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**TECHNIQUES FOR CORRECTING FOR PHASE AND AMPLITUDE
OFFSETS IN A MIMO RADIO DEVICE**

This application claims priority to U.S. Provisional Application No.
5 60/409,677, filed September 10, 2002, the entirety of which is incorporated herein
by reference.

BACKGROUND OF THE INVENTION

The present invention relates to techniques for correcting for the effects of
10 phase and amplitude offsets in radio devices that employ multiple-input multiple-
output (MIMO) radio communication.

MIMO radio communication involves simultaneously transmitting a
plurality of signals from a first device via corresponding ones of a plurality of
antennas and receiving a plurality of signals at a plurality of antennas of a second
15 device. Each device has a plurality of transmitters to upconvert the signals to be
transmitted, and a plurality of receivers to downconvert the signals received at each
of the plurality of antennas.

Many MIMO signal processing algorithms are known in the art. There are
some MIMO radio algorithms that use information about the radio channel between
20 the two devices to maximize the received signal-to-noise ratio (SNR) at each
device. These MIMO radio algorithms rely on channel symmetry of the link
between the two devices. Examples of MIMO radio algorithms that rely on
channel symmetry are disclosed in, for example, commonly assigned U.S. Patent
Application No. 10/174,728, filed June 19, 2002, entitled "System and Method for
25 Antenna Diversity Using Joint Maximal Ratio Combining," U.S. Patent
Application No. 10/174,689 filed June 19, 2002, entitled "System and Method for
Antenna Diversity Using Equal Power Joint Maximal Ratio Combining," and U.S.
Patent Application No. 10/064,482 filed July 18, 2002, entitled "System and
Method for Joint Maximal Ratio Combining Using Time-Domain Signal
30 Processing." These algorithms substantially increase the received signal-to-noise
ratio, and in so doing, extend the range at which devices can communicate with
each other.

Channel symmetry is lost if the transmitter and receiver paths of one device on the link are not identical, which degrades the performance of the MIMO radio algorithm. Mismatches in amplitude (gain) and phase responses between the data converters and antennas in each antenna path of a device due to analog circuit non-idealities in the transmitter and receiver for each antenna path may cause the channel response to become asymmetrical.

In order to fully exploit the benefits of MIMO radio algorithms that depend on channel symmetry in the link between the two devices, techniques are needed for correcting for amplitude and phase mismatches in each device on the MIMO radio link. These techniques are also useful when one device on the link has a MIMO radio and the other device has a single antenna or switched diversity antenna system.

SUMMARY OF THE INVENTION

Briefly, techniques employed by example embodiments of the present invention provide correction for phase and amplitude mismatches (also referred to herein as offsets or imbalances) in a device in order to maintain channel symmetry when communicating with another device using MIMO radio communication techniques that depend on channel symmetry. Correction for the amplitude and phase mismatches among the plurality of transmitters and plurality of receivers of a device may be made at baseband using digital logic (such as in the modem) in the receiver path, the transmitter path or both paths of that device. In a device, amplitude and phase offsets are determined among the plurality of radio transmitter and radio receiver paths by measuring phase and amplitude responses when supplying a signal to a transmitter in a first antenna path of the device and coupling the radio signal from a first antenna to a second antenna path of that device where the signal is downconverted by a receiver associated with the second antenna path, and similarly measuring phase and amplitude responses when coupling a signal from the second antenna path to the first antenna path. Measurements are obtained between the first antenna path and each of the other antenna paths when coupling a signal in both directions between them. Phase and amplitude offset correction values are computed from the phase and amplitude measurements during a self-calibration operation or mode of the

device, and are used during a run-time operation or mode when processing the baseband transmit and/or receive signals to compensate for the phase and amplitude offsets among the plurality of transceiver paths of a device.

Amplitude offset correction may not be necessary (or optional) for certain radio implementations or MIMO radio algorithms. The device may execute the self-calibration mode on device power-up, and then periodically thereafter. Self-calibration may also be performed at the factory on a device.

When a first device calibrated as described herein communicates with a second device similarly calibrated, the channel response between the digital input (DAC input) of the transmit paths of the first device to the digital output (ADC output) of the receive paths of the second device is symmetrical to the channel response between the digital input (DAC input) of the transmit paths of the second device to the digital output (ADC output) of the receive paths of the first device. Thus, the channel responses between the two devices at the baseband signal processing level are symmetrical, which is desirable for MIMO radio algorithms that depend on channel symmetry.

These techniques are useful for single carrier modulation systems as well as multi-carrier modulation systems, such as an orthogonal frequency division multiplex (OFDM) system.

In accordance with one aspect of the present invention, there is provided a radio device comprising: a. a plurality of transmitters that upconvert corresponding ones of a plurality of baseband transmit signals for simultaneous transmission via corresponding ones of a plurality of antennas; b. a plurality of receivers that downconvert a plurality of radio signals detected by corresponding ones of the plurality of antennas to produce a corresponding plurality of baseband receive signals; and c. a processor coupled to the plurality of transmitters and the plurality of receivers, wherein the processor measures differences in phase responses among the plurality of transmitters and plurality of receivers by measuring a first phase difference between an input to a transmitter associated with a first antenna and an output of a receiver associated with antenna i , and a second phase difference between an input to a transmitter associated with antenna i and an output of a receiver associated with the first antenna, for $i = 2$ to N , where N is the number of antennas, and the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding correction values that correct for differences in broadband phase responses among the plurality of transmitters and plurality of receivers.

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In accordance with a second aspect of the present invention, there is provided a radio device comprising: a. a plurality of transmitters that upconvert corresponding ones of a plurality of baseband transmit signals for simultaneous transmission via corresponding ones of a plurality of antennas; b. a plurality of receivers that downconvert a plurality of radio signals detected by corresponding ones of the plurality of antennas to produce a corresponding plurality of baseband receive signals; and c. a processor coupled to the plurality of transmitters and the plurality of receivers that measures phase offsets at a plurality of sub-carriers k associated with a multi-carrier baseband modulation process used for the plurality of baseband transmit signals and the plurality of baseband receive signals, by measuring at each sub-carrier k a first phase difference when a multi-carrier baseband signal is applied at an input to the transmitter associated with the first antenna and coupled as receive input to the receiver associated with antenna i via an over-the-air link or a cable connection, and measuring at each sub-carrier k a second phase difference when a multi-carrier signal is applied at an input to the transmitter associated with antenna i and coupled as a receive input to the receiver associated with the first antenna via an over-the-air link or a cable connection, for $i = 2$ to N , where N is the number of antennas, and wherein the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with correction values that correct for the phase offsets measured at each of the plurality of sub-carriers k .

In accordance with a third aspect of the present invention, there is provided a method for calibrating a radio device that comprises a plurality of antennas, a corresponding plurality of receivers and a corresponding plurality of transmitters, the method comprising steps of: a. measuring phase responses of the plurality of transmitters and the plurality of receivers; comprising measuring a first phase difference between an input to a transmitter associated with a first antenna and an output of a receiver associated with antenna i , and a second phase difference between an input to a transmitter associated with antenna i and an output of a receiver associated with the first antenna, for $i = 2$ to N , where N is the number of antennas; and b. computing a plurality of correction values from the phase differences to correct for differences in broadband phase responses of the plurality of transmitters and the plurality of receivers.

Advantages of the present invention will become more apparent when reference is made to the following description taken in conjunction with the accompanying drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing two communication devices that communicate with each other using MIMO radio techniques.

FIG. 2 is a more detailed block diagram of a device and showing sources of phase offsets among a plurality of radio transmitters and receivers.

FIG. 3 is a general block diagram of a communication device that employs techniques to correct for the phase offsets shown.

FIG. 4 is a block diagram of a device in which phase and amplitude offsets are corrected for using all pass filters and alignment matrices for single carrier or orthogonal frequency division multiplex (OFDM) systems.

FIG. 5 is a block diagram of a device in which phase and amplitude offsets are corrected for using alignment matrices for OFDM systems.

FIG. 6 is a block diagram showing how correction for offsets can be made in the receive path, transmit path, or both paths of a device.

FIG. 7 is a block diagram showing how a low pass filter may be shared between transmit and receive paths to simplify correction or calibration.

FIG. 8 is a contour plot that shows the average loss in link margin due to amplitude and phase offsets, when correction is not made.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring first to FIG. 1, the effects of amplitude and phase mismatches in an $N \times M$ MIMO channel will be described. L_1 and L_2 denote the channel response matrix from a first device 100, e.g., an AP to a second device 200, e.g., a STA, and STA to AP, respectively. A symmetrical MIMO channel has the property that $L_1 = L_2^T$.

Device 100 has N antennas 110(1) to 110(N) and device 200 has M antennas 210(1) to 210(M). Thus, device 100 has N transmit paths and N receive paths and device 200 has M transmit paths and M receive paths. Associated with each transmit path in device 100, there is a digital-to-analog converter (DAC) 115(1) to 115(N) that converts a digital baseband signal to an analog signal for transmission via a corresponding one of the antennas 110(1) through 110(N). Associated with each receive path in device 100 there is an analog-to-digital converter (ADC) 130(1) to 130(N) that converts an analog receive signal to a digital baseband signal. Likewise, in device 200, there is a DAC 220(1) to 220 (M) in each transmit path and an ADC 230(1) to 230(M) in each receive path. Furthermore, device 100 has a modem 140 and device 200 has a modem 240. The modems 140 and 240 are processors that may be implemented by digital logic gates in application specific integrated circuits (ASICs).

For indoor radio communication systems such as an IEEE 802.11x wireless local area network (WLAN) in which a group of network terminals use carrier sense multiple access (CSMA) to exchange data at the same carrier frequency, the channel response between any two terminals is indeed symmetrical, but only

5 between their antenna arrays. For example, the amplitude and phase response between the DAC 115(1) and antenna 110(1) for a first transmit path of the first device 100 is generally different from the amplitude and phase response between the antenna 110(1) and ADC 130(1) of a first receive path of the same device 100. Moreover, the amplitude and phase response between the DAC 115(2) and the

10 antenna 110(2) for a second transmit path of the first device 100 is different from the amplitude and phase response between the DAC 220(1) and antenna 210(1) for a first transmit path of the second device 200. In order to exploit MIMO radio algorithms that depend on channel symmetry, the channel responses at baseband where the MIMO radio algorithm computations are applied need to be symmetric.

15 Therefore, the effects of the amplitude and phase responses for the entire non-digital portion of the channel (e.g., from the DAC input to the transmitter paths to the ADC output of the receiver paths) must be accounted for, which includes the amplitude and phase responses of the transmitter components between each DAC and the corresponding antenna, and the amplitude and phase responses of the

20 receiver components between an antenna and the corresponding ADC.

With amplitude and phase mismatch, the channel response matrices as seen by the logic of the modems 140 and 240 are modified as follows:

$$\text{Device 100 to Device 200: } L_1 = B_2 H A_1$$

$$\text{Device 200 to Device 100: } L_2 = B_1 H^T A_2$$

25 where A_1 , A_2 are diagonal matrices that represent phase and amplitude imbalance caused by the transmitters in devices 100 and 200, respectively, and B_1 , B_2 are diagonal matrices that represent phase and amplitude imbalance caused by the receivers in devices 100 and 200, respectively, where:

$$\begin{aligned} A_1 &= \text{diag}(\alpha_{11}e^{j\phi_{11}}, \dots, \alpha_{1N}e^{j\phi_{1N}}) \\ 30 \quad A_2 &= \text{diag}(\alpha_{21}e^{j\phi_{21}}, \dots, \alpha_{2M}e^{j\phi_{2M}}) \\ B_1 &= \text{diag}(\beta_{11}e^{j\phi_{11}}, \dots, \beta_{1N}e^{j\phi_{1N}}) \\ B_2 &= \text{diag}(\beta_{21}e^{j\phi_{21}}, \dots, \beta_{2M}e^{j\phi_{2M}}) \end{aligned}$$

The phase and amplitude effects in the transmit and receive paths of each device are represented by corresponding values of the diagonal matrices A_1 , A_2 and B_1 , B_2 .

The transmit weights for the n -th iteration of a MIMO radio algorithm disclosed in the aforementioned co-pending applications are:

$$\begin{aligned} 5 \quad w_{T,AP,n} &= \gamma_n (L_2^* L_1)^n w_{T,AP,0} \\ w_{T,STA,n} &= \rho_n L_1^* (L_2 L_1^*)^n w_{T,AP,0}, \end{aligned}$$

where γ_n and ρ_n are scale factors used to normalize the transmit power to unity. It can be shown that the weights converge via a power iteration to the dominant eigenvectors for $L_2^* L_1$ and $L_1^* L_2$, respectively.

10 With reference to FIG. 2, further details of a device 100 (having N antennas) are shown to explain sources of phase offsets. There is a plurality of radio transceivers, each radio transceiver associated with a corresponding one of the plurality of antennas 110(1) to 110(N). Each radio transceiver comprises a transmitter 120(i) and a receiver 135(i) associated with a corresponding one of the
15 plurality of antennas, for $i = 1$ to N . The radio transmitter 120(i) upconverts a baseband signal supplied by the associated DAC 115(i) to a radio frequency signal for transmission by a corresponding antenna 110(i). The receiver 135(i) downconverts a radio frequency signal detected by a corresponding antenna 110(i). The plurality of radio transceivers may be referred to as a MIMO radio.

20 The components contained in each transmitter 120(i) and receiver 135(i) can vary depending on the type of radio architecture employed, e.g., superheterodyne or direct-conversion. FIG. 2 shows, as an example only, components that may be found in a direct-conversion architecture, but it should be understood that the concepts of the calibration techniques described herein may
25 apply to any type of radio architecture. For example, FIG. 2 shows that each transmitter 120(i) comprises an upconverter mixer 150(i), a power amplifier 165(i) and other miscellaneous components. Each receiver 135(i) comprises, for example, among other components, a low noise amplifier 167(i) and a downconverter mixer 155(i). A switch 137(i) associated with each antenna 110(i) selects whether the
30 transmitter 120(i) or receiver 135(i) is connected to the antenna 110(i). On the baseband side, there is a low pass filter 125(i) in the transmitter path between the

DAC 115(i) and RF portion of the transmitter 120(i), and a low pass filter 127(i) in the receiver path between the ADC 130(i) and the receiver 135(i).

As indicated in FIG. 2, the plurality of transmitters and plurality of receivers may be implemented on a single semiconductor integrated circuit (IC). A fully integrated MIMO radio is disclosed in co-pending commonly assigned U.S. Patent Application No. 10/065,388, filed October 11, 2002, the entirety of which is incorporated herein by reference. Thus, a MIMO radio may consist of a plurality of separate radio transceivers, or a single IC on which a plurality of radio transceivers are implemented.

Sources of phase offsets ϕ_{ITx} , ϕ_{IRx} to ϕ_{NTx} , ϕ_{NRx} may include differences in local oscillator phase at the mixers 150(i) and 155(i) for each path, and small group delay differences among other radio components. Phase offsets may vary over process, voltage, and temperature. Group delay differences $\tau_{RFTx(1)}$, $\tau_{RFRx(1)}$, to $\tau_{RFTx(N)}$, $\tau_{RFRx(N)}$ among radio frequency (RF) components are on the order of tens of picoseconds, which cause phase offsets that vary slowly over the entire band of operation. For example, a 50 ps group delay offset causes a phase offset of 92.7 degrees at 5.15 GHz, and 96.3 degrees at 5.35 GHz. These types of offsets, therefore, may be corrected for at one frequency for each band of operation. Group delay differences among intermediate frequency (IF) components in a superheterodyne radio architecture (e.g., IF filters, AGC amplifiers, not shown in FIG. 2) may be 1 or 2 orders of magnitude larger than RF group delay offsets, thereby causing phase offsets that vary more rapidly across the band. Therefore, correction may be needed in each radio channel for designs using IF components. Group delay differences $\tau_{BBTx(1)}$, $\tau_{BBRx(1)}$, to $\tau_{BBTx(N)}$, $\tau_{BBRx(N)}$ among baseband components (e.g., lowpass filters, pipeline latency differences among ADCs and DACs) are, for IEEE 802.11x signal bandwidths, on the order of nanoseconds, and can therefore cause significant phase changes that vary even within the bandwidth of one channel.

One way to ensure optimal performance of the MIMO radio algorithms that depend on channel symmetry is to calibrate each device to ensure channel symmetry after calibration. In some cases, this involves correcting for phase and amplitude offsets, and in other cases, for phase offsets only. For example,

simulations have shown that the equal-power MIMO radio algorithm disclosed in the aforementioned co-pending and commonly assigned application has advantages over a non-equal power MIMO radio algorithm because the equal-power algorithm is immune to even relatively large amplitude offsets.

- 5 Generally, correction in the transmit side for each device may be achieved by multiplying the transmit weights by a correction matrix $C = \text{diag}(c_1, \dots, c_N)$, where $c_1 = \gamma_1 \exp(j\chi_1), \dots, c_N = \gamma_N \exp(j\chi_N)$, where γ_i is the amplitude correction component and χ_i is the phase correction component. The modified channel response matrices become $L_1 = B_2 H A_1 C_1$ and $L_2 = B_1 H^T A_2 C_2$.

- 10 A sufficient condition to ensure channel symmetry in the link is

$$B_1 = A_1 C_1 \text{ and } B_2 = A_2 C_2 \quad (1)$$

This condition guarantees a symmetric channel since

$$L_2^T = (B_1 H^T A_2 C_2)^T = B_2^T H A_1^T C_1^T = B_2 H A_1 C_1 = L_1.$$

Referring back to FIG. 1, an equivalent way to write condition (1) for an N

- 15 x M symmetric MIMO radio channel is:

$$\gamma_{11}\alpha_{11}/\beta_{11}\exp[j(\chi_{11} + \theta_{11} - \phi_{11})] = \gamma_{12}\alpha_{12}/\beta_{12}\exp[j(\chi_{12} + \theta_{12} - \phi_{12})] = \dots = \gamma_{1N}\alpha_{1N}/\beta_{1N}\exp[j(\chi_{1N} + \theta_{1N} - \phi_{1N})]; \text{ and}$$

$$\gamma_{21}\alpha_{21}/\beta_{21}\exp[j(\chi_{21} + \theta_{21} - \phi_{21})] = \gamma_{22}\alpha_{22}/\beta_{22}\exp[j(\chi_{22} + \theta_{22} - \phi_{22})] = \dots = \gamma_{2M}\alpha_{2M}/\beta_{2M}\exp[j(\chi_{2M} + \theta_{2M} - \phi_{2M})],$$

- 20 θ and ϕ are the phase responses and α and β are the amplitude responses of the transmitters and receivers, respectively, of the devices 100 and 200. The subscripts i,j used in FIG. 1 indicates the device i , (device 1 meaning device 100, or device 2 meaning device 200), and the j -th antenna (or corresponding antenna path) of device i .

Still another equivalent way to write condition (1) is:

- 25 For amplitude,

$$\gamma_{11}\alpha_{11}/\beta_{11} = \gamma_{12}\alpha_{12}/\beta_{12} = \dots = \gamma_{1N}\alpha_{1N}/\beta_{1N}; \text{ and}$$

$$\gamma_{21}\alpha_{21}/\beta_{21} = \gamma_{22}\alpha_{22}/\beta_{22} = \dots = \gamma_{2M}\alpha_{2M}/\beta_{2M};$$

For phase,

$$[\chi_{11} + \theta_{11} - \phi_{11}] = [\chi_{12} + \theta_{12} - \phi_{12}] = \dots = [\chi_{1N} + \theta_{1N} - \phi_{1N}]; \text{ and}$$

- 30 $[\chi_{21} + \theta_{21} - \phi_{21}] = [\chi_{22} + \theta_{22} - \phi_{22}] = \dots = [\chi_{2M} + \theta_{2M} - \phi_{2M}]$

$2(N-1)$ and $2(M-1)$ linearly independent equations are required to specify

this condition for side 1 and side 2, respectively:

$$[\chi_{11} + \theta_{11} - \phi_{11}] = [\chi_{12} + \theta_{12} - \phi_{12}]; \gamma_{11}\alpha_{11}/\beta_{11} = \gamma_{12}\alpha_{12}/\beta_{12}$$

$$[\chi_{11} + \theta_{11} - \phi_{11}] = [\chi_{13} + \theta_{13} - \phi_{13}]; \gamma_{11}\alpha_{11}/\beta_{11} = \gamma_{13}\alpha_{13}/\beta_{13}$$

...

$$[\chi_{11} + \theta_{11} - \phi_{11}] = [\chi_{1N} + \theta_{1N} - \phi_{1N}]; \gamma_{11}\alpha_{11}/\beta_{11} = \gamma_{1N}\alpha_{1N}/\beta_{1N}; \text{ and}$$

$$5 \quad [\chi_{21} + \theta_{21} - \phi_{21}] = [\chi_{22} + \theta_{22} - \phi_{22}]; \gamma_{21}\alpha_{21}/\beta_{21} = \gamma_{22}\alpha_{22}/\beta_{22}$$

$$[\chi_{21} + \theta_{21} - \phi_{21}] = [\chi_{23} + \theta_{23} - \phi_{23}]; \gamma_{21}\alpha_{21}/\beta_{21} = \gamma_{23}\alpha_{23}/\beta_{23}$$

...

$$[\chi_{21} + \theta_{21} - \phi_{21}] = [\chi_{2M} + \theta_{2M} - \phi_{2M}]; \gamma_{21}\alpha_{21}/\beta_{21} = \gamma_{2M}\alpha_{2M}/\beta_{2M}$$

The above-equations may be re-written for one device on the link, e.g., the

10 N-side, as follows:

$$[\chi_1 + \theta_1 - \phi_1] = [\chi_2 + \theta_2 - \phi_2]; \gamma_1\alpha_1/\beta_1 = \gamma_2\alpha_2/\beta_2$$

$$[\chi_1 + \theta_1 - \phi_1] = [\chi_3 + \theta_3 - \phi_3]; \gamma_1\alpha_1/\beta_1 = \gamma_3\alpha_3/\beta_3$$

...

$$[\chi_1 + \theta_1 - \phi_1] = [\chi_N + \theta_N - \phi_N]; \gamma_1\alpha_1/\beta_1 = \gamma_N\alpha_N/\beta_N; \quad (2a)$$

15 After some algebraic manipulation, equation (2a) may be equivalently written as follows:

$$[\chi_1 + \theta_1 + \phi_2] = [\chi_2 + \theta_2 + \phi_1]; \gamma_1\alpha_1\beta_2 = \gamma_2\alpha_2\beta_1$$

$$[\chi_1 + \theta_1 + \phi_3] = [\chi_3 + \theta_3 + \phi_1]; \gamma_1\alpha_1\beta_2 = \gamma_3\alpha_3\beta_1$$

...

$$20 \quad [\chi_1 + \theta_1 + \phi_N] = [\chi_N + \theta_N + \phi_1]; \gamma_1\alpha_1\beta_2 = \gamma_N\alpha_N/\beta_1 \quad (2b)$$

In equations (2a) and (2b), the first subscript has been dropped to indicate that without loss of generality, the equations can be used on either side of the link.

To ensure channel symmetry, the relationship of equations (2a) or (2b), which are equivalent, must hold at both devices on the link. The relationships of equations (2a) and (2b) are described below. Some basic nomenclature is first provided. At a device, for each antenna there is a corresponding transmitter that upconverts a signal for transmission by that antenna and a corresponding receiver that downconverts a signal detected by that antenna. Moreover, each antenna has a corresponding antenna path in both transmit and receive directions. The signal path from the input of a transmitter to the output of its corresponding antenna may be referred to as a transmit path for that antenna. Likewise, the signal path from

the input of an antenna to the output of the corresponding receiver may be referred to as a receive path for that antenna. Phase and (optionally) amplitude offset correction values are applied to signals (in the transmit path direction, receive path direction, or both directions) for each antenna path associated with the plurality of antennas.

One way to describe the relationship of equation (2a) is that in a device, the difference between (a) the amplitude and phase response from an input of a transmitter to the output of its corresponding antenna and (b) the amplitude and phase response from the input of that antenna to the output of its corresponding receiver is the same (and is constant) for all antennas ($i = 1$ to N of an N -antenna device). One way to describe the relationship of equation (2b) is that in a device, (a) the amplitude and phase response from an input to a transmitter associated with one antenna (e.g., antenna 1) to the output of the receiver associated with another antenna (e.g., antenna i) is equal to (b) the amplitude and phase response from the input of the transmitter associated with antenna i to the output of the receiver associated with antenna 1, for all antennas ($i = 2$ to N of an N -antenna device).

The explanation of equation (2b) suggests a loop-back configuration, described hereinafter, may be used to obtain measurements needed to compute the correction values γ_i and χ_i to correct for the amplitude and phase offsets among the plurality of transmitters and plurality of receivers of a device, thereby satisfying the condition of equation (2b) when that device transmits and receives signals. To reiterate, correction values that satisfy equation (2b) will also satisfy the equivalent equation (2a).

FIG. 3 shows device 100 having a MIMO radio 160 for which correction values (χ_i and γ_i) are computed in order to achieve the condition of equations (2a) or (2b). The modem 140 comprises a calibration computation block 145 that generates the signals to be used for the calibration measurement procedure, makes the measurements and computes and stores the correction values. The modem 140 also has a correction block 147 that applies correction values to the baseband transmit signals or transmit weights, or to the baseband receive signals, or to both the baseband transmit signals and baseband receive signals to achieve a desired net correction. There are many techniques for generating the calibration parameters

and applying those parameters as described hereinafter. A controller processor 170, such as a microprocessor, may generate a signal coupled to the modem 140 to initiate a self-calibration mode at initial power up of the device, and/or periodically or occasionally thereafter to update the calibration parameters. Each device that
5 relies on a symmetrical link with another device will self-calibrate in a similar manner. The correction values are also referred herein as alignment values and/or calibration parameters.

In the case where variable gain amplifiers are used in the receivers and/or transmitters, calibration can take into account the changes in phase with respect to
10 the applied gain setting of these components. One technique is to determine the phase versus gain setting relationship of receiver and transmitter components, and store adjustments to gain-independent correction values (such as in a table) in the memory 165, or alternatively, hard-code those adjustments in the digital logic of the modem 140 as shown in FIG. 3. These gain-dependent adjustments to the
15 correction values may be generated at the factory one time, and then during a run-time operation or mode of the device in the field, the adjustments are used according to the current gain setting(s) of the device. Alternatively, gain-dependent adjustments for the correction values may be computed in the field during a self-calibration mode or operation. Gain-independent correction values
20 may be computed during a self-calibration mode of a device in the field and/or at the factory. Gain-dependent adjustments to the correction values may be generated (at the factory or in the field) using techniques as described below in conjunction with FIGs. 4 and 5 at each gain setting.

The calibration logic is located in the modem 140 because the modem is
25 typically implemented with digital logic gates in an ASIC that processes the baseband signals. It should be understood that for certain applications, or with the advancement of microprocessor capabilities for portable or embedded applications, the calibration logic may be implemented in software stored or encoded in a processor readable memory medium and executed by the processor 170 (that also
30 executes the modem logic).

After a calibration session is performed, correction values are used when processing baseband transmit signals and/or baseband receive signals to achieve

the condition of equations (2a) or (2b). When a first device calibrated to these conditions communicates with a second device similarly calibrated, the channel response between the digital input (DAC input) of the transmit paths of the first device to the digital output (ADC output) of the receive paths of the second device is symmetrical to the channel response between the digital input (DAC input) of the transmit paths of the second device to the digital output (ADC output) of the receive paths of the first device. Thus, the channel response between the two devices at the baseband signal processing level is symmetrical, which is desirable for MIMO radio algorithms that depend on channel symmetry.

For relatively large group delay offsets (usually caused by baseband transmitter and/or receiver components), the phase mismatch among transceiver paths will vary within the bandwidth of the transmitted signal, thus requiring phase alignment that varies over frequency. As shown in FIG. 5 and described hereinafter, for multi-carrier modulation systems such as orthogonal frequency division multiplexed (OFDM) systems, this may be accomplished by using different phase alignment matrices $C(k)$ for each OFDM sub-carrier in either the transmitter, the receiver, or both. Another approach shown in FIG. 4 and described hereinafter is to align the group delay of each transceiver path using (1) an all pass filter (e.g., a re-sampler) in the either the transmitter, receiver or both, and (2) frequency non-selective phase correction values (a single frequency independent correction matrix) to compensate for broadband phase offsets. The re-sampler may be a Farrow type re-sampler process, as an example.

Turning to FIG. 4, the relevant portions of an N-antenna device (such as device 100 shown in FIG. 3) capable of MIMO radio communication are shown where correction for amplitude and phase offsets are made. The approach of FIG. 4 is useful for single carrier or multi-carrier modulation systems. The modem 140 is shown comprising the calibration computation block 145 and the correction block 147. The correction block 147 comprises all pass filters 180(1) to 180(N) and multipliers 190(1) to 190(N). The multipliers 190(1) to 190(N) apply corresponding elements of the single (frequency-nonselective) correction matrix $C = \text{diag}(c_1, \dots, c_N)$, where c_i is defined as $\gamma_i \exp(j\chi_i)$ to compensate for phase offsets

and amplitude offsets. The components of phase correction values χ_i are described in more detail below.

The approach shown in FIG. 4 performs the baseband group delay alignment in the receiver portion of the modem. This approach is attractive from a gate count perspective because an all pass filter (e.g., re-sampler) is already required in most receiver modem architectures for data timing recovery, and may be useful for single carrier systems, such as IEEE 802.11b, but may also be attractive for multi-carrier systems, such as OFDM systems. As described hereinafter in conjunction with FIG. 6, digital logic gates that implement the all pass filters and multipliers may be in the transmitter paths, receiver paths or both paths to compensate for amplitude and phase offsets.

The multipliers 190(1) to 190(N) may be the same multipliers used to apply the transmit weights w_T to the baseband transmit signals prior to upconversion and transmission. In this case, the transmit weight w_T (a complex number) is multiplied by the corresponding element c_i of the diagonal matrix C .

A procedure to generate the calibration parameters for an N-antenna device shown in FIG. 4 follows. The calibration computation block 145 contains the logic to perform the calibration procedure and to generate the calibration parameters for the all pass filters 180(1) to 180(N) and for the multipliers 190(1) to 190(N).

Step 1. A frequency synthesizer 195 is tuned to a known frequency channel in the radio frequency band of interest. The modem generates a baseband continuous wave (CW) tone $e^{2\pi j\phi_k t}$ that is coupled to the DAC 115(1) associated with antenna 110(1) (antenna path 1) for transmission via antenna 110(1) through transmitter 120(1), and, using either a cable or an over-the-air link, the transmit RF output of antenna path 1 is looped back to the RF input at antenna 110(2) (antenna path 2). A first phase difference between the signal at the input to the DAC 115(1) in antenna path 1 and the signal at the output of the ADC 130(2) in antenna path 2 is measured at a number of frequencies (e.g., $f_k = \{-3f_s/8, -f_s/8, f_s/8, 3f_s/8\}$, where f_s = symbol rate). In general, measurements are made at frequencies that sufficiently span the bandwidth of the baseband signal. The first phase difference $\psi_{12}(k) = [\theta_1(k) + \phi_2(k) + \phi_{ant}(1,2)]$, where $\theta_1(k)$ and $\phi_2(k)$ represent phase shifts through transmitter 120(1) and receiver 135(2) at frequency f_k , respectively, and $\phi_{ant}(1,2)$

represents the phase shifts of the over-the-air or cable connection between antenna 110(1) and antenna 110(2). In addition, a first amplitude $\gamma_{12}(k)$ of the signal at the output of the ADC 130(2) is measured at each frequency f_k .

Step 2. Repeat step 1 using antenna path 2 as the transmitter and antenna path 1 as the receiver to measure a second phase difference $\psi_{21}(k) = [\theta_2(k) + \phi_1(k) + \phi_{ant}(1,2)]$ and to measure a second amplitude $\gamma_{21}(k)$ of the signal at the output of the ADC 130(1) at each of the frequencies f_k .

In steps 1 and 2 above, since the signal transmitted (via a cable or over-the-air) from one antenna path to another will not experience sufficient attenuation before being received, the (low noise) amplifier in the receive path may be turned off or its gain setting turned down (lowered) so that the received signal does not damage the mixer and other components in the receive path.

Step 3. The in-band group delay offset or mismatch between antenna path 1 and antenna path 2 is estimated using the equation:

$\delta\tau_2 = -(1/2\pi) * \text{slope of a best fit line through points } \{(f_k, \psi_{12}(k) - \psi_{21}(k))\}$ across the frequencies f_k .

Step 4. The broadband phase offset or mismatch between the antenna path 1 and an antenna path 2 is estimated using the equation:

$\delta\theta_2 = \text{y-intercept of a best fit line through points } \{(f_k, \psi_{12}(k) - \psi_{21}(k))\}$ across the frequencies f_k .

The amplitude mismatch γ_2 is estimated from an average of the ratios of the first and second measured amplitudes, i.e., $\{(f_k, \gamma_{12}(k)/\gamma_{21}(k))\}$, across the frequencies f_k .

Step 5. Steps 1 - 4 are repeated between antenna paths 1 and i to compute group delay offsets $\delta\tau_i$ and broadband phase offsets $\delta\theta_i$ from points $\{(f_k, \psi_{1i}(k) - \psi_{i1}(k))\}$ across the frequencies f_k , and amplitude offsets γ_i , for $i = 3, \dots, N$ from $\{(f_k, \gamma_{1i}(k)/\gamma_{i1}(k))\}$. The values for $\delta\tau_1, \dots, \delta\tau_N, \delta\theta_1, \dots, \delta\theta_N$, and $\gamma_1, \dots, \gamma_N$ are stored as calibration parameters or correction values, where for the antenna path associated with the first antenna, the group delay offset $\delta\tau_1 = 0$, the broadband phase offset $\delta\theta_1 = 0$ and the amplitude offset $\gamma_1 = 1$. The units for $\delta\tau_i$ are samples at an appropriate sampling rate.

Step 6. The in-band group delay mismatch among transceiver paths may be corrected during normal operation by creating a group delay of $\delta\tau_i$ samples in receiver path i using an all pass filter i for $i = 1, \dots, N$ as shown in FIG. 4. $\delta\tau_i > 0$ implies a delay and $\delta\tau_i < 0$ implies an advance. The broadband phase offsets (and optionally amplitude offsets) among the transceiver paths may be removed by multiplying the transmit weights or the baseband transmit signals with a diagonal alignment matrix, C , where:

$$\begin{aligned} c_1 &= 1 \\ c_2 &= \gamma_2 \exp(j\delta\theta_2) \\ 10 \quad c_3 &= \gamma_3 \exp(j\delta\theta_3) \\ &\dots \\ c_N &= \gamma_N \exp(j\delta\theta_N) \end{aligned}$$

If amplitude offset correction is not performed, then $\gamma_i = 1$ for all i .

Step 7. If necessary, steps 1-6 may be repeated at multiple channels within the RF band to account for slowly varying phase offsets. The phase shifts through the antennas and/or coupling cables do not affect the results of any of the computations. Correction values for each channel may be stored, or a set of channel-independent correction values is stored and channel-dependent adjustments to the channel-independent set of calibration parameters are stored for each channel.

The process of FIG. 4 may be modified by using a multi-carrier modulated signal, e.g., an OFDM signal, instead of multiple tones at frequencies f_k . Moreover, the procedure described above can be generalized or extended to a multi-carrier modulation scheme, such as OFDM, where instead of making phase difference measurements at frequencies f_k across the bandwidth of a single-carrier baseband signal, measurements are made at a plurality of sub-carriers k (not necessarily all sub-carriers k) of a multi-carrier baseband signal, sufficient to perform the linear analysis (slope and y-intercept computations) described above.

To summarize, offsets values are computed for antenna paths corresponding to antennas $i = 1$ to N , where the corresponding broadband phase offset values $\delta\theta_i$ and the corresponding in-band group delay values $\delta\tau_i$, are estimated from the sequence $\{\psi_{1i}(k) - \psi_{1i}(k)\}$ derived from frequencies f_k across the bandwidth of the

baseband signal, where $\psi_{i1}(k)$ is the phase difference (also referred to as a first phase difference) between the input to a transmitter associated with a first antenna and the output of a receiver associated with antenna i at a frequency f_k , and $\psi_{i2}(k)$ is the phase difference (also referred to as a second phase difference) between the
5 input to a transmitter associated with antenna i and the output of a receiver associated with the first antenna at frequency f_k , and where $\delta\theta_1 = 0 = \delta\tau_1$.
Corresponding amplitude offsets γ_i are computed from the amplitude ratios described above.

Using the phase (and optionally amplitude) offsets computed by the
10 calibration computation block as described above in conjunction with FIG. 4, the correction block 147 in the modem 140 processes (e.g., multiplies) the plurality of baseband transmit signals (or transmit weights) and/or plurality of baseband receive signals with corresponding correction values that correct for differences in phase (and optionally) amplitude among the plurality of transmitters and plurality
15 of receivers such that when signals are transmitted by the plurality of transmitters and/or signals are received by the plurality of receivers, the difference between (1) the phase response from an input to a transmitter to the output of its corresponding antenna and (2) the phase response from the input of that antenna to the output of its corresponding receiver is the same for each of the plurality of antennas (i.e.,
20 constant for all antenna paths).

Specifically, when correcting for (broadband) phase offsets, the modem 140 processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with corresponding broadband phase offset correction values that achieves a net phase offset correction equal to the broadband phase offsets
25 computed for the antenna paths associated with antennas for $i = 1$ to N . Similarly, when correcting for amplitude offsets, the modem 140 (using the correction block 147) processes the plurality of baseband transmit signals and/or the plurality receive signals with corresponding amplitude correction values that achieves a net amplitude offset correction equal to amplitude offsets computed for antenna paths
30 associated with the corresponding antennas $i = 1$ to N . Furthermore, when correcting for in-band phase offsets, the modem 140 processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with

corresponding group delay correction values that achieves a net group delay offset correction equal to the group delay offsets computed for antenna paths of the corresponding antennas $i = 1$ to N .

FIG. 5 shows an approach suitable for a multi-carrier modulation scheme, such as OFDM. The correction block 147 comprises a plurality of multipliers 197(1) to 197(N) that apply transmit alignment or correction matrices C_k to remove phase and optionally amplitude offsets at each OFDM sub-carrier k . The multipliers 197(1) to 197(N) may be the same multipliers used to apply the transmit weights w_{Ti} (for $i = 1$ to N) to the baseband transmit signals to be transmitted. A technique to generate the transmit alignment matrices C_k is as follows.

Step 1. The frequency synthesizer 195 is tuned to a known frequency channel in the radio frequency band of interest. A baseband OFDM signal is transmitted using a known BPSK modulation pattern through the DAC 115(1) in antenna path 1, and, using either a cable or an over-the-air connection, that signal is looped back from antenna 110(1) of antenna path 1 to the RF input at antenna 110(2) of antenna path 2. A first phase difference is measured between the input to the DAC 115(1) of antenna path 1 and the output of the ADC 130(2) of antenna path 2 at each OFDM sub-carrier. The first phase difference $\psi_{12}(k) = [\theta_1(k) + \phi_2(k) + \phi_{ant}(1,2)]$, where $\theta_1(k)$ and $\phi_2(k)$ represent phase shifts through the transmitter of antenna path 1 and the receiver of antenna path 2 at the k -th OFDM sub-carrier, respectively, and $\phi_{ant}(1,2)$ represents the phase shift of the over-the-air or cable connection between antenna 110(1) and antenna 110(2), which is the same in either direction. In addition, a first amplitude $\gamma_{12}(k)$ of the signal at the output of the ADC 130(2) is measured.

Step 2. Repeat step 1 using antenna path 2 as the transmitter and antenna path 1 as the receiver to measure a second phase difference $\psi_{21}(k) = [\theta_2(k) + \phi_1(k) + \phi_{ant}(1,2)]$ and to measure a second amplitude $\gamma_2(k)$ of the signal at the output of the ADC 130(1).

Step 3. Repeat steps 1 and 2 between antenna path 1 and i , for $i = 3$ to N , to measure the first phase difference $\psi_{1i}(k)$ and the second phase difference $\psi_{i1}(k)$ and the first and second amplitudes $\gamma_{1i}(k)$ and $\gamma_{i1}(k)$.

Step 4. A diagonal phase alignment or correction matrix $C(k)$ is computed as follows:

$$c_1(k) = 1$$

$$c_2(k) = \gamma_2(k) \exp(j [\psi_{12}(k) - \psi_{21}(k)]) = \gamma_2(k) \exp(j ([\theta_1(k) + \phi_2(k)] -$$

$$5 \quad [\theta_2(k) + \phi_1(k)]))$$

$$c_3(k) = \gamma_3(k) \exp(j [\psi_{13}(k) - \psi_{31}(k)]) = \gamma_3(k) \exp(j ([\theta_1(k) + \phi_3(k)] -$$

$$[\theta_3(k) + \phi_1(k)]))$$

...

$$c_N(k) = \gamma_N(k) \exp(j [\psi_{1N}(k) - \psi_{N1}(k)]) = \gamma_N(k) \exp(j ([\theta_1(k) + \phi_N(k)] -$$

$$10 \quad [\theta_N(k) + \phi_1(k)]))$$

where $\gamma_i(k)$ is computed from a ratio of the first and second measured amplitudes, i.e., $(\gamma_{1i}(k)/\gamma_{i1}(k))$, and $\gamma_1 = 1$. The values for the matrices $C(k)$ are stored as calibration parameters. This selection of $C(k)$ satisfies the symmetry condition (3) for all k . The phase offset and optionally amplitude offset among the transceiver paths may be removed at each sub-carrier by multiplying the data symbol at sub-carrier k by the diagonal alignment matrix $C(k)$. Thus, while not specifically shown in FIG. 5, multipliers 197(i) include an array of multipliers to perform multiplication of $c_i(k)$ at all of the sub-carriers k .

Step 5. If necessary, steps 1 - 4 may be repeated at multiple channels within the RF band to account for slowly varying phase offsets. The phase shifts through the antennas and/or coupling cables do not affect the results of any of the computations.

To summarize, a diagonal offset matrix $C(k)$ is computed for each sub-carrier k comprised of values $c_i(k)$, where $c_i(k) = \gamma_i(k) \exp(j [\psi_{1i}(k) - \psi_{i1}(k)])$ for $i =$
 25 2 to N , where N is the number of antennas, and where $\psi_{1i}(k)$ is a phase difference (also referred to as a first phase difference) between an input to a transmitter associated with a first antenna and an output of a receiver associated with antenna i at sub-carrier k , $\psi_{i1}(k)$ is a phase difference (also referred to as a second phase difference) between an input to a transmitter associated with antenna i and an
 30 output of a receiver associated with the first antenna at sub-carrier k , $\gamma_i(k) = (\gamma_{1i}(k)/\gamma_{i1}(k))$, and where $c_1(k) = 1$. When processing baseband signals, the modem

140 processes the plurality of plurality of baseband transmit signals and/or the plurality of baseband receive signals with phase offset correction values for each sub-carrier k that achieves a net phase offset correction equal to a matrix $\text{diag}[c_1(k), c_2(k), \dots, c_N(k)]$, where $c_i(k) = \exp(j[\psi_{1i}(k) - \psi_{i1}(k)])$, and where $\psi_{1i}(k)$ is the first
 5 phase difference and $\psi_{i1}(k)$ is the second phase difference, for $i = 2$ to N , and where $c_1(k) = 1$.

In some situations, examples of which are described hereinafter, it may not be necessary to generate frequency selective or dependent correction matrices for multi-carrier systems. A single frequency non-selective (frequency independent)
 10 correction matrix may suffice to correct for broadband phase shifts. For these cases, instead of computing a phase shift offset correction value at each sub-carrier k for each antenna path, a single offset correction value for each antenna path is computed from a y-intercept of a line fit through points $\{(\text{sub-carrier } k, \psi_{1i}(k) - \psi_{i1}(k))\}$ associated with a plurality of sub-carriers k , where $\psi_{1i}(k)$ is the first phase
 15 difference measured at sub-carrier k and $\psi_{i1}(k)$ is the second phase difference measured at frequency sub-carrier k , and where the phase offset for the antenna path associated with the first antenna is 0. Similarly, for amplitude offsets, rather than computing an amplitude offset at each sub-carrier k for each antenna, a single amplitude offset is computed for each antenna from an average of a ratio between
 20 the first amplitude and the second amplitude across a plurality of sub-carriers k . The phase difference measurements need not be made at each of the plurality of sub-carriers k , but at a sufficient number to perform the linear analysis (y-intercept) described above. This procedure then becomes very similar to the process described above in conjunction with FIG. 4.

25 An advantage of the calibration techniques described herein is that they do not require any external equipment. They can be performed by embedding logic within the device to enable the device to perform self-calibration.

On the other hand, the techniques described herein may be conducted with the use of RF test equipment to measure the phase and amplitude offsets between
 30 antenna loop back paths instead of DSP logic, if so desired, for laboratory or experimental situations. When test equipment is used, a reference signal (either

CW or OFDM) is injected into the radio receiver; the signal is looped back at baseband to measure the phase difference at RF using test equipment.

With reference to FIG. 6, the offset correction values may be applied in the transmit path, receive path or both paths, of the modem. For example, when the offsets c_1 to c_N are computed as described above in conjunction with FIGs. 4 or 5, the correction can be made in the receiver path with multipliers 191(i) where c_i' is the inverse of c_i , or if amplitude correction is not performed, then c_i' is the conjugate of c_i . Alternatively, the correction can be made in both the transmit paths and receiver paths such that the cumulative or net correction in the antenna paths is equal to the corresponding offset c_i computed for that antenna path. Likewise, transmit all pass filters 181(i) (e.g., re-samplers) may be used instead of receive all pass filters where the values $\delta\tau_i$ are computed as described above in conjunction with FIGs. 4, and $\delta\tau_i'$ is the inverse (delay instead of advance, or advance instead of delay) of $\delta\tau_i$. Alternatively, all pass filters may be used in the receive paths and transmit paths such that the cumulative or net correction in the antenna paths is equal to the corresponding group delay offset $\delta\tau_i$ computed for that path. The sequence of the multipliers and all pass filters in each receive and transmit baseband paths shown in FIG. 6 is not restrictive and can be switched.

Of all the sources of group delay mismatch in a MIMO transceiver, group delay differences among baseband components are the most troublesome because they cause relatively large frequency-dependent phase differences that vary within the bandwidth of the signal being transmitted. One way to remove the effect of baseband delay differences is to share the same lowpass filter (LPF) between the transmitter and receiver for each antenna path. This has the obvious additional benefit of saving silicon area.

Referring to FIG. 2, the group delay in the path from transmitter 1 to receiver i is

$$\tau_{BBTX}(1) + \tau_{RFTX}(1) + \tau_{ant}(i) + \tau_{RFRX}(i) + \tau_{BBRX}(i)$$

and from transmitter i to receiver 1 is

$$\tau_{BBTX}(i) + \tau_{RFTX}(i) + \tau_{ant}(i) + \tau_{RFRX}(1) + \tau_{BBRX}(1)$$

If the same filter is shared for transmit and receive in each path, then $\tau_{BBTX}(1) = \tau_{BBRX}(1)$, $\tau_{BBTX}(i) = \tau_{BBRX}(i)$, and the difference in group delay between the two

paths is $\tau_{\text{RFTX}}(1) + \tau_{\text{RFRX}}(i) - (\tau_{\text{RFTX}}(i) + \tau_{\text{RFRX}}(1))$, which depends only on RF components. Since the symmetry condition (equations 1 and 2) only depends on the phase offsets between these paths, the above analysis shows that if a shared LPF is used, channel symmetry will hold regardless of the group delay uncertainty of the LPF. FIG. 7 illustrates an example of filter sharing in which a switch 128(1) to 128(N) is provided that selects either the output of the DAC in the transmit path or the output of downconverter in the receive path as the input to the LPF in each radio transceiver.

These observations imply that there is no need to compensate for baseband group delay mismatch if the radio transceiver design shares an LPF for transmit and receive operations. In this case, only a single frequency non-selective (frequency independent) transmit phase alignment matrix is required for an OFDM scheme and no all pass group delay alignment is required for an OFDM or a single carrier scheme.

Another observation holds for the delay contributions of the ADC and the DAC, in which pipelining delay may cause relatively large group delay differences between transmit and receive paths. Since the total group delay in each transmit-to-receive loop-back path is the sum of the DAC and ADC group delays, the sum of these delays will be the same for all loop-back paths, and therefore the symmetry condition will hold regardless of group delay differences between these components (assuming all DACs and ADCs have the same group delay, which is typically the case).

Simulations were performed to determine the impact of phase and amplitude offsets (when not corrected) on a MIMO radio algorithm that relies on channel symmetry. The simulations used 200 random channels between 4 antennas at one device and 2 antennas at another device.

For each channel H , random mismatch matrices A_1, B_1, A_2, B_2 were generated, and the loss in link margin was computed. Both amplitude and phase mismatch were used for the transmit matrices A_1 and A_2 . Only random phase mismatch was used for the receive matrices B_1 and B_2 , since amplitude error in the receiver is presumably not a concern with some types of radio transceiver architectures. Amplitude mismatch $20\log(\alpha)$ was generated using a normal

distribution with standard deviation σ_α dB. Phase mismatch θ, ϕ was uniformly distributed between $-U_\theta/2$ and $U_\theta/2$ degrees. One set of mismatch matrices was generated for each value of σ_α in $\{1, 2, 3, 6\}$ dB and for each value of U_θ in $\{10, 20, 45, 90, 180\}$ degrees. A total of 20 sets of 4 random mismatch matrices were generated for each random channel.

FIG. 8 shows data plots for an equal-power CBF algorithm used between the two devices and shows, among other things, that equal-power CBF is significantly less sensitive to both phase and amplitude imbalance than non-equal power CBF, and also shows that amplitude offset correction is not necessary.

In sum, a radio device is provided comprising a plurality of transmitters that upconvert corresponding ones of a plurality of baseband transmit signals for simultaneous transmission via corresponding ones of a plurality of antennas; a plurality of receivers that downconvert a plurality of radio signals detected by corresponding ones of the plurality of antennas to produce a corresponding plurality of baseband receive signals; and a processor coupled to the plurality of transmitters and the plurality of receivers, wherein the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding correction values that correct for differences in phase responses among the plurality of transmitters and plurality of receivers.

In addition, a method is provided for calibrating a radio device that comprises a plurality of antennas, a corresponding plurality of receivers and a corresponding plurality of transmitters, the method comprising steps of measuring phase responses of the plurality of transmitters and the plurality of receivers; and computing a plurality of correction values to correct for differences in the phase responses of the plurality of transmitters and the plurality of receivers.

Further, a method is provided for radio communication between a first radio device and a second radio device, the first radio device comprising a plurality of antennas, a corresponding plurality of transmitters and a corresponding plurality of receivers, the method at the first radio device comprising the step of processing a plurality of baseband transmit signals to be transmitted and/or baseband receive signals with corresponding correction values that correct for differences in phase

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responses of the plurality of transmitters and the plurality of receivers of the first radio device.

- Further still, a method is provided for measuring characteristics of a radio device having a plurality of antennas, a corresponding plurality of transmitters and
- 5 a corresponding plurality of receivers, comprising steps of coupling a signal to a first transmitter for transmission via a corresponding first antenna; and receiving the signal with a receiver associated with a second antenna.

The above description is intended by way of example only and is not intended to limit the present invention in any way.

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Claims:

1. A radio device comprising:
 - a. a plurality of transmitters that upconvert corresponding ones of a plurality of baseband transmit signals for simultaneous transmission via corresponding ones of a plurality of antennas;
 - b. a plurality of receivers that downconvert a plurality of radio signals detected by corresponding ones of the plurality of antennas to produce a corresponding plurality of baseband receive signals; and
 - c. a processor coupled to the plurality of transmitters and the plurality of receivers, wherein the processor measures differences in phase responses among the plurality of transmitters and plurality of receivers by measuring a first phase difference between an input to a transmitter associated with a first antenna and an output of a receiver associated with antenna i , and a second phase difference between an input to a transmitter associated with antenna i and an output of a receiver associated with the first antenna, for $i = 2$ to N , where N is the number of antennas, and the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding correction values that correct for differences in broadband phase responses among the plurality of transmitters and plurality of receivers.
2. The device of claim 1, wherein the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding correction values such that when signals are transmitted by the plurality of transmitters and/or signals are received by the plurality of receivers, the difference between (1) the phase response from an input to a transmitter to the output of its corresponding antenna and (2) the phase response from the input of that antenna to the output of its corresponding receiver is the same for each of the plurality of antennas.

3. The device of claim 1, wherein the processor measures the first phase difference when a signal is applied at an input to the transmitter associated with the first antenna and coupled as receive input to the receiver associated with antenna i via an over-the-air link or a cable connection and measures the second phase difference when a signal is applied at an input to the transmitter associated with antenna i and coupled as receive input to the receiver associated with the first antenna via an over-the-air link or a cable connection.
4. The device of claim 3, wherein the processor generates the signal as a digital signal representing a continuous wave tone at frequency f_k , and wherein the processor measures the first phase difference and second phase difference at a plurality of continuous wave tone frequencies f_k across a bandwidth of a baseband signal.
5. The device of claim 4, wherein the processor measures the first phase difference between a digital signal at an input to a digital-to-analog converter coupled to the transmitter associated with the first antenna and a digital signal at an output of an analog-to-digital converter coupled to the output of the receiver associated with antenna i , and measures the second phase difference between a digital signal at an input to a digital-to-analog converter coupled to the transmitter associated with antenna i and a digital signal at an output of an analog-to-digital converter coupled to the output of the receiver associated with the first antenna.
6. The device of claim 4, wherein the processor computes broadband phase offsets for antenna paths corresponding to antennas $i = 1$ to N , from a y -intercept of a line fit through points $\{(f_k, \psi_{1i}(k) - \psi_{ii}(k))\}$ associated with the frequencies f_k , where $\psi_{1i}(k)$ is the first phase

difference measured at frequency f_k and $\psi_{ii}(k)$ is the second phase difference measured at frequency f_k , and where the broadband phase offset for the antenna path associated with the first antenna is 0.

7. The device of claim 6, wherein the processor processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with corresponding broadband phase offset correction values to achieve a net phase offset correction equal to the corresponding broadband phase offsets.
8. The device of claim 7, wherein the processor further processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with corresponding amplitude offset correction values that correct for amplitude offsets among the plurality of transmitters and plurality of receivers.
9. The device of claim 8, wherein the processor measures a first amplitude of a signal at the output of the receiver associated with antenna i when the continuous wave tone is applied at the input of the transmitter associated with the first antenna and measures a second amplitude of a signal at the output of the receiver associated with the first antenna when the continuous wave tone is applied at the input of the transmitter associated with antenna i , for $i = 2$ to N ,
10. The device of claim 9, wherein the processor computes a plurality of amplitude offsets for the antenna paths of the corresponding antennas for $i = 1$ to N , from an average of a ratio between the first amplitude and the second amplitude associated with frequencies f_k , and where the amplitude offset for the antenna path associated with the first antenna is 1
11. The device of claim 10, wherein the processor further processes the plurality of baseband transmit signals and/or the plurality receive signals with corresponding amplitude correction values that achieves a net amplitude offset correction equal to corresponding amplitude offsets.
12. The device of claim 1, wherein the processor measures the differences in phase responses when the plurality of transmitters and plurality of

receivers are tuned to each of a plurality of frequency channels in a radio frequency band of operation.

13. The device of claim 1, wherein the processor further processes the plurality of baseband receive signals and/or the plurality of baseband transmit signals with corresponding group delay correction values that correct for group delay offsets among the plurality of transmitters and plurality of receivers within a bandwidth of a baseband signal.
14. The device of claim 13, wherein the processor computes a plurality of group delay offsets for the antenna paths of corresponding antennas $i = 1$ to N from the first phase difference and the second phase difference at frequencies f_k , and where the group delay offset for the antenna path associated with the first antenna is 0.
15. The device of claim 14, wherein the processor computes the group delay offsets equal to $-(1/2\pi) * \text{slope of a line fit through points } \{(f_k, \psi_{1i}(k) - \psi_{ii}(k))\}$ associated with the plurality of frequencies f_k where $\psi_{1i}(k)$ is the first phase difference measured at frequency f_k and $\psi_{ii}(k)$ is the second phase difference measured at frequency f_k , for $i = 2$ to N .
16. The device of claim 15, wherein the processor processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with corresponding group delay correction values that achieves a net group delay offset correction equal to the corresponding group delay offsets.
17. The device of claim 16, wherein the processor implements the group delay correction values using all-pass filter processes.
18. A radio device comprising:
 - a. a plurality of transmitters that upconvert corresponding ones of a plurality of baseband transmit signals for simultaneous transmission via corresponding ones of a plurality of antennas;
 - b. a plurality of receivers that downconvert a plurality of radio signals detected by corresponding ones of the plurality of antennas to produce a corresponding plurality of baseband receive signals; and
 - c. a processor coupled to the plurality of transmitters and the plurality of receivers that measures phase offsets at a plurality of sub-carriers k

and coupled as receive input to the receiver associated with antenna i via an over-the-air link or a cable connection, and measuring at each sub-carrier k a second phase difference when a multi-carrier signal is applied at an input to the transmitter associated with antenna i and coupled as a receive input to the receiver associated with the first antenna via an over-the-air link or a cable connection, for $i = 2$ to N , where N is the number of antennas, and wherein the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with correction values that correct for the phase offsets measured at each of the plurality of sub-carriers k .

19. The device of claim 18, wherein the processor processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with phase offset correction values for each sub-carrier k that achieves a net phase offset correction equal to a matrix $\text{diag}[c_1(k), c_2(k), \dots, c_N(k)]$, where $c_i(k) = \exp(j[\psi_{1i}(k) - \psi_{ii}(k)])$, and where $\psi_{1i}(k)$ is the first phase difference and $\psi_{ii}(k)$ is the second phase difference, for $i = 2$ to N , and where $c_1(k) = 1$.
20. The device of claim 18, wherein the processor computes phase offsets for antenna paths of corresponding antennas $i = 1$ to N , from a y- intercept of a line fit through points $\{(f_k, \psi_{1i}(k) - \psi_{ii}(k))\}$ associated with the plurality of sub-carriers k , where $\psi_{1i}(k)$ is the first phase difference measured at sub-carrier k and $\psi_{ii}(k)$ is the second phase difference measured at frequency sub-carrier k , and where the phase offset for the antenna path associated with the first antenna is 0.
21. The device of claim 20, wherein the processor processes the plurality of baseband transmit signals and/or plurality of baseband receive signals

- with corresponding phase offset correction values that achieves a net phase offset correction equal to the corresponding phase offsets.
22. The device of claim 21, wherein the processor further processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding amplitude offset correction values that correct for amplitude offsets among the plurality of transmitters and plurality of receivers.
 23. The device of claim 21, wherein the processor measures a first amplitude of a signal at the output of the receiver associated with antenna i at the plurality of sub-carriers k when a multi-carrier signal is applied at the input of the transmitter associated with the first antenna and measures a second amplitude of a signal at the output of the receiver associated with the first antenna at the plurality of sub-carriers k when the multi-carrier signal is applied at the input of the transmitter associated with antenna i , for $i = 2$ to N .
 24. The device of claim 23, wherein the processor computes amplitude offsets for antenna paths corresponding to antennas $i = 1$ to N , from an average of a ratio between the first amplitude and the second amplitude across the plurality of sub-carriers k , and where the amplitude offset for the antenna path associated with the first antenna is 1.
 25. The device of claim 24, wherein the processor further processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding amplitude correction values that achieves a net amplitude offset correction equal to the corresponding amplitude offsets.
 26. The device of claim 19, wherein the processor further processes the plurality of baseband transmit signals and/or the plurality of baseband receive signals with corresponding amplitude offset correction values that correct for amplitude offsets among the plurality of transmitters and plurality of receivers.
 27. The device of claim 26, wherein the processor measures a first amplitude at each sub-carrier k of a signal at the output of the receiver

associated with antenna i when the multi-carrier signal is applied at the input of the transmitter associated with the first antenna and measures a second amplitude at each sub-carrier k of a signal at the output of the receiver associated with the first antenna when the multi-carrier signal is applied at the input of the transmitter associated with antenna i , for $i = 2$ to N .

28. The device of claim 27, wherein the processor computes an amplitude offset at each sub-carrier k for antenna paths corresponding to antennas $i = 1$ to N , from a ratio between the first amplitude and the second amplitude at each frequency sub-carrier k , and where the amplitude offset at each sub-carrier for the antenna path associated with the first antenna is 1.
29. The device of claim 28, wherein the processor further processes the plurality of baseband transmit signals and/or plurality of baseband receive signals with corresponding amplitude offset correction values at each sub-carrier k that achieves a net amplitude offset correction equal to the corresponding amplitude offsets.
30. The device of claim 1, wherein the processor comprises a baseband signal processor that performs baseband modulation to produce the plurality of baseband transmit signals and baseband demodulation of the plurality of baseband receive signals.
31. The device of claim 30, wherein the baseband signal processor is implemented by digital logic gates.
32. The device of claim 1, wherein the plurality of transmitters and plurality of receivers are implemented on a single semiconductor integrated circuit.
33. The device of claim 1, and further comprising a low pass filter that is shared by the transmitter and receiver associated with a corresponding antenna.
34. The device of claim 1, wherein the processor measures offsets and computes correction values to correct for offsets during a self-calibration mode, and the processor processes the plurality of baseband

transmit signals and/or plurality of baseband receive signals with the correction values during a run-time mode.

35. The device of claim 34, wherein the processor executes the self- calibration mode at device power-up and periodically thereafter.
36. The device of claim 1, and further comprising a memory that stores information to allow for adjustment of correction values according to gain settings of the plurality of transmitters and/or gain settings of the plurality of receivers.
37. The device of claim 36, wherein the processor measures offsets in phase responses and computes gain-independent correction values, and wherein the processor adjusts the gain-independent correction values according to the gain settings using the information stored in the memory.
38. A method for calibrating a radio device that comprises a plurality of antennas, a corresponding plurality of receivers and a corresponding plurality of transmitters, the method comprising steps of:
 - a. measuring phase responses of the plurality of transmitters and the plurality of receivers, comprising measuring a first phase difference between an input to a transmitter associated with a first antenna and an output of a receiver associated with antenna i ; and a second phase difference between an input to a transmitter associated with antenna i and an output of a receiver associated with the first antenna, for $i = 2$ to N , where N is the number of antennas; and
 - b. computing a plurality of correction values from the phase differences to correct for differences in broadband phase responses of the plurality of transmitters and the plurality of receivers.
39. The method of claim 38, wherein the step of computing comprises computing the plurality of correction values used in processing the plurality of baseband signals and/or plurality of baseband receive signals such that when signals are transmitted by the plurality of transmitters and/or signals are received by the plurality of receivers, the difference between (1) the phase response from an input to a transmitter to the output of its corresponding antenna and (2) the phase response from the input of that antenna to the output of its corresponding receiver is the same for each of the plurality of antennas.

40. The method of claim 38, wherein the step of measuring comprises measuring the first phase difference when a signal is applied at an input to the transmitter associated with the first antenna and coupled as receive input to the receiver associated with antenna i via an over-the-air link or a cable connection and measuring the second phase difference when a signal is applied at an input to the transmitter associated with antenna i and coupled as a receive input to the receiver associated with the first antenna via an over-the-air link or a cable connection, for $i = 2$ to N .
41. The method of claim 40, wherein the step of measuring the first phase difference and second phase difference is repeated for a continuous wave tone applied at a plurality of frequencies f_k across the bandwidth of a baseband signal.
42. The method of claim 41, wherein the step of measuring comprises measuring the first phase difference between a digital signal at an input to a digital-to-analog converter coupled to the transmitter associated with the first antenna and a digital signal at an output of an analog-to-digital converter coupled to the output of the receiver associated with antenna i , and measuring the second phase difference between a digital signal at an input to a digital-to-analog converter coupled to the transmitter associated with antenna i and a digital signal at an output of

an analog-to-digital converter coupled to the output of the receiver associated with the first antenna.

43. The method of claim 42, wherein the step of computing comprises computing broadband phase offset correction values for antenna paths corresponding to antennas $i = 2$ to N , from a y-intercept of a line fit through the points $\{(f_k, \psi_{1i}(k) - \psi_{i1}(k))\}$ associated with the frequencies f_k , where $\psi_{1i}(k)$ is the first phase difference measured at frequency f_k and $\psi_{i1}(k)$ is the second phase difference measured at frequency f_k , and where the broadband phase offset correction value for the antenna path associated with the first antenna is 0.
44. The method of claim 41, wherein the step of measuring comprises measuring amplitude offsets among the plurality of transmitters and plurality of receivers.
45. The method of claim 44, wherein the step of measuring comprises measuring a first amplitude of a signal at the output of the receiver associated with antenna i when the continuous wave tone is applied at the input of the transmitter associated with the first antenna and measures a second amplitude of a signal at the output of the receiver associated with the first antenna when the continuous wave tone is applied at the input of the transmitter associated with antenna i , for $i = 2$ to N .
46. The method of claim 45, wherein the step of computing comprises computing amplitude offset correction values for antenna paths corresponding to antennas $i = 1$ to N , from an average of a ratio between the first amplitude and the second amplitude associated with the plurality of frequencies f_k , and where the amplitude offset correction value for the antenna path, associated with the first antenna is 1.
47. The method of claim 38, wherein the step of measuring comprises measuring the first and second phase differences when the plurality of transmitters and plurality of receivers are tuned to each of a plurality of frequency channels in a radio frequency band of operation.

48. The method of claim 41, wherein the step of measuring comprises measuring group delay differences among the plurality of transmitters and plurality of receivers.
49. The method of claim 48, wherein the step of computing further comprises computing a plurality of group delay offset correction values for antenna paths corresponding to antennas $i = 1$ to N , from the first phase difference and the second phase difference, and where the group delay offset correction value for the antenna path associated with the first antenna is 0.
50. The method of claim 49, wherein the step of computing the plurality of group delay offset correction values for antenna paths corresponding to antennas $i = 2$ to N from $-(1/2\pi) \cdot \text{slope of a line fit through points } \{(f_k, \psi_{1i}(k) - \psi_{1i}(k))\}$ associated with the plurality of frequencies f_k , where $\psi_{1i}(k)$ is the first phase difference measured at frequency f_k and $\psi_{1i}(k)$ is the second phase difference measured at frequency f_k .
51. The method of claim 38, wherein the step of measuring comprises measuring at sub-carriers k associated with a multi-carrier baseband modulation process a first phase difference when a multi-carrier baseband signal is applied at an input to the transmitter associated with the first antenna and coupled as receive input to the receiver associated with antenna i via an over-the-air link or a cable connection, and measuring at each sub-carrier k the second phase difference when a multi-carrier signal is applied at an input to the transmitter associated with antenna i and coupled as a receive input to the receiver associated with the first antenna via an over-the-air link or a cable connection, for $i = 2$ to N .
52. The method of claim 51, wherein the step of computing comprises computing a diagonal correction matrix $\text{diag}[c_1(k), c_2(k), \dots, C_N(k)]$, for each sub-carrier k , where $c_i(k) = \exp(j[\psi_{1i}(k) - \psi_{1i}(k)])$, for $i = 2$ to N , where N is the number of antennas, and where $\psi_{1i}(k)$ is a first phase difference between an input to a first transmitter and an output of receiver i at sub-carrier k , and $\psi_{1i}(k)$ is a second phase difference

between an input to transmitter i and an output of a first receiver at sub-carrier k , and where $c_i(k) = 1$.

53. The method of claim 51, wherein the step of computing comprises computing broadband phase offsets for antenna paths corresponding to antennas $i = 2$ to N , from a y -intercept of a line fit through points $\{(f_k, \psi_{1i}(k) - \psi_{ii}(k))\}$ associated with a plurality of sub-carriers k , where $\psi_{1i}(k)$ is the first phase difference measured at sub-carrier k and $\psi_{ii}(k)$ is the second phase difference measured at frequency sub-carrier k , and the broadband phase offset for the antenna path associated with the first antenna is 0.
54. The method of claim 51, wherein the step of measuring further comprises measuring a first amplitude at sub-carriers k of a signal at the output of the receiver associated with antenna i when the multi-carrier signal is applied at the input of the transmitter associated with the first antenna and measuring a second amplitude at sub-carriers k of a signal at the output of the receiver associated with the first antenna when the multi-carrier signal is applied at the input of the transmitter associated with antenna i , for $i = 2$ to N .
55. The method of claim 54, wherein the step of computing comprises computing amplitude offset correction values for antenna paths corresponding to antennas $i = 1$ to N , from a ratio of the first amplitude and second amplitude at each sub-carrier k , and where the amplitude offset correction value for the antenna path associated with the first antenna is 1.
56. The method of claim 54, wherein the step of computing comprises computing amplitude offsets correction values for antenna paths corresponding to antennas $i = 1$ to N , from an average of a ratio between the first amplitude to the second amplitude across a plurality of sub-carriers k , and where the amplitude offset for the antenna path associated with the first antenna is 1.

57. The method of claim 40, and further comprising the step of lowering a gain of an amplifier in the receiver associated with one of the plurality of antennas when a signal is coupled to the associated antenna transmitted from one of the plurality of other antennas.