AN ANTENNA ARRAY AND A METHOD OF CALIBRATING AN ANTENNA ARRAY

TECHNICAL FIELD

The present disclosure relates broadly to an antenna array and a method of calibrating an antenna array.

BACKGROUND

Large scale phased array antennas are one of the most important enabling techniques for future high capacity wireless and satellite communications and have wide-spread applications. With proper amplitude tapering and phase control of the antenna elements / array elements, phased arrays can agilely steer the beam to the targeted direction to achieve high gain directivity, low sidelobe levels, and desired null pointing angle for high data rate, coverage management and interference suppression.

In order to obtain these desired array pattern features, each individual array element needs to be precisely excited in both amplitude and phase. However, practical implementations are challenged by manufacturing imperfections, circuit differences, and environmental factors, which lead to variations and/or misalignments in amplitude and phase among the array elements. These discrepancies can result in unintended beam distortion, increased sidelobe levels, and degraded overall system performance. Consequently, accurate calibration of the array elements is required to compensate for these deviations and maintain the desired radiation pattern characteristics.

The importance of accurate array calibration becomes even more pronounced in advanced applications such as satellite communications and 5G-based beamforming systems. These systems not only require initial calibration before deployment but also demand continuous or periodic recalibration during operation to counteract dynamic factors such as temperature variations, component aging, and mechanical stresses. Without such ongoing

calibration, performance degradation can accumulate over time, leading to reduced signal integrity, increased interference, and diminished communication efficiency. Therefore, effective calibration techniques are important to ensure long-term stability and high performance of large-scale phased array antennas in demanding operational environments.

Thus, there is a need for an antenna array and a method of calibrating an antenna array that seek to address or at least alleviate one of the above problems.

SUMMARY

In accordance with a first aspect of the present disclosure, there is provided a method of calibrating an antenna array comprising a plurality of subarray modules, each subarray module comprising a plurality of antenna elements, said method comprising, performing an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and performing an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.

In the method as disclosed herein, the antenna array may be a transmitter antenna array, and the intra-module calibration may comprise, (i) setting radiofrequency (RF) phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence; (ii) transmitting an intra-module calibration packet into beamformers and radiating out by the antenna elements of the subarray module; (iii) receiving the intra-module calibration packet by a calibration network using calibration probes; (iv) measuring a vector response from the received intra-module calibration packet; repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module; and (v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

In the method as disclosed herein, the antenna array may be a receiver antenna array, and the intra-module calibration may comprise, (i) setting RF phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence; (ii) transmitting an intra-module calibration packet into a calibration network and radiating out by calibration

probes of the subarray module; (iii) receiving the intra-module calibration packet by antenna elements and beamformers of the subarray module; (iv) measuring a vector response from the received intra-module calibration packet; repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module; and (v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

In the method as disclosed herein, the antenna array may be a transmitter antenna array, and the inter-module calibration may comprise, (i) setting a calibration channel of a selected subarray module as a calibration receiver; (ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence; (iii) transmitting an inter-module calibration packet into beamformers of all the subarray modules and radiating out by array antennas; (iv) receiving the inter-module calibration packet from the calibration channel of the selected subarray module with calibration probes; (v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet; repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response; (vi) computing transmission coefficients from all the subarray modules to the calibration channel of the calibration receiver; repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver; and (vii) computing mismatches among the subarray modules based on the transmission coefficients.

In the method as disclosed herein, the antenna array may be a receiver antenna array, and the inter-module calibration may comprise, (i) setting a calibration channel of a selected subarray module as a calibration transmitter; (ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence; (iii) transmitting an inter-module calibration packet into calibration channels of all the subarray modules and radiating out the inter-module calibration packet by calibration probes; (iv) receiving the inter-module calibration packet from beamformers of all the subarray modules with antenna elements; (v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet; repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response; (vi) computing transmission coefficients from the calibration channel of the

calibration transmitter to all the subarray modules; repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver; and (vii) computing mismatches among the subarray modules based on the transmission coefficients.

In the method as disclosed herein, each intra-module orthogonal sequence for each iteration of the repeated steps (i) to (iv) of the intra-module calibration may be a row in a Hadamard matrix, said intra-module orthogonal sequence providing specific encoding states for each of the antenna elements; and wherein a corresponding vector response is measured for each iteration of the repeated steps (i) to (iv).

In the method as disclosed herein, each inter-module orthogonal sequence for each iteration of the repeated steps (ii) to (v) of the inter-module calibration may be a row in a second Hadamard matrix, said inter-module orthogonal sequence providing specific encoding states for each of the subarray modules; and wherein a corresponding combined vector response is measured for each iteration of the repeated steps (ii) to (v) of the inter-module calibration.

In the method as disclosed herein, computing transmission coefficients to the calibration channel of the calibration receiver may comprise, collating the measured combined vector responses to obtain a subarray column vector; and obtaining the transmission coefficients based on the subarray column vector and the second Hadamard matrix.

In the method as disclosed herein, computing mismatches among subarray modules based on the transmission coefficients may comprise, calculating amplitude and phase mismatches between a first transmission signal from a first subarray, G_{si} and a second transmission signal from a second subarray G_{sj} to obtain a complex ratio

$$\frac{G_{Sj}}{G_{Si}} = \sqrt{\frac{H_{jj} * H_{ij}}{H_{ii} * H_{ji}}}$$

wherein for the transmitter antenna array, H_{ij} represents the transmission coefficients from the signal channel input of subarray module *i* to the calibration channel output of subarray module *j*, and for the receiver antenna array, H_{ij} represents the transmission coefficients from the calibration channel input of subarray module *i* to the signal channel output of subarray module *j*.

In the method as disclosed herein, the antenna elements within each subarray module may be calibrated in parallel during intra-module calibration.

In the method as disclosed herein, the intra-module calibration may be performed sequentially for the plurality of subarray modules.

In the method as disclosed herein, the plurality of subarray modules may comprise identical structures, each subarray module comprising the same number of antenna elements arranged in a square lattice.

In the method as disclosed herein, the intra-module calibration and inter-module calibration may be performed during online operation of the antenna array.

In the method as disclosed herein, the method may be devoid of using an external calibration device or external antenna for calibrating the antenna array.

In accordance with a second aspect of the present disclosure, there is provided an antenna array comprising, a plurality of subarray modules, each subarray module comprising a plurality of antenna elements and a calibration network configured to perform calibration of the subarray module; and a processing unit coupled to the plurality of subarray modules; wherein the processing unit is configured to: perform an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and perform an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.

In the antenna array as disclosed herein, the antenna array may be a transmitter antenna array, and the processing module may be configured to perform the intra-module calibration by, (i) setting radiofrequency (RF) phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence; (ii) transmitting an intra-module calibration packet into beamformers and radiating out by the antenna elements of the subarray module; (iii) receiving the intra-module calibration packet by a calibration network using calibration probes; (iv) measuring a vector response from the received intra-module calibration packet; repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module; and computing the mismatches in the

amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

In the antenna array as disclosed herein, the antenna array may be a receiver antenna array, and the processing module may be configured to perform the intra-module calibration by, (i) setting RF phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence; (ii) transmitting an intra-module calibration packet into a calibration network and radiating out by calibration probes of the subarray module; (iii) receiving the intra-module calibration packet by the antenna elements and beamformers of the subarray module; (iv) measuring a vector response from the received intra-module calibration packet; repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module; and (v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

In the antenna array as disclosed herein, the antenna array may be a transmitter antenna array, the processing module may be configured to perform the inter-module calibration by, (i) setting a calibration channel of a selected subarray module as a calibration receiver; (ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence; (iii) transmitting an inter-module calibration packet into beamformers of all the subarray modules and radiating out by array antennas; (iv) receiving the inter-module calibration packet from the calibration channel of the selected subarray module with calibration probes; (v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet; repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response; (vi) computing transmission coefficients from all the subarray modules to the calibration channel of the calibration receiver; repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver; and (vii) computing mismatches among the subarray modules based on the transmission coefficients.

In the antenna array as disclosed herein, the antenna array may be a receiver antenna array, the processing module may be configured to perform the inter-module calibration by, (i) setting a calibration channel of a selected subarray module as a calibration transmitter; (ii) setting RF phase shifters of each subarray module as a single unit according to an inter-

module orthogonal sequence; (iii) transmitting an inter-module calibration packet into calibration channels of all the subarray modules and radiating out by calibration probes; (iv) receiving the inter-module calibration packet from beamformers of all the subarray modules with antenna elements; (v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet; repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response; (vi) computing transmission coefficients from the calibration channel of the calibration transmitter to all the subarray modules; repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver; and (vii) computing mismatches among the subarray modules based on the transmission coefficients.

In the antenna array as disclosed herein, the plurality of subarray modules may be coupled to the processing unit based on a hybrid analog and digital beamforming system architecture.

In accordance with a third aspect of the present disclosure, there is provided a computer readable storage medium having stored thereon instructions for instructing a processing unit of an antenna array to execute a method of calibrating an antenna array comprising a plurality of subarray modules, each subarray module comprising a plurality of antenna elements, said method comprising, performing an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and performing an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 is a schematic drawing of an antenna array, e.g., phased array antenna in an example embodiment.

FIG. 2 is a schematic drawing showing a section of a board structure of a subarray module in an example embodiment.

FIG. 3 is a schematic drawing of a modular subarray in an example embodiment.

FIG. 4A is a circuit diagram of a complete modular phase array antenna system architecture in an example embodiment.

FIG. 4B is a circuit diagram of a hybrid analog and digital beamforming system architecture in another example embodiment.

FIG. 5 is a schematic flowchart for illustrating a method of calibrating an antenna array, e.g., transmitter (TX) / receiver (RX) phased array antenna, in an example embodiment.

FIG. 6 is a schematic flowchart illustrating a method of performing an intra-module calibration scheme for a TX subarray antenna board in an example embodiment.

FIG. 7 is a schematic flowchart illustrating a method of performing an intra-module calibration scheme for a RX subarray antenna board in an example embodiment.

FIG. 8A is a first schematic diagram of a modular array architecture in an example embodiment.

FIG. 8B is a second schematic diagram of the modular array architecture in the example embodiment.

FIG. 9 is a schematic flowchart illustrating a method of performing an inter-module calibration scheme for a modular scalable TX phased array comprising N subarray modules in an example embodiment.

FIG. 10 is a schematic flowchart illustrating a method of performing an inter-module calibration scheme for a modular scalable RX phased array comprising N subarray modules in an example embodiment.

FIG. 11 is a composite of schematic drawings of a phased array antenna in an example embodiment.

FIG. 12 is a graph showing simulated two-dimensional (2D) radiation patterns of the 64-element phased array antenna in the example embodiment.

FIG. 13 is a schematic drawing of a computer system suitable for implementing an example embodiment.

DETAILED DESCRIPTION

Example, non-limiting embodiments may provide an antenna array and a method of calibrating an antenna array. In various embodiments, the abbreviation "RX" may denote the terms "receiver" or "receiving", and the abbreviation "TX" may denote the terms "transmitter" or "transmitting".

FIG. 1 is a schematic drawing of an antenna array, e.g., phased array antenna 100 in an example embodiment. The phased array antenna 100 comprises a plurality of subarray modules, e.g., 102 (see the larger squares demarcated by dotted lines). Each subarray module 102 comprises a plurality of array elements / antenna elements e.g., 104 (see the smaller squares demarcated by dotted lines). Each array element / antenna element 104 may further comprise a radiofrequency (RF) amplifier, an attenuator and a phase shifter (not shown), collectively known as a beamformer, configured to perform RF signal amplitude and phase adjusting. Each subarray module 102 further comprises a calibration network (not shown) configured to perform calibration of the subarray module 102. The phased array antenna 100 further comprises a processing unit 106 coupled to the plurality of subarray modules, e.g., 102. The processing unit 106 is configured to perform an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements, e.g., 104, within each subarray module 102 of the plurality of subarray modules, e.g., 102. The processing unit 106 is further configured to perform an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules, e.g., 102.

In the example embodiment, the phased array antenna 100 is designed based on a scalable modular system architecture where antenna elements are grouped into subarrays, and multiple subarrays form an entire large array. The subarray modules, e.g., 102, have an identical structure, e.g., identical number of antenna elements, e.g., 104, identical calibration network structure etc. The identical or uniform structure advantageously allows the antenna array 100 to be scaled up easily to any array size. The identical or uniform structure also advantageously facilitates accurate and efficient parallel characterisation of the array elements. As shown in FIG. 1, the phased array antenna 100 is assembled from a plurality of 9 subarray modules, e.g., 102, arranged in a 3 x 3 square lattice configuration. Each subarray module 102 comprises a plurality of 64 antenna elements e.g., 104, arranged in an 8 x 8 square lattice configuration. It will be appreciated that the number of antenna elements, e.g., 104, in each subarray module 102 and the number of subarray modules, e.g., 102, forming the entire phased array antenna 100 is not limited as illustrated in FIG. 1, the phased array antenna 100 may comprise any number of subarray modules and the subarray module may comprise any number of antenna elements.

In the example embodiment, the calibration network is a built-in calibration network for allowing the phased array antenna 100 to perform in-situ self-calibration. The calibration network may be embedded in an antenna subarray board of the subarray module 102. The calibration network may comprise components including, but not limited to, calibration signal distribution network, phase shifters, variable gain amplifiers (VGAs), analog to digital converters (ADCs), digital to analog converters (DACs), RF switches, RF upconverters, RF downconverters, splitters, switch/combiner and the like. The calibration network may be used with a calibration algorithm executed by the processing unit 106 for online measurements of excitation errors in both amplitude and phase of the antenna elements, e.g., 104.

In the example embodiment, the processing unit 106 is configured to manage and adjust operational settings of the plurality of subarray modules, e.g., 102, including but not limited to beamforming parameters, amplitude and phase settings, and signal routing configurations. The processing unit 106 is further configured to execute a calibration algorithm, which detects, analyses, and compensates for excitation errors, phase mismatches, and amplitude variations among the subarray modules, e.g., 102, to ensure optimal array performance and maintain accurate beamforming characteristics over time.

In the example embodiment, the processing unit 106 is configured to execute both intra-module calibration and inter-module calibration schemes. This advantageously allow the phased array antenna 100 to be well calibrated by measuring and equalizing the amplitude and phase effects of all array elements, e.g., 104. As a result, the phased array antenna 100 may advantageously achieve a desired radiation pattern performance, such as main beam pointing and scanning accuracy, side lobe levels, and directivity, by setting and controlling the amplitude and phase tolerances of each array element.

In the example embodiment, the intra-module calibration and inter-module calibration may be performed during online operation of the antenna array 100. That is, calibration may be performed under actual array loading operating conditions. The antenna elements, e.g., 104, within each subarray module 102 may be calibrated in parallel during intra-module calibration. Intra-module calibration may be performed sequentially, one subarray module by one subarray module, for the plurality of subarray modules. The intra-module calibration and inter-module calibration may be repeated periodically after the phased array antenna 100 is deployed and during operation of the phased array antenna 100. This advantageously allows the phased array antenna 100 to compensate for any amplitude and phase shifts at each array element 104 occurring with time, temperature, and frequency changes, as the amplitude and phase characteristics of most RF devices vary with frequency and temperature and usually drift over time. Advantageously, the intra-module calibration and inter-module calibration schemes executed by the processing unit 106 do not require the use of external hardware/antenna, e.g., external calibration equipment, thereby reducing system complexity and resulting in a relatively low computational complexity.

FIG. 2 is a schematic drawing showing a section of a board structure of a subarray module 200 in an example embodiment.

In the example embodiment, the subarray module 200 comprises a plurality of array / antenna elements, e.g., patch antennas 202A, 202B, 202C, 202D, configured to radiate and receive electromagnetic signals within a predefined frequency band. The subarray module 200 further comprises four antenna feeds 204A, 204B, 204C, and 204D operatively coupled to the four patch antennas 202A, 202B, 202C, and 202D, respectively, said antenna feeds configured to provide excitation signals to the patch antennas during transmission and to receive signals during reception.

In the example embodiment, the subarray module 200 further comprises an embedded calibration network. The calibration network is used with a calibration algorithm executed by a processing unit (compare 106 of FIG. 1) for online measurements of excitation errors in both amplitude and phase of the patch antennas 202A, 202B, 202C, and 202D. The calibration network comprises four calibration probes 206A, 206B, 206C, and 206D electrically connected to the antenna feeds 204A, 204B, 204C, and 204D, said calibration probes configured to monitor phase and amplitude variations due to factors such as component mismatches, temperature changes, and aging effects. Calibration probe 206D is not visible on FIG. 2 as it is blocked by the drawing of patch antenna 202D. It will be appreciated that calibration probe 206D is configured in a similar manner as the other calibration probes 206A, 206B, and 206C. The calibration network further comprises a calibration combiner network 208 coupled to the calibration probes 206A, 206B, 206C, and 206D. As shown, the calibration combiner network 208, e.g., a multi-section power combiner/splitter is connected to the four calibration probes 206A, 206B, 206C, and 206D, e.g., short-length calibration probes implemented immediately below the corner of each patch antenna / radiating patch 202A, 202B, 202C, and 202D, to obtain certain energy coupling between the array elements and the calibration path. The calibration network may further comprise a power combiner (not shown) configured to be in a receive mode or a transmit mode. When in receive mode, the power combiner is configured to combine RF signals from the patch antennas / radiating patches 202A, 202B, 202C, and 202D into a single output. When in transmit mode, the power combiner is configured to distribute RF signal to the patch antennas / radiating patches 202A, 202B, 202C, and 202D from a single input.

During calibration, the calibration algorithm / process uses feedback measurements to detect any errors at the array elements and to take corrective actions to compensate for such errors.

For TX antenna array calibration, a calibration signal is applied to a TX signal input port. The calibration signal is equally power-split and fed into beamformers through a transmission signal distribution network. The beamformers amplify and transmit the calibration signal to each patch antenna for radiation. Specifically, the beamformers control the amplitude and phase of the calibration signal through on-chip digital attenuators and phase shifters. Each calibration probe / proximity calibration probe picks up a radiated calibration signal from a corresponding patch antenna and feeds the radiated calibration signal to the power combiner of the calibration network. The signal collected from multiple array elements 202A, 202B,

202C, and 202D by the calibration probes 206A, 206B, 206C, and 206D are combined and then frequency down-converted and digitized through an RF board and a main board / mother board for further processing to detect any amplitude and phase errors among the array elements based on the corresponding calibration algorithm.

For RX antenna array calibration, a calibration signal is distributed / supplied through the calibration network. The calibration signal is equally power-split and fed to the calibration probes 206A, 206B, 206C, and 206D. The calibration probes 206A, 206B, 206C, and 206D couple the calibration signal to their corresponding patch antennas 202A, 202B, 202C, and 202D. The calibration signal collected from the array elements are fed to the beamformers which amplify and control the signal amplitude and phase through the on-chip digital attenuators and phase shifters. The calibration signal from each array element is combined by an array signal combiner and then frequency down-converted and digitized for further processing to detect any amplitude and phase errors among the array elements using the corresponding calibration algorithm.

In the example embodiment, the built-in calibration network design is advantageously completely embedded in the phased array antenna board so that in-situ self-calibration can be performed on-demand or periodically without the need of external probes and additional peripheral hardware.

FIG. 3 is a schematic drawing of a modular subarray 300 in an example embodiment. In the present disclosure, antenna arrays are designed based on a scalable modular system architecture where antenna elements are grouped into subarrays and an entire large array may be formed from multiple subarrays. The modular subarray 300 is implemented as a scalable self-contained phased array antenna module with a relatively small number e.g., 64 array elements and a built-in calibration network. The modular subarray 300 has the flexibility to be used as a standalone antenna array or as a subarray module in a large-scale antenna array. In applications such as satellite communication a very large-scale antenna array with thousands or tens of thousands of antenna elements is needed to obtain the required effective isotropic radiated power (EIRP) or gain-to-noise temperature ratio (G/T).

As shown in FIG. 3, a scalable big array can be easily constructed by simply adding more of the compact modular subarray 300 with optimized antenna and RF performance. For example, antenna array 302 is a 256-element array constructed using four modular 64-

element subarray modules 300, and antenna array 304 is a 576-element array constructed using nine modular 64-element subarray modules 300. The modular subarray 300 advantageously provides scalability and flexible reconfigurability to meet the needs of different applications. Furthermore, the scalable modular array design has significant cost benefits in terms of both system fabrication, maintenance and repair, as a faulty subarray module can be quickly replaced by a functional one.

FIG. 4A is a circuit diagram of a complete modular phase array antenna system architecture 400 in an example embodiment. The modular phased array antenna system architecture 400 comprises a plurality of compact antenna/RF subarray modules, e.g., 402, (compare 102 of FIG. 1), each compact antenna/RF subarray module 402 comprising a plurality of antenna elements, e.g., 404 (compare 104 of FIG. 1). The plurality of compact antenna/RF subarray modules, e.g., 402, are coupled to a main mother board 406 (compare 106 of FIG. 1) that controls the settings of the antenna/RF subarray modules, e.g., 402 and runs a calibration algorithm.

In the example embodiment, the subarray module 402 is a scalable self-contained phased array antenna module with a plurality of antenna elements, e.g., 404. The subarray module 402 comprises beamformers, e.g., 408, which are integrated circuits (ICs) implemented / assembled by components including, but not limited to, RF amplifiers, digital attenuators, phase shifters, etc. As shown in FIG. 4A, each beamformer 408 comprises one or more RF amplifiers or digital attenuators, e.g., 410, and one or more phase shifters, e.g., 412. In the example embodiment, each subarray module 402 further comprises feeding and calibration networks. Each subarray 402 is also supported by its own RF transmit and receive path for performing signal amplification, filtering, and up-/down-conversion that may be integrated on an antenna board 414 or implemented as a separate RF board 416. The various components of the modular phase array antenna system architecture 400 are detailed in Table 1 below.

Table 1: List of components in the modular phase array antenna system architecture

Symbol	Description	Function
MCU	Microcontroller Unit	Controls system functions, beam steering, and calibration
BPF	Band-Pass Filter	Filters signals to allow only a specific frequency band

UpCon	Up-Converter	Converts baseband/intermediate frequency (IF) signals to RF for transmission
DonCon	Down-Converter	Converts RF signals to IF/baseband for processing
FPGA	Field-Programmable Gate Array	Processes digital beamforming and high-speed signal operations
XTRL	Crystal Oscillator	Provides a stable clock signal for synchronization
VCO + Syn	Voltage-Controlled Oscillator + Synthesizer	Generates precise RF frequencies for transmission/reception
DAC	Digital-to-Analog Converter	Converts digital signals to analog for RF transmission.
ADC	Analog-to-Digital Converter	Converts received analog signals to digital for processing
X2	Frequency Doubler or Multiplier	Doubles the frequency of an input RF signal

For such a large scalable antenna array built with multiple subarray modules, both mismatches among array elements in each individual subarray module i.e. intra-module errors and mismatches between different antenna/RF subarray modules i.e. inter-module errors need to be calibrated.

With each subarray having its own built-in calibration network, the inventors recognised that one efficient self-calibration technique for intra-module errors is to use multi element measurement methods relying on orthogonal code modulation to simultaneously calibrate all the array elements on the same subarray antenna board. The number of the measurements required is at least the same as the number of the array elements to be calibrated. As compared to calibrating single / individual array elements in series (i.e., calibrating element by element), this parallel measurement method can significantly reduce the calibration time.

The inventors also recognised that it is challenging to calibrate the inter-module errors as mismatches due to the transmit and the receiver RF paths between different antenna / RF subarray modules are serially combined with the element mismatches of each subarray and thus cannot be separated and characterized by the orthogonal-coded parallel measurement

method. Thus, in order for a scalable large array to perform on-demand or periodical calibration after deployment, it is important to develop an efficient in-situ self-calibration technique for correcting the inter-module errors.

FIG. 4B is a circuit diagram of a hybrid analog and digital beamforming system architecture 420 in another example embodiment. The hybrid analog and digital beamforming system architecture 420 comprises a plurality of compact antenna/RF subarray modules, e.g., 402, (compare 102 of FIG. 1), each compact antenna/RF subarray module 402 comprising a plurality of antenna elements, e.g., 404 (compare 104 of FIG. 1). The subarray module 402 comprises beamformers, each beamformer 408 comprising one or more RF amplifiers or digital attenuators, e.g., 410, and one or more phase shifters, e.g., 412. The plurality of compact antenna/RF subarray modules, e.g., 402, are segregated into a plurality of RF chains coupled to a MCU / FPGA Baseband / Digital Beamformer. Each RF chain comprises a dedicated DAC and ADC, and associated beamformers, e.g., 408.

Hybrid beamforming is an enabling technology for massive multiple-input and multiple-output (MIMO) antenna arrays since it can achieve the performance of conventional fully digital beamforming schemes, with significantly lower hardware implementation complexity and power consumption. In the example embodiment, the hybrid analog and digital beamforming system architecture 420 has calibration channels incorporated therein. The hybrid beamforming architecture provides sharp beams with phase shifters (PSs) at analog domain and flexibility of multiple beams and data streams at digital domain. This is achieved with dedicated DACs and ADCs for each RF chain as illustrated in FIG. 4B. As each RF chain with its associated beamformers, DAC and ADC can be treated as a subarray module, the array calibration technique as disclosed herein may be naturally applied to the hybrid beamforming system architecture 420 without any change. In the case of hybrid beamforming, the received calibration packet from all the subarrays are combined in digital domain as they are already digitized by the ADCs of each RF chain subarray. Both intra-module calibration and inter-module calibration procedures and algorithms as disclosed herein may thus be naturally employed to calibrate hybrid beamforming systems.

FIG. 5 is a schematic flowchart 500 for illustrating a method of calibrating an antenna array, e.g., TX / RX phased array antenna, in an example embodiment. The method may be implemented on the modular phase array antenna system architecture 400 of FIG. 4A and the hybrid analog and digital beamforming system architecture 420 of FIG. 4B.

In the example embodiment, the antenna array (compare 100 of FIG. 1) comprises a plurality of subarray modules (compare 102 of FIG. 1), each subarray module comprising a plurality of array elements / antenna elements (compare 104 of FIG. 1). Each subarray module further comprises a TX / RX calibration network, e.g., in-built calibration network, configured to perform calibration of the subarray module 102. The antenna array further comprises a processing unit (compare 106 of FIG. 1) coupled to the plurality of subarray modules, said processing unit configured for controlling settings of the plurality of subarray modules and for executing a calibration algorithm. The subarray modules have a substantially identical structure.

At step 502, an intra-module calibration is performed by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules. At step 504, an inter-module calibration is performed by measuring and correcting misalignments between the plurality of subarray modules. In the example embodiment, the calibration process involves two calibration stages: stage one is the intra-module calibration and stage two is the inter-module calibration. The intra-module calibration measures and corrects amplitude and phase mismatches of the array elements within each individual antenna subarray module while the inter-module calibration takes care of the misalignments among all subarray modules.

Advantageously, the method provides an efficient in-situ self-calibration technique for correcting both intra-module errors and inter-module errors of a scalable large array constructed using uniform subarrays. The method provides on-demand or periodical phased array calibration after deployment of the antenna array. No external hardware is required for the calibration method. Even more advantageously, the identical structure of all the subarray modules allows for easy scaling up of the array size, accurate and efficient parallel characterization of the elements under actual array loading operating conditions, and low computational complexity.

It will be appreciated that phased array calibration for both transmit and receive operations are similar. The primary differences lie in the test-signal distribution at the input and the combination at the output. For TX array calibration, a calibration source signal is fed / distributed into each antenna element through an array beamformer and radiated, and then coupled to calibration probes, and an additional beam combiner is used for combined signal

monitoring. For RX array calibration, a calibration signal is applied to and radiated by the calibration probes and coupled to the array antennas / array elements. The received calibration signal by the array antennas are then fed to the beamformers. A calibration source and a distribution network are required to inject a test signal into the input of each antenna element, the array beamformer can be used as a test signal combiner. Apart from the above difference, the calibration procedure and algorithm are the same for transmit array calibration and receive array calibration.

FIG. 6 is a schematic flowchart 600 illustrating a method of performing an intra-module calibration scheme for a TX subarray antenna board in an example embodiment. FIG. 6 further describes the intra-module calibration stage of FIG. 5, where mismatches among antenna elements in the same subarray module are corrected during intra-module calibration of the TX subarray antenna board. The intra-module calibration technique illustrated in FIG. 6 is described with reference to FIG. 2 showing a TX subarray antenna board structure with antenna elements and an embedded calibration network.

At step 602, radiofrequency (RF) phase shifters of beamformers within a subarray module (compare 200 of FIG. 2) are set/configured according to an intra-module orthogonal sequence, e.g., j^{th} orthogonal sequence. The intra-module orthogonal sequence may be an intra-module orthogonal sequence for TX calibration. Specifically, an excitation of each array element (compare 202A-202D of FIG. 2) is encoded by applying the intra-module orthogonal sequences to control the phase settings of the beamformers.

At step 604, an intra-module calibration packet is transmitted into beamformers and radiated out by the array antennas / antenna elements of the subarray module. The intra-module calibration packet may be an intra-module calibration packet for TX calibration. Specifically, the intra-module calibration packet is a known calibration signal transmitted to check the transmission performance of the subarray module. In this step, the calibration signal is applied to / injected into a transmission signal input port. The calibration signal is distributed through a transmission signal distribution network, such that the calibration signal is equally power-split and fed into to a plurality of beamformers. The beamformer may be a circuit that controls a phase and an amplitude of a signal to steer a beam electronically. Each beamformer receives a portion of the TX signal and adjusts it to shape the desired radiation pattern. The beamformer outputs are amplified to ensure the signal is sufficiently strong for transmission. Each antenna element, e.g., patch antenna receives the amplified signal for radiation. The

amplitude and phase of the amplified signal are controlled through on-chip digital attenuators and phase shifters, respectively.

At step 606, the intra-module calibration packet is received by the calibration network using calibration probes. Specifically, the calibration signal radiated by each patch antenna is received / picked up by a corresponding proximity calibration probe (compare 206A-206D of FIG. 2). A plurality of radiated calibration signals from the antenna elements is fed to a power combiner of the calibration network. The signal collected from the array elements by the calibration probes are combined for further processing to detect any amplitude and phase errors among the array elements using a calibration algorithm.

At step 608, a vector response is measured from the received intra-module calibration packet. Specifically, the received intra-module calibration packet is used for measuring how each antenna element responds to the calibration packet in terms of amplitude and phase.

At step 610, steps 602 to 608 are repeated with a different orthogonal sequence for every antenna element in the subarray module. Each orthogonal sequence for each iteration of the repeated steps 602 to 608 is a row in a Hadamard matrix, said orthogonal sequence providing specific encoding states for each of the antenna elements. A corresponding vector response is measured for each iteration of the repeated steps 602 to 608.

At step 612, the mismatches in the amplitude and phase of the antenna elements in the subarray module are computed to obtain amplitude and phase compensations required for the subarray module. Specifically, the measured vector responses are collated to obtain a column vector. An unknown weights vector is obtained based on the column vector and the Hadamard matrix, wherein said unknown weights vector is representative of the compensations required for the antenna elements of the subarray module.

FIG. 7 is a schematic flowchart 700 illustrating a method of performing an intra-module calibration scheme for an RX subarray antenna board in an example embodiment. FIG. 7 further describes the intra-module calibration stage of FIG. 5, where mismatches among antenna elements in the same subarray module are corrected during intra-module calibration of the RX subarray antenna board.

At step 702, radiofrequency (RF) phase shifters of beamformers within a subarray module are set/configured according to an intra-module orthogonal sequence, e.g., j^{th} orthogonal sequence. The intra-module orthogonal sequence may be an intra-module orthogonal sequence for RX calibration.

At step 704, an intra-module calibration packet is transmitted into a calibration network and radiated out by calibration probes of the subarray module.

At step 706, the intra-module calibration packet is received from array antennas / antenna elements and beamformers of the subarray module. The intra-module calibration packet may be an intra-module calibration packet for RX calibration. Specifically, the intra-module calibration packet radiated by the calibration probes is received using the array antennas and beamformers of the subarray module.

At step 708, a vector response is measured from the received intra-module calibration packet. Specifically, the received intra-module calibration packet is used for measuring how each antenna element responds to the calibration packet in terms of amplitude and phase.

At step 710, steps 702 to 708 are repeated with a different orthogonal sequence for every antenna element in the subarray module. Each orthogonal sequence for each iteration of the repeated steps 702 to 708 is a row in a Hadamard matrix, said orthogonal sequence providing specific encoding states for each of the antenna elements. A corresponding vector response is measured for each iteration of the repeated steps 702 to 708.

At step 712, the mismatches in the amplitude and phase of the antenna elements in the subarray module are computed to obtain amplitude and phase compensations required for the subarray module. Specifically, the measured vector responses are collated to obtain a column vector. An unknown weights vector is obtained based on the column vector and the Hadamard matrix, wherein said unknown weights vector is representative of the compensations required for the antenna elements of the subarray module.

During the intra-module calibration process, the excitations of each array element is encoded by applying the orthogonal codes to control the phase settings of the beamformers. Since the array elements are encoded with a mutually orthogonal code, the relative complex weights containing both amplitude and phase information of the individual elements can be

decoded through correlation of the received composite signal with the original code. Compared to a series single element-by-element calibration method, this parallel measurement method significantly reduces the calibration time especially for a large size array with many elements.

In the intra-module calibration algorithm, the Walsh-Hadamard orthogonal codes made up of orthogonal sequences are used for pre-determined complex weight vectors to reduce computational complexity. The Hadamard matrix formed using each sequence as a row has the property that its rows are mutually orthogonal, and its inverse is simply the transpose divide by the matrix order. The calibration algorithm controls the encoding states of all array elements during a single measurement by setting the phase shifters of the beamformers according to the values of a row in the Hadamard matrix. Accordingly, each measurement sample (i.e., each measured vector response) is obtained under a specific encoding state of all array elements corresponding to a row of the Hadamard matrix represented by H. The number of measurements required is at least the same as the number of the antenna elements in the subarray to be calibrated, in accordance with the properties of the Hadamard matrix. The method is more efficient in terms of time of test and cost of test as it is capable of parallel characterization of all the elements.

For an M-element array, all the M measured samples may be taken to form a column vector denoted by R and the unknown complex weights containing the amplitude and phase of all M array elements may be taken to form a column vector W. The following linear matrix equation about the weights vector can be created with the measured samples.

$$[H]_{MXM}[W]_{MX1} = [R]_{MX1} \quad (1)$$

If only the relative amplitude information between the array elements is concerned, the unknown weights vector of the array elements can be calculated as:

$$[W]_{MX1} = [H]^{T}_{MXM}[R]_{MX1} \quad (2)$$

Where H^T represents the transpose of Hadamard matrix H. The orthogonal properties of the Hadamard matrix allow the extraction of each individual element complex weights with the lowest complexity matrix operation from the simultaneous measurement samples of all array elements.

The computed mismatches among antenna elements in the same subarray module are compensated using the on-chip digital attenuators and phase shifters of the RF beamformers. For an antenna array having N subarray modules, in stage one, the above intra-module calibration is performed sequentially for the plurality of N subarray modules, i.e., one subarray module at a time for a total of N intra-module calibrations.

Once the intra-module calibration is completed for all the subarray modules, the amplitude and phase of all antenna elements within each individual subarray module are aligned. Any remaining misalignments are among different subarray modules made up of both the antenna subarray board and the RF board and they are measured and corrected in stage two by the inter-module calibration.

It will be appreciated that the intra-module calibration packet, intra-module orthogonal code and sequence used in the intra-module calibration of the TX and RX subarray board may be the same or different from each other.

FIG. 8A is a first schematic diagram of a modular array architecture 800 in an example embodiment. As shown in FIG. 8A, a first stage of intra-module calibration may be performed within each subarray module and a second stage of inter-module calibration may be performed between the different subarray modules, after intra-module calibration is completed for the N subarray modules. FIG. 8B is a second schematic diagram of the modular array architecture 800 in the example embodiment. FIG. 8B further describes how inter-module calibration is performed between subarray modules.

The modular array architecture 800 comprises N subarray modules, each subarray module comprising an M-element antenna subarray board, an RF upconverter coupled to the subarray board, an RF downconverter coupled to the subarray board, and an intermediate frequency phase shifter (IF PS), and variable gain amplifier (VGA) coupled to the RF upconverter. The modular array architecture 800 further comprises an intermediate frequency (IF) splitter coupled to the RF upconverters of the subarray modules via the respective IF PS and VGA. The modular array architecture 800 further comprises an intermediate frequency (IF) switch/combiner coupled to the RF downconverters of the subarray modules. The modular array architecture 800 further comprises a central processing unit (CPU) / Modem, an analog

to digital converter (ADC), and a digital to analog converter (DAC). The CPU modem is coupled to the IF splitter via the DAC and coupled to the IF switch/combiner via the ADC.

After calibration and compensation of the intra-module mismatches in stage one, the M antenna elements in each individual subarray module together with the associated RF upconverter and downconverter may be treated as one combined TX signal channel and one combined RX calibration channel with the complex weights denoted by G_S and G_C respectively. In general, the complex weights of the signal channels among the N modules, i.e. G_{S1}, G_{S2}, …, G_{SN} are not matched. Similarly, the calibration channels, i.e. G_{C1}, G_{C2}, …, G_{CN} are also not matched. In stage two of inter-module calibration, the mismatches between G_{S1}, G_{S2}, …, G_{SN} are characterized using an in-situ inter-module calibration technique.

Among the N subarray modules, inter-module calibration starts by using only the calibration channel of module 1 as the calibration receiver by either powering down all other modules calibration channels or switching the DAC to module 1 only through the IF switch. As all TX signal channels of the N subarray modules are working at the actual transmitting mode, the transmission coefficients from each module TX signal channel input to module 1 RX channel output are defined as H_{11}, H_{12}, …, H_{1N} respectively. By treating each subarray module as one unit cell, the parallel calibration method may again be used to measure and extract the complex transmission coefficients of the modules. Here, the calibration algorithm controls the encoding states of the subarray modules by setting/configuring either the IF phase shifters or the phase shifters of the RF beamformers on the M-element subarray board as a whole / as a single unit according to the values of a Hadamard code. At least N measurements are taken, and each measurement sample is obtained under specific encoding states of each of the subarray module units. All the N measured samples may be taken to form a column vector R and the unknown complex weights containing the amplitude and phase of all N subarray modules may be taken to form a column vector W. Then, according to equation (2) the unknown weights vector, corresponding to the complex transmission coefficients H_{11}, H_{12}, …, H_{1N}, can be extracted based on the orthogonal properties of the Hadamard matrix.

Next, the calibration channel of module 2 is used as the calibration receiver and the above measurements are conducted again with all TX signal channels of the N subarray modules working at the actual transmitting mode. From the newly measured N samples, the complex transmission coefficients H_{21}, H_{22}, …, H_{2N}, can be extracted by the same method described above. These measurement procedures are repeated N times till the calibration

channel of every subarray module has been used as the calibration receiver in one set of measurements. Thus, all the complex transmission coefficients H_{n1}, H_{n2}, …, H_{nN} where n=1, 2, …, N can be estimated from the measurements.

Since H_{11} is the complex transmission coefficients from the signal channel input of subarray module 1 to the calibration channel output of subarray module 1, it can be written as:

$$H_{11} = G_{S1} * T_{11} * G_{C1}$$

where T_{11} represents the overall energy passive coupling from the antennas to the calibration probes on subarray module 1.

In the same way, H_{12}, H_{21}, H_{22} can be written as:

$$H_{12} = G_{S2} * T_{12} * G_{C1}$$

$$H_{21} = G_{S1} * T_{21} * G_{C2}$$

$$H_{22} = G_{S2} * T_{22} * G_{C2}$$

where T_{12}, T_{21}, T_{22} represents the overall energy passive couplings between the antennas and the calibration probes from subarray module 2 to subarray module 1, from subarray module 1 to subarray module 2, and within subarray module 2 respectively.

Then, the following calculation is performed:

$$\frac{H_{22} * H_{12}}{H_{11} * H_{21}} = \frac{G_{S2} * T_{22} * G_{C2} * G_{S2} * T_{12} * G_{C1}}{G_{S1} * T_{11} * G_{C1} * G_{S1} * T_{21} * G_{C2}} = \frac{T_{22} * T_{12}}{T_{11} * T_{21}} * \left(\frac{G_{S2}}{G_{S1}}\right)^2$$

Since T_{11}, T_{12}, T_{21}, T_{22} are only related to the on-board passive array antennas and calibration probes, very well matching between adjacent modules can be expected:

$$T_{11} = T_{22} \qquad T_{12} = T_{21}$$

Now the amplitude and phase mismatches between G_{S1} and G_{S2} can be obtained as a complex ratio given by:

$$\frac{G_{S2}}{G_{S1}} = \sqrt{\frac{H_{22} * H_{12}}{H_{11} * H_{21}}}$$

In the same way and with all the complex transmission coefficients H_{n1}, H_{n2}, ..., H_{nN} where n=1, 2, ..., N extracted from the measurements, the amplitude and phase mismatches between all the subarray modules, i.e., the mismatches between G_{S1}, G_{S2}, ..., G_{SN}, can be estimated.

In general, the amplitude and phase mismatch between a first transmission signal from a first subarray, G_{si} and a second transmission signal from a second subarray G_{sj} may be expressed by the calculated complex ratio:

$$\frac{G_{Sj}}{G_{St}} = \sqrt{\frac{H_{jj} * H_{ij}}{H_{ii} * H_{ji}}}$$

For TX antenna arrays, H_{ij} represents the transmission coefficients from the signal channel input of subarray module *i* to the calibration channel output of subarray module *j*; H_{ji} represents the transmission coefficients from the signal channel input of subarray module *j* to the calibration channel output of subarray module *i*; H_{ii} represents the transmission coefficients from the signal channel input of subarray module *i* to the calibration channel output of subarray module *i*; and H_{jj} represents the transmission coefficients from the signal channel input of subarray module *j* to the calibration channel output of subarray module *j*.

For RX antenna arrays, H_{ij} represents the transmission coefficients from the calibration channel input of subarray module *i* to the signal channel output of subarray module *j*; H_{ji} represents the transmission coefficients from the calibration channel input of subarray module *j* to the signal channel output of subarray module *i*; H_{ii} represents the transmission coefficients from the calibration channel input of subarray module *i* to the signal channel output of subarray module *i*; and H_{jj} represents the transmission coefficients from the calibration channel input of subarray module *j* to the signal channel output of subarray module *j*.

Therefore, the misalignments among all subarray modules can be characterized and then corrected through this inter-module calibration scheme.

FIG. 9 is a schematic flowchart 900 illustrating a method of performing an inter-module calibration scheme for a modular scalable TX phased array comprising N subarray modules in an example embodiment. The flowchart describes the inter-module calibration scheme for a modular scalable TX phased array comprising N subarray modules as described with respect to FIG. 8A and FIG. 8B.

At step 902, a calibration channel of a selected subarray module (compare e.g., Module #1 of FIG. 8A) is set as a calibration receiver. Specifically, the calibration channel of the selected subarray module may be set/configured as the calibration receiver by powering down calibration channels of all other subarray modules of the antenna array. Alternatively, the calibration channel of the selected subarray module may be set as calibration receiver by switching an analog to digital converter to the selected subarray module through a switch, e.g., intermediate frequency (IF) switch.

At step 904, RF phase shifters of each subarray module as a single unit are set/configured according to an inter-module orthogonal sequence. The inter-module orthogonal sequence may be an inter-module orthogonal sequence for TX calibration. For example, either IF phase shifters (compare IF PS of FIG. 8A) or phase shifters of RF beamformers of the subarray module may be set according to the values of the orthogonal sequence of an orthogonal code, e.g., Hadamard code.

At step 906, an inter-module calibration packet is transmitted into beamformers of all the subarray modules and radiated out by array antennas / subarray modules. The inter-module calibration packet may be an inter-module calibration packet for TX calibration.

At step 908, the inter-module calibration packet is received from the calibration channel of the selected subarray module with calibration probes.

At step 910, a combined vector response of all the subarray modules is measured from the received inter-module calibration packet.

At step 912, steps 904 to 910 are repeated with a different orthogonal sequence for every subarray module to obtain a respective combined vector response. Each orthogonal sequence for each iteration of the repeated steps 904 to 910 is a row in a second Hadamard matrix, said orthogonal sequence providing specific encoding states for each of the subarray modules. A corresponding combined vector response of all the subarray modules is measured for each iteration of the repeated steps 904 to 910 of the inter-module calibration.

At step 914, transmission coefficients from all the subarray modules to the calibration channel of the calibration receiver are computed. Specifically, the measured combined vector

responses are collated to obtain a subarray column vector. The transmission coefficients are then obtained based on the subarray column vector and the second Hadamard matrix.

At step 916, steps 902 to 914 are repeated with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver.

At step 918, mismatches among subarray modules are computed based on the transmission coefficients. Specifically, passive couplings between adjacent subarrays are cancelled off. The amplitude and phase mismatch between a first transmission signal from a first subarray, G_{si} and a second transmission signal from a second subarray, G_{sj} may be calculated and given by the calculated complex ratio

$$\frac{G_{Sj}}{G_{Si}} = \sqrt{\frac{H_{jj} * H_{ij}}{H_{ii} * H_{ji}}}$$

Wherein for the transmitter antenna array, H_{ij} represents the transmission coefficients from the signal channel input of subarray module *i* to the calibration channel output of subarray module *j*.

FIG. 10 is a schematic flowchart 1000 illustrating a method of performing an inter-module calibration scheme for a modular scalable RX phased array comprising N subarray modules in an example embodiment.

At step 1002, a calibration channel of a selected subarray module is set as a calibration transmitter.

At step 1004, RF phase shifters of each subarray module as a single unit are set/configured according to an inter-module orthogonal sequence. The inter-module orthogonal sequence may be an inter-module orthogonal sequence for RX calibration.

At step 1006, an inter-module calibration packet is transmitted into calibration channels of all the subarray modules and radiated out by calibration probes. The inter-module calibration packet may be an inter-module calibration packet for RX calibration.

At step 1008, the inter-module calibration packet is received from beamformers of all the subarray modules with array antennas.

At step 1010, a combined vector response of all the subarray modules is measured from the received inter-module calibration packet.

At step 1012, steps 1004 to 1010 are repeated with a different orthogonal sequence for every subarray module to obtain a respective subarray vector response. Each orthogonal sequence for each iteration of the repeated steps 1004 to 1010 is a row in a second Hadamard matrix, said orthogonal sequence providing specific encoding states for each of the subarray modules. A corresponding subarray vector response is measured for each iteration of the repeated steps 1004 to 1010 of the inter-module calibration.

At step 1014, transmission coefficients from the calibration channel of the calibration transmitter to all subarray modules are computed. Specifically, the measured combined vector responses are collated to obtain a subarray column vector. The transmission coefficients are then obtained based on the subarray column vector and the second Hadamard matrix.

At step 1016, steps 1002 to 1014 are repeated with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration transmitter.

At step 1018, mismatches among subarray modules are computed based on the transmission coefficients. Specifically, passive couplings between adjacent subarrays are cancelled off. The amplitude and phase mismatch between a first transmission signal from a first subarray, G_{si} and a second transmission signal from a second subarray, G_{sj} may be calculated and given by the calculated complex ratio

$$\frac{G_{Sj}}{G_{Si}} = \sqrt{\frac{H_{jj} * H_{ij}}{H_{ii} * H_{ji}}}$$

Wherein for the receiver antenna array, H_{ij} represents the transmission coefficients from the calibration channel input of subarray module *i* to the signal channel output of subarray module *j*.

It will be appreciated that the inter-module calibration packet, inter-module orthogonal code and sequence used in the inter-module calibration of the modular scalable TX and RX phased arrays may be the same or different from each other.

FIG. 11 is a composite of schematic drawings of a phased array antenna 1100 in an example embodiment. The structure of the phased array antenna 1100 is illustrated in the plane view drawing and the board design of the phased array antenna 1100 is illustrated in the perspective view drawing.

To verify the performance of the inter-module self-calibration technique, a 64-element circularly polarised (CP) patch antenna array operating at K-band is designed. The 64-element phased array is formed by four identical 16-element subarray modules 1102, 1104, 1106, and 1108. The antenna elements, e.g., 1110, are arranged as a square lattice with element spacing of 7.5-mm ($0.5\lambda_0$ at 20 GHz) and are excited in a sequentially rotated manner to increase the 3dB AR bandwidth. The antenna element 1110 is a dual feed stacked antenna element used to generate two modes (vertical and horizontal) for circularly polarized phased array design. Inter-module amplitude and phase mismatches are randomly introduced to the subarray modules. The maximum amplitude and phase mismatches among the four modules are 5 dB and 47°, respectively. The entire array system is simulated in computer simulation technology (CST). The inter-module misalignments are greatly reduced to 0.3 dB in amplitude and 1.7° in phase after they are characterized by using the inter-module calibration method and then corrected accordingly.

FIG. 12 is a graph showing simulated 2D radiation patterns of the 64-element phased array antenna 900 in the example embodiment. The graph shows the simulated 2D radiation patterns of the 64-element phased array antenna 1100 by controlling phase settings to steer the main beam to 15°. It shows that before calibration, the simulated main beam of the antenna array 900 is pointing at around 12.5° with an array boresight gain of around 1 dBic and a side lobe level of below -9 dBc. After applying the inter-module calibration method to correct the amplitude and phase mismatches among the subarray modules 1102, 1104, 1106, and 1108, the main beam is now correctly pointing at 15° with the array boresight gain increased to 1.8 dBic and the side lobe level reduced to around -12 dBc. Thus, the simulation results confirm that the inter-module calibration technique can effectively characterize and compensate the mismatches among the subarray modules to improve beam pointing accuracy, increase array gain and reduce side lobe levels.

Therefore, with this real-time in-situ self-calibration scheme, strict amplitude and phase tolerances can be achieved and maintained at each antenna element for a scalable multi-modules large scale phased array. Thus, it ensures that the beam can be agilely steered to the targeted direction to achieve high gain directivity, low sidelobe levels, and desired null pointing angle for high data rate, coverage management and interference suppression. Furthermore, the fast parallel calibration scheme with low calibration computation complexity greatly reduces the system downtime and resources usage.

In the described example embodiments, an antenna array, e.g., a scalable modular antenna array, and a method of calibrating the antenna array are provided. Advantageously, the scalable modular antenna array comprises uniform subarrays with a substantially identical structure. The substantially identical structure of the subarrays allows for easy scaling-up of the array size, as well as accurate and efficient parallel characterization of the array elements. Advantageously, the method provides an efficient, in-situ, self-calibration technique for correcting both the intra-module errors and the inter-module errors of a scalable modular antenna array with uniform subarrays. Advantageously, the method does not require any external hardware/antenna for performing the calibration. Advantageously, the method allows real-time calibration under actual array loading operating conditions. Another advantage of the method is its relatively low computational complexity.

In the described embodiments, the terms "orthogonal code" and "orthogonal sequence" are used when describing the intra-module and inter-module calibration schemes. An orthogonal code refers to a set of sequences that exhibit mutual orthogonality. That is, an orthogonal code is made up of orthogonal sequences. This means that when any two distinct sequences from the set are compared using a predefined mathematical operation, such as an inner product or cross-correlation, the result is zero or minimal interference. An example of an orthogonal code is a Walsh-Hadamard code.

The terms "coupled" or "connected" as used in this description are intended to cover both directly connected or connected through one or more intermediate means, unless otherwise stated.

The description herein may be, in certain portions, explicitly or implicitly described as algorithms and/or functional operations that operate on data within a computer memory or an

electronic circuit. These algorithmic descriptions and/or functional operations are usually used by those skilled in the information/data processing arts for efficient description. An algorithm is generally relating to a self-consistent sequence of steps leading to a desired result. The algorithmic steps can include physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transmitted, transferred, combined, compared, and otherwise manipulated.

Further, unless specifically stated otherwise, and would ordinarily be apparent from the following, a person skilled in the art will appreciate that throughout the present specification, discussions utilizing terms such as "scanning", "calculating", "determining", "replacing", "generating", "initializing", "outputting", and the like, refer to action and processes of an instructing processor/computer system, or similar electronic circuit/device/component, that manipulates/processes and transforms data represented as physical quantities within the described system into other data similarly represented as physical quantities within the system or other information storage, transmission or display devices etc.

The description also discloses relevant device/apparatus for performing the steps of the described methods. Such apparatus may be specifically constructed for the purposes of the methods, or may comprise a general purpose computer/processor or other device selectively activated or reconfigured by a computer program stored in a storage member. The algorithms and displays described herein are not inherently related to any particular computer or other apparatus. It is understood that general purpose devices/machines may be used in accordance with the teachings herein. Alternatively, the construction of a specialized device/apparatus to perform the method steps may be desired.

In addition, it is submitted that the description also implicitly covers a computer program, in that it would be clear that the steps of the methods described herein may be put into effect by computer code. It will be appreciated that a large variety of programming languages and coding can be used to implement the teachings of the description herein. Moreover, the computer program if applicable is not limited to any particular control flow and can use different control flows without departing from the scope of the invention.

Furthermore, one or more of the steps of the computer program if applicable may be performed in parallel and/or sequentially. Such a computer program if applicable may be stored on any computer readable medium. The computer readable medium may include

storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a suitable reader/general purpose computer. In such instances, the computer readable storage medium is non-transitory. Such storage medium also covers all computer-readable media e.g. medium that stores data only for short periods of time and/or only in the presence of power, such as register memory, processor cache and Random Access Memory (RAM) and the like. The computer readable medium may even include a wired medium such as exemplified in the Internet system, or wireless medium such as exemplified in Bluetooth technology. The computer program when loaded and executed on a suitable reader effectively results in an apparatus that can implement the steps of the described methods.

The example embodiments may also be implemented as hardware modules. A module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using digital or discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). A person skilled in the art will understand that the example embodiments can also be implemented as a combination of hardware and software modules.

Additionally, when describing some embodiments, the disclosure may have disclosed a method and/or process as a particular sequence of steps. However, unless otherwise required, it will be appreciated the method or process should not be limited to the particular sequence of steps disclosed. Other sequences of steps may be possible. The particular order of the steps disclosed herein should not be construed as undue limitations. Unless otherwise required, a method and/or process disclosed herein should not be limited to the steps being carried out in the order written. The sequence of steps may be varied and still remain within the scope of the disclosure.

Further, in the description herein, the word "substantially" whenever used is understood to include, but not restricted to, "entirely" or "completely" and the like. In addition, terms such as "comprising", "comprise", and the like whenever used, are intended to be non-restricting descriptive language in that they broadly include elements/components recited after such terms, in addition to other components not explicitly recited. For an example, when "comprising" is used, reference to a "one" feature is also intended to be a reference to "at least one" of that feature. Terms such as "consisting", "consist", and the like, may, in the appropriate context, be considered as a subset of terms such as "comprising", "comprise", and the like.

Therefore, in embodiments disclosed herein using the terms such as "comprising", "comprise", and the like, it will be appreciated that these embodiments provide teaching for corresponding embodiments using terms such as "consisting", "consist", and the like. Further, terms such as "about", "approximately" and the like whenever used, typically means a reasonable variation, for example a variation of +/- 5% of the disclosed value, or a variance of 4% of the disclosed value, or a variance of 3% of the disclosed value, a variance of 2% of the disclosed value or a variance of 1% of the disclosed value.

Furthermore, in the description herein, certain values may be disclosed in a range. The values showing the end points of a range are intended to illustrate a preferred range. Whenever a range has been described, it is intended that the range covers and teaches all possible sub-ranges as well as individual numerical values within that range. That is, the end points of a range should not be interpreted as inflexible limitations. For example, a description of a range of 1% to 5% is intended to have specifically disclosed sub-ranges 1% to 2%, 1% to 3%, 1% to 4%, 2% to 3% etc., as well as individually, values within that range such as 1%, 2%, 3%, 4% and 5%. The intention of the above specific disclosure is applicable to any depth/breadth of a range.

Different example embodiments can be implemented in the context of data structure, program modules, program and computer instructions executed in a computer implemented environment. A general purpose computing environment is briefly disclosed herein. One or more example embodiments may be embodied in one or more computer systems, such as is schematically illustrated in FIG. 13.

One or more example embodiments may be implemented as software, such as a computer program being executed within a computer system 1300, and instructing the computer system 1300 to conduct a method of an example embodiment.

The computer system 1300 comprises a computer unit 1302, input modules such as a keyboard 1304 and a pointing device 1306 and a plurality of output devices such as a display 1308, and printer 1310. A user can interact with the computer unit 1302 using the above devices. The pointing device can be implemented with a mouse, track ball, pen device or any similar device. One or more other input devices (not shown) such as a joystick, game pad, satellite dish, scanner, touch sensitive screen or the like can also be connected to the computer unit 1302. The display 1308 may include a cathode ray tube (CRT), liquid crystal

display (LCD), field emission display (FED), plasma display or any other device that produces an image that is viewable by the user.

The computer unit 1302 can be connected to a computer network 1312 via a suitable transceiver device 1314, to enable access to e.g. the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN) or a personal network. The network 1312 can comprise a server, a router, a network personal computer, a peer device or other common network node, a wireless telephone or wireless personal digital assistant. Networking environments may be found in offices, enterprise-wide computer networks and home computer systems etc. The transceiver device 1314 can be a modem/router unit located within or external to the computer unit 1302, and may be any type of modem/router such as a cable modem or a satellite modem.

It will be appreciated that network connections shown are exemplary and other ways of establishing a communications link between computers can be used. The existence of any of various protocols, such as TCP/IP, Frame Relay, Ethernet, FTP, HTTP and the like, is presumed, and the computer unit 1302 can be operated in a client-server configuration to permit a user to retrieve web pages from a web-based server. Furthermore, any of various web browsers can be used to display and manipulate data on web pages.

The computer unit 1302 in the example comprises a processor 1318, a Random Access Memory (RAM) 1320 and a Read Only Memory (ROM) 1322. The ROM 1322 can be a system memory storing basic input/ output system (BIOS) information. The RAM 1320 can store one or more program modules such as operating systems, application programs and program data.

The computer unit 1302 further comprises a number of Input/Output (I/O) interface units, for example I/O interface unit 1324 to the display 1308, and I/O interface unit 1326 to the keyboard 1304. The components of the computer unit 1302 typically communicate and interface/couple connectedly via an interconnected system bus 1328 and in a manner known to the person skilled in the relevant art. The bus 1328 can be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures.

It will be appreciated that other devices can also be connected to the system bus 1328. For example, a universal serial bus (USB) interface can be used for coupling a video or digital camera to the system bus 1328. An IEEE 1394 interface may be used to couple additional devices to the computer unit 1302. Other manufacturer interfaces are also possible such as FireWire developed by Apple Computer and i.Link developed by Sony. Coupling of devices to the system bus 1328 can also be via a parallel port, a game port, a PCI board or any other interface used to couple an input device to a computer. It will also be appreciated that, while the components are not shown in the figure, sound/audio can be recorded and reproduced with a microphone and a speaker. A sound card may be used to couple a microphone and a speaker to the system bus 1328. It will be appreciated that several peripheral devices can be coupled to the system bus 1328 via alternative interfaces simultaneously.

An application program can be supplied to the user of the computer system 1300 being encoded/stored on a data storage medium such as a CD-ROM or flash memory carrier. The application program can be read using a corresponding data storage medium drive of a data storage device 1330. The data storage medium is not limited to being portable and can include instances of being embedded in the computer unit 1302. The data storage device 1330 can comprise a hard disk interface unit and/or a removable memory interface unit (both not shown in detail) respectively coupling a hard disk drive and/or a removable memory drive to the system bus 1328. This can enable reading/writing of data. Examples of removable memory drives include magnetic disk drives and optical disk drives. The drives and their associated computer-readable media, such as a floppy disk provide nonvolatile storage of computer readable instructions, data structures, program modules and other data for the computer unit 1302. It will be appreciated that the computer unit 1302 may include several of such drives. Furthermore, the computer unit 1302 may include drives for interfacing with other types of computer readable media.

The application program is read and controlled in its execution by the processor 1318. Intermediate storage of program data may be accomplished using RAM 1320. The method(s) of the example embodiments can be implemented as computer readable instructions, computer executable components, or software modules. One or more software modules may alternatively be used. These can include an executable program, a data link library, a configuration file, a database, a graphical image, a binary data file, a text data file, an object file, a source code file, or the like. When one or more computer processors execute one or

more of the software modules, the software modules interact to cause one or more computer systems to perform according to the teachings herein.

The operation of the computer unit 1302 can be controlled by a variety of different program modules. Examples of program modules are routines, programs, objects, components, data structures, libraries, etc. that perform particular tasks or implement particular abstract data types. The example embodiments may also be practiced with other computer system configurations, including handheld devices, multiprocessor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

The example embodiments may also be practiced with other computer system configurations, including handheld devices, multiprocessor systems/servers, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, personal digital assistants, mobile telephones and the like. Furthermore, the example embodiments may also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wireless or wired communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

It will be appreciated by a person skilled in the art that other variations and/or modifications may be made to the specific embodiments without departing from the scope of the invention as broadly described. For example, in the description herein, features of different exemplary embodiments may be mixed, combined, interchanged, incorporated, adopted, modified, included etc. or the like across different exemplary embodiments. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

CLAIMS

1. A method of calibrating an antenna array comprising a plurality of subarray modules, each subarray module comprising a plurality of antenna elements, said method comprising,

performing an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and

performing an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.

2. The method according to claim 1, wherein the antenna array is a transmitter antenna array, and the intra-module calibration comprises,

(i) setting radiofrequency (RF) phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence;

(ii) transmitting an intra-module calibration packet into beamformers and radiating out by the antenna elements of the subarray module;

(iii) receiving the intra-module calibration packet by a calibration network using calibration probes;

(iv) measuring a vector response from the received intra-module calibration packet;

repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module;

and

(v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

3. The method according to claim 1, wherein the antenna array is a receiver antenna array, and the intra-module calibration comprises,

(i) setting RF phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence;

(ii) transmitting an intra-module calibration packet into a calibration network and radiating out by calibration probes of the subarray module;

(iii) receiving the intra-module calibration packet by antenna elements and beamformers of the subarray module;

(iv) measuring a vector response from the received intra-module calibration packet;

repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module;

and

(v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

4. The method according to claim 2, wherein the inter-module calibration comprises,

(i) setting a calibration channel of a selected subarray module as a calibration receiver;

(ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence;

(iii) transmitting an inter-module calibration packet into beamformers of all the subarray modules and radiating out by array antennas;

(iv) receiving the inter-module calibration packet from the calibration channel of the selected subarray module with calibration probes;

(v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet;

repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response;

(vi) computing transmission coefficients from all the subarray modules to the calibration channel of the calibration receiver;

repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver;

and

(vii) computing mismatches among the subarray modules based on the transmission coefficients.

5. The method according to claim 3, wherein the inter-module calibration comprises,

(i) setting a calibration channel of a selected subarray module as a calibration transmitter;

(ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence;

(iii) transmitting an inter-module calibration packet into calibration channels of all the subarray modules and radiating out the inter-module calibration packet by calibration probes;

(iv) receiving the inter-module calibration packet from beamformers of all the subarray modules with antenna elements;

(v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet;

repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response;

(vi) computing transmission coefficients from the calibration channel of the calibration transmitter to all the subarray modules;

repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver;

and

(vii) computing mismatches among the subarray modules based on the transmission coefficients.

6. The method according to claim 2 or 3,

wherein each intra-module orthogonal sequence for each iteration of the repeated steps (i) to (iv) of the intra-module calibration is a row in a Hadamard matrix, said intra-module orthogonal sequence providing specific encoding states for each of the antenna elements; and

wherein a corresponding vector response is measured for each iteration of the repeated steps (i) to (iv).

7. The method according to claim 4 or 5,

wherein each inter-module orthogonal sequence for each iteration of the repeated steps (ii) to (v) of the inter-module calibration is a row in a second Hadamard matrix, said inter-module orthogonal sequence providing specific encoding states for each of the subarray modules; and

wherein a corresponding combined vector response is measured for each iteration of the repeated steps (ii) to (v) of the inter-module calibration.

8. The method according to claim 4, 5 or 7, wherein computing transmission coefficients to the calibration channel of the calibration receiver comprises,

collating the measured combined vector responses to obtain a subarray column vector; and

obtaining the transmission coefficients based on the subarray column vector and the second Hadamard matrix.

9. The method according to claim 8, wherein computing mismatches among subarray modules based on the transmission coefficients comprises,

calculating amplitude and phase mismatches between a first transmission signal from a first subarray, G_{si} and a second transmission signal from a second subarray G_{sj} to obtain a complex ratio

$$\frac{G_{Sj}}{G_{Si}} = \sqrt{\frac{H_{jj} * H_{ij}}{H_{ii} * H_{ji}}}$$

wherein for the transmitter antenna array, H_{ij} represents the transmission coefficients from the signal channel input of subarray module *i* to the calibration channel output of subarray module *j*, and for the receiver antenna array, H_{ij} represents the transmission coefficients from the calibration channel input of subarray module *i* to the signal channel output of subarray module *j*.

10. The method according to any one of claims 1 to 9, wherein the antenna elements within each subarray module are calibrated in parallel during intra-module calibration.

11. The method according to any one of claims 1 to 10, wherein the intra-module calibration is performed sequentially for the plurality of subarray modules.

12. The method according to any one of claims 1 to 11, wherein the plurality of subarray modules comprises identical structures, each subarray module comprising the same number of antenna elements arranged in a square lattice.

13. The method according to any one of claims 1 to 12, wherein the intra-module calibration and inter-module calibration are performed during online operation of the antenna array.

14. The method according to any one of claims 1 to 13, wherein the method is devoid of using an external calibration device or external antenna for calibrating the antenna array.

15. An antenna array comprising,

a plurality of subarray modules, each subarray module comprising a plurality of antenna elements and a calibration network configured to perform calibration of the subarray module; and

a processing unit coupled to the plurality of subarray modules;

wherein the processing unit is configured to:

perform an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and

perform an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.

16. The antenna array according to claim 15, wherein the antenna array is a transmitter antenna array, and the processing module is configured to perform the intra-module calibration by,

(i) setting radiofrequency (RF) phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence;

(ii) transmitting an intra-module calibration packet into beamformers and radiating out by the antenna elements of the subarray module;

(iii) receiving the intra-module calibration packet by a calibration network using calibration probes;

(iv) measuring a vector response from the received intra-module calibration packet;

repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module;

and

computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

17. The antenna array according to claim 15, wherein the antenna array is a receiver antenna array, and the processing module is configured to perform the intra-module calibration by,

(i) setting RF phase shifters of beamformers within the subarray module according to an intra-module orthogonal sequence;

(ii) transmitting an intra-module calibration packet into a calibration network and radiating out by calibration probes of the subarray module;

(iii) receiving the intra-module calibration packet by the antenna elements and beamformers of the subarray module;

(iv) measuring a vector response from the received intra-module calibration packet;

repeating steps (i) to (iv) with a different intra-module orthogonal sequence for every antenna element in the subarray module;

and

(v) computing the mismatches in the amplitude and phase of the antenna elements in the subarray module to obtain amplitude and phase compensations required for the subarray module.

18. The antenna array according to claim 16, wherein the processing module is configured to perform the inter-module calibration by,

(i) setting a calibration channel of a selected subarray module as a calibration receiver;

(ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence;

(iii) transmitting an inter-module calibration packet into beamformers of all the subarray modules and radiating out by array antennas;

(iv) receiving the inter-module calibration packet from the calibration channel of the selected subarray module with calibration probes;

(v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet;

repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response;

(vi) computing transmission coefficients from all the subarray modules to the calibration channel of the calibration receiver;

repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver;

and

(vii) computing mismatches among the subarray modules based on the transmission coefficients.

19. The antenna array according to claim 17, wherein the processing module is configured to perform the inter-module calibration by,

(i) setting a calibration channel of a selected subarray module as a calibration transmitter;

(ii) setting RF phase shifters of each subarray module as a single unit according to an inter-module orthogonal sequence;

(iii) transmitting an inter-module calibration packet into calibration channels of all the subarray modules and radiating out by calibration probes;

(iv) receiving the inter-module calibration packet from beamformers of all the subarray modules with antenna elements;

(v) measuring a combined vector response of all the subarray modules from the received inter-module calibration packet;

repeating steps (ii) to (v) with a different inter-module orthogonal sequence for every subarray module to obtain a respective combined vector response;

(vi) computing transmission coefficients from the calibration channel of the calibration transmitter to all the subarray modules;

repeating steps (i) to (vi) with a next selected subarray module as the calibration channel, until the calibration channel of every subarray module has been used as the calibration receiver;

and

(vii) computing mismatches among the subarray modules based on the transmission coefficients.

20. The antenna array according to any one of claims 15 to 19, wherein the plurality of subarray modules are coupled to the processing unit based on a hybrid analog and digital beamforming system architecture.

21. A computer readable storage medium having stored thereon instructions for instructing a processing unit of an antenna array to execute a method of calibrating an antenna array comprising a plurality of subarray modules, each subarray module comprising a plurality of antenna elements, said method comprising,

performing an intra-module calibration by measuring and correcting mismatches in amplitude and phase of antenna elements within each subarray module of the plurality of subarray modules; and

performing an inter-module calibration by measuring and correcting misalignments between the plurality of subarray modules.