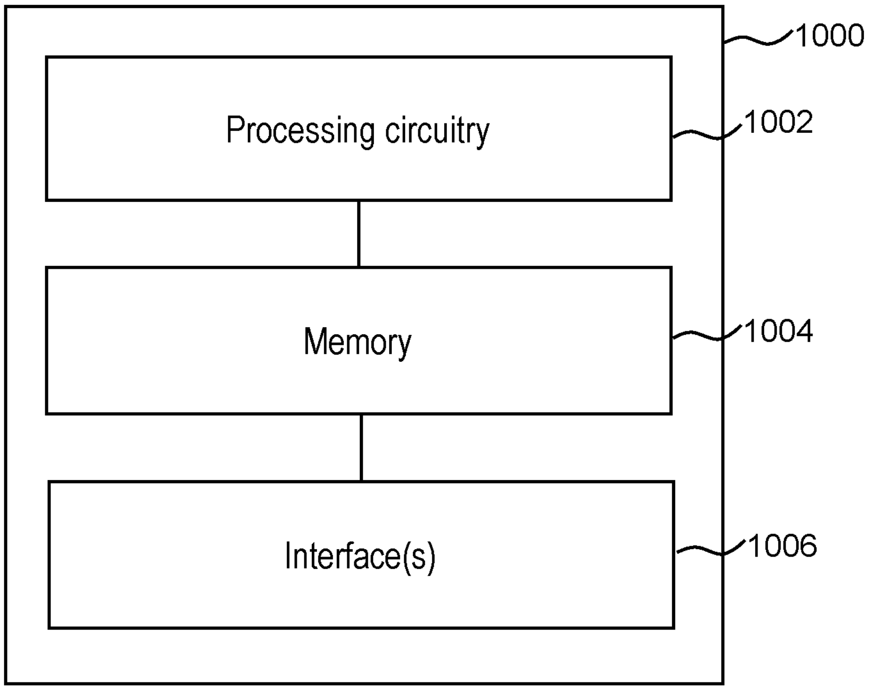

Figure 10

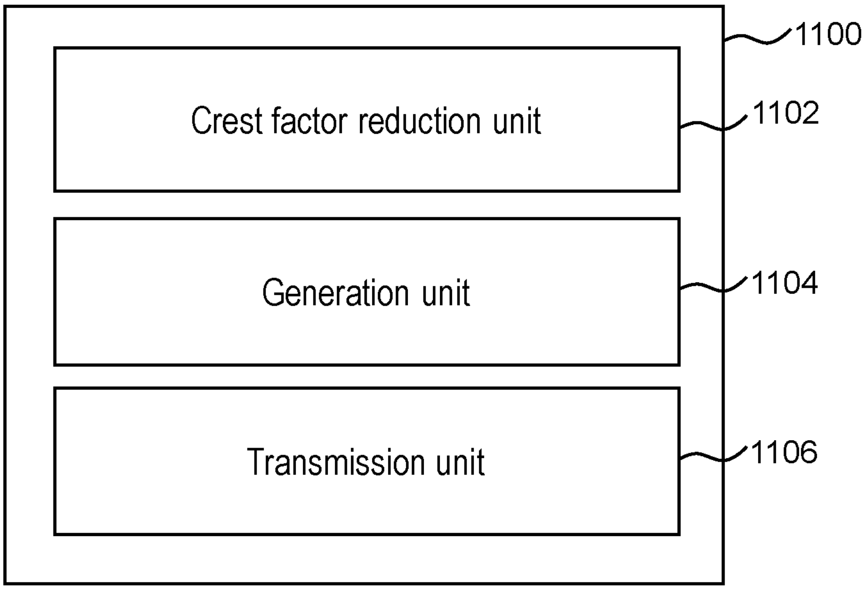

Figure 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2021/050643

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

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)

IPC: H04B, H04L

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

SE, DK, FI, NO classes as above

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

EPO-Internal, PAJ, WPI data, BIOSIS, COMPENDEX, EMBASE, INSPEC, MEDLINE, IBM-TDB, IPRally

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2017076353 A1 (HUAWEI TECH CO LTD), 11 May 2017 (2017-05-11); abstract; paragraphs [0002]-[0003], [0008]-[0009], [0035]-[0036], [0045]-[0046], [0051]; figures 1,9; claims 20-21,25	1-9, 11-23, 25-31
Y	--	10, 24
Y	Liu, X., et al, Energy-efficient power amplifiers and linearization techniques for massive MIMO transmitters: a review, Frontiers of Information Technology & Electronic Engineering, 2020-01-01; figure 15 --	10, 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
“D” document cited by the applicant in the international application
“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 01-03-2022	Date of mailing of the international search report 01-03-2022
Name and mailing address of the ISA/SE Patent- och registreringsverket Box 5055 S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Authorized officer Anders Edlund Telephone No. + 46 8 782 28 00

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2021/050643

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Abdelaziz, M., et at, Reduced-complexity digital predistortion for massive MIMO, IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2017-03-05; figure 1 --	10, 24
Y	Soltani, A., et al, A Comparative Analysis of the Complexity/Accuracy Tradeoff in Power Amplifier Behavioral Models, IEEE Transactions on Microwave Theory and Techniques, 2010-06-01; page 1511, B. Types of Complexity --	10, 24
A	Yoji, M., Tomoya, K., An investigation on current collapse induced memory effects of GaN power amplifier for LTE base station applications, 12th European Microwave Integrated Circuits Conference (EuMIC), 2017-10-08; abstract; Introduction -- --------	11-12, 25-26

Continuation of: second sheet

International Patent Classification (IPC)

H04L 27/26 (2006.01)
H04B 1/62 (2006.01)
H04B 7/0456 (2017.01)
H04L 27/34 (2006.01)
H04L 27/36 (2006.01)

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