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### Active antenna system and method thereof

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#### Abstract

A controller performs an intra-subunit transmission calibration to compensate for relative differences in amplitude and phase among multiple transmitter RF chains within each subunit of an active antenna system (AAS). The controller further performs inter-subunit transmission calibration to compensate for relative differences in amplitude and phase among multiple representative transmitter RF chains, each included in a respective one of the multiple subunits.

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<b>Patent No.</b>	<b>Issued Date</b>	<b>Patentee Name</b>	<b>U.S. Cl.</b>	<b>CPC</b>
6963742	12/2004	Boros	455/67.11	H04B 7/0615
6983173	12/2005	Miyatani	455/193.1	H01Q 3/2605
7110794	12/2005	Iinuma	455/562.1	H01Q 3/2605
7643852	12/2009	Noll	455/66.1	H04B 7/0848
8045926	12/2010	Martikkala	455/63.4	H04B 17/327
8615204	12/2012	Husted	455/88	H04B 17/11
8712475	12/2013	Noll	455/67.11	H04B 7/0848
8965433	12/2014	Liao	455/509	H04B 17/12
9025575	12/2014	McGowan	370/336	H04W 72/541
9054415	12/2014	Goransson	N/A	H04B 17/21
9094254	12/2014	Da Silveira	N/A	H04B 17/12
9113346	12/2014	Pivit	N/A	H01Q 3/267
9461730	12/2015	Wilhelmsson	N/A	H04B 15/00
9648630	12/2016	McGowan	N/A	H04W 72/541
9825716	12/2016	Zhu	N/A	H04B 7/024
10128894	12/2017	O'Brien	N/A	H04B 17/12
10164334	12/2017	Kareisto	N/A	G01S 7/40
10615890	12/2019	Wu	N/A	H04B 17/14
10644813	12/2019	McGowan	N/A	H01Q 1/246
10749254	12/2019	Arnett	N/A	H04B 17/14
11025350	12/2020	Wilson	N/A	H04B 17/345
11121731	12/2020	Ravi	N/A	H03L 7/24
11838065	12/2022	Yu	N/A	H04B 17/11
12191897	12/2024	Ravi	N/A	H04B 1/0483
2010/0075594	12/2009	Kim	455/7	H04L 25/0242
2012/0020396	12/2011	Hohne	375/224	H01Q 3/267
2012/0220331	12/2011	Luo	455/517	H04B 17/14
2012/0252366	12/2011	Aoki et al.	N/A	N/A
2020/0067184	12/2019	Arnett	N/A	H04B 17/11
2020/0274629	12/2019	Wilson	N/A	H04B 7/0413

**FOREIGN PATENT DOCUMENTS**

<b>Patent No.</b>	<b>Application Date</b>	<b>Country</b>	<b>CPC</b>
2011/074031	12/2010	WO	N/A
2019/176388	12/2018	WO	N/A
2021/019885	12/2020	WO	N/A

**OTHER PUBLICATIONS**

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## **Background/Summary**

### INCORPORATION BY REFERENCE

(1) This application is based upon and claims the benefit of priority from Japanese patent application No. 2021-202676, filed on Dec. 14, 2021, the disclosure of which is incorporated herein in its entirety by reference.

### TECHNICAL FIELD

(2) The present disclosure relates to an active antenna system, and in particular to its calibration.

### BACKGROUND ART

(3) Massive Multi-Input Multi-Output (MIMO) and Multi-User MIMO (MU-MIMO) using Active Antenna Systems (AAS) are important technologies to improve network capacity in wireless communication systems such as Fifth Generation (5G) cellular systems. An AAS supports full digital beamforming. An AAS can be applied, for example, to a base station in a 5G cellular system, specifically a Radio Unit (RU). For example, but not limited to, when an AAS is used as an RU, the AAS performs low Physical layer signal processing and beamforming in the digital domain.

(4) An AAS includes an antenna array, multiple radio frequency (RF) chains, and a digital front end. Each RF chain includes a transmitter (or transmit) RF chain and a receiver (or receive) RF chain. One transmitter RF chain includes a transmitter, one or more power amplifiers (e.g., high power amplifier (HPA)), and one or more RF filters (e.g., bandpass filters). The transmitter includes, for example, a digital-to-analog converter (DAC), a baseband filter (e.g., low-pass filter), and an IQ modulator. Meanwhile, one receiver RF chain includes a receiver, one or more low-noise amplifiers (LNAs), and one or more RF filters (e.g., bandpass filters). The receiver includes, for example, an analog-to-digital converter (ADC), a baseband filter (e.g., low-pass filter), and an IQ demodulator.

(5) To obtain accurate directivity in beamforming, multiple elements (or multiple RF chains) of an antenna array need to have the same phase and amplitude response. If there is a mismatch in the amplitude and phase relationship among the elements of the antenna array, this will cause relative changes in amplitude and phase among the radiated or received signals and affect the radiation pattern characteristics. Relative differences in amplitude (or gain) and phase among RF chains can result from, for example, thermal effects, aging of components, and manufacturing tolerances. To solve this problem, calibration of multiple antenna elements (or multiple RF chains) is required.

(6) Discussions and proposals for calibration of an AAS can be found, for example, in two international applications by the inventor of the present application (see Patent Literature 1 and 2). Patent Literature 1 discloses a method for calibrating multiple RF chains across multiple AASs when these multiple AASs are connected and used as a single active antenna system. Patent Literature 2 provides a configuration and method for simultaneously and collectively calibrating multiple transmitters (or multiple transmitter RF chains) of an AAS.

### PATENT LITERATURE

(7) Patent Literature 1: WO 2019/176388 A1 Patent Literature 2: WO 2021/019885 A1

## SUMMARY

(8) The inventor has devised a product architecture in which subunits, each having multiple antenna elements and multiple RF chains, are manufactured and combined to form a single AAS. In one example, these multiple subunits are installed (or assembled) in a single antenna system enclosure. The subunits can be referred to as modules or cards. Calibration appropriate to the configuration of such an AAS product is required.

(9) One of the objects to be attained by example embodiments disclosed herein is to provide an apparatus, a method, and a program that enable calibration suitable for the AAS product architecture described above. It should be noted that this object is merely one of the objects to be attained by the example embodiments disclosed herein. Other objects or problems and novel features will be made apparent from the following description and the accompanying drawings.

(10) In a first aspect, an active antenna system includes first and second subunits and a controller. The first subunit includes a first set of antenna elements, a first set of transmitter Radio Frequency (RF) chains coupled to the first set of antenna elements, a first set of receiver RF chains coupled to the first set of antenna elements, and a first digital front end coupled to the first set of transmitter RF chains and the first set of receiver RF chains. Similarly, the second subunit includes a second set of antenna elements, a second set of transmitter RF chains coupled to the second set of antenna elements, a second set of receiver RF chains coupled to the second set of antenna elements, and a second digital front end coupled to the second set of transmitter RF chains and the second set of receiver RF chains. The controller is configured to perform a first transmission calibration, a second transmission calibration, and a third transmission calibration. The first transmission calibration compensates for relative differences in amplitude and phase among the transmitter RF chains in the first set of transmitter RF chains. The second transmission calibration compensates for relative differences in amplitude and phase among the transmitter RF chains in the second set of transmitter RF chains. The third transmission calibration compensates for relative differences in amplitude and phase between a first representative transmitter RF chain in the first set of transmitter RF chains and a second representative transmitter RF chain in the second set of transmitter RF chains.

(11) In a second aspect, a method performed by a controller of an active antenna system includes the following steps: (a) performing a first transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter radio frequency (RF) chains in a first subunit of the active antenna system; (b) performing a second transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter RF chains in a second subunit of the active antenna system; and (c) performing a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the plurality of transmitter RF chains of the first subunit and a second representative transmitter RF chain in the plurality of transmitter RF chains of the second subunit.

(12) In a third aspect, a program includes a set of instructions (software codes) that, when loaded into a computer (e.g., a controller of an active antenna system), causes the computer to perform the method of the second aspect described above.

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## Description

### BRIEF DESCRIPTION OF DRAWINGS

(1) The above and other aspects, features, and advantages of the present invention will become more apparent from the following description of certain example embodiments when taken in conjunction with the accompanying drawings, in which:

(2) FIG. 1 is a diagram showing an example configuration of an active antenna of an example

embodiment;

- (3) FIG. 2A is a flowchart showing an example of a transmission calibration procedure for an active antenna system according to an example embodiment;
- (4) FIG. 2B is a flowchart showing an example of a reception calibration procedure for an active antenna system according to an example embodiment;
- (5) FIG. 3 shows a configuration example of a subunit in an active antenna system according to an example embodiment;
- (6) FIG. 4 shows a configuration example of a subunit in an active antenna system according to an example embodiment;
- (7) FIG. 5A shows a configuration example of a transmitter RF chain and a receiver RF chain in an active antenna system according to an example embodiment;
- (8) FIG. 5B shows a configuration example of a transmitter RF chain and a receiver RF chain in an active antenna system according to an example embodiment;
- (9) FIG. 6 shows an example of a signal path in an intra-subunit transmission calibration of an active antenna system according to an example embodiment;
- (10) FIG. 7 shows an example of a signal path in an intra-subunit reception calibration of an active antenna system according to an example embodiment;
- (11) FIG. 8 is a flowchart showing an example of an inter-subunit transmission calibration procedure for an active antenna system according to an example embodiment;
- (12) FIG. 9 is a flowchart showing an example of an inter-subunit transmission calibration procedure for an active antenna system according to an example embodiment;
- (13) FIG. 10 is a flowchart showing an example of an inter-subunit reception calibration procedure for an active antenna system according to an example embodiment;
- (14) FIG. 11 is a flowchart showing an example of an inter-subunit reception calibration procedure for an active antenna system according to an example embodiment;
- (15) FIG. 12 shows a configuration example of a subunit in an active antenna system according to an example embodiment;
- (16) FIG. 13 is a flowchart showing an example of an inter-subunit transmission calibration procedure for an active antenna system according to an example embodiment;
- (17) FIG. 14 is a flowchart showing an example of an inter-subunit reception calibration procedure for an active antenna system according to an example embodiment;
- (18) FIG. 15 shows a configuration example of a subunit in an active antenna system according to an example embodiment;
- (19) FIG. 16 shows a configuration example of a subunit in an active antenna system according to an example embodiment;
- (20) FIG. 17 shows an example of a signal path in an intra-subunit transmission calibration of an active antenna system according to an example embodiment;
- (21) FIG. 18 shows an example of a signal path in an intra-subunit reception calibration of an active antenna system according to an example embodiment;
- (22) FIG. 19 shows an example of a signal path in an inter-subunit transmission calibration of an active antenna system according to an example embodiment;
- (23) FIG. 20 shows an example of a signal path in an inter-subunit transmission calibration of an active antenna system according to an example embodiment;
- (24) FIG. 21 shows an example of a signal path in an inter-subunit reception calibration of an active antenna system according to an example embodiment;
- (25) FIG. 22 shows an example of a signal path in an inter-subunit reception calibration of an active antenna system according to an example embodiment;
- (26) FIG. 23 is a flowchart showing an example of an intra-subunit transmission calibration procedure for an active antenna system according to an example embodiment;
- (27) FIG. 24 is a flowchart showing an example of an intra-subunit reception calibration procedure

for an active antenna system according to an example embodiment;

(28) FIG. 25 is a flowchart showing an example of an inter-subunit transmission calibration procedure for an active antenna system according to an example embodiment;

(29) FIG. 26 is a flowchart showing an example of an inter-subunit reception calibration procedure for an active antenna system according to an example embodiment;

(30) FIG. 27 shows a configuration example of a subunit in an active antenna system according to an example embodiment;

(31) FIG. 28 shows a configuration example of a subunit in an active antenna system according to an example embodiment;

(32) FIG. 29 shows an example of a signal path in an intra-subunit transmission calibration of an active antenna system according to an example embodiment;

(33) FIG. 30 shows an example of a signal path in an intra-subunit transmission calibration of an active antenna system according to an example embodiment;

(34) FIG. 31 shows an example of a signal path in an inter-subunit transmission calibration of an active antenna system according to an example embodiment;

(35) FIG. 32 shows an example of a signal path in an inter-subunit transmission calibration of an active antenna system according to an example embodiment;

(36) FIG. 33 shows an example of a signal path in an inter-subunit reception calibration of an active antenna system according to an example embodiment;

(37) FIG. 34 shows an example of a signal path in an inter-subunit reception calibration of an active antenna system according to an example embodiment; and

(38) FIG. 35 shows a configuration example of a controller according to an example embodiment.

#### EXAMPLE EMBODIMENT

(39) Specific example embodiments will be described hereinafter in detail with reference to the drawings. The same or corresponding elements are denoted by the same symbols throughout the drawings, and duplicated explanations are omitted as necessary for the sake of clarity.

(40) Each of the example embodiments described below may be used individually, or two or more of the example embodiments may be combined with one another as appropriate. These example embodiments include novel features different from each other. Accordingly, these example embodiments contribute to attaining objects or solving problems different from one another and also contribute to obtaining advantages different from one another.

(41) As used in this specification, “if” may be interpreted as meaning “when”, “at or around the time”, “after”, “upon”, “in response to determining”, “in accordance with a determination”, or “in response to detecting”, depending on the context. These expressions may be interpreted to mean the same thing, depending on the context.

#### First Example Embodiment

(42) FIG. 1 shows a configuration example of an AAS **100** in this example embodiment. The AAS **100** may be used for a base station in a 5G cellular system, specifically as a Radio Unit (RU). The AAS **100** includes a plurality of subunits and a controller **150**. A subunit may be referred to as a module or a card. Each subunit has a plurality of antennas (or antenna elements), a plurality of transmitter RF chains, a plurality of receiver RF chains, and a digital front end (DFE).

(43) One transmitter RF chain includes a transmitter, one or more power amplifiers (e.g., HPA), and one or more RF filters (e.g., bandpass filters). The transmitter includes, for example, a plurality of DACs, a plurality of baseband filters (e.g., low-pass filters), and an IQ modulator. On the other hand, one receiver RF chain includes a receiver, one or more power amplifiers (e.g., LNAs), and one or more RF filters (e.g., bandpass filters). The receiver includes, for example, multiple ADCs, multiple baseband filters (e.g., low-pass filters), and an IQ demodulator. The DFE may perform, for example, but not limited to, low physical layer signal processing and digital radio signal processing. The low physical layer signal processing includes, for example, fast Fourier Transform (FFT) and inverse FFT (IFFT). The digital radio signal processing may include, for example,

digital pre-distortion (DPD), crest factor reduction (CFR), digital up conversion (DUC), digital down conversion (DDC), and baseband channel filtering for transmission and reception.

(44) By way of example, not limitation, the AAS **100** may have four subunits **110**, **120**, **130**, and **140**, as shown in FIG. **1**. Each subunit may have 16 transmitter RF chains, 16 receiver RF chains, and 16 or more antenna elements. In this case, the AAS **100** may operate as an active phased array antenna with 64 or more antenna elements.

(45) One particular subunit (e.g., subunit **110**) is connected to the other subunits (e.g., subunits **120**, **130**, and **140**) via RF lines (e.g., RF lines **162**, **163**, and **164**). Each RF line may include a coaxial cable, coaxial connector, or distributed constant line or any combination thereof. These RF lines are used for inter-subunit calibration as described below.

(46) The controller **150** performs first-stage transmission calibration and second-stage transmission calibration to compensate for relative differences in amplitude and phase among all the transmitter RF chains of the plurality of subunits (e.g., subunits **110**, **120**, **130**, and **140**). The first-stage transmission calibration may also be referred to as intra-subunit transmission calibration, while the second-stage transmission calibration is also referred to as inter-subunit transmission calibration. Similarly, the controller **150** performs first-stage reception calibration and second-stage reception calibration to compensate for relative differences in amplitude and phase among all the receiver RF chains of the plurality of subunits (e.g., subunits **110**, **120**, **130**, and **140**). The first-stage reception calibration is also referred to as intra-subunit reception calibration, while the second-stage reception calibration is also referred to as inter-subunit reception calibration.

(47) In some implementations, the plurality of subunits **110**, **120**, **130**, and **140** may be implemented on their respective circuit boards. The AAS **100** may have a single enclosure housing the plurality of subunits **110**, **120**, **130**, and **140** and the controller **150**. The first subunit **110** may be connected to the other subunits **120**, **130**, and **140** with the RF lines **162**, **163**, and **164** within this enclosure.

(48) FIG. **2A** shows an example of a transmission calibration method or procedure. Step **201** is an intra-subunit transmission calibration and step **202** is an inter-subunit transmission calibration.

(49) In step **201**, the controller **150** performs transmission calibration among the transmitter RF chains within each subunit. Specifically, the controller **150** compensates for relative differences in amplitude and phase among the multiple transmitter RF chains within the first subunit (e.g., subunit **110**). Similarly, the controller **150** corrects for relative differences in amplitude and phase among the multiple transmitter RF chains in the second subunit (e.g., subunit **120**). If there are more than three subunits, the controller **150** performs the same transmission calibration for each of the third and subsequent subunits (e.g., subunits **130** and **140**). The controller **150** is able to perform multiple first-stage transmission calibrations of multiple subunits independently. In other words, the multiple first-stage transmission calibrations of the multiple subunits may be performed simultaneously or at different times.

(50) In the intra-subunit transmission calibration (step **201**), the controller **150** may control a subunit in such a manner that the transmitters of a plurality of transmitter RF chains in the subunit transmit calibration signals and the receiver of any one receiver RF chain in the subunit receives these calibration signals. The calibration signal may be, for example, a multi-tone signal consisting of multiple known OFDM subcarriers superimposed on each other. The controller **150** may control all the transmitter RF chains in the subunit (except those in failure) to transmit calibration signals. Based on the reception results of the calibration signals, the controller **150** may calculate a correction factor (or offset or weight) to be applied to each transmitter RF chain to compensate for relative differences in amplitude and phase among the multiple transmitter RF chains in the subunit.

(51) One transmitter RF chain in the subunit may be used (or chosen) as a reference transmitter RF chain. The reference transmitter RF chain is used as a reference in determining the correction factor for each transmitter RF chain except the reference transmitter RF chain to correct for relative

differences in amplitude and phase. The correction factor for each transmitter RF chain may be the ratio of transmission line characteristics (or frequency response) of that transmitter RF chain to transmission line characteristics (or frequency response) of the reference transmitter RF chain. The correction factor may be referred to as a calibration factor, calibration weight, or offset.

(52) As an example, consider the case where the AAS **100** has four subunits **110**, **120**, **130**, and **140**, each subunit having 16 transmitter RF chains. For transmission calibration within subunit #i (where i is an integer from 1 to 4), the calibration weight  $W_{1,\text{sub},i,n,\text{sup.TX}}$  of transmitter RF chain #n (where n is an integer from 1 to 16) may be calculated by the following Equation (1):

$$(53) \quad W_{1,i,n}^{\text{TX}} = \frac{\text{TX}_{i,\text{Ref}}}{\text{TX}_{i,n}}, i = 1, \text{.Math.}, 4; n = 1, \text{.Math.}, 16 \quad (1)$$

where  $\text{TX}_{\text{sub},i,\text{Ref}}$  is the amplitude and phase characteristics of the reference transmitter RF chain of subunit #i and  $\text{TX}_{\text{sub},i,n}$  is the amplitude and phase characteristics of the transmitter RF chain #n of subunit #i. If transmitter RF chain #1 is chosen as the reference transmitter RF chain, then the calibration weight  $W_{1,\text{sub},i,1,\text{sup.TX}}$  of transmitter RF chain #1 is equal to 1 and may be referred to as  $W_{1,\text{sub},i,\text{Ref},\text{sup.TX}}$ . For example, the calibration weight  $W_{1,\text{sub},i,n,\text{sup.TX}}$  may be added as an offset in the digital domain to the signal of the corresponding transmitter RF chain #n of subunit #i. This allows the 16 transmitter RF chains in subunit #i to be regarded as if they have the same amplitude and phase characteristics, i.e., the amplitude and phase characteristics  $\text{TX}_{\text{sub},i,\text{Ref}}$  of the reference transmitter RF chain. Thus, the relative amplitude differences and relative phase differences among the 16 transmitter RF chains in subunit #i are compensated for. As noted above, the calibration weight  $W_{1,\text{sub},i,1,\text{sup.TX}}$  for the reference transmitter RF chain is equal to 1, so the multiplication process of this weight may be omitted.

(54) The characteristics (or frequency response) of passive components (e.g., a circulator and an RF filter) and lines located between a signal branch point for calibration (e.g., splitter) and a connection point of the corresponding antenna element in each transmission RF chain, as well as the characteristics of the antenna element itself, are measured at a factory before shipment of the AAS **100**, and if there are virtually no factors that could cause these characteristics to vary, representative fixed values based on these measurements are preset and stored in the AAS **100**. These measured and stored characteristics may be recorded or stored in a memory of the controller **150** or corresponding subunit. These measured and stored characteristics may be used for the intra-subunit calibration described above. Specifically, in Equation (1), instead of  $\text{TX}_{\text{sub},i,n}$ , a value obtained by multiplying  $\text{TX}_{\text{sub},i,n}$  by  $\text{TX}_{\text{sub},i,n}, \text{const}$  may be used. Similarly, in Equation (1), instead of  $\text{TX}_{\text{sub},i,\text{Ref}}$ , a value obtained by multiplying  $\text{TX}_{\text{sub},i,\text{Ref}}$  by  $\text{TX}_{\text{sub},i,\text{Ref}}, \text{const}$  may be used.  $\text{TX}_{\text{sub},i,n}, \text{const}$  is the sum of the characteristics of the passive components and lines between the signal branch point of the transmitter RF chain #n of subunit #i and the connection point of the corresponding antenna element with the characteristics of the antenna element itself. Meanwhile,  $\text{TX}_{\text{sub},i,\text{Ref}}, \text{const}$  is the sum of the characteristics of the passive components and lines between the signal branch point of the reference transmitter RF chain of subunit #i and the connection point of the corresponding antenna element with the characteristics of the antenna element itself. As mentioned above, if the variation of the amplitude-phase-frequency characteristics of the passive components up to the antenna among the transmitter RF chains is small and its temperature-dependent variation is flat and small, the amplitude-phase frequency characteristics up to the antenna in each chain can be added in advance as a fixed value.

(55) After completion of the first-stage transmission calibration on a subunit-by-subunit basis, the controller **150** performs an inter-subunit transmission calibration (step **202**). Specifically, the controller **150** compensates for relative differences in amplitude and phase among multiple representative transmitter RF chains, each included in a respective one of the multiple subunits. In the configuration example of FIG. **1**, the controller **150** corrects for relative differences in amplitude and phase among four representative transmitter RF chains, chosen respectively from the four subunits **110**, **120**, **130**, and **140**. The representative transmitter RF chain for each subunit may



be the same as the reference transmitter RF chain in the first stage transmission calibration.

(56) In inter-subunit transmission calibration (step **202**), the controller **150** may control the multiple representative transmitter RF chains of the multiple subunits to transmit calibration signals and the receiver of any one receiver RF chain of any one subunit to receive these calibration signals. In the configuration example in FIG. **1**, calibration signals transmitted from the three representative transmitter RF chains in the second through fourth subunits **120**, **130**, and **140** are supplied to the first subunit **110** via the RF lines **162**, **163**, and **163**. Thus, the receiver of one receiver RF chain in the first subunit **110** is used to receive these calibration signals. The receiver in any subunit that receives the calibration signals in the inter-subunit transmission calibration may be the same as or different from the receiver used to receive the calibration signals during the intra-subunit transmission calibration of that subunit.

(57) The controller **150** may calculate a correction factor (or offset or weight) applied to each representative transmitter RF chain to compensate for relative differences in amplitude and phase among the plurality of representative transmitter RF chains based on the reception results of the calibration signals. In other words, the controller **150** may calculate a correction factor (or offset) to be applied to each representative transmitter RF chain to correct for relative differences in amplitude and phase among the subunits. One of the multiple representative transmitter RF chains may be used (or selected) as a reference representative transmitter RF chain. The correction factor for each representative transmitter RF chain may be the ratio of the transmission line characteristics (or frequency response) of that representative transmitter RF chain to the transmission line characteristics (or frequency response) of the reference representative transmitter RF chain.

(58) As an example, consider the case where the AAS **100** has four subunits **110**, **120**, **130**, and **140**. In inter-subunit transmission calibration, the calibration weight  $W2.sub.i.sup.TX$  of the representative transmitter RF chain of subunit # $i$  (where  $i$  is an integer from 1 to 4) may be calculated by the following Equation (2):

$$(59) \quad W2_i^{TX} = \frac{TX_{Ref, Rep}}{TX_{i, Rep}}, i = 1, .Math. , 4 \quad (2)$$

where  $TX.sub.Ref,Rep$  is the amplitude and phase characteristics of the reference representative transmitter RF chain, and  $TX.sub.i,Rep$  is the amplitude and phase characteristics of the representative transmitter RF chain of subunit # $i$ . If the representative transmitter RF chain of subunit #**1** (i.e., subunit **110**) is chosen as the reference representative transmitter RF chain, then the calibration weight  $W2.sub.1.sup.TX$  of subunit #**1** is equal to 1 and may be referred to as  $W2.sub.Ref.sup.TX$ . For example, after completion of the inter-subunit transmission calibration, the calibration weight  $W2.sub.i.sup.TX$  may be added as an offset in the digital domain to the signals of all the transmitter RF chains in the corresponding subunit # $i$ . This results in all (e.g., 64) transmitter RF chains in all four subunits to be regarded as if they have identical amplitude and phase characteristics. Thus, the relative amplitude differences and relative phase differences among all the transmitter RF chains of the four subunits is compensated. As noted above, the calibration weight  $W2.sub.Ref.sup.TX$  of the reference representative transmitter RF chain is equal to 1, so the multiplication process of this weight may be omitted.

(60) Equation (2) may be transformed as follows. For the sake of illustration, consider the case where the representative transmitter RF chain of subunit #**1** is the reference representative transmitter RF chain. In this case, the calibration weight  $W3.sub.i.sup.TX$  defined in Equation (3) below may be used instead of the calibration weight  $W2.sub.i.sup.TX$  in Equation (2):

$$(61) \quad W3_i^{TX} = \frac{W2_i^{TX}}{W2_{Ref}^{TX}}, i = 2, .Math. , 4 \quad (3)$$

(62) That is,  $W3.sub.i.sup.TX$  is obtained by the ratio of the calibration weight  $W2.sub.i.sup.TX$  of a non-reference representative transmitter RF chain obtained by inter-subunit transmission calibration to the calibration weight  $W2.sub.Ref.sup.TX$  (or  $W2.sub.1.sup.TX$ ) obtained by the same inter-subunit calibration. In other words, by dividing the calibration weight  $W2.sub.i.sup.TX$

of a subunit by the calibration weight  $W2_{sub.i.sup.TX}$  of the reference subunit #1, as in Equation (3), it is possible to obtain  $W2_{sub.i.sup.TX}$  in Equation (2) and  $W3_{sub.i.sup.TX}$  in Equation (3), which is equivalent to Equation (2)  $W2_{sub.i.sup.TX}$ .

(63) The following explains that  $W3_{sub.i.sup.TX}$  in Equation (3) is equivalent to  $W2_{sub.i.sup.TX}$  in Equation (2). In other words, it explains that the relational equation shown in Equation (4) can be derived:

$$(64) \quad W3_i^{TX} = \frac{W2_i^{TX}}{W2_{Ref}^{TX}} (i = 2, \text{Math.}, 4) = \frac{TX_{Ref, Rep}}{TX_{i, Rep}} \quad (4)$$

(65) The calibration weight  $W2_{sub.i.sup.TX}$  for each subunit is obtained by the following Equation (5):

$$(66) \quad W2_i^{TX} = \frac{1}{TX_{CalActual} \times \frac{TX_{ChainPre-obtained}}{TX_{CalPre-obtained}}} = \frac{TX_{CalPre-obtained}}{TX_{CalActual} \times TX_{ChainPre-obtained}} = \frac{1}{TX_{i, Rep}} \quad (5)$$

where “TX Cal Pre-obtained” is the amplitude-phase-frequency characteristic pre-measured through a TX calibration network of the transmitter, obtained during AAS internal calibration in product testing performed in a factory prior to shipment. Meanwhile, “TX Chain Pre-obtained” is the amplitude-phase-frequency characteristic of the main signal transmission system up to the antenna of each transmitter TX chain, obtained during AAS internal calibration in product testing performed in a factory prior to shipment. The ratio of “TX Chain Pre-obtained” to “TX Cal Pre-obtained” may be written to a memory in the AAS **100** as a pre-stored correction factor by calibration. On the other hand, “TX Cal Actual” is obtained as a result of calibration measured via the TX calibration network of that transmitter under field operation, including the aspect of amplitude and phase variation of the TX system, with successive updates. Consequently,  $W2_{sub.i.sup.TX}$  is expressed as the rightmost side of Equation (5), i.e., the inverse of the estimated amplitude-phase-frequency characteristic  $TX_{sub.i, Rep}$  of the representative transmitter in each subunit, including its antenna, which is estimated through calibration and updated periodically.

(67) Similarly, the calibration weight  $W2_{sub.Ref.sup.TX}$  of the reference representative transmitter RF chain is obtained by the following Equation (6):

$$(68) \quad W2_{Ref}^{TX} = \frac{1}{TX_{RefCalActual} \times \frac{TX_{RefChainPre-obtained}}{TX_{RefCalPre-obtained}}} = \frac{TX_{RefCalPre-obtained}}{TX_{RefCalActual} \times TX_{RefChainPre-obtained}} = \frac{1}{TX_{Ref, Rep}} \quad (6)$$

where “TX Ref Cal Pre-obtained” is the amplitude-phase-frequency characteristic pre-measured through a TX calibration network of the reference representative transmitter, obtained during AAS internal calibration in product testing performed in a factory prior to shipment. Meanwhile, “TX Ref Chain Pre-obtained” is the amplitude-phase-frequency characteristic of the main signal transmission system up to the antenna of the reference representative transmitter TX chain, obtained during AAS internal calibration in product testing performed in a factory prior to shipment. The ratio of “TX Ref Cal Pre-obtained” to “TX Ref Chain Pre-obtained” may be written to a memory in the AAS **100** as a pre-stored correction factor by calibration. On the other hand, “TX Ref Cal Actual” is obtained as a result of calibration measured via the TX calibration network of the reference representative transmitter under field operation, including the aspect of amplitude and phase variation of the TX system, with successive updates. Consequently,  $W2_{sub.Ref.sup.TX}$  is expressed as the rightmost side of Equation (6), i.e., the inverse of the estimated amplitude-phase-frequency characteristic  $TX_{sub.Ref, Rep}$  of the representative transmitter of the reference subunit, including its antenna, which is estimated through calibration and updated periodically.

(69) From the above, it can be seen that by dividing  $W2_{sub.i.sup.TX}$  in Equation (5) by  $W2_{sub.Ref.sup.TX}$  in Equation (6), the following relationship in Equation (7) can be obtained, as well as the relationship in Equation (4):

$$(70) \quad W3_i^{TX} = \frac{W2_i^{TX}}{W2_{Ref}^{TX}} = (1 / TX_{i, Rep}) / (1 / TX_{Ref, Rep}) = \frac{TX_{Ref, Rep}}{TX_{i, Rep}} = W2_i^{TX} \quad (7)$$

(71) By using the correction factors obtained from the intra-subunit transmission calibrations (step

**201**) and the inter-subunit transmission calibration (step **202**), the controller **150** can remove (or compensate for, or correct for) mismatches in amplitude and phase relationships among all the transmitter RF chains in the multiple subunits. In some implementations, the controller **150** may calculate the correction factor to be applied to each transmitter RF chain by multiplying the correction factor obtained from the intra-subunit transmission calibration with the correction factor obtained from the inter-subunit transmission calibration. This calculation is suitable when the representative transmitter RF chain for each subunit is the same as the reference transmitter RF chain in the first stage transmission calibration. The controller **150** may control the DFE of each subunit to add the corresponding phase and amplitude difference as an offset in the digital domain based on the obtained correction factor.

(72) As an example, consider the case where the AAS **100** has four subunits **110**, **120**, **130**, and **140**, each subunit having 16 transmitter RF chains. The controller **150** may calculate the total calibration weight  $W_{total.sub.i,n.sup.TX}$  to be applied to the signal of transmitter RF chain # $n$  in subunit # $i$  by the following Equation (8):

$$W_{total.sub.in.sup.TX} = W_{2.sub.i.sup.TX} \times W_{1.sub.i,n.sup.TX}, i=1, \dots, 4; n=1, \dots, 16. \quad (8)$$

where  $W_{1.sub.i,n.sup.TX}$  is the calibration weight for the transmission RF chain # $n$  in subunit # $i$ , obtained by the intra-subunit calibration and calculated by Equation (1). Meanwhile,  $W_{2.sub.i.sup.TX}$  is the calibration weight for subunit # $i$ , obtained in the inter-subunit calibration and calculated using Equation (2) or Equation (3). For example, the total calibration weight  $W_{total.sub.i,n.sup.TX}$  may be added as an offset in the digital domain to the signal of the corresponding transmitter RF chain # $n$  in subunit # $i$ . This allows the total of 64 transmitter RF chains in the four subunits to be regarded as if they have identical amplitude and phase characteristics. Thus, the relative amplitude and phase differences among the 64 transmitter RF chains of the four subunits are compensated for.

(73) Alternatively, the controller **150** may calculate the total calibration weight  $W_{total.sub.i,n.sup.TX}$  to be applied to the signals of the transmitter RF chain # $n$  in subunit # $i$  by the following Equation (9):

$$W_{total.sub.in.sup.TX} = W_{3.sub.i.sup.TX} \times W_{1.sub.i,n.sup.TX}, i=1, \dots, 4; n=1, \dots, 16. \quad (9)$$

where  $W_{1.sub.i,n.sup.TX}$  is the calibration weight for the transmission RF chain # $n$  in subunit # $i$ , obtained by the intra-subunit calibration and calculated by Equation (1). Meanwhile,  $W_{3.sub.i.sup.TX}$  is the calibration weight for subunit # $i$ , obtained in the inter-subunit calibration and calculated using Equation (4) or Equation (7). For example, the total calibration weight  $W_{total.sub.i,n.sup.TX}$  may be added as an offset in the digital domain to the signal of the corresponding transmitter RF chain # $n$  in subunit # $i$ . This allows the total of 64 transmitter RF chains in the four subunits to be regarded as if they have identical amplitude and phase characteristics. Thus, the relative amplitude and phase differences among the 64 transmitter RF chains of the four subunits are compensated for.

(74) FIG. 2B shows an example of a reception calibration method or procedure. Step **241** is an intra-subunit reception calibration and step **242** is an inter-subunit reception calibration. The intra-subunit and inter-subunit reception calibrations may be performed in a manner similar to the intra-subunit and inter-subunit transmission calibrations described above.

(75) In step **241**, the controller **150** performs reception calibration among the reception RF chains within each subunit. Specifically, the controller **150** compensates for relative differences in amplitude and phase among the multiple receiver RF chains within the first subunit (e.g., subunit **110**). Similarly, the controller **150** corrects for relative differences in amplitude and phase among the multiple receiver RF chains in the second subunit (e.g., subunit **120**). If there are more than three subunits, the controller **150** performs the same reception calibration for each of the third and subsequent subunits (e.g., subunits **130** and **140**). The controller **150** is able to perform multiple first-stage reception calibrations of multiple subunits independently. In other words, the multiple first-stage reception calibrations of the multiple subunits may be performed simultaneously or at

different times.

(76) In the intra-subunit reception calibration (step **241**), the controller **150** controls a subunit in such a manner that the transmitter of one transmitter RF chain in the subunit transmits a calibration signal and the receivers of a plurality of receiver RF chains in the subunit receive this calibration signal. The controller **150** may control all the receiver RF chains in the subunit (except those in failure) to receive the calibration signal. Based on the results of receiving the calibration signal, the controller **150** may calculate a correction factor (or offset or weight) to be applied to each receiver RF chain to compensate for relative differences in amplitude and phase among the multiple receiver RF chains in the subunit.

(77) One receiver RF chain in the subunit may be used (or chosen) as a reference receiver RF chain. The reference receiver RF chain is used as a reference in determining the correction factor for each receiver RF chain except the reference receiver RF chain to correct for relative differences in amplitude and phase. The correction factor for each receiver RF chain may be the ratio of transmission line characteristics (or frequency response) of that receiver RF chain to transmission line characteristics (or frequency response) of the reference receiver RF chain. The correction factor may be referred to as a calibration factor, calibration weight, or offset.

(78) After completion of the first-stage reception calibration on a subunit-by-subunit basis, the controller **150** performs an inter-subunit reception calibration (step **242**). Specifically, the controller **150** compensates for relative differences in amplitude and phase among multiple representative receiver RF chains, each included in a respective one of the multiple subunits. In the configuration example of FIG. **1**, the controller **150** corrects for relative differences in amplitude and phase among four representative receiver RF chains, chosen respectively from the four subunits **110**, **120**, **130**, and **140**. The representative receiver RF chain for each subunit may be the same as the reference receiver RF chain in the first stage reception calibration.

(79) In the inter-subunit transmission calibration (step **242**), the controller **150** may control the multiple subunits in such a manner that any one transmitter in any one transmitter RF chain of any one subunit transmits a calibration signal, and the multiple representative receiver RF chains of the multiple subunits receive this calibration signal. In the configuration example in FIG. **1**, the calibration signal output from one of the transmitters in the first subunit **110** is fed to the three representative transmitter RF chains in the second through fourth subunits **120**, **130**, and **140** via the RF lines **162**, **163**, and **163**. The transmitter of any of the subunits transmitting the calibration signal in the inter-subunit transmission calibration may be the same as or different from the transmitter used to transmit the calibration signal during the intra-subunit reception calibration of that subunit.

(80) The controller **150** may calculate a correction factor (or offset or weight) applied to each representative receiver RF chain to compensate for relative differences in amplitude and phase among the plurality of representative receiver RF chains based on the reception results of the calibration signal. In other words, the controller **150** may calculate a correction factor (or offset) to be applied to each representative receiver RF chain to correct for relative differences in amplitude and phase among the subunits. One of the multiple representative receiver RF chains may be used (or selected) as a reference representative receiver RF chain. The correction factor for each representative receiver RF chain may be the ratio of the transmission line characteristics (or frequency response) of that representative receiver RF chain to the transmission line characteristics (or frequency response) of the reference representative receiver RF chain.

(81) By using the correction factors obtained from the intra-subunit reception calibrations (step **241**) and the inter-subunit reception calibration (step **242**), the controller **150** can remove (or compensate for, or correct for) mismatches in amplitude and phase relationships among all the receiver RF chains in the multiple subunits. In some implementations, the controller **150** may calculate the correction factor to be applied to each receiver RF chain by multiplying the correction factor obtained from the intra-subunit reception calibration with the correction factor obtained from

the inter-subunit reception calibration. This calculation is suitable when the representative receiver RF chain for each subunit is the same as the reference receiver RF chain in the first stage reception calibration. The controller **150** may control the DFE of each subunit to add the corresponding phase and amplitude difference as an offset in the digital domain based on the obtained correction factor. (82) The calculation of correction factors or calibration weights in the reception calibrations may be performed in the same manner as the calculation of correction factors or calibration weights in the transmission calibrations described with reference to Equations (1) through (9).

(83) The calibrations described with reference to FIG. 2A and FIG. 2B may be performed at the time the AAS **100** is manufactured (prior to product shipment). In addition, the calibrations described with reference to FIG. 2A and FIG. 2B may be performed as appropriate while the AAS **100** is in operation.

(84) As an example, not a limitation, the intra-subunit transmission and reception calibrations in step **201** of FIG. 2A and step **241** of FIG. 2B may be performed according to the method described in International Publication WO 2021/019885 A1 (Patent Literature 2).

(85) Adopting the AAS architecture with multiple subunits described with reference to FIG. 1 and the two-stage calibration described with reference to FIGS. 2A and 2B can bring the following advantages, for example. In one example, the first stage calibration and the second stage calibration can be performed independently and separately. This can contribute to improving the first pass yield of the AAS **100** during pre-shipment inspection. Specifically, the first pass yield during inspection of each subunit can be improved. In addition, by stocking manufactured subunits for which the first-stage transmission and reception calibration has been completed and then assembling the AAS **100** with these subunits as needed, the first pass yield of the AAS **100** during equipment inspection can also be improved. Furthermore, separating the first-stage calibration and second-stage calibration would alleviate the time constraints of calibrations performed while the AAS **100** is in operation.

#### Second Example Embodiment

(86) This example embodiment provides a specific example of the configuration and calibration method of the AAS **100** described in the first example embodiment. FIG. 3 shows an example configuration of the first subunit **110** and FIG. 4 shows an example configuration of the second subunit **120**. If the AAS **100** has three or more subunits, the configuration of the third and subsequent subunits (e.g., subunits **130** and **140**) may be identical to that of the second subunit **120**. As shown in FIG. 3 and FIG. 4, all subunits may have the same configuration, except for the connection relationship between the subunits and the RF lines **162-164**.

(87) Referring to FIG. 3, the subunit **110** includes multiple transceiver RF chains. In the example in FIG. 3, the number of transceiver RF chains in the subunit **110** is 16. A transceiver RF chain **10** is configured to provide a calibration signal during intra-subunit reception calibration to a receiver RF chain **16** in the transceiver RF chain **10** and to receiver RF chains **26** in the other 15 transceiver RF chains **20**. In addition, the transceiver RF chain **10** is configured to receive calibration signals from a transmitter RF chain **15** in the transceiver RF chain **10** and from transmitter RF chains **25** in the other 15 transceiver RF chains **20** during intra-subunit transmission calibration. The transceiver RF chain **10** is also configured to provide a calibration signal to representative receiver RF chains of other subunits (e.g., subunits **120**, **130**, and **140**) during inter-subunit reception calibration. Similarly, the transceiver RF chain **10** is configured to receive calibration signals from representative transmitter RF chains of other subunits (e.g., subunits **120**, **130**, and **140**) during inter-subunit transmission calibration.

(88) The transceiver RF chain **10** includes the transmitter RF chain **15** and the receiver RF chain **16**. The transmitter RF chain **15** is connected to a DFE **30** and also connected to one or more antenna elements **11** via RF passive components such as a circulator **14** and RF filter **13** (e.g., bandpass filter). The reference sign **12** represents a connection point (e.g., Transceiver Array Boundary (TAB) connector) to the antenna element(s) **11**. A splitter **17** is located at the output end

of the transmitter RF chain **15** and splits an output signal of the transmitter RF chain **15** for transmission calibration and feeds it to a calibration signal path via a divider **19**. A splitter (or combiner) **18** is located at the input end of the receiver RF chain **16** and feeds a calibration signal from the calibration signal path to the receiver RF chain **16** for reception calibration.

(89) Each of the **15** transceiver RF chains **20** has components similar to those of the transceiver RF chains **10**. Specifically, each transceiver RF chain **20** includes the transmitter RF chain **25** and receiver RF chain **26**. The transmitter RF chain **25** is connected to the DFE **30** and also connected to one or more antenna elements **21** via RF passive components such as a circulator **24** and RF filter **23** (e.g., bandpass filter). The reference sign **22** represents a connection point (e.g., TAB connector) to the antenna element(s) **21**. A splitter **27** is located at the output end of the transmitter RF chain **25** and splits an output signal of the transmitter RF chain **25** for transmission calibration and feeds it to the calibration signal path via a divider **29**. A splitter (or combiner) **28** is located at the input end of the receiver RF chain **26** and feeds a calibration signal from the calibration signal path to the receiver RF chain **26** for reception calibration.

(90) However, the transmitter RF chain **15** of the transceiver RF chain **10** requires a switch to select the output destination of its transmitter between the path directed to the antenna element **11** and the signal path including a switch **42** for calibration. Similarly, the receiver RF chain **16** of the transceiver RF chain **10** requires a switch to select its receiver input between the path connected to the antenna element **11** and the signal path including the switch **42** for calibration. In contrast, each of the other 20 transceiver RF chains does not require such a switch.

(91) The switch **42**, a switch **43**, and a 16-way divider network **41** are used as the signal path for intra-subunit transmission calibration and reception calibration. In intra-subunit transmission calibration, the 16-way divider network **41** operates to provide calibration signals from the 16 transmitter RF chains (**15**, **25**) to the receiver in the receiver RF chain **16** via the switches **42** and **43**. In addition, in intra-subunit reception calibration, the 16-way divider network **41** operates to receive a calibration signal from the transmitter in the transmitter RF chain **15** via the switches **42** and **43** and feed it to the 16 receiver RF chains (**16**, **26**).

(92) The switches **42** and **43** and a 4-way divider network **51** are used as a signal path for inter-subunit transmission calibration and reception calibration. In inter-subunit transmission calibration, the 4-way divider network **51** operates to receive calibration signals from the representative transmitter RF chains of the other three subunits **120**, **130**, and **140** via the RF lines **162**, **163**, and **164**, and supply them to the receiver in the receiver RF chain **16** via the switches **42** and **43**. In addition, in inter-subunit reception calibration, the 4-way divider network **51** operates to receive a calibration signal from the transmitter in the transmitter RF chain **15** via the switches **42** and **43** and feed it to the representative receiver RF chains in the other three subunits **120**, **130**, and **140**. The 4-way divider network **51** may be connected to the RF lines **162**, **163**, and **164** via RF connectors **54** (e.g., coaxial connectors).

(93) The subunit **110** does not necessarily require a switch **52** and an RF connector **53**, and thus these may be omitted. If the switch **52** is provided in the subunit **110**, the switch **52** may always select the line to the 16-way divider network **41**.

(94) The DFE **30** may perform, for example, but not limited to, low physical layer signal processing and digital radio signal processing. The low physical layer signal processing includes, for example, FFT and IFFT. The digital radio signal processing includes, for example, DPD, CFR, DUC, and DDC. Although not illustrated, the DFE **30** is communicatively coupled to the controller **150**. The controller **150** controls the DFE **30** for intra-subunit and inter-subunit calibration. The controller **150** also controls the DFE **30** of each subunit to multiply a calibration weight of each transmitter RF chain obtained by transmission calibration with the transmission signal of that transmitter RF chain. In this way, the controller **150** matches the amplitude-phase characteristics among all the transmitters in all the subunits. Similarly, the controller **150** controls the DFE **30** of each subunit to multiply a calibration weight of each receiver RF chain obtained by reception

calibration with the received signal of that receiver RF chain. In this way, the controller **150** matches the amplitude phase characteristics among all the receivers of all the subunits. The DFE **30** may have an interface to communicate with a digital baseband unit (e.g., Distributed Unit (DU) of 5G gNB).

(95) Referring to FIG. **4**, the subunit **120** has the same configuration as the subunit **110** shown in FIG. **3**. However, for inter-subunit transmission calibration and reception calibration, the transceiver RF chain **10** can be connected to the RF line **162** via a switch **52**. In inter-subunit transmission calibration, the transmitter RF chain **15** of the transceiver RF chain **10** acts as the representative transmitter RF chain and provides a calibration signal to the first subunit **110** via the RF line **162**. In inter-subunit reception calibration, the receiver RF chain **16** of the transceiver RF chain **10** acts as the representative receiver RF chain and receives a calibration signal from the first subunit **110** via the RF line **162**.

(96) The subunit **120** does not necessarily require the switch **43**, the 4-way divider network **51**, and the multiple RF connectors **54**, and thus these may be omitted. If the switch **43** is provided in the subunit **120**, the switch **43** may always select the line to the 16-way divider network **41**.

(97) FIG. **5A** shows a non-limiting example of the configuration of the transmitter RF chain **15** and receiver RF chain **16** in the transceiver RF chain **10**. In this example, the transmitter RF chain **15** includes two DACs **501**, two low-pass filters **502**, an IQ modulator **503**, a variable attenuator **504**, a driver amplifier **505** and a high-power amplifier (HPA) **506**. Meanwhile, the receiver RF chain **16** includes two ADCs **521**, two low-pass filters **522**, an IQ demodulator **523**, a variable gain amplifier **524**, and an LNA **525**. As an example, not a limitation, the elements from the DAC **501** to the variable attenuator **504** in the transmitter RF chain **15** and the elements from the ADC **521** to the variable gain amplifier **524** in the receiver RF chain **16** may be implemented as one transceiver integrated circuit (IC) **540**.

(98) Additionally, in the example in FIG. **5A**, a switch **531** is located in the transmitter RF chain **15** and a switch **532** is located in the receiver RF chain **16**. The switch **531** enables a calibration signal output from the transmitter (including the DAC **501**, low-pass filter **502**, IQ modulator **503**) to be fed to the path for calibration during intra-subunit and inter-subunit reception calibration. Meanwhile, the switch **532** allows calibration signals to be fed from the path for calibration to the receiver (including the ADC **521**, low-pass filter **522**, and IQ demodulator **523**) during intra-subunit and inter-subunit transmission calibration.

(99) FIG. **5B** shows another non-limiting example of the configuration of the transmitter RF chain **15** and receiver RF chain **16** of the transceiver RF chain **10**. FIG. **5B** differs from FIG. **5A** in that the switch **531** is located at the output of the driver amplifier **505**. According to the configuration in FIG. **5B**, the calibration signal for intra-subunit and inter-subunit reception calibration is amplified by the gain of the driver amplifier **505** before being sent to the path for calibration (i.e., switch **42**). This can contribute to an improved signal to noise ratio (SNR) of the calibration signal for intra-subunit and inter-subunit reception calibration.

(100) The following paragraphs describe the calibration in the configuration of the subunits **110**, **120**, **130**, and **140** described in FIGS. **3**, **4**, **5A**, and **5B**. The path shown in FIG. **6** with bold lines represents the signal path used during intra-subunit transmission calibration of the first subunit **110**. In this case, following the control of the controller **150**, a calibration signal generated by the DFE **30** is sent to the 16 transmitter RF chains **15** and **25** and received by the receiver in the receiver RF chain **16** through the 16-way divider network **41**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates a correction factor (or offset or weight) to be applied to each transmitter RF chain. The correction factor may be referred to as a calibration factor, calibration weight, or offset. The signal paths used during intra-subunit transmission calibration of the other subunits **120**, **130**, and **140** are similar to that in FIG. **6**.

(101) For example, for intra-subunit transmission calibration, the controller **150** may calculate the

calibration weights according to the specific example described in the first example embodiment with reference to Equation (1). As described in the first example embodiment, the characteristics (or frequency response) of the passive components (e.g., circulator **14** and RF filter **13**) and lines existing between the splitters **17** and **18** and the connection point **12** of the antenna element **11** in the transceiver RF chain **10** may be measured at a factory before shipment of the AAS **100**. Similarly, the characteristics of the passive components and lines located between the splitters **27** and **28** and the connection point **22** of the antenna element **21** in each of the other transceiver RF chains **20** may be measured at the factory prior to shipment of the AAS **100**. These measured characteristics may be stored in a memory of the controller **150** or corresponding subunit and used for calibration.

(102) The path shown in FIG. 7 with bold lines indicates the signal path used during intra-subunit reception calibration of the first subunit **110**. In this case, according to the control of the controller **150**, a calibration signal is generated by the DFE **30**, sent to the calibration path by the transmitter in the transmitter RF chain **15**, and then received by the 16 receiver RF chains **16** and **26** via the 16-way divider network **41**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates a correction factor (or offset or weight) to be applied to each receiver RF chain. The signal paths used during intra-subunit reception calibration of the other subunits **120**, **130**, and **140** are similar to that in FIG. 7. The correction factors may be referred to as calibration factors, calibration weights, or offsets. For example, the controller **150** may calculate the calibration weights in intra-subunit reception calibration in a manner similar to the transmission calibration case described in the first example embodiment with reference to Equation (1).

(103) The path shown in FIG. 8 with a bold line represents the signal path of the first subunit **110** used during inter-subunit transmission calibration. In this case, following the control of the controller **150**, a calibration signal generated by the DFE **30** is sent to the transmitter RF chain **15** (i.e., the representative transmitter RF chain of the subunit **110**) and received by the receiver of the receiver RF chain **16** via the 16-way divider network **41**. In addition, the switch **43** is switched to select the 4-way divider network **51**, and calibration signals transmitted from the representative transmitter RF chains of the second through fourth subunits **120**, **130**, and **140** are received by the receiver of the receiver RF chain **16** through the 4-way divider network **51**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates correction factors (or offsets or weights) to remove (or compensate for or correct) mismatches in the amplitude and phase relationships among the four representative transmitter RF chains.

(104) The path shown in FIG. 9 with bold lines represents the signal path of the second subunit **120** used during inter-subunit transmission calibration. In this case, a calibration signal generated by the DFE **30** of the subunit **120** is sent to the transmitter RF chain **15** (i.e., the representative transmitter RF chain of the subunit **120**) and output to the RF line **162**, according to the control of the controller **150**. The signal paths of the third and fourth subunits **130** and **140** used during inter-subunit transmission calibration are similar to that in FIG. 9.

(105) The correction factors may be referred to as calibration factors, calibration weights, or offsets. For example, in inter-subunit transmission calibration, the controller **150** may calculate the calibration weights according to any of the specific examples described in the first example embodiment with reference to Equations (2) through (7). In addition, the controller **150** may calculate the total calibration weights according to any of the specific examples described in the first example embodiment with reference to Equations (8) through (9).

(106) The path shown in FIG. 10 with bold lines represents the signal path of the first subunit **110** used during inter-subunit reception calibration. In this case, following the control of the controller **150**, a calibration signal is generated by the DFE **30**, sent to the path for calibration by the transmitter in the transmitter RF chain **15**, and received by the receiver RF chain **16** (i.e., the



representative receiver RF chain of the subunit **110**) via the 16-way divider network **41**. In addition, the switch **43** is switched to select the 4-way divider network **51**, and the calibration signal is sent to the representative receiver RF chains of the second through fourth subunits **120**, **130**, and **140**. (107) The path shown in FIG. **11** with bold lines indicates the signal path of the second subunit **120** used during inter-subunit reception calibration. In this case, the receiver RF chain **16** (i.e., the representative receiver RF chain of the subunit **120**) receives the calibration signal from the first subunit **110**, according to the control of the controller **150**. The signal paths of the third and fourth subunits **130** and **140** used during inter-subunit reception calibration are similar to that in FIG. **11**. (108) In the examples in FIG. **10** and FIG. **11**, the DFE **30** of each subunit detects the received calibration signal. Based on the results of the calibration signal reception, the controller **150** calculates correction factors (or offsets or weights) to remove (or compensate for or correct) mismatches in the amplitude and phase relationships among the four representative receiver RF chains.

(109) For example, the controller **150** may calculate the calibration weights in inter-subunit reception calibration in a manner similar to the case of transmission calibration described in the first example embodiment with reference to equations (2) through (7). The controller **150** may also calculate the total calibration weights in reception calibration in a manner similar to the transmission calibration case described in the first example embodiment with reference to equations (8) through (9).

(110) As shown in FIG. **8**, in the inter-subunit transmission calibration of this example embodiment, the calibration signal transmitted from the representative transmitter RF chain **15** of the first subunit **110** does not pass through a line outside the circuit board of the first subunit **110**, but is input within that circuit board to the receiver of the receiver RF chain **16**. Similarly, as shown in FIG. **10**, in the inter-subunit reception calibration of this example embodiment, the transmission calibration signal sent from the transmitter in the transmitter RF chain **15** of the first subunit **110** is provided to the representative receiver RF chain **16** of the first subunit **110** within the circuit board of the first subunit **110**, rather than through a line outside the circuit board of the first subunit **110**.

#### Third Example Embodiment

(111) This example embodiment provides other specific examples of the configuration and calibration method of the AAS **100** described in the first embodiment. FIG. **12** shows an example configuration of the first subunit **110**. The configuration shown in FIG. **12** is identical to that shown in FIG. **3**. However, in the example in FIG. **12**, an RF line **901** is provided. This allows, as shown in FIG. **13**, during inter-subunit transmission calibration, the calibration signal transmitted from the representative transmitter RF chain **15** of the first subunit **110** is output to the line **901** outside the circuit board of the first subunit **110** and then folded back inside that circuit board and input to the receiver in receiver RF chain **16**. Similarly, as shown in FIG. **14**, during inter-subunit reception calibration, the calibration signal transmitted from the transmitter in the transmitter RF chain **15** of the first subunit **110** is sent out on the line **901** outside the circuit board of the first subunit **110** and then folded back into that circuit board and fed to the representative receiver RF chain **16** of the first subunit **110**.

#### Fourth Example Embodiment

(112) This example embodiment provides yet another specific example of the configuration and calibration method of the AAS **100** described in the first embodiment. FIG. **15** shows an example configuration of the first subunit **110** and FIG. **16** shows an example configuration of the second subunit **120**. If the AAS **100** has three or more subunits, the configuration of the third and subsequent subunits (e.g., subunits **130** and **140**) may be identical to that of the second subunit **120**. As shown in FIGS. **15** and **16**, all the subunits may have the same configuration, only the connection relationship to the RF lines **162-164** may be different.

(113) Comparing FIG. **15** with FIG. **12**, FIG. **15** differs from FIG. **12** in that the 4-way divider network **51** for inter-subunit calibration is connected via a switch **81** to a different transceiver RF

chain **70** than the transceiver RF chain **10**. The configuration of the transceiver RF chain **70** may be identical to the configuration of the transceiver RF chain **10**. The configuration of the transceiver RF chains **10** and **70** shown in FIG. **15** may be identical to the configuration of the transceiver RF chain **10** described with reference to FIGS. **3**, **5A**, and **5B**.

(114) Referring to FIG. **16**, the subunit **120** has the same configuration as the subunit **110** shown in FIG. **15**. However, for inter-subunit transmission calibration and reception calibration, the transceiver RF chain **10** can be connected to the RF line **162** via the switch **52**. The subunit **120** does not necessarily require the switch **81**, 4-way divider network **51**, and multiple RF connectors **54**, and thus these may be omitted.

(115) The following paragraphs describe the calibration in the configuration of the subunits **110**, **120**, **130**, and **140** described in FIGS. **15** and **16**. The path shown in FIG. **17** with bold lines represents the signal path used during intra-subunit transmission calibration of the first subunit **110**. The signal path shown in FIG. **17** is identical to that shown in FIG. **6**. Specifically, following the control of the controller **150**, a calibration signal generated by the DFE **30** is sent to the 16 transmitter RF chains **15**, **25** and **75** and received by the receiver in the receiver RF chain **16** through the 16-way divider network **41**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates a correction factor (or offset or weight) to be applied to each transmitter RF chain. The signal paths used during intra-subunit transmission calibration of the other subunits **120**, **130**, and **140** are similar to that in FIG. **17**.

(116) The correction factors may be referred to as calibration coefficients, calibration weights, or offsets. For example, in intra-subunit transmission calibration, the controller **150** may calculate the calibration weights according to the specific example described in the first example embodiment with reference to Equation (1).

(117) The path shown in FIG. **18** with bold lines represents the signal path used during intra-subunit reception calibration of the first subunit **110**. The signal path shown in FIG. **18** is identical to that shown in FIG. **7**. Specifically, according to the control of the controller **150**, a calibration signal is generated by the DFE **30**, sent to the calibration path by the transmitter in the transmitter RF chain **15**, and then received by the 16 receiver RF chains **16**, **26** and **76** via the 16-way divider network **41**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates a correction factor (or offset or weight) to be applied to each receiver RF chain. The signal paths used during intra-subunit reception calibration of the other subunits **120**, **130**, and **140** are similar to that in FIG. **18**.

(118) The correction factors may be referred to as calibration factors, calibration weights, or offsets. For example, the controller **150** may calculate the calibration weights in intra-subunit reception calibration in a manner similar to the transmission calibration case described in the first example embodiment with reference to Equation (1).

(119) The path shown in FIG. **19** with bold lines represents the signal path of the first subunit **110** used during inter-subunit transmission calibration. The signal path shown in FIG. **19** is basically identical to that shown in FIG. **13**. The calibration signal transmitted from the representative transmitter RF chain **15** of the first subunit **110** is sent out to the line **901** outside the circuit board of the first subunit **110** and then folded back into that circuit board. FIG. **19** differs from FIG. **13**, however, in that the folded calibration signal is input to the receiver in the receiver RF chain **76** instead of the receiver in the receiver RF chain **16**. Similarly, the calibration signals from the representative transmitter RF chains of the second through fourth subunits **120**, **130**, and **140** are also input to the receiver of the receiver RF chain **76** via the 4-way divider network **51**. The DFE **30** detects the received calibration signals. Based on the reception results of the calibration signals, the controller **150** calculates correction factors (or offsets or weights) to remove (or compensate for or correct) mismatches in amplitude and phase relationships among the four representative transmitter RF chains.

(120) The path shown in FIG. 20 with bold lines represents the signal path of the second subunit **120** used during inter-subunit transmission calibration. The signal path shown in FIG. 20 is identical to that shown in FIG. 9. Specifically, a calibration signal generated by the DFE **30** of the subunit **120** is sent to the transmitter RF chain **15** (i.e., the representative transmitter RF chain of the subunit **120**) and output to the RF line **162**, according to the control of the controller **150**. The signal paths of the third and fourth subunits **130** and **140** used during inter-subunit transmission calibration are similar to that in FIG. 20.

(121) The correction factors may be referred to as calibration factors, calibration weights, or offsets. For example, in inter-subunit transmission calibration, the controller **150** may calculate the calibration weights according to any of the specific examples described in the first example embodiment with reference to Equations (2) through (7). In addition, the controller **150** may calculate the total calibration weights according to any of the specific examples described in the first example embodiment with reference to Equations (8) through (9).

(122) The path shown in FIG. 21 with bold lines represents the signal path of the first subunit **110** used during inter-subunit reception calibration. The signal path shown in FIG. 21 is basically identical to that shown in FIG. 14. FIG. 21 differs from FIG. 14, however, in that the transmitter in the transmitter RF chain **75**, not the transmitter RF chain **15**, transmits a calibration signal. The calibration signal transmitted by the transmitter in the transmitter RF chain **75** is sent out to the line **901** outside the circuit board of the first subunit **110** and then folded back into that circuit board and fed to the representative receiver RF chain **16** of the first subunit **110**. In addition, this calibration signal is supplied via the RF lines **162-164** to the representative receiver RF chains of the second through fourth subunits **120**, **130**, and **140**.

(123) The path shown in FIG. 22 with bold lines represents the signal path of the second subunit **120** used during inter-subunit reception calibration. The signal path shown in FIG. 22 is identical to that shown in FIG. 11. Specifically, the receiver RF chain **16** (i.e., the representative receiver RF chain of the subunit **120**) receives the calibration signal from the first subunit **110**, according to the control of the controller **150**. The signal paths of the third and fourth subunits **130** and **140** used during inter-subunit reception calibration are similar to that in FIG. 11.

(124) In the examples in FIG. 21 and FIG. 22, the DFE **30** of each subunit detects the received calibration signal. Based on the results of the calibration signal reception, the controller **150** calculates correction factors (or offsets or weights) to remove (or compensate for or correct) mismatches in the amplitude and phase relationships among the four representative receiver RF chains.

(125) For example, the controller **150** may calculate the calibration weights in inter-subunit reception calibration in a manner similar to the case of transmission calibration described in the first example embodiment with reference to equations (2) through (7). The controller **150** may also calculate the total calibration weights in reception calibration in a manner similar to the transmission calibration case described in the first example embodiment with reference to equations (8) through (9).

(126) In this example embodiment, the receiver used for calibration signal reception (e.g., the receiver in the receiver RF chain **16**) in the intra-subunit transmission calibration of the subunit **110** is different from the receiver used for calibration signal reception (e.g., the receiver in the receiver RF chain **76**) in the inter-subunit transmission calibration. Similarly, the transmitter used for calibration signal transmission (e.g., the transmitter in the transmitter RF chain **15**) in the intra-subunit reception calibration of the subunit **110** is different from the transmitter used for calibration signal transmission (e.g., the transmitter in the transmitter RF chain **75**) in the inter-subunit reception calibration.

#### Fifth Example Embodiment

(127) This example embodiment provides for fallback operation when an amplifier in a transceiver RF chain has failed or is unavailable. The example configuration of the AAS **100** in this example

embodiment may be the same as that described in any of the first four embodiments.

(128) If an amplifier (e.g., driver amplifier **505** or HPA **506** in FIG. 5A) in the reference transmitter RF chain **15** of the in-subunit transmission calibration has failed, the controller **150** uses one of the other transmitter RF chains **25** in that subunit as an alternative reference transmitter RF chain. The controller **150** continues to use the receiver in the receiver RF chain **16** associated with the transmitter RF chain **15**, in which its amplifier has failed, to receive calibration signals from all of the other transmitter RF chains **25** in the intra-subunit transmission calibration.

(129) FIG. 23 illustrates adjustments made by the controller **150** when an amplifier in the reference transmitter RF chain **15** of intra-subunit transmission calibration has failed. In step **2301**, the controller **150** detects that an amplifier of the reference transmitter RF chain **15** for the intra-subunit transmission calibration has failed. For example, the controller **15** may detect that the reception level at the receiver (e.g., the receiver of the receiver RF chain **16**) that receives calibration signals in the intra-subunit transmission calibration is below a certain level, thereby detecting a transmission amplifier failure, i.e., a failure or anomaly of that transmission system. In step **2302**, the controller **150** uses one of the other transmitter RF chains **25** in the subunit as an alternative reference transmitter RF chain. In step **2303**, the controller **150** uses the receiver in the receiver RF chain **16** associated with the transmitter RF chain **15**, in which its amplifier has failed, to receive calibration signals from the other transmitter RF chains **25** in that subunit.

(130) If an amplifier (e.g., LNA **525** in FIG. 5A) in the reference receiver RF chain **16** of the intra-subunit reception calibration has failed, then the controller **150** uses one of the other receiver RF chains **26** in that subunit as an alternative reference receiver RF chain. The controller **150** continues to use the transmitter in the transmitter RF chain **15** associated with the receiver RF chain **16**, in which its amplifier has failed, to transmit a calibration signal to all of the other receiver RF chains **26** in the intra-subunit reception calibration.

(131) FIG. 24 shows adjustments made by the controller **150** in the event of a failure of an amplifier in the reference receiver RF chain **16** of intra-subunit reception calibration. In step **2401**, the controller **150** detects that an amplifier in the reference receiver RF chain **16** for the intra-subunit reception calibration has failed. For example, the controller **15** may detect that the reception level at the receiver of the reference receiver RF chain **16** of a calibration signal in the intra-subunit reception calibration is below a certain level, thereby detecting a failure of the low-noise amplifier for reception, i.e., a failure or anomaly of that reception system. In step **2402**, the controller **150** uses one of the other receiver RF chains **26** in the subunit as an alternative reference receiver RF chain. In step **2403**, the controller **150** uses the transmitter of the transmitter RF chain **15** associated with the receiver RF chain **16**, in which its amplifier has failed, to transmit a calibration signal to the other receiver RF chains **26** in that subunit.

(132) If an amplifier in the representative transmitter RF chain **15** of the first subunit **110** for inter-subunit transmission calibration has failed, then the controller **150** uses one of the other transmitter RF chains **25** in that subunit **110** as an alternative representative transmitter RF chain. The controller **150** continues to use, in the inter-subunit transmission calibration, the receiver in the receiver RF chain **16** associated with the transmitter RF chain **15**, in which its amplifier has failed, to receive calibration signals from the alternative representative transmitter RF chain and the representative transmitter RF chains of the other subunits.

(133) Similarly, if an amplifier in the representative transmitter RF chain **15** of the second subunit **120** for inter-subunit transmission calibration has failed, then the controller **150** uses one of the other transmitter RF chains **25** in that subunit **120** as an alternative representative transmitter RF chain.

(134) FIG. 25 shows adjustments made by the controller **150** in the event of a failure of an amplifier in the representative transmitter RF chain **15** of inter-subunit transmission calibration. In step **2501**, the controller **150** detects that an amplifier in the representative transmitter RF chain **15** of the first subunit **110** for the inter-subunit transmission calibration has failed. In step **2502**, the

controller **150** uses one of the other transmitter RF chains **25** in that subunit **110** as an alternative representative transmitter RF chain. In step **2503**, the controller **150** uses the receiver of the receiver RF chain **16** associated with the transmitter RF chain **15**, whose amplifier has failed, to receive calibration signals from the alternative representative transmitter RF chain and from the representative transmitter RF chains of the other subunits.

(135) If an amplifier in the representative receiver RF chain **16** of the first subunit **110** for inter-subunit reception calibration has failed, then the controller **150** uses one of the other receiver RF chains **26** in that subunit **110** as an alternate representative receiver RF chain. The controller **150** continues to use, in inter-subunit reception calibration, the transmitter in the transmitter RF chain **15** associated with the receiver RF chain **16**, whose amplifier has failed, to transmit a calibration signal to the alternative representative receiver RF chain and the representative receiver RF chains of the other subunits.

(136) Similarly, if the amplifier in the representative receiver RF chain **16** of the second subunit **120** for inter-subunit reception calibration has failed, then the controller **150** uses one of the other receiver RF chains **26** in that subunit **120** as an alternative representative receiver RF chain.

(137) FIG. **26** shows adjustments made by the controller **150** in the event of a failure of an amplifier in the representative receiver RF chain **16** of inter-subunit reception calibration. In step **2601**, the controller **150** detects that an amplifier in the representative receiver RF chain **16** of the first subunit **110** for inter-subunit reception calibration has failed. In step **2602**, the controller **150** uses one of the other receiver RF chains **26** in that subunit **110** as an alternative representative receiver RF chain. In step **2603**, the controller **150** uses the transmitter of the transmitter RF chain **15** associated with the receiver RF chain **16**, whose amplifier has failed, to transmit a calibration signal to the alternative representative transmitter RF chain and to the representative receiver RF chains of the other subunits.

(138) The following paragraphs describe improvements to the subunit configuration to allow for the fallback operations in the event of amplifier failures described with reference to FIGS. **23** to **26**. FIG. **27** shows an example configuration of the first subunit **110** and FIG. **28** shows an example configuration of the second subunit **120**. If the AAS **100** has three or more subunits, the configuration of the third and subsequent subunits (e.g., subunits **130** and **140**) may be identical to that of the second subunit **120**. As shown in FIGS. **27** and **28**, all subunits may have the same configuration, except for the connection relationship between the subunits and the RF lines **162-164**.

(139) Comparing FIG. **27** with FIG. **12**, FIG. **27** differs from FIG. **12** in that the placement of the switch **52** has been moved from one of the 16 output ports of the 16-way divider network **41** to the input port of the network **41**. This allows the output of any of the 16 transmitter RF chains to be used for inter-subunit transmission calibration. In addition, any of the 16 receiver RF chains can be provided with a calibration signal for inter-subunit reception calibration.

(140) Similarly, according to the arrangement of the switch **52** shown in FIG. **28**, the output of any of the 16 transmitter RF chains can be transmitted to the first subunit **110** for inter-subunit transmission calibration. In addition, any of the 16 receiver RF chains can be supplied with a calibration signal from the first subunit **110** for inter-subunit reception calibration.

(141) Note that, FIGS. **27** and **28** show a variation of the subunit configuration example (FIG. **12**) described in the third example embodiment. Likewise, in the subunit configuration example of the second example embodiment (FIG. **3** and FIG. **4**), the placement of the switch **52** may be moved from one of the 16 output ports of the 16-way divider network **41** to the input port of the network **41**.

(142) The path shown in FIG. **29** with bold lines indicates the signal path used during intra-subunit transmission calibration of the first subunit **110**. If an amplifier in the reference transmitter RF chain **15** has failed, then one of the other transmitter RF chains **25** is chosen as the alternative reference transmitter RF chain. The reception calibration signals transmitted from the alternative

reference transmitter RF chain **25** and the other 14 transmitter RF chains are received by the receiver in the receiver RF chain **16** via the 16-way divider network **41**.

(143) The path shown in FIG. **30** with bold lines indicates the signal path used during intra-subunit reception calibration of the first subunit **110**. If an amplifier in the reference receiver RF chain **16** has failed, one of the other receiver RF chains **26** is chosen as an alternative reference receiver RF chain. The calibration signal transmitted from the transmitter RF chain **15** is received by the alternative reference receiver RF chain **26** and the other 14 receiver RF chains via the 16-way divider network **41**.

(144) The path shown in FIG. **31** with bold lines represents the signal path of the first **110** subunit used during inter-subunit transmission calibration. If an amplifier in the representative transmitter RF chain **15** has failed, then one of the other transmitter RF chains **25** is chosen as an alternative representative transmitter RF chain. The calibration signal transmitted from the alternative representative transmitter RF chain **25** is fed through the 4-way divider network **51** to the receiver in the receiver RF chain **16**. Similarly, the calibration signals from the representative transmitter RF chains of the second through fourth subunits **120**, **130**, and **140** are also fed into the receiver of the receiver RF chain **16** via the 4-way divider network **51**.

(145) The path shown in FIG. **32** with bold lines represents the signal path of the second subunit **120** used during inter-subunit transmission calibration. If an amplifier in the representative transmitter RF chain **15** of the second subunit **120** has failed, one of the other transmitter RF chains **25** is chosen as an alternative representative transmitter RF chain. The calibration signal transmitted from the alternative representative transmitter RF chain **25** is sent to the first subunit **110**.

(146) The path shown in FIG. **33** with bold lines represents the signal path of the first subunit **110** used during inter-subunit reception calibration. If an amplifier in the representative receiver RF chain **16** of the first subunit **110** has failed, one of the other receiver RF chains **26** is chosen as an alternative representative receiver RF chain. The alternative representative receiver RF chain **26** receives the calibration signal transmitted from the transmitter in the transmitter RF chain **15**.

(147) The path shown in FIG. **34** with bold lines represents the signal path of the second subunit **120** used during inter-subunit reception calibration. If an amplifier in the representative receiver RF chain **16** of the second subunit **120** has failed, one of the other receiver RF chains **26** is chosen as an alternative representative receiver RF chain. The alternative representative receiver RF chain **26** receives the calibration signal transmitted from the transmitter of the transmitter RF chain **15** of the first subunit **110**.

(148) FIG. **35** shows an example configuration of the controller **150** of the example embodiments described above. The controller **150** includes a processor **3501** and a memory **3502**. The processor **3501** may include a plurality of processors. The memory **3502** may store one or more software modules (or computer programs) containing a set of instructions and data for processing by the controller **150** described in the above example embodiments. In some implementations, the processor **3501** may be configured to load the software modules from the memory **3502** and execute them, thereby performing the processing of the controller **150** described with reference to the drawings in the example embodiments described above.

(149) As explained with FIG. **35**, the processor contained in the controller **150** according to the example embodiments described above can execute one or more programs containing a set of instructions to cause a computer to perform the algorithm described with reference to the drawings. The program(s) contains a set of instructions (or software codes) that, when loaded into a computer, causes the computer to perform one or more of the functions described in the example embodiments. The program(s) may be stored in a non-transitory computer readable medium or a tangible storage medium. By way of example, and not limitation, non-transitory computer readable media or tangible storage media can include a random-access memory (RAM), a read-only memory (ROM), a flash memory, a solid-state drive (SSD) or other memory technologies, CD-ROM, digital

versatile disk (DVD), Blu-ray (registered mark) disc or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices. The program(s) may be transmitted on a transitory computer readable medium or a communication medium. By way of example, and not limitation, transitory computer readable media or communication media can include electrical, optical, acoustical, or other form of propagated signals.

(150) An example advantage according to the above-described example embodiments is to provide an apparatus, method, and program to enable calibration suitable for a product architecture in which subunits, each having multiple antenna elements and multiple RF chains, are manufactured and combined to form a single AAS.

(151) The above-described example embodiment is merely examples of the application of the technical ideas obtained by the inventors. These technical ideas are not limited to the above-described example embodiment and various modifications can be made thereto.

(152) The whole or part of the example embodiments disclosed above can be described as, but not limited to, the following supplementary notes.

(153) (Supplementary Note 1)

(154) An active antenna system comprising first and second subunits; and a controller, wherein the first subunit comprises: a first set of antenna elements; a first set of transmitter Radio Frequency (RF) chains coupled to the first set of antenna elements; a first set of receiver RF chains coupled to the first set of antenna elements; and a first digital front end coupled to the first set of transmitter RF chains and the first set of receiver RF chains, the second subunit comprises: a second set of antenna elements; a second set of transmitter RF chains coupled to the second set of antenna elements; a second set of receiver RF chains coupled to the second set of antenna elements; and a second digital front end coupled to the second set of transmitter RF chains and the second set of receiver RF chains, and the controller is configured to perform: a first transmission calibration to compensate for relative differences in amplitude and phase among transmitter RF chains in the first set of transmitter RF chains; a second transmission calibration to compensate for relative differences in amplitude and phase among transmitter RF chains in the second set of transmitter RF chains; and a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the first set of transmitter RF chains and a second representative transmitter RF chain in the second set of transmitter RF chains.

(Supplementary Note 2)

(155) The active antenna system according to Supplementary Note 1, wherein the controller is configured to perform: a first reception calibration to compensate for relative differences in amplitude and phase among receiver RF chains in the first set of receiver RF chains; a second reception calibration to compensate for relative differences in amplitude and phase among receiver RF chains in the second set of receiver RF chains; and a third reception calibration to compensate for relative differences in amplitude and phase between a first representative receiver RF chain in the first set of receiver RF chains and a second representative receiver RF chain in the second set of receiver RF chains.

(Supplementary Note 3)

(156) The active antenna system according to Supplementary Note 1 or 2, wherein the controller is configured to: in the first transmission calibration, use a first receiver included in one of the first sets of receiver RF chains to receive calibration signals from the first set of transmitter RF chains; in the second transmission calibration, use a second receiver included in one of the second sets of receiver RF chains to receive calibration signals from the second set of transmitter RF chains; and in the third transmission calibration, use a third receiver included in one of the first set of receiver RF chains to receive calibration signals from the first representative transmitter RF chain and the second representative transmitter RF chain.

(Supplementary Note 4)

(157) The active antenna system according to Supplementary Note 3, wherein the third receiver is

the same as the first receiver.

(Supplementary Note 5)

(158) The active antenna system according to Supplementary Note 3, wherein the third receiver is different from the first receiver.

(Supplementary Note 6)

(159) The active antenna system according to Supplementary Note 3 or 4, wherein the first subunit is configured such that in the third transmission calibration, the calibration signal transmitted from the first representative transmitter RF chain is input to the third receiver in a circuit board of the first subunit without going through a line outside the circuit board.

(160) (Supplementary Note 7)

(161) The active antenna system according to Supplementary Note 3 or 5, wherein the first subunit is configured such that in the third transmission calibration, the calibration signal transmitted from the first representative transmitter RF chain is sent out on a line outside a circuit board of the first subunit and then folded back into the circuit board and input to the third receiver.

(162) (Supplementary Note 8)

(163) The active antenna system according to Supplementary Note 2, wherein the controller is configured to: in the first reception calibration, use a transmitter included in one of the first set of transmitter RF chains to transmit a calibration signal to the first set of receiver RF chains; in the second reception calibration, use a transmitter included in one of the second set of transmitter RF chains to transmit a calibration signal to the second set of receiver RF chains; and in the third reception calibration, using a transmitter included in one of the first set of transmitter RF chains to transmit a calibration signal to the first representative receiver RF chain and the second representative receiver RF chain.

(Supplementary Note 9)

(164) The active antenna system according to Supplementary Note 8, wherein a transmitter RF chain used to transmit the calibration signal in the first reception calibration comprises a first transmitter, a first amplifier connected to the output of the first transmitter, and a first RF switch located at the output of the first amplifier, wherein the first RF switch is configured to switch between a signal line connected to one or more of the first set of antenna elements and a signal line for calibration.

(Supplementary Note 10)

(165) The active antenna system according to Supplementary Note 8 or 9, wherein a transmitter RF chain used to transmit the calibration signal in the second reception calibration comprises a second transmitter, a second amplifier connected to the output of the second transmitter, and a second RF switch located at the output of the second amplifier, and the second RF switch is configured to switch between a signal line connected to one or more of the second set of antenna elements and a signal line for calibration.

(Supplementary Note 11)

(166) The active antenna system according to any one of Supplementary Notes 1 to 10, wherein the first representative transmitter RF chain in the third transmission calibration is the same as a reference transmitter RF chain in the first transmission calibration, and the reference transmitter RF chain is used as a reference in determining a correction factor or offset for each transmitter RF chain other than the reference transmitter RF chain to compensate for the relative differences in amplitude and phase.

(Supplementary Note 12)

(167) The active antenna system according to any one of Supplementary Notes 1 to 11, wherein the controller is configured to, if an amplifier in a reference transmitter RF chain for the first transmission calibration has failed, use another transmitter RF chain in the first set of transmitter RF chains as an alternative reference transmitter RF chain.

(168) (Supplementary Note 13)



(169) The active antenna system according to Supplementary Note 12, wherein the controller is configured to use a receiver in a receiver RF chain associated with the transmitter RF chain in which the amplifier thereof has failed, to receive calibration signals from other transmitter RF chains in the first set of transmitter RF chains in the first transmission calibration.

(170) (Supplementary Note 14)

(171) The active antenna system according to Supplementary Note 2, wherein the controller is configured to, if an amplifier in a reference receiver RF chain for the first reception calibration has failed, use another receiver RF chain in the first set of receiver RF chains as an alternative reference receiver RF chain.

(172) (Supplementary Note 15)

(173) The active antenna system according to Supplementary Note 14, wherein the controller is configured to use a transmitter in a transmitter RF chain associated with the receiver RF chain in which the amplifier thereof has failed, to transmit a calibration signal to other receiver RF chains in the first set of receiver RF chains in the first reception calibration.

(174) (Supplementary Note 16)

(175) The active antenna system according to any one of Supplementary Notes 1 to 15, wherein the controller is configured to, if an amplifier in the first representative transmitter RF chain for the third transmission calibration has failed, use another transmitter RF chain in the first set of transmitter RF chains as an alternative first representative transmitter RF chain.

(176) (Supplementary Note 17)

(177) The active antenna system according to Supplementary Note 16, wherein the controller is configured to use a receiver in a receiver RF chain associated with the transmitter RF chain in which the amplifier thereof has failed, to receive calibration signals from the alternative first representative transmitter RF chain and the second representative transmitter RF chain in the third transmission calibration.

(178) (Supplementary Note 18)

(179) The active antenna system according to any one of Supplementary Notes 1 to 17, wherein the controller is configured to, if an amplifier in the second representative transmitter RF chain for the third transmission calibration has failed, use another transmitter RF chain in the second set of transmitter RF chains as an alternative second representative transmitter RF chain.

(180) (Supplementary Note 19)

(181) The active antenna system according to Supplementary Note 2, wherein the controller is configured to, if an amplifier in the first representative receiver RF chain for the third reception calibration has failed, use another receiver RF chain in the first set of receiver RF chains as an alternative first representative receiver RF chain.

(182) (Supplementary Note 20)

(183) The active antenna system according to Supplementary Note 19, wherein the controller is configured to use a transmitter in a transmitter RF chain associated with the receiver RF chain in which the amplifier thereof has failed, to transmit a calibration signal to the alternative first representative receiver RF chain and the second representative receiver RF chain in the third reception calibration.

(184) (Supplementary Note 21)

(185) The active antenna system according to any one of Supplementary Notes 2, 19, and 20, wherein the controller is configured to, if an amplifier in the second representative receiver RF chain for the third reception calibration has failed, use another receiver RF chain in the second set of receiver RF chains as an alternative second representative receiver RF chain.

(186) (Supplementary Note 22)

(187) The active antenna system according to any one of Supplementary Notes 1 to 21, wherein the first and second subunits are implemented on respective circuit boards.

(188) (Supplementary Note 23)

- (189) The active antenna system according to any one of Supplementary Notes 1 to 22, further comprising a single enclosure housing the first and second subunits and the controller.
- (190) (Supplementary Note 24)
- (191) The active antenna system according to Supplementary Note 23, further comprising an RF line connecting the first subunit and the second subunit within the enclosure.
- (192) (Supplementary Note 25)
- (193) A method performed by a controller of an active antenna system, the method comprising: performing a first transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter radio frequency (RF) chains in a first subunit of the active antenna system; performing a second transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter RF chains in a second subunit of the active antenna system; and performing a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the plurality of transmitter RF chains of the first subunit and a second representative transmitter RF chain in the plurality of transmitter RF chains of the second subunit.
- (Supplementary Note 26)
- (194) A computer program for causing a controller of an active antenna system to perform a method, wherein the method comprises: performing a first transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter radio frequency (RF) chains in a first subunit of the active antenna system; performing a second transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter RF chains in a second subunit of the active antenna system; and performing a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the plurality of transmitter RF chains of the first subunit and a second representative transmitter RF chain in the plurality of transmitter RF chains of the second subunit.

## Claims

1. An active antenna system comprising first and second subunits; and a controller, wherein the first subunit comprises: a first set of antenna elements; a first set of transmitter Radio Frequency (RF) chains coupled to the first set of antenna elements; a first set of receiver RF chains coupled to the first set of antenna elements; and a first digital front end coupled to the first set of transmitter RF chains and the first set of receiver RF chains, the second subunit comprises: a second set of antenna elements; a second set of transmitter RF chains coupled to the second set of antenna elements; a second set of receiver RF chains coupled to the second set of antenna elements; and a second digital front end coupled to the second set of transmitter RF chains and the second set of receiver RF chains, and the controller is configured to perform: a first transmission calibration to compensate for relative differences in amplitude and phase among transmitter RF chains in the first set of transmitter RF chains; a second transmission calibration to compensate for relative differences in amplitude and phase among transmitter RF chains in the second set of transmitter RF chains; and a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the first set of transmitter RF chains and a second representative transmitter RF chain in the second set of transmitter RF chains.
2. The active antenna system according to claim 1, wherein the controller is configured to perform: a first reception calibration to compensate for relative differences in amplitude and phase among receiver RF chains in the first set of receiver RF chains; a second reception calibration to compensate for relative differences in amplitude and phase among receiver RF chains in the second set of receiver RF chains; and a third reception calibration to compensate for relative differences in amplitude and phase between a first representative receiver RF chain in the first set of receiver RF

chains and a second representative receiver RF chain in the second set of receiver RF chains.

3. The active antenna system according to claim 2, wherein the controller is configured to: in the first reception calibration, use a transmitter included in one of the first set of transmitter RF chains to transmit a calibration signal to the first set of receiver RF chains; in the second reception calibration, use a transmitter included in one of the second set of transmitter RF chains to transmit a calibration signal to the second set of receiver RF chains; and in the third reception calibration, using a transmitter included in one of the first set of transmitter RF chains to transmit a calibration signal to the first representative receiver RF chain and the second representative receiver RF chain.

4. The active antenna system according to claim 3, wherein a transmitter RF chain used to transmit the calibration signal in the first reception calibration comprises a first transmitter, a first amplifier connected to the output of the first transmitter, and a first RF switch located at the output of the first amplifier, and the first RF switch is configured to switch between a signal line connected to one or more of the first set of antenna elements and a signal line for calibration.

5. The active antenna system according to claim 2, wherein the controller is configured to, if an amplifier in a reference receiver RF chain for the first reception calibration has failed, use another receiver RF chain in the first set of receiver RF chains as an alternative reference receiver RF chain.

6. The active antenna system according to claim 5, wherein the controller is configured to use a transmitter in a transmitter RF chain associated with the receiver RF chain in which the amplifier thereof has failed, to transmit a calibration signal to other receiver RF chains in the first set of receiver RF chains in the first reception calibration.

7. The active antenna system according to claim 2, wherein the controller is configured to, if an amplifier in the first representative receiver RF chain for the third reception calibration has failed, use another receiver RF chain in the first set of receiver RF chains as an alternative first representative receiver RF chain.

8. The active antenna system according to claim 7, wherein the controller is configured to use a transmitter in a transmitter RF chain associated with the receiver RF chain in which the amplifier thereof has failed, to transmit a calibration signal to the alternative first representative receiver RF chain and the second representative receiver RF chain in the third reception calibration.

9. The active antenna system according to claim 1, wherein the controller is configured to: in the first transmission calibration, use a first receiver included in one of the first sets of receiver RF chains to receive calibration signals from the first set of transmitter RF chains; in the second transmission calibration, use a second receiver included in one of the second sets of receiver RF chains to receive calibration signals from the second set of transmitter RF chains; and in the third transmission calibration, use a third receiver included in one of the first set of receiver RF chains to receive calibration signals from the first representative transmitter RF chain and the second representative transmitter RF chain.

10. The active antenna system according to claim 9, wherein the third receiver is the same as the first receiver.

11. The active antenna system according to claim 9, wherein the third receiver is different from the first receiver.

12. The active antenna system according to claim 9, wherein the first subunit is configured such that in the third transmission calibration, the calibration signal transmitted from the first representative transmitter RF chain is input to the third receiver in a circuit board of the first subunit without going through a line outside the circuit board.

13. The active antenna system according to claim 9, wherein the first subunit is configured such that in the third transmission calibration, the calibration signal transmitted from the first representative transmitter RF chain is sent out on a line outside a circuit board of the first subunit and then folded back into the circuit board and input to the third receiver.

14. The active antenna system according to claim 1, wherein the first representative transmitter RF

chain in the third transmission calibration is the same as a reference transmitter RF chain in the first transmission calibration, and the reference transmitter RF chain is used as a reference in determining a correction factor or offset for each transmitter RF chain other than the reference transmitter RF chain to compensate for the relative differences in amplitude and phase.

15. The active antenna system according to claim 1, wherein the controller is configured to, if an amplifier in a reference transmitter RF chain for the first transmission calibration has failed, use another transmitter RF chain in the first set of transmitter RF chains as an alternative reference transmitter RF chain.

16. The active antenna system according to claim 15, wherein the controller is configured to use a receiver in a receiver RF chain associated with the transmitter RF chain in which the amplifier thereof has failed, to receive calibration signals from other transmitter RF chains in the first set of transmitter RF chains in the first transmission calibration.

17. The active antenna system according to claim 1, wherein the controller is configured to, if an amplifier in the first representative transmitter RF chain for the third transmission calibration has failed, use another transmitter RF chain in the first set of transmitter RF chains as an alternative first representative transmitter RF chain.

18. The active antenna system according to claim 17, wherein the controller is configured to use a receiver in a receiver RF chain associated with the transmitter RF chain in which the amplifier thereof has failed, to receive calibration signals from the alternative first representative transmitter RF chain and the second representative transmitter RF chain in the third transmission calibration.

19. A method performed by a controller of an active antenna system, the method comprising: performing a first transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter radio frequency (RF) chains in a first subunit of the active antenna system; performing a second transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter RF chains in a second subunit of the active antenna system; and performing a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the plurality of transmitter RF chains of the first subunit and a second representative transmitter RF chain in the plurality of transmitter RF chains of the second subunit.

20. A non-transitory computer readable medium storing a computer program for causing a controller of an active antenna system to perform a method, wherein the method comprises: performing a first transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter radio frequency (RF) chains in a first subunit of the active antenna system; performing a second transmission calibration to compensate for relative differences in amplitude and phase among a plurality of transmitter RF chains in a second subunit of the active antenna system; and performing a third transmission calibration to compensate for relative differences in amplitude and phase between a first representative transmitter RF chain in the plurality of transmitter RF chains of the first subunit and a second representative transmitter RF chain in the plurality of transmitter RF chains of the second subunit.

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