US 20100123618A1

(19) **United States**

(12) **Patent Application Publication**

Martin et al.

(10) **Pub. No.: US 2010/0123618 A1**

(43) **Pub. Date: May 20, 2010**

(54) **CLOSED LOOP PHASE CONTROL BETWEEN DISTANT POINTS**

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(21) Appl. No.: **12/273,839**

(22) Filed: **Nov. 19, 2008**

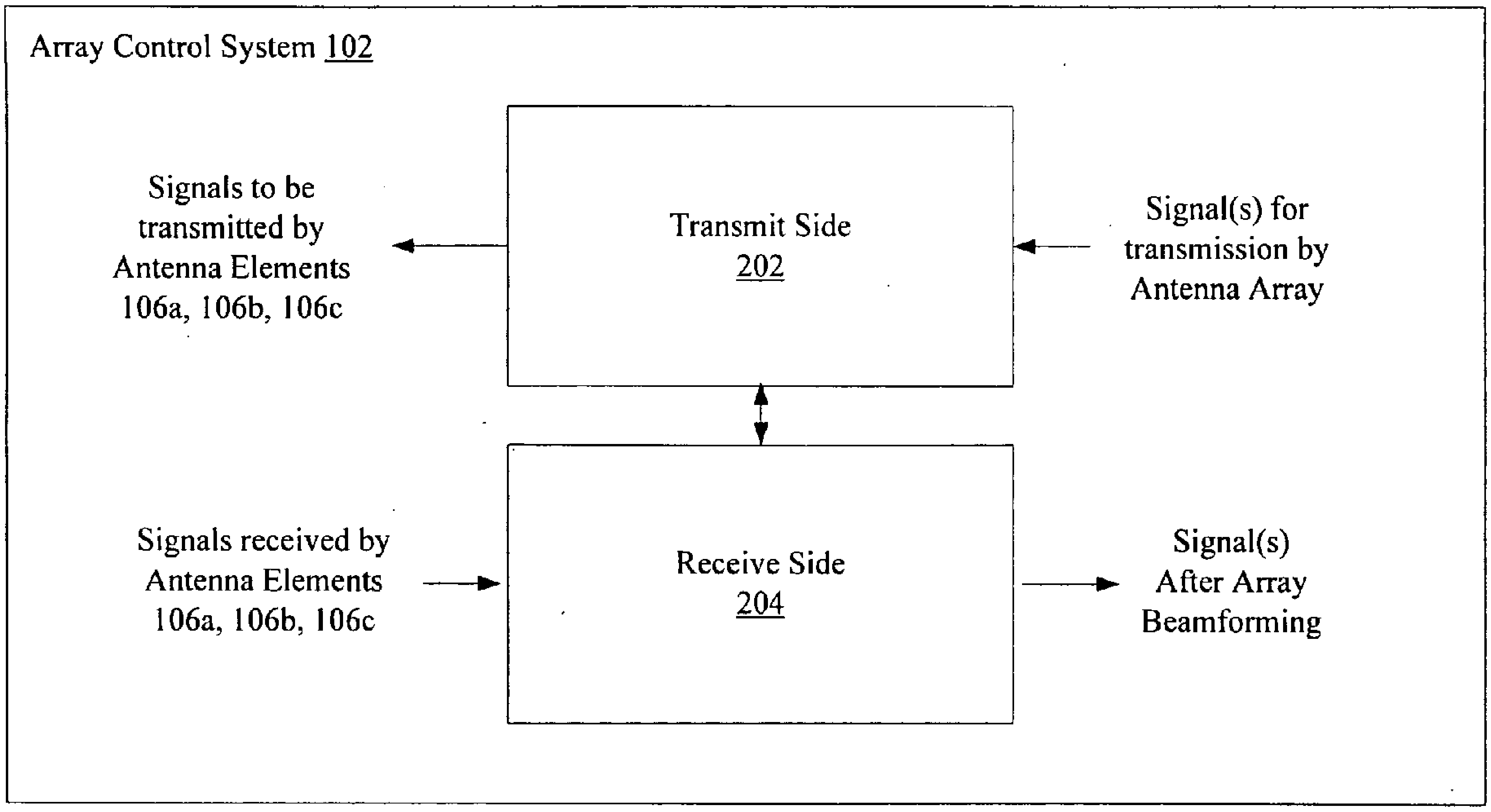
Publication Classification

(51) **Int. Cl.**
G01S 7/40 (2006.01)

(52) **U.S. Cl.** **342/174**

(57) **ABSTRACT**

Methods for compensating for phase shifts of a communication signal. The methods involve determining a first reference signal ($V_{ref\text{-}1}$) at a first location along a transmission path and a second reference signal ($V_{ref\text{-}2}$) at a second location along the transmission path. $V_{ref\text{-}2}$ is the same as $V_{ref\text{-}1}$. At the first location, a first phase offset is determined using $V_{ref\text{-}1}$ and a first communication signal. At the second location, a second phase offset is determined using $V_{ref\text{-}2}$ and a second communication signal. A phase of a third communication signal is adjusted at the second location using the first and second phase offsets to obtain a modified communication signal. The first, second, and third communication signals are the same communication signal obtained at different locations along the transmission path.



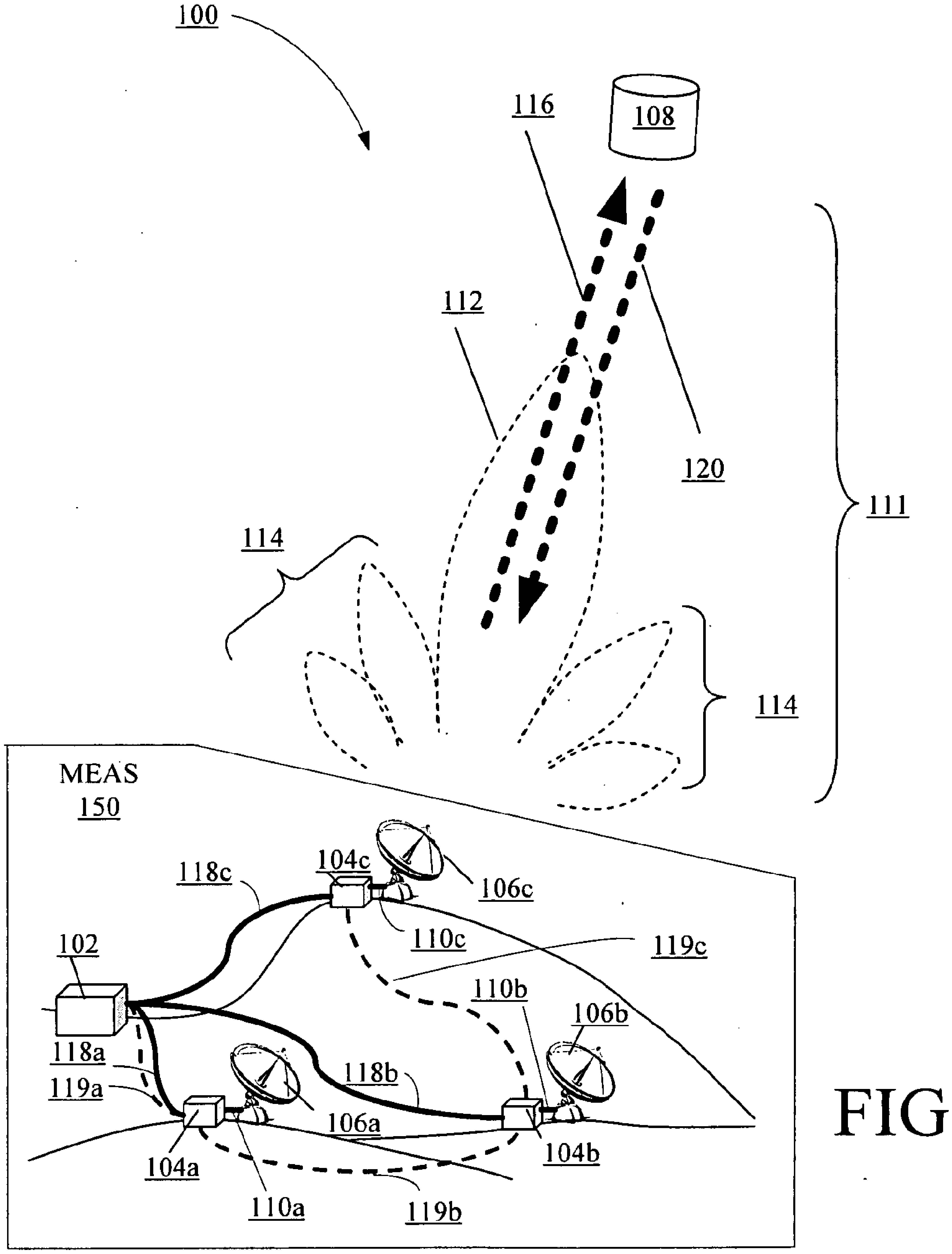

100
116
108
112
120
111
114
114
MEAS
150
118c
104c
106c
110c
119c
102
110b
106b
118a
118b
119a
106a
104a
104b
110a
119b

FIG. 1

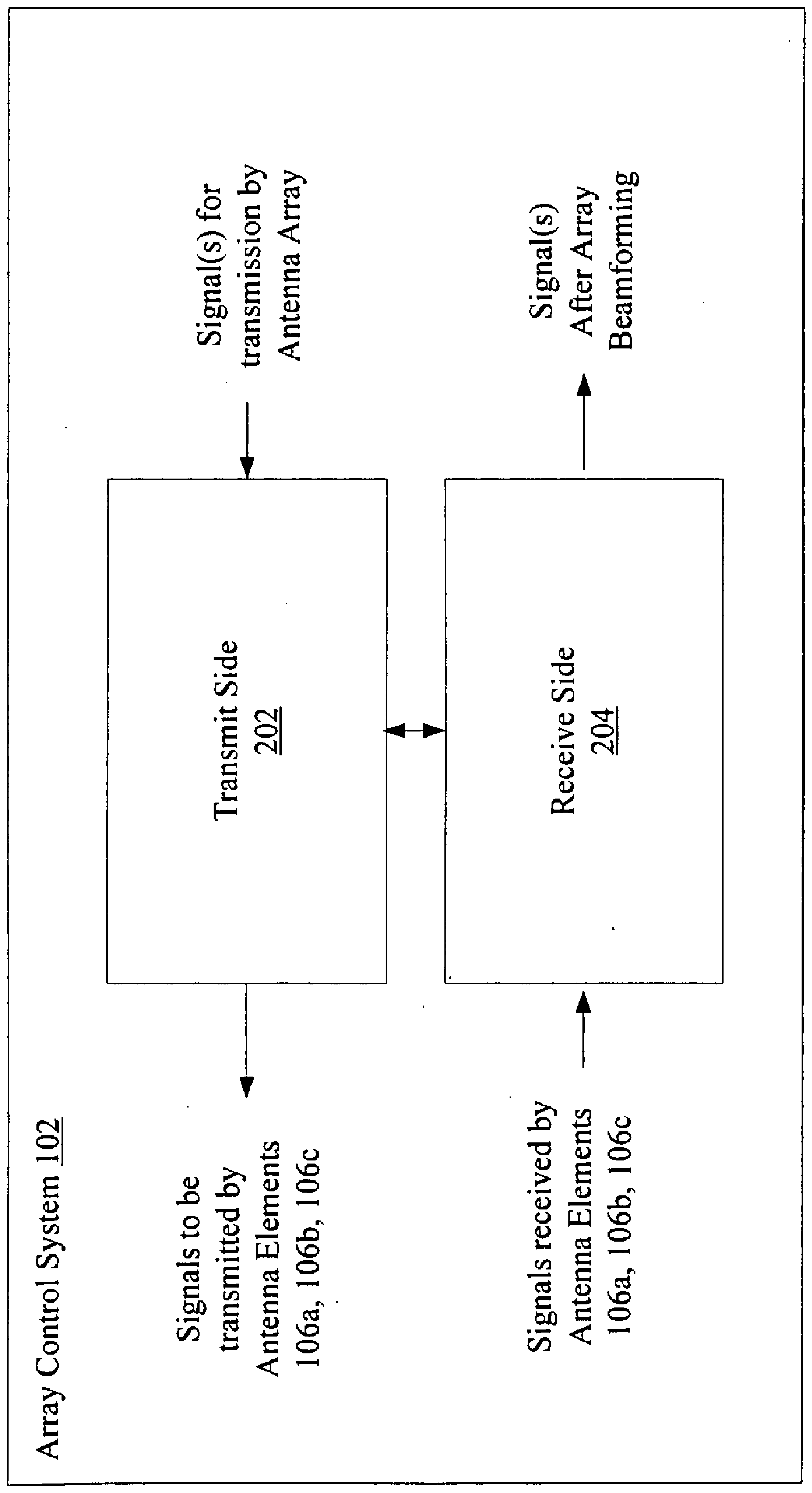

Array Control System 102
Signal(s) for transmission by Antenna Array
Transmit Side 202
Signals to be transmitted by Antenna Elements 106a, 106b, 106c
Signal(s) After Array Beamforming
Receive Side 204
Signals received by Antenna Elements 106a, 106b, 106c

FIG. 2

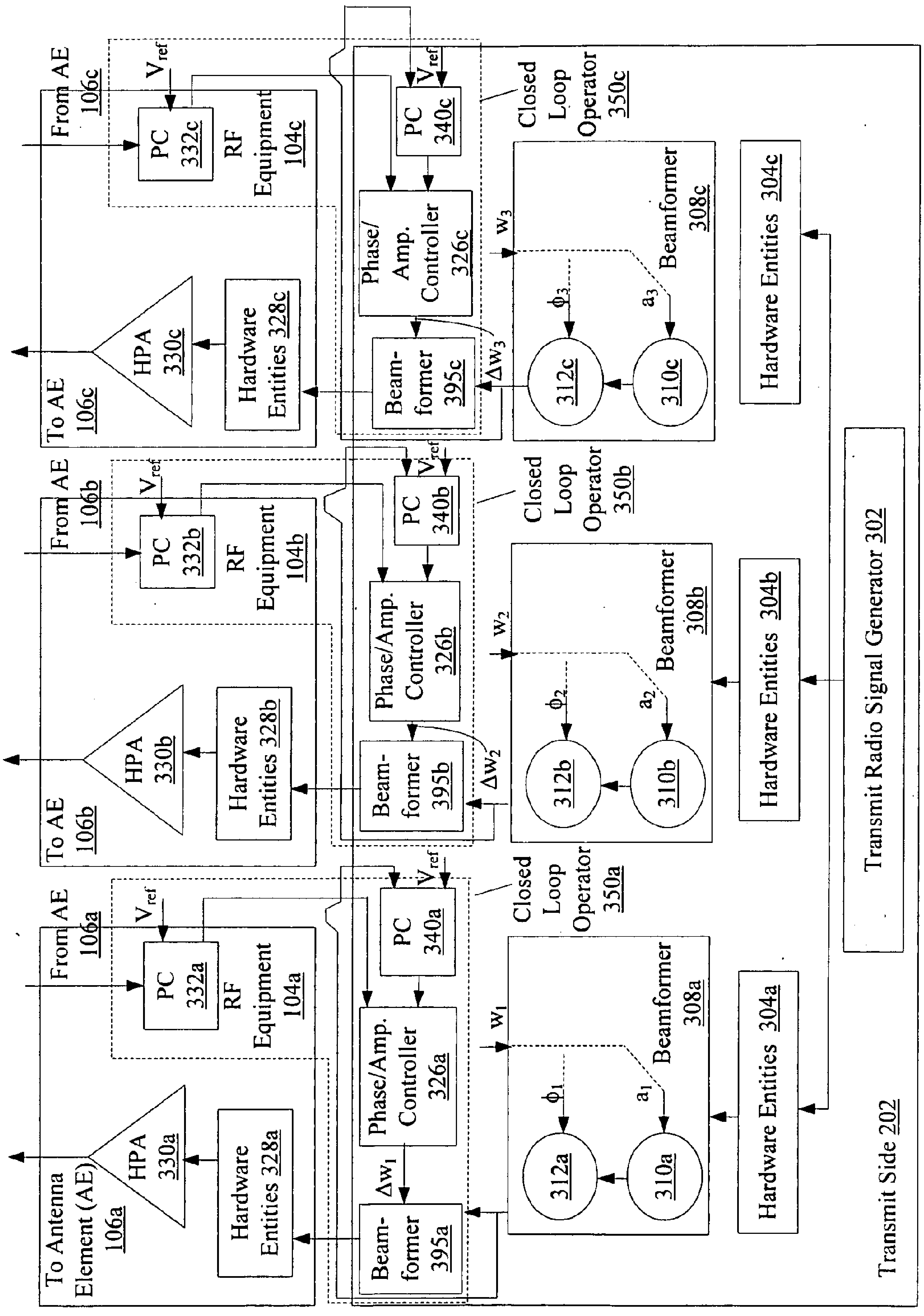

To Antenna Element (AE) 106a
HPA 330a
Hardware Entities 328a
From AE 106a
V_{ref}
PC 332a
RF Equipment 104a
Beam-former 395a
Δw_1
Phase/Amp. Controller 326a
PC 340a
V_{ref}
Closed Loop Operator 350a
w_1
312a
310a
ϕ_1
a_1
Beamformer 308a
Hardware Entities 304a
Transmit Side 202
To AE 106b
HPA 330b
Hardware Entities 328b
From AE 106b
V_{ref}
PC 332b
RF Equipment 104b
Beam-former 395b
Δw_2
Phase/Amp. Controller 326b
PC 340b
V_{ref}
Closed Loop Operator 350b
w_2
312b
310b
ϕ_2
a_2
Beamformer 308b
Hardware Entities 304b
Transmit Radio Signal Generator 302
To AE 106c
HPA 330c
Hardware Entities 328c
From AE 106c
V_{ref}
PC 332c
RF Equipment 104c
Beam-former 395c
Δw_3
Phase/Amp. Controller 326c
PC 340c
V_{ref}
Closed Loop Operator 350c
w_3
312c
310c
ϕ_3
a_3
Beamformer 308c
Hardware Entities 304c

FIG. 3

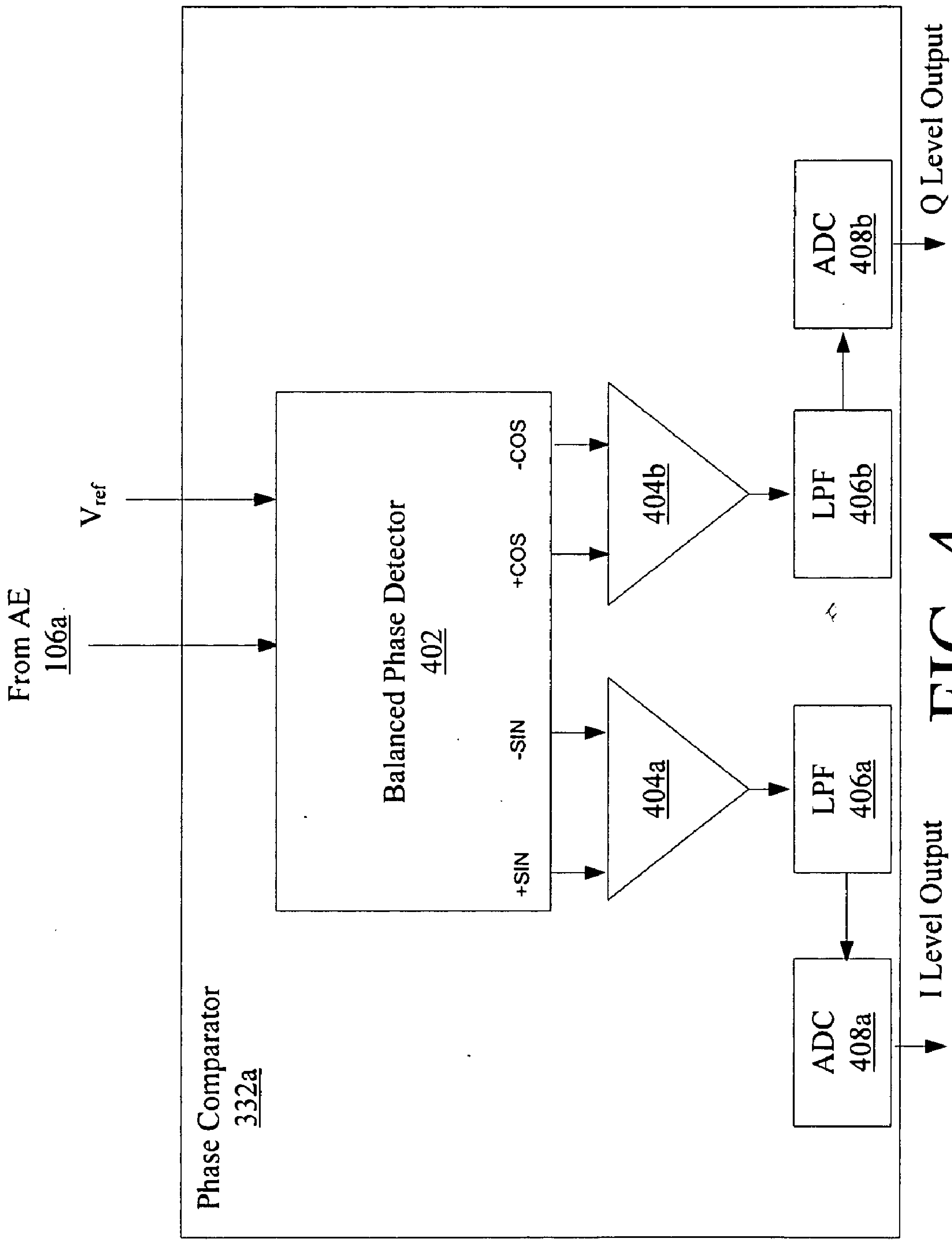

From AE
106a
V_ref
Balanced Phase Detector
402
+SIN
-SIN
+COS
-COS
404a
404b
LPF
406a
LPF
406b
ADC
408a
ADC
408b
I Level Output
Q Level Output
Phase Comparator
332a

FIG. 4

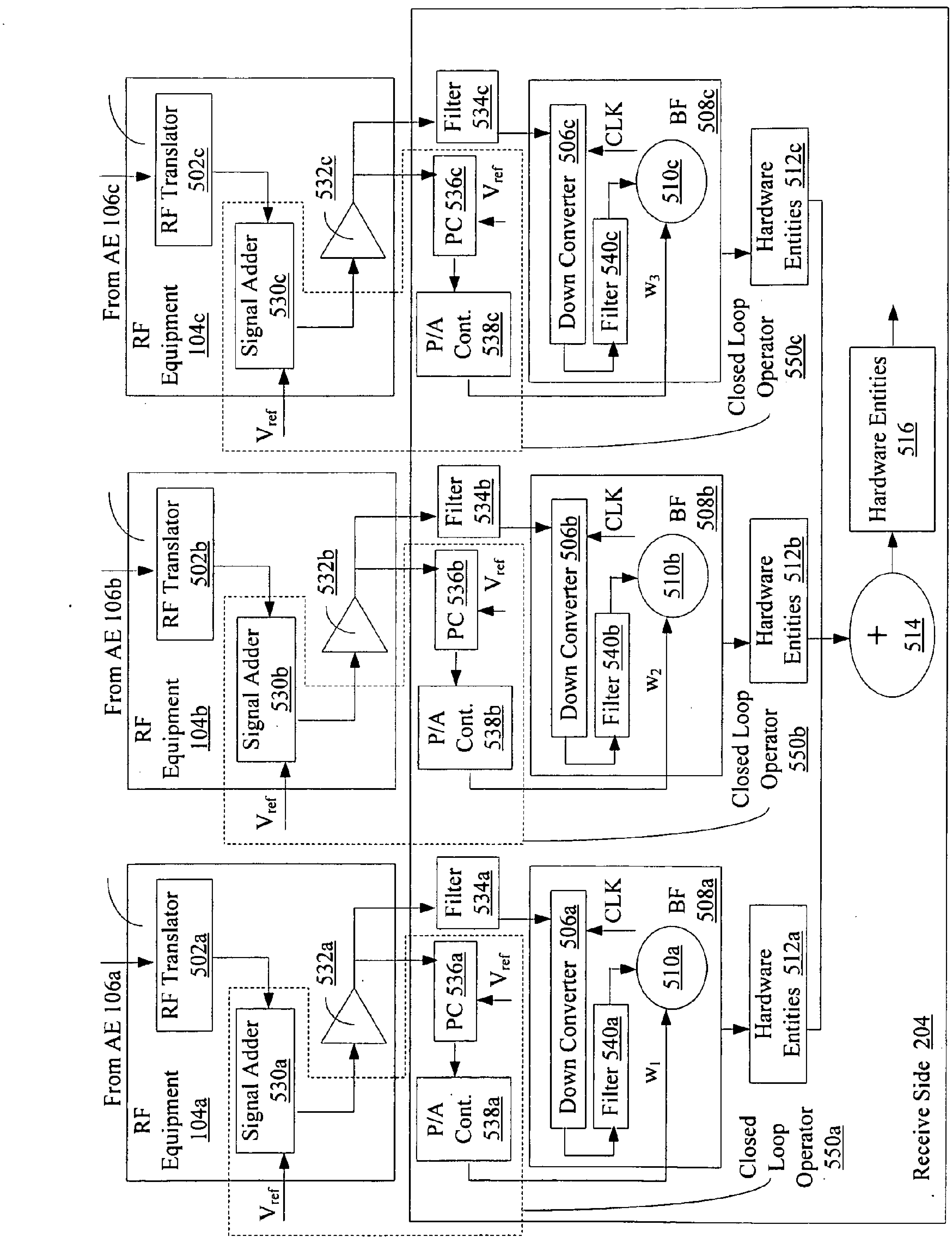

From AE 106a
RF Equipment 104a
RF Translator 502a
Signal Adder 530a
V_{ref}
532a
Filter 534a
PC 536a
V_{ref}
P/A Cont. 538a
Down Converter 506a
Filter 540a
CLK
510a
w_1
BF 508a
Hardware Entities 512a
Closed Loop Operator 550a
Receive Side 204
From AE 106b
RF Equipment 104b
RF Translator 502b
Signal Adder 530b
V_{ref}
532b
Filter 534b
PC 536b
V_{ref}
P/A Cont. 538b
Down Converter 506b
Filter 540b
CLK
510b
w_2
BF 508b
Hardware Entities 512b
Closed Loop Operator 550b
From AE 106c
RF Equipment 104c
RF Translator 502c
Signal Adder 530c
V_{ref}
532c
Filter 534c
PC 536c
V_{ref}
P/A Cont. 538c
Down Converter 506c
Filter 540c
CLK
510c
w_3
BF 508c
Hardware Entities 512c
Closed Loop Operator 550c
+
514
Hardware Entities 516

FIG. 5

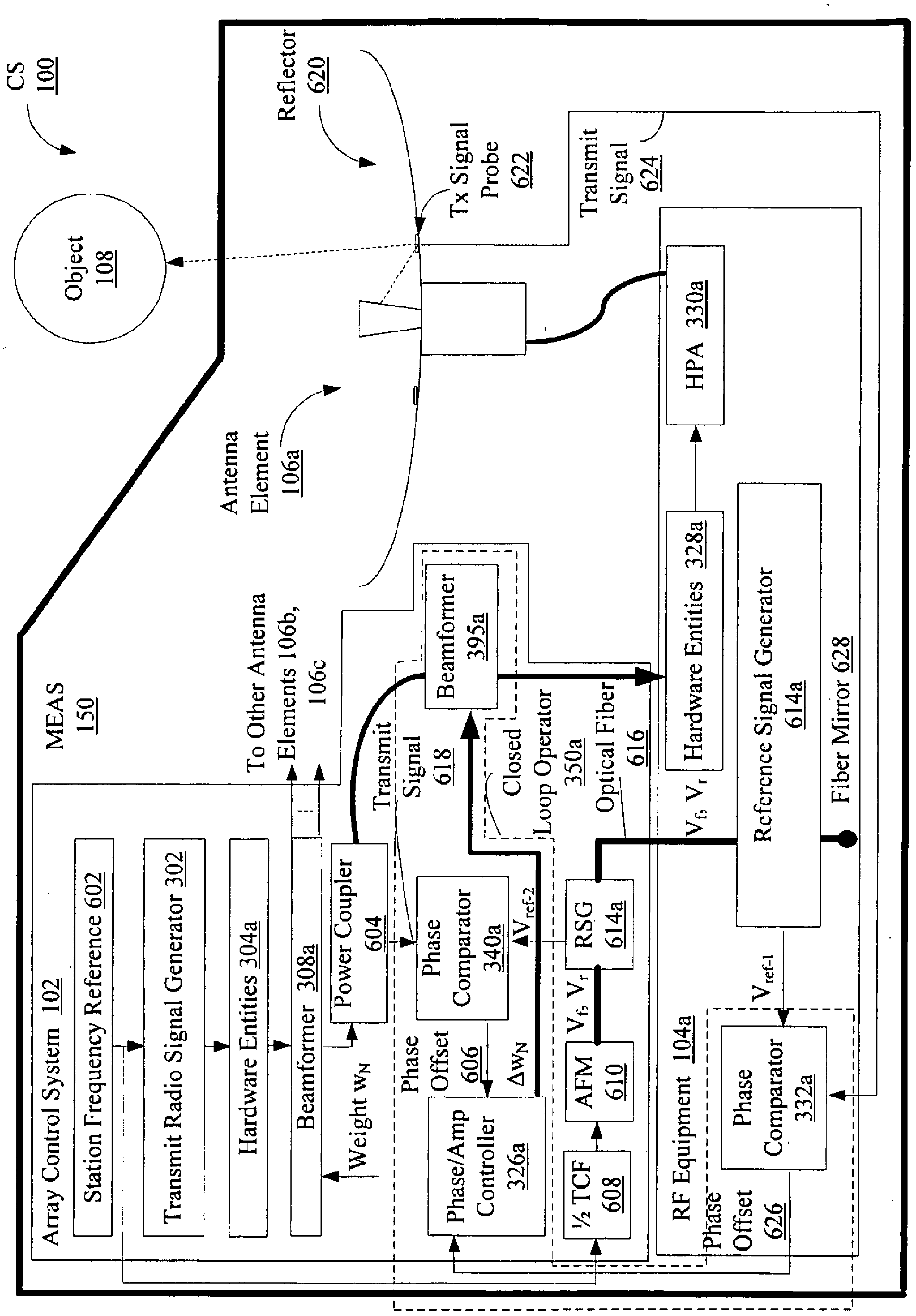

CS 100
Object 108
Reflector 620
Tx Signal Probe 622
Transmit Signal 624
Antenna Element 106a
HPA 330a
MEAS 150
To Other Antenna Elements 106b, 106c
Beamformer 395a
Hardware Entities 328a
Reference Signal Generator 614a
Fiber Mirror 628
Transmit Signal 618
Closed Loop Operator 350a
Optical Fiber 616
V_f, V_r
Array Control System 102
Station Frequency Reference 602
Transmit Radio Signal Generator 302
Hardware Entities 304a
Beamformer 308a
Power Coupler 604
Phase Comparator 340a
V_{ref-2}
RSG 614a
V_f, V_r
V_{ref-1}
Weight w_N
Phase Offset 606
Δw_N
AFM 610
Phase/Amp Controller 326a
½ TCF 608
RF Equipment 104a
Phase Comparator 332a
Phase Offset 626

FIG. 6A

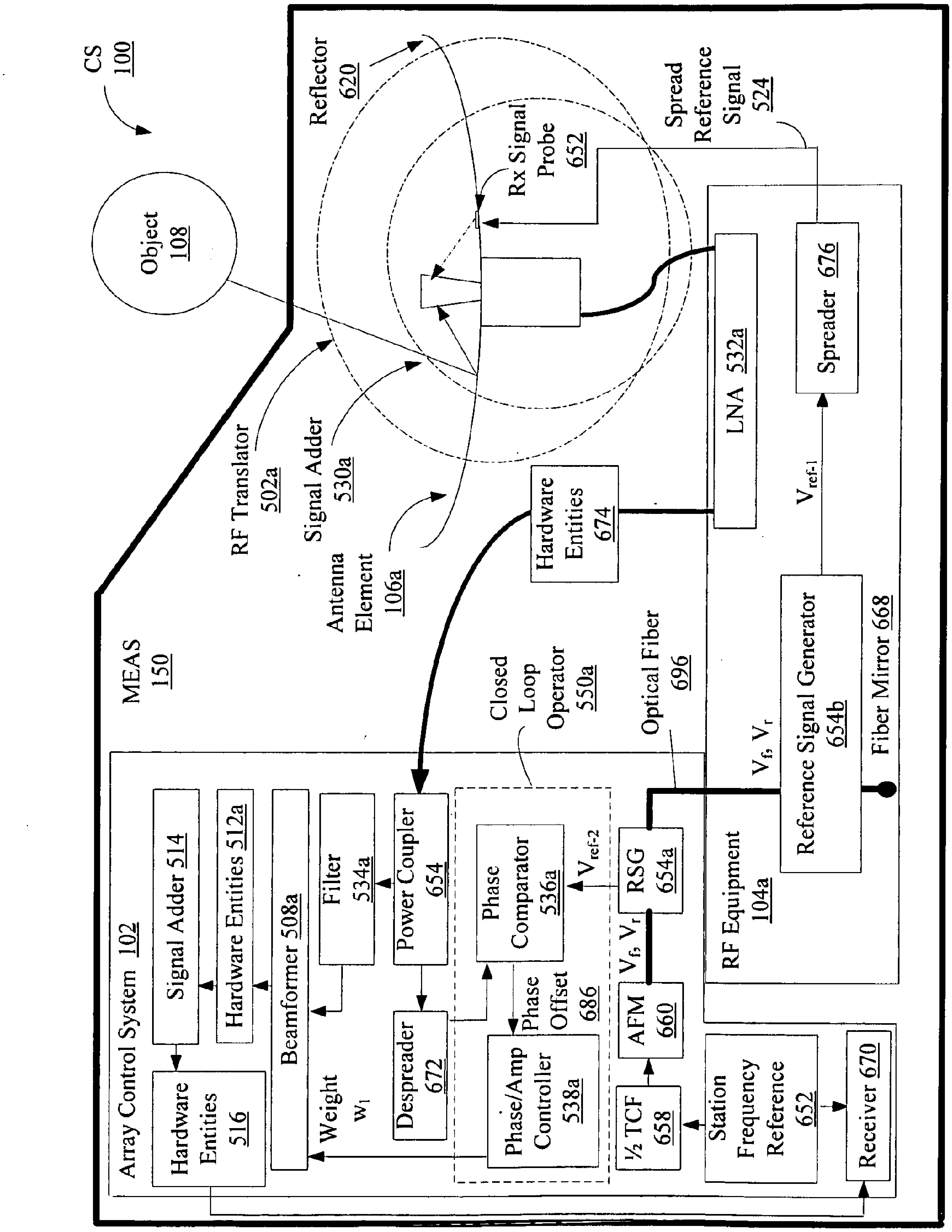

CS 100
Object 108
Reflector 620
Rx Signal Probe 652
Spread Reference Signal 524
RF Translator 502a
Signal Adder 530a
Antenna Element 106a
MEAS 150
Hardware Entities 674
LNA 532a
Spreader 676
V_{ref-1}
Closed Loop Operator 550a
Optical Fiber 696
V_f, V_r
Reference Signal Generator 654b
Fiber Mirror 668
RF Equipment 104a
Array Control System 102
Signal Adder 514
Hardware Entities 512a
Beamformer 508a
Filter 534a
Power Coupler 654
Phase Comparator 536a
V_{ref-2}
RSG 654a
V_f, V_r
AFM 660
Phase Offset 686
Despreader 672
Phase/Amp Controller 538a
Weight w_1
Hardware Entities 516
½ TCF 658
Station Frequency Reference 652
Receiver 670

FIG. 6B

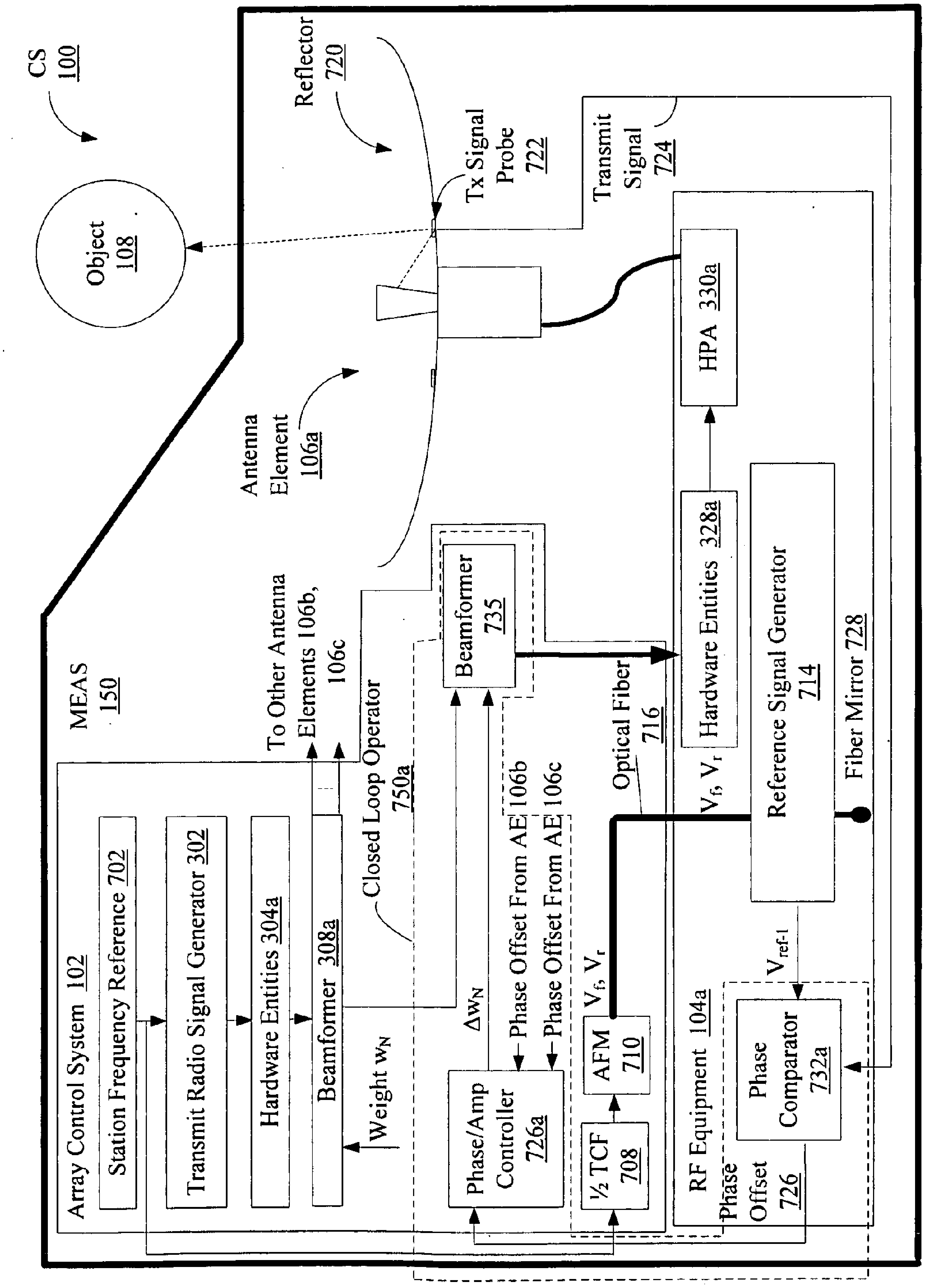

CS 100
Object 108
Reflector 720
Tx Signal Probe 722
Transmit Signal 724
Antenna Element 106a
MEAS 150
To Other Antenna Elements 106b, 106c
Closed Loop Operator 750a
Beamformer 735
Optical Fiber 716
Hardware Entities 328a
HPA 330a
Reference Signal Generator 714
Fiber Mirror 728
V_f, V_r
Array Control System 102
Station Frequency Reference 702
Transmit Radio Signal Generator 302
Hardware Entities 304a
Beamformer 308a
Weight w_N
Δw_N
Phase Offset From AE 106b
Phase Offset From AE 106c
V_f, V_r
Phase/Amp Controller 726a
½ TCF 708
AFM 710
RF Equipment 104a
V_{ref-1}
Phase Comparator 732a
Phase Offset 726

FIG. 7

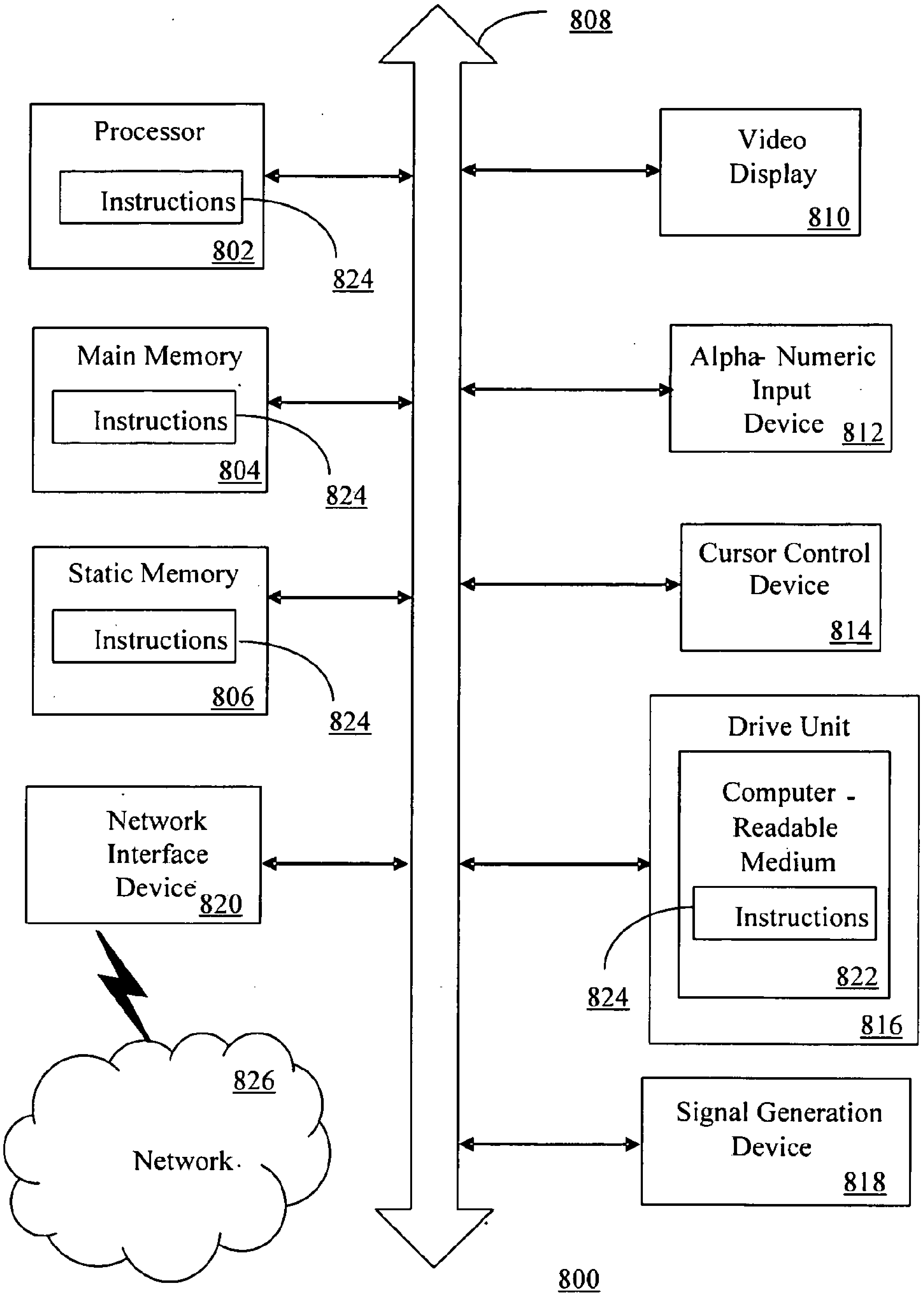

808
Processor
Instructions
802
824
Main Memory
Instructions
804
824
Static Memory
Instructions
806
824
Network Interface Device 820
826
Network
Video Display 810
Alpha- Numeric Input Device 812
Cursor Control Device 814
Drive Unit
Computer - Readable Medium
Instructions
822
824
816
Signal Generation Device 818
800

FIG. 8

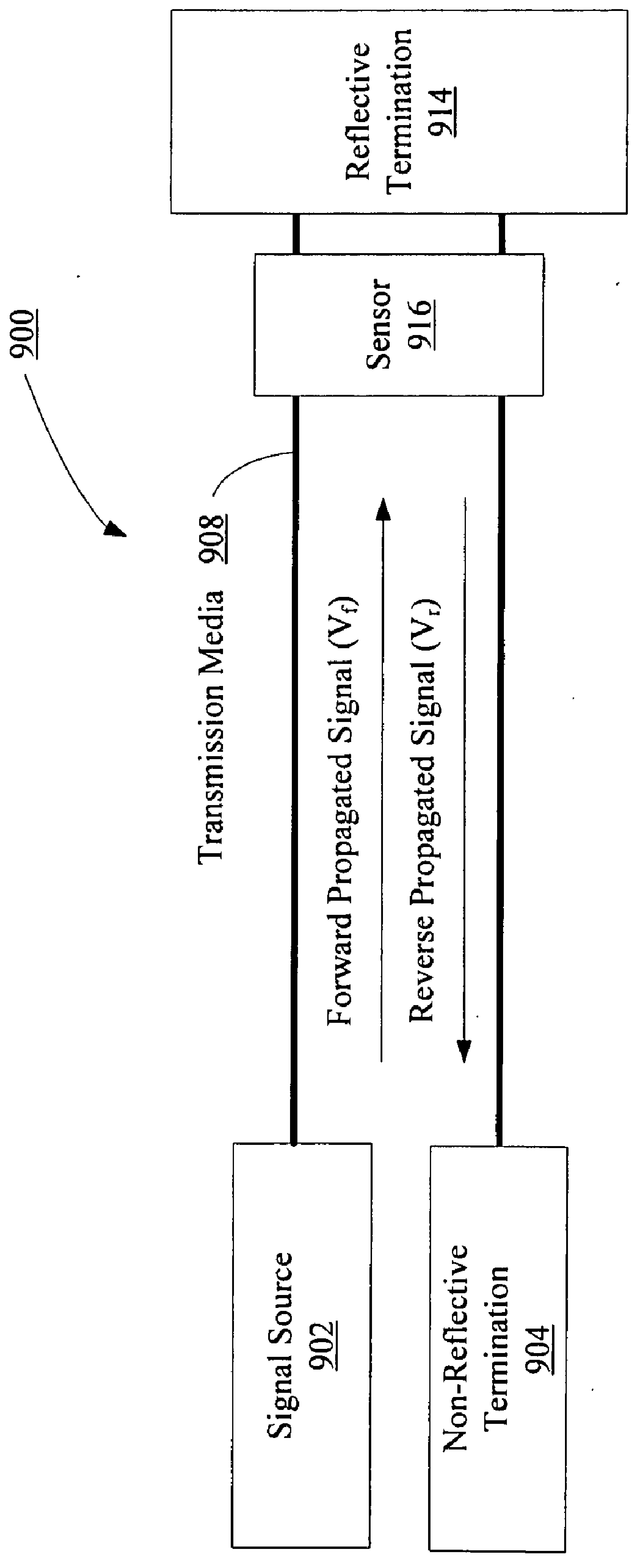
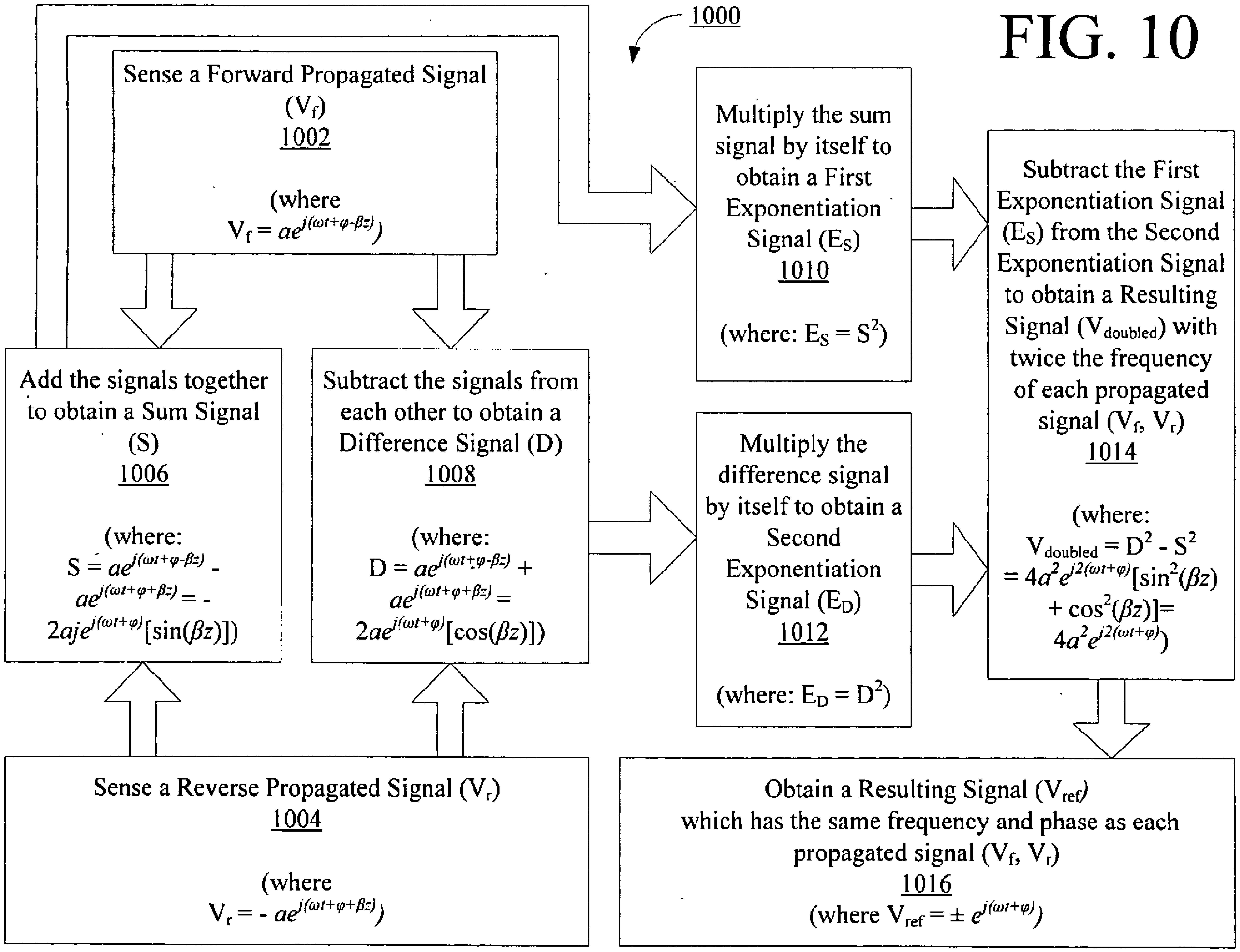

900
Reflective Termination 914
Sensor 916
Transmission Media 908
Forward Propagated Signal (V_f)
Reverse Propagated Signal (V_r)
Signal Source 902
Non-Reflective Termination 904

FIG. 9

FIG. 10


1000
Sense a Forward Propagated Signal (V_f) 1002 (where $V_f = ae^{j(\omega t+\varphi-\beta z)}$)
Sense a Reverse Propagated Signal (V_r) 1004 (where $V_r = -ae^{j(\omega t+\varphi+\beta z)}$)
Add the signals together to obtain a Sum Signal (S) 1006 (where: $S = ae^{j(\omega t+\varphi-\beta z)} - ae^{j(\omega t+\varphi+\beta z)} = -2aje^{j(\omega t+\varphi)}[\sin(\beta z)]$)
Subtract the signals from each other to obtain a Difference Signal (D) 1008 (where: $D = ae^{j(\omega t+\varphi-\beta z)} + ae^{j(\omega t+\varphi+\beta z)} = 2ae^{j(\omega t+\varphi)}[\cos(\beta z)]$)
Multiply the sum signal by itself to obtain a First Exponentiation Signal (E_S) 1010 (where: $E_S = S^2$)
Multiply the difference signal by itself to obtain a Second Exponentiation Signal (E_D) 1012 (where: $E_D = D^2$)
Subtract the First Exponentiation Signal (E_S) from the Second Exponentiation Signal to obtain a Resulting Signal ($V_{doubled}$) with twice the frequency of each propagated signal (V_f, V_r) 1014 (where: $V_{doubled} = D^2 - S^2 = 4a^2e^{j2(\omega t+\varphi)}[\sin^2(\beta z) + \cos^2(\beta z)] = 4a^2e^{j2(\omega t+\varphi)}$)
Obtain a Resulting Signal (V_{ref}) which has the same frequency and phase as each propagated signal (V_f, V_r) 1016 (where $V_{ref} = \pm e^{j(\omega t+\varphi)}$)

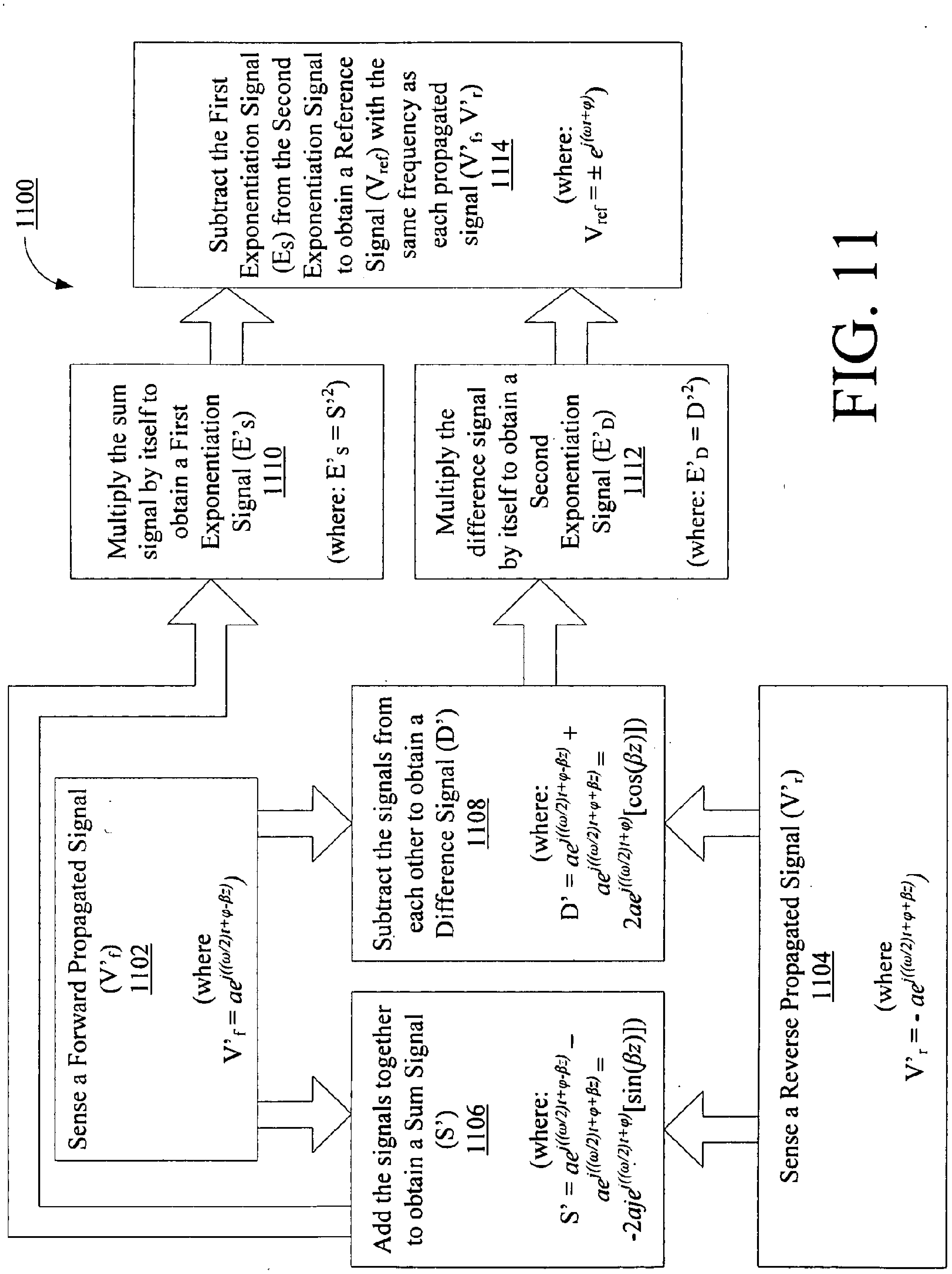

1100
Sense a Forward Propagated Signal (V'_f) 1102 (where $V'_f = ae^{j((\omega/2)t+\varphi-\beta z)}$)
Sense a Reverse Propagated Signal (V'_r) 1104 (where $V'_r = -ae^{j((\omega/2)t+\varphi+\beta z)}$)
Add the signals together to obtain a Sum Signal (S') 1106 (where: $S' = ae^{j((\omega/2)t+\varphi-\beta z)} - ae^{j((\omega/2)t+\varphi+\beta z)} = -2aje^{j((\omega/2)t+\varphi)}[\sin(\beta z)]$)
Subtract the signals from each other to obtain a Difference Signal (D') 1108 (where: $D' = ae^{j((\omega/2)t+\varphi-\beta z)} + ae^{j((\omega/2)t+\varphi+\beta z)} = 2ae^{j((\omega/2)t+\varphi)}[\cos(\beta z)]$)
Multiply the sum signal by itself to obtain a First Exponentiation Signal (E'_S) 1110 (where: $E'_S = S'^2$)
Multiply the difference signal by itself to obtain a Second Exponentiation Signal (E'_D) 1112 (where: $E'_D = D'^2$)
Subtract the First Exponentiation Signal (E_S) from the Second Exponentiation Signal to obtain a Reference Signal (V_{ref}) with the same frequency as each propagated signal (V'_f, V'_r) 1114 (where: $V_{ref} = \pm e^{j(\omega t+\varphi)}$)

FIG. 11

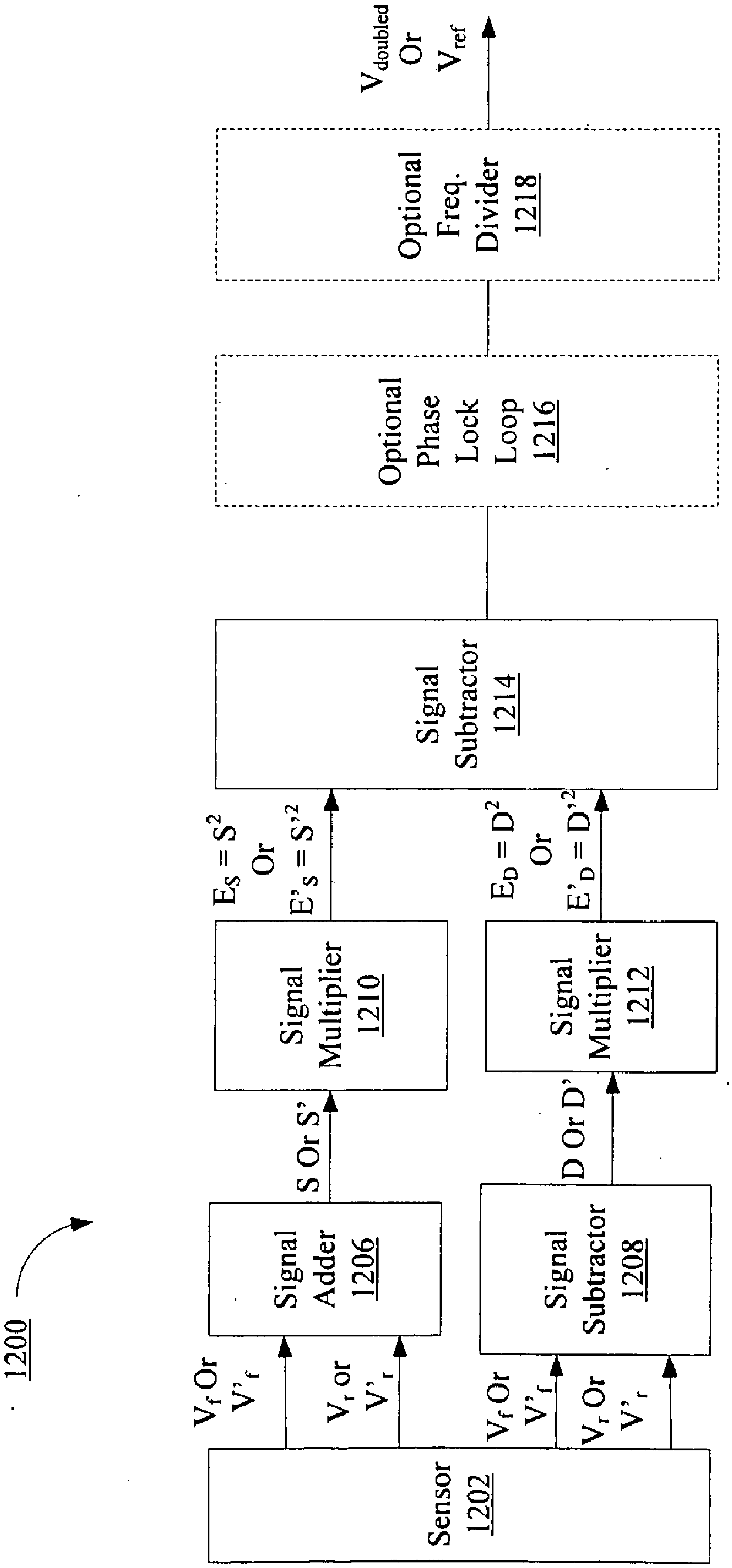

1200
Sensor 1202
V_f Or V'_f
V_r or V'_r
V_f Or V'_f
V_r Or V'_r
Signal Adder 1206
Signal Subtractor 1208
S Or S'
D Or D'
Signal Multiplier 1210
Signal Multiplier 1212
$E_S = S^2$ Or $E'_S = S'^2$
$E_D = D^2$ Or $E'_D = D'^2$
Signal Subtractor 1214
Optional Phase Lock Loop 1216
Optional Freq. Divider 1218
$V_{doubled}$ Or V_{ref}

FIG. 12

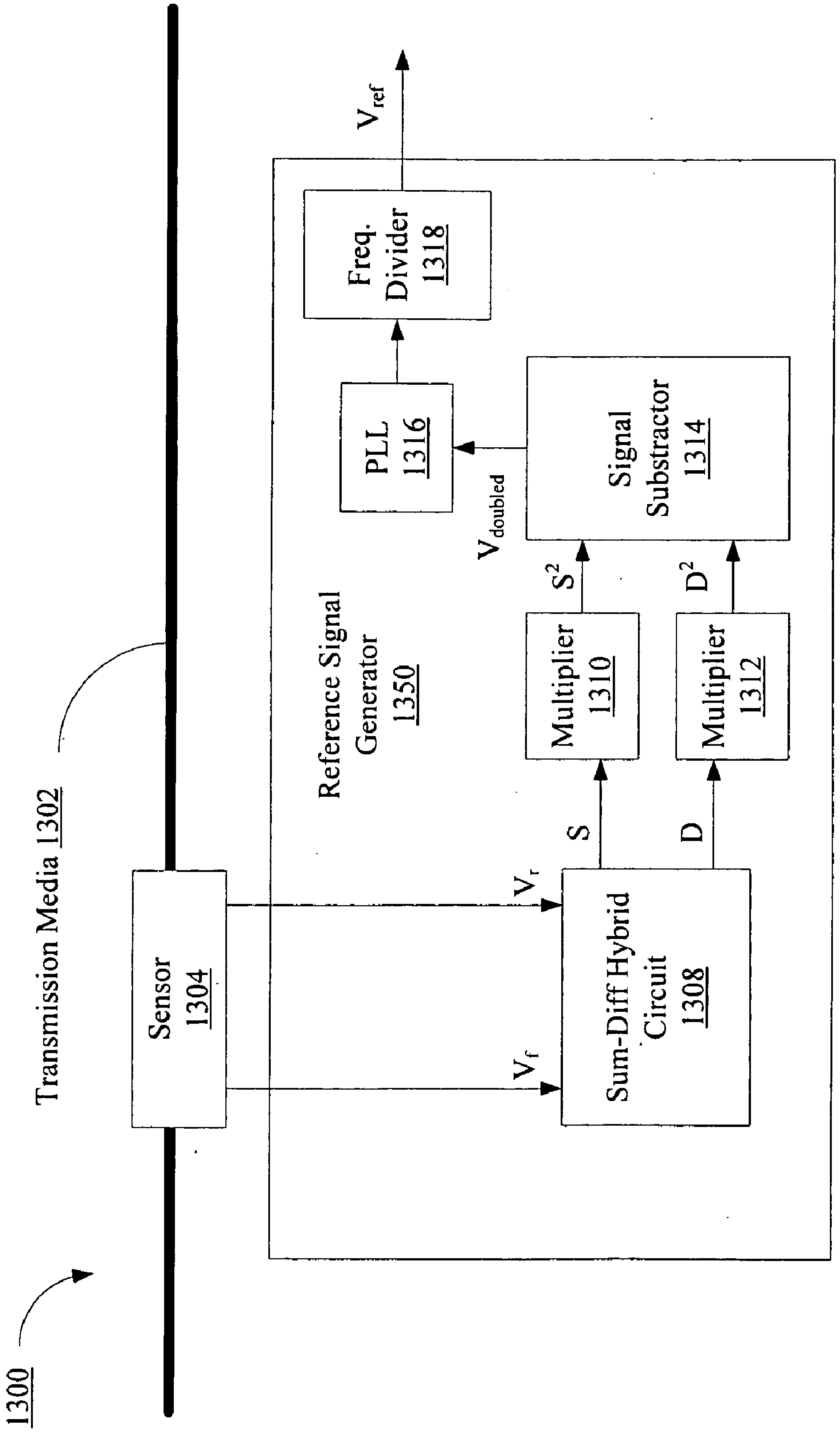

1300
Transmission Media 1302
Sensor 1304
V_f
V_r
Sum-Diff Hybrid Circuit 1308
S
D
Multiplier 1310
Multiplier 1312
S^2
D^2
Signal Substractor 1314
$V_{doubled}$
PLL 1316
Freq. Divider 1318
V_{ref}
Reference Signal Generator 1350

FIG. 13

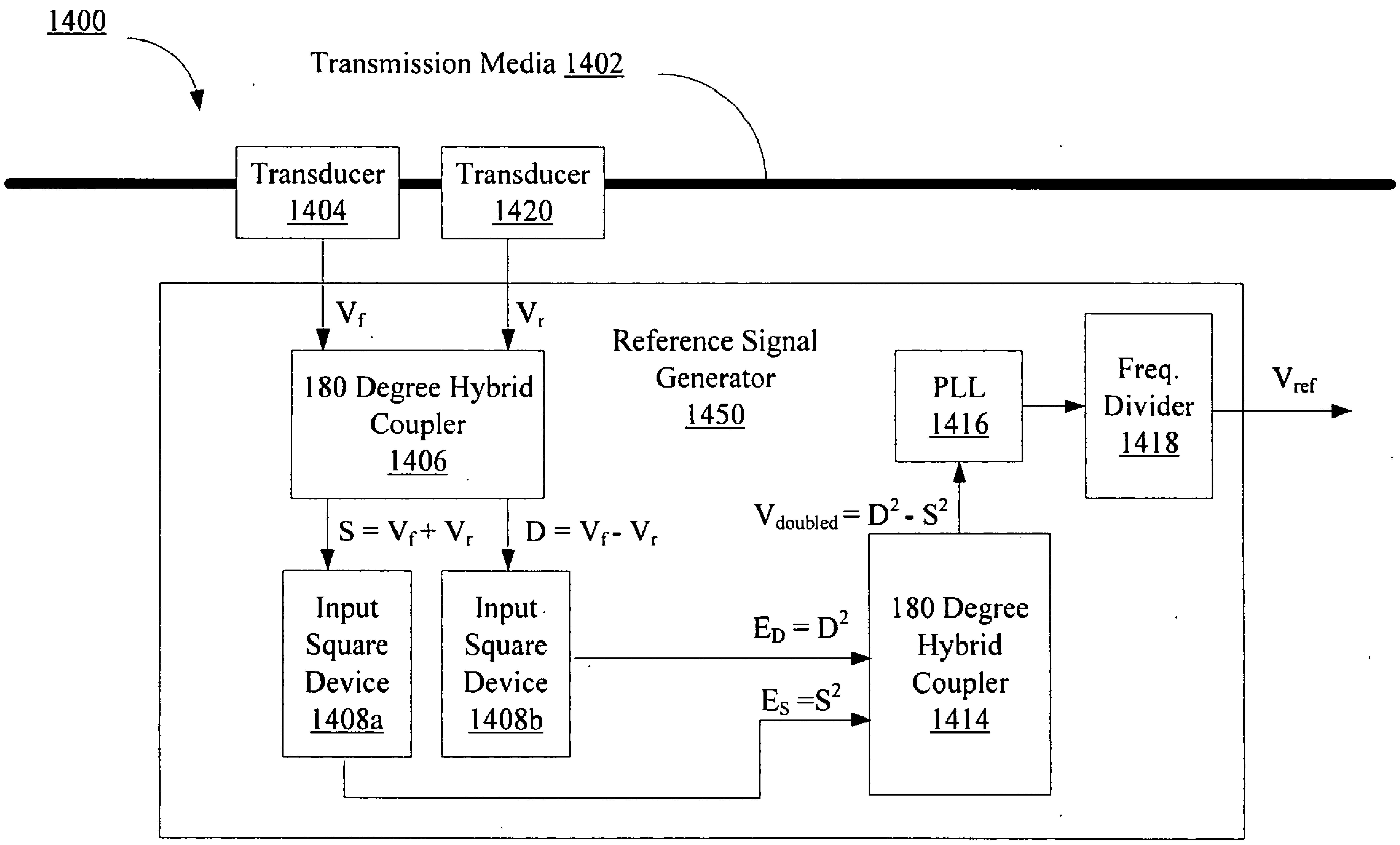

1400
Transmission Media 1402
Transducer 1404
Transducer 1420
V_f
V_r
Reference Signal Generator 1450
180 Degree Hybrid Coupler 1406
$S = V_f + V_r$
$D = V_f - V_r$
Input Square Device 1408a
Input Square Device 1408b
$E_D = D^2$
$E_S = S^2$
180 Degree Hybrid Coupler 1414
$V_{doubled} = D^2 - S^2$
PLL 1416
Freq. Divider 1418
V_{ref}

FIG. 14

CLOSED LOOP PHASE CONTROL BETWEEN DISTANT POINTS

BACKGROUND OF THE INVENTION

[0001] 1. Statement of the Technical Field

[0002] The invention concerns communication systems. More particularly, the invention concerns communication systems and methods for controlling the phase between distant points using a closed loop configuration.

[0003] 2. Description of the Related Art

[0004] Multiple element antenna arrays are widely used in wireless communications systems to enhance the transmission and reception of signals. In particular, the enhanced performance is generally provided by using such antenna arrays in conjunction with beamforming techniques. In conventional beamforming, the naturally occurring interference between the different antenna elements in the antenna array is typically used to change the overall directionality for the array. For example, during transmission, the phase and relative amplitude of the transmitted signal at each antenna element is adjusted, in order to create a desired pattern of constructive and destructive interferences at the wavefront of the transmitted signal. During signal reception, the different antenna elements are modified in phase and amplitude in such a way that a pre-defined pattern of radiation is preferentially observed by the antenna elements.

[0005] In general, such antenna arrays typically include a system controller, a plurality of antenna controllers, and a plurality of antenna elements (e.g., dish antennas). Each of the antenna elements is communicatively coupled to the system controller and a respective one of the antenna controllers via cables. During transmission and reception, each antenna element converts electrical signals into electromagnetic waves, and vice versa. The system controller, using conventional beamforming techniques, varies the configuration of the various components in the antenna array to provide a particular radiation pattern during transmission or reception. However, as the dimensions of the array, the number of antenna elements, and the precision required in certain beamforming application increase, properly concerting the actions of the various components becomes more difficult.

SUMMARY OF THE INVENTION

[0006] Embodiments of the present invention concern methods for compensating for phase shifts of a communication signal. The methods involve determining a first reference signal at a first location along a transmission path and a second reference signal at a second location along the transmission path. The second reference signal is the same as the first reference signal. The methods also involve determining at the first location a first phase offset using the first reference signal and a first communication signal. A second phase offset is determined at the second location using the second reference signal and a second communication signal. A phase of a third communication signal is adjusted at the second location using the first and second phase offsets to obtain a modified communication signal. More particularly, a weight is computed at the second location using the first and second phase offsets. The weight is then combined with the third communication signal to obtain the modified communication signal. The first, second, and third communication signals are the same communication signal obtained at different locations along the transmission path.

[0007] According to an aspect of the invention, the first reference signal is determined by sensing at the first location a transmit signal propagated over a transmission media in a forward direction and a reverse signal propagated over the transmission media in a reverse direction opposed from the forward direction. The reverse signal being a reflected version of the transmit signal. A first sum signal is computed by adding the transmit and reverse signals together. A first difference signal is computed by subtracting the reverse signal from the transmit signal. Thereafter, a first exponentiation signal is determined using the first sum signal and a second exponentiation signal is determined using the first difference signal. The first exponentiation signal is subtracted from the second exponentiation signal to obtain the first reference signal. The first reference signal can have a first frequency equal to a second frequency of the transmit signal. Alternatively, the first reference signal can have a first frequency different than a second frequency of the transmit signal. In such a scenario, the first reference signal can be processed to obtain an adjusted reference signal with a third frequency equal to the second frequency of the transmit signal.

[0008] The second reference signal is determined by sensing at the second location the transmit and reverse signals. Thereafter, the second reference signal is determined using the transmit and reverse signals sensed at the second location. More particularly, the second reference signal is determined by computing a second sum signal by adding the transmit and reverse signals sensed at the second location together and a second difference signal by subtracting the reverse signal sensed at the second location from the transmit signal sensed at the second location. A third exponentiation signal is determined using the second sum signal and a fourth exponentiation signal using the second difference signal. The third exponentiation signal is subtracted from the fourth exponentiation signal to obtain the second reference signal.

[0009] Embodiments of the present invention also relate to methods for compensating for phase shifts of received communication signals. The methods generally involve determining a third reference signal at a third location along the transmission path and a fourth reference signal at a fourth location along the transmission path. At the third location, the communication signal is combined with the third reference signal to obtain a modified received communication signal. At the fourth location, a third phase offset is determined using the modified received communication signal and the fourth reference signal. Thereafter, a phase of the modified received communication signal is adjusted using the third phase offset to obtain a phase adjusted received signal.

[0010] Embodiments of the present invention further relate to systems implementing at least one of the above described methods. The systems generally include at least one reference signal generator and at least one closed loop operator communicatively coupled to the reference signal generator. The reference signal generator is configured for determining the first reference signal at the first location along a transmission path and the second reference signal at the second location along the transmission path. The closed loop operator is configured for determining at the first location the first phase offset using the first reference signal and the first communication signal. The closed loop operator is also configured for determining at the second location the second phase offset using the second reference signal and the second communication signal. The closed loop operator is further configured for adjusting at the first location the phase of a third communication signal using the first and second phase offsets to obtain the modified communication signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Embodiments will be described with reference to the following drawing figures, in which like numerals represent like items throughout the figures, and in which:

[0012] FIG. **1** is a schematic illustration of an exemplary communications system configured according to an embodiment of the present invention.

[0013] FIG. **2** is a block diagram of the antenna control system shown in FIG. **1**.

[0014] FIG. **3** is a block diagram of the transmit side of the antenna control system shown in FIGS. **1-2** communicatively coupled to the RF equipment shown in FIG. **1**.

[0015] FIG. **4** is a more detailed block diagram of the phase comparator of FIG. **3**.

[0016] FIG. **5** is a block diagram of the receive side of the antenna control system shown in FIGS. **1-2** communicatively coupled to the RF equipment shown in FIG. **1**.

[0017] FIG. **6**A is a more detailed block diagram of the communication system of FIG. **1** that is useful for understanding the phase and/or amplitude adjustment functions thereof.

[0018] FIG. **6**B is a more detailed block diagram of the communication system of FIG. **1** that is useful for understanding the phase and/or amplitude adjustment functions thereof.

[0019] FIG. **7** is a more detailed block diagram of the communication system of FIG. **1** that is useful for understanding the phase and/or amplitude adjustment functions thereof.

[0020] FIG. **8** is a schematic view of a computer system within which a set of instructions operate according to an embodiment of the present invention.

[0021] FIG. **9** is a block diagram of a communication system that is useful for understanding how a reference signal is determined.

[0022] FIG. **10** is a conceptual diagram of a first method embodiment for determining a reference signal that is useful for understanding the present invention.

[0023] FIG. **11** is a conceptual diagram of a second method embodiment for determining a reference signal that is useful for understanding the present invention.

[0024] FIG. **12** is a block diagram of a first system embodiment implementing a method of FIGS. **10** and **11**.

[0025] FIG. **13** is a block diagram of a second system embodiment implementing the method of FIG. **10**.

[0026] FIG. **14** is a block diagram of a third system embodiment implementing the method of FIG. **10**.

DETAILED DESCRIPTION

[0027] The present invention is described with reference to the attached figures, wherein like reference numbers are used throughout the figures to designate similar or equivalent elements. The figures are not drawn to scale and they are provided merely to illustrate the instant invention. Several aspects of the invention are described below with reference to example applications for illustration. It should be understood that numerous specific details, relationships, and methods are set forth to provide a full understanding of the invention. One having ordinary skill in the relevant art, however, will readily recognize that the invention can be practiced without one or more of the specific details or with other methods. In other instances, well-known structures or operation are not shown in detail to avoid obscuring the invention. The present invention is not limited by the illustrated ordering of acts or events, as some acts may occur in different orders and/or concurrently with other acts or events. Furthermore, not all illustrated acts or events are required to implement a methodology in accordance with the present invention.

[0028] In conventional multi-beam antenna systems, the phases of the signals to be transmitted from the antenna elements can be shifted as a result of environmental effects on hardware components of the system including the antenna, Radio Frequency (RF) components and the cables connecting the antenna elements to the controllers. These phase shifts typically result in the steering of the radiated main beam in the wrong direction.

[0029] To overcome the various limitations of the conventional multi-beam antenna systems, embodiments of the present invention provide systems implementing an improved beam forming solution. The improved beam forming solution is facilitated by novel methods for determining a reference signal at any location along a transmission media. The methods generally involve determining a first reference signal at a first location along a transmission path and a second reference signal at a second location along the transmission path. The second reference signal must be substantially the same as the first reference signal. At the first location, the first reference signal is combined with a communications signal to obtain a first phase adjusted signal. At the second location, a phase offset is determined using the second reference signal and the first phase adjusted signal. The phase of the first phase adjusted signal is subsequently adjusted using the phase offset to obtain a modified communications signal.

[0030] Before describing the systems and methods of the present invention, it will be helpful in understanding an exemplary environment in which the invention can be utilized. In this regard, it should be understood that the systems and methods of the present invention can be utilized in a variety of different applications where phases of transmit signals need to be adjusted so as to counteract the environmental effects on hardware components of communication systems. Such applications include, but are not limited to, mobile/cellular telephone applications, military communication applications, and space communication applications. Accordingly, the present invention will be described in relation to space communication applications.

[0031] The word "exemplary" is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the word exemplary is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or". That is, unless specified otherwise, or clear from context, "X employs A or B" is intended to mean any of the natural inclusive permutations. That is if, X employs A; X employs B; or X employs both A and B, then "X employs A or B" is satisfied under any of the foregoing instances.

Communication System Architecture

[0032] FIG. **1** shows an exemplary communication system **100** according to an embodiment of the present invention. As shown in FIG. **1**, the communication system **100** comprises a multi-element antenna system (MEAS) **150** for transmitting signals to and receiving signals from at least one object of interest **108** remotely located from the MEAS **150**. In FIG. **1**, the object of interest **108** is shown as an airborne or spaceborne object, such as an aircraft, a spacecraft, a natural or artificial satellite, or a celestial object (e.g., a planet, a moon, an asteroid, a comet, etc. . . .). However, embodiments of the present invention are not limited in this regard. The MEAS **150** can also be used for transmitting and receiving signals from objects of interest **108** that are not airborne or spaceborne but are still remotely located with respect to MEAS **150**. For example, a ground-based MEAS **150** can be used to provide communications with objects of interest **108** at other ground-based or sea-based locations.

[0033] In FIG. **1**, the ACS **102** is shown as controlling the operation of antenna elements **106***a*, **106***b*, **106***c* and associated RF equipment **104***a*, **104***b*, **104***c*. The antenna elements **106***a*, **106***b*, **106***c* provide wireless communications. For example, if the MEAS **150** is in a transmit mode, then each antenna element **106***a*, **106***b*, **106***c* converts electrical signals into electromagnetic waves. The radiation pattern **111** resulting from the interference of the electromagnetic waves transmitted by the different antenna elements **106***a*, **106***b*, **106***c* can then be adjusted to a central beam **112** in the radiation pattern **111** aimed in the direction **116** of the object of interest **108**. The radiation pattern **111** of the antenna elements **106***a*, **106***b*, **106***c* also generates smaller side beams (or side lobes) **114** pointing in other directions with respect to the direction of the central beam **112**. However, because of the relative difference in magnitude between the side beams **114** and the central beam **112**, the radiation pattern **111** preferentially transmits the signal in the direction of the central beam **112**. Therefore, by varying the phases and the amplitudes of the signals transmitted by each antenna element **106***a*, **106***b*, **106***c*, the magnitude and direction of the central beam **112** can be adjusted. If the MEAS **150** is in a receive mode, then each of the antenna elements **106***a*, **106***b*, **106***c* captures energy from passing waves propagated over transmission media (not shown) in the direction **120** and converts the captured energy to electrical signals. In the receive mode, the MEAS **150** can be configured to combine the electrical signals according to the radiation pattern **111** to improve reception from direction **120**, as described below.

[0034] In FIG. **1**, the antenna elements **106***a*, **106***b*, **106***c* are shown as reflector-type (e.g., a dish) antenna elements, which generally allow adjustment of azimuth (or rotation) and elevation (angle with respect to a ground plane). Therefore, in addition to adjustment of phase and amplitude of the signal transmitted by each of the antenna elements **106***a*, **106***b*, **106***c*, the azimuth and elevation of each antenna element **106***a*, **106***b*, **106***c* can also be used to further steer the central beam **112** and adjust the radiation pattern **111**. However, embodiments of the present invention are not limited on this regard. The antenna elements **106***a*, **106***b*, **106***c* can comprise directional or omni-directional antenna elements.

[0035] Although three (3) antenna elements **106***a*, **106***b*, **106***c* are shown in FIG. **1**, the various embodiments of the present invention are not limited in this regard. Any number of antenna elements **106***a*, **106***b*, **106***c* can be used without limitation. Furthermore, the spacing between the antenna elements **106***a*, **106***b*, **106***c* with respect to each other is not limited. Accordingly, the antenna elements **106***a*, **106***b*, **106***c* can be widely spaced or closely spaced. However, as the spacing between the antenna elements **106***a*, **106***b*, **106***c* increases, the central beam **112** generally becomes narrower and the side beams (or side lobes) **114** generally become larger. The antenna elements **106***a*, **106***b*, **106***c* can also be regularly spaced (not shown) with respect to one another or arbitrarily spaced (or non-linearly spaced) with respect to one another (as shown in FIG. **1**) to form a three dimensional (3D) array of antenna elements. As shown in FIG. **1**, the arbitrary spacing of the antenna elements **106***a*, **106***b*, **106***c* can include locations having different altitudes and locations having different distances between each other.

[0036] As shown in FIG. **1**, each of the antenna elements **106***a*, **106***b*, **106***c* is communicatively coupled to a respective RF equipment **104***a*, **104***b*, **104***c* via a respective cable assembly **110***a*, **110***b*, **110***c* (collectively **110**). Each of the cable assemblies **110***a*, **110***b*, **110***c* can have the same or different lengths. As used herein, the phrase "cable assembly" refers to any number of cables provided or interconnecting two different components. In the various embodiments of the present invention, the cables in the cable assemblies **110***a*, **110***b*, **110***c* can be bundled or unbundled.

[0037] Notably, the cables **110***a*, **110***b*, **110***c* can delay transmit signals. In effect, the phases of the transmit signals can be shifted thereby resulting in phasing errors. As such, the communication system **100** implements a closed loop method to counteract phasing errors due to cable delay effects. The closed loop method will become more evident as the discussion progresses.

[0038] The RF equipment **104***a*, **104***b*, **104***c* control the antenna elements **106***a*, **106***b*, **106***c*, respectively. For example, for the directional antenna elements **106***a*, **106***b*, **106***c* shown in FIG. **1**, the RF equipment **104***a*, **104***b*, **104***c* are configured to control antenna motors (not shown), antenna servo motors (not shown), and antenna rotators (not shown). The RF equipment **104***a*, **104***b*, **104***c* can also include hardware entities for processing transmit signals and receive signals. Notably, the phases of transmit signals can be shifted as a result of environmental effects on the cabling, antenna, and/or RF equipment **104***a*, **104***b*, **104***c*. These phase shifts can result in the steering of the radiated central beam **112** in a direction other than the direction **116** of the object of interest **108**. The RF equipment **104***a*, **104***b*, **104***c* will be described in more detail below in relation to FIGS. **3** and **5**.

[0039] As shown in FIG. **1**, each of the RF equipment **104***a*, **104***b*, **104***c* is communicatively coupled to the ACS **102** via a respective communications link **118***a*, **118***b*, **118***c*. Generally, such communications links are provided via a cable assembly. However, embodiments of the present invention are not limited in this regard. In the various embodiments of the present invention, the communications links **118***a*, **118***b*, **118***c* can comprise wireline, optical, or wireless communication links. The cable assemblies for the communications links **118***a*, **118***b*, **118***c* can have the same or different lengths. Although the communications links **118***a*, **118***b*, **118***c* are shown to couple the RF equipment **104***a*, **104***b*, **104***c* to the ACS **102** in parallel, embodiments of the present invention are not limited in this regard. The RF equipment **104***a*, **104***b*, **104***c* can also be coupled to the ACS **102** in a series arrangement, such as that shown by communication links **119***a*, **119***b*, **119***c*.

[0040] Notably, the cable assemblies of the communication links **118***a*, **118***b*, **118***c*, **119***a*, **119***b*, **119***c* can delay transmit signals. In effect, the phases of the transmit signals can be shifted thereby resulting in phasing errors. As such, the communication system **100** implements a closed loop method to counteract phasing errors due to cable delay effects. The closed loop method will become more evident as the discussion progresses.

[0041] In operation, the ACS **102** modulates signals to be transmitted by the antenna elements **106***a*, **106***b*, **106***c*. The ACS **102** also demodulates signals received after beamforming. The ACS **102** further controls beam steering. Notably, the interconnecting cables and/or elements can be affected by surrounding environmental conditions (e.g., heat). Such phase shifts can result in the steering of the radiated central beam **112** in a direction other than the direction **116** of the object of interest **108**. As such, the communication system **100** implements a closed loop method to counteract phasing errors due to environmental effects on ACS **102**. The closed loop method will become more evident as the discussion progresses. The ACS **102** will be described in more detail below in relation to FIGS. **2**-**3** and **5**.

[0042] Referring now to FIG. **2**, there is provided a block diagram of the ACS **102** shown in FIG. **1**. As shown in FIG. **2**, the ACS **102** includes a transmit side **202** and a receive side **204**. Furthermore, the ACS **102** is configured to manage both transmission and reception operations of the MEAS **150** based on signals for transmission and control signals. In particular, the transmit side **202** can generate signals to be transmitted by the antenna elements **106***a*, **106***b*, **106***c*. Additionally or alternatively, the transmit side **202** can receive one or more signals from one or more signal generators (not shown). The transmit side **202** is also configured for modulating each of the generated or received signals and communicating the modulated signals to the RF equipment **104***a*, **104***b*, **104***c* for transmission of the same over a transmission media (not shown). The transmit side **202** will be described in more detail below in relation to FIG. **3**.

[0043] The receive side **204** is configured for receiving signals received by the transmission elements. The receive side **204** is also configured for demodulating the electrical signal and communicating the demodulated electrical signal to an output device (not shown). The receive side **204** will be described below in more detail in relation to FIG. **5**.

[0044] Although the transmit side **202** and receive side **204** can operate separately or independently in some embodiments of the present invention, in other embodiments, operation of the transmit side **202** can be further adjusted based on one or more signals generated in the receiver side **204** of the ACS **102**, as shown in FIG. **2**.

[0045] Referring now to FIG. **3**, there is provided a block diagram of the transmit side **202** of FIG. **2** communicatively coupled to the RF equipment **104***a*, **104***b*, **104***c* of FIG. **1**. As shown in FIG. **3**, the transmit side **202** is comprised of a Transmit Radio Signal Generator (TRSG) **302**, hardware entities **304***a*, **304***b*, **304***c*, beamformers **308***a*, **308***b*, **308***c*, **395***a*, **395***b*, **395***c*, phase/amplitude controllers **326***a*, **326***b*, **326***c*, and phase comparators **340***a*, **340***b*, **340***c*. Each RF equipment **104***a*, **104***b*, **104***c* comprises hardware entities **328***a*, **328***b*, **328***c*, high power amplifiers (HPAs) **330***a*, **330***b*, **330***c*, and phase comparators **332***a*, **332***b*, **332***c*.

[0046] The TRSG **302** of the transmit side **202** can generate signals to be transmitted from the array of antenna elements **106***a*, **106***b*, **106***c*. The TRSG **302** is communicatively coupled to the hardware entities **304***a*, **304***b*, **304***c*. The phrase "hardware entities", as used herein, refers to signal processing devices, including but not limited to, filters and amplifiers. Each of the hardware entities **304***a*, **304***b*, **304***c* is communicatively coupled to a respective one of the beamformers **308***a*, **308***b*, **308***c*.

[0047] Each of the beamformers **308***a*, **308***b*, **308***c* can be utilized to control the phase and/or the amplitude of transmit signals. In general, the phase and/or amplitude of the transmit signal can be used to adjust formation of the central beam **112**, the side beams (or side lobes) **114**, and nulls in the radiation pattern **111**. Nulls correspond to directions in which destructive interference results in a transmit signal's strength that is significantly reduced with respect to the directions of the central beam **112** and the side beams **114**. The combined amplitude a_1, a_2, a_3 and phase shift ϕ_1, ϕ_2, ϕ_3 is referred to herein as a complex weight w_1, w_2, w_3, respectively. Each of the beamformers **308***a*, **308***b*, **308***c* combines a respective complex weight w_1, w_2, w_3 with the transmit signals to be provided to a respective RF equipment **104***a*, **104***b*, **104***c*. For example, as shown in FIG. **3**, each beamformer **308***a*, **308***b*, **308***c* includes a respective amplitude adjuster **310***a*, **310***b*, **310***c* for adjusting the amplitude of the transmit signals from respective hardware entities **304***a*, **304***b*, **304***c* based on an amplitude a_1, a_2, a_3. Each beamformer **308***a*, **308***b*, **308***c* includes a respective phase adjuster **312***a*, **312***b*, **312***c* for adjusting the phases of transmit signals from respective hardware entities **304***a*, **304***b*, **304***c* based on a phase shift ϕ_1, ϕ_2, ϕ_3.

[0048] Each beamformer **308***a*, **308***b*, **308***c* is communicatively coupled to a respective closed loop operator **350***a*, **350***b*, **350***c*. The closed loop operators **350***a*, **350***b*, **350***c* will be described below. However, it should be understood that the closed loop operators **350***a*, **350***b*, **350***c* are generally configured to adjust the phase and/or amplitude of transmit signals and communicate the phase and/or amplitude adjusted transmit signals to the hardware entity **328***a*, **328***b*, **328***c* of the RF equipment **104***a*, **104***b*, **104***c*. The hardware entities **328***a*, **328***b*, **328***c* are communicatively coupled to a respective HPA **330***a*, **330***b*, **330***c*. HPAs are well known to those having ordinary skill in the art, and therefore will not be described herein. However, it should be understood that the HPAs **330***a*, **330***b*, **330***c* communicate signals to the antenna elements **106***a*, **106***b*, **106***c* for transmission therefrom in the direction **116** of an object of interest **108**.

[0049] Each closed loop operator **350***a*, **350***b*, **350***c* is generally configured for controlling the phases and/or amplitudes of transmit signals so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102**, **104***a*, **104***b*, **104***c* of a communication system **100**. Accordingly, each closed loop operator **350***a*, **350***b*, **350***c* includes a phase comparator **332***a*, **332***b*, **332***c*, a phase comparator **340***a*, **340***b*, **340***c*, a phase/amplitude controller **326***a*, **326***b*, **326***c*, and a beamformer **395***a*, **395***b*, **396***c*.

[0050] The phase comparator **332***a*, **332***b*, **332***c* is configured to receive a transmit signal from the antenna element **106***a* and a reference signal V_{ref} from a first reference signal generator (not shown). In this regard, it should be understood that each of the antenna elements **106***a*, **106***b*, **106***c* has a transmit (Tx) signal sensor disposed thereon for sensing the transmit signal. Each of the antenna elements **106***a*, **106***b*, **106***c* also has a reference radiator disposed thereon for sensing a receive signal. A schematic illustration of the antenna element **106***a* having a transmit (Tx) signal sensor **608** positioned on its reflector **604** is provided in FIG. **6**. It should be noted that a sensing location on the reflector **604** enables signal path phase compensation over a maximum extent of components subject to variation. However in some applications, the sensing location may, for operational convenience, reside instead within the feed or on a transmission line leading to the feed. The result of such a sensing location is the exclusion of the omitted components from closed loop phase compensation. The first reference signal generator (not shown) and the manner in which the reference signal V_{ref} is determined will be described below in relation to FIGS. **9-14**.

[0051] Subsequent to receiving the transmit signal and the reference signal V_{ref}, the phase comparator **332***a*, **332***b*, **332***c* performs a comparison operation to determine a phase offset between the signals. The phase offset can be represented in terms of an imaginary part Q and a real part I. After determining the phase offset, the phase comparator **332***a*, **332***b*, **332***c* communicates the phase offset value(s) to the phase/amplitude controller **326***a*, **326***b*, **326***c*. The phase comparators **332***a*, **332***b*, **332***c* will be described in more detail below in relation to FIG. **4**.

[0052] The phase comparator **340***a*, **340***b*, **340***c* is configured to receive a transmit signal from the beamformer **308***a*, **308***b*, **308***c*. The phase comparator **340***a*, **340***b*, **340***c* is also configured to receive a reference signal V_{ref} from a second reference signal generator (not shown). The manner in which the reference signal V_{ref} is determined will be described below in relation to FIGS. **9-14**.

[0053] The second reference signal generator (not shown) is the same as or substantially similar to the first reference signal generator (not shown) that provided the reference signal V_{ref} to the phase comparator **332***a*, **332***b*, **332***c*. However, the first and second signal generators (not shown) are positioned at different locations within the communication system **100**. For example, the first signal generator (not shown) can reside in the RF equipment **104***a*, **104***b*, **104***c*. In contrast, the second signal generator (not shown) can reside in the transmit side **202** of the ACS **102**. The first and second reference signal generators (not shown) will be described below in relation to FIGS. **9-14**.

[0054] After receiving the transmit signal and the reference signal V_{ref}, the phase comparator **340***a*, **340***b*, **340***c* performs a comparison operation to determine a phase offset between the signals. The phase offset can be represented in terms of an imaginary part Q and a real part I. The phase comparators **340***a*, **340***b*, **340***c* will be described in more detail below in relation to FIG. **4**.

[0055] The phase/amplitude controller **326***a*, **326***b*, **326***c* determines a phase and/or amplitude adjustment value Δw_1, Δw_2, Δw_3 that is to be used by a beamformer **395***a*, **395***b*, **395***c* to control the phase and/or amplitude of transmit signals. The phase and/or amplitude adjustment value Δw_1, Δw_2, Δw_3 is determined using the phase offset values received from the phase comparators **332***a*, **332***b*, **332***c*, **340***a*, **340***b*, **340***c*.

[0056] Referring now to FIG. **4**, there is provided a detailed block diagram of the phase comparator **332***a*. Each of the phase comparators **332***b*, **332***c*, **340***a*, **340***b*, **340***c* is the same as or substantially similar to the phase comparator **332***a*. As such, the following description of the phase comparator **332***a* is sufficient for understanding the phase comparators **332***b*, **332***c*, **340***a*, **340***b*, **340***c*.

[0057] As shown in FIG. **4**, the phase comparator **332***a* comprises a balanced phase detector **402**, operational amplifiers (or comparators) **404***a*, **404***b*, low power filters (LPFs) **406***a*, **406***b*, and analog to digital converters (ADC) **408***a*, **408***b*. The balanced phase detector **402** is configured to receive a transmit signal from the antenna element **106***a* and a reference signal V_{ref} from a reference signal generator (not shown in FIG. **4** and will be described below in relation to FIGS. **8-13**). The balanced phase detector **402** is also configured to generate a +SIN output, a −SIN output, a +COS output, and a −COS output using the received signals. The SIN outputs represent the real parts I of the phases of the signals. In contrast, the COS outputs represent the imaginary parts Q of the phases of the signals. The SIN outputs are communicated from the balanced phase detector **402** to the operational amplifier (or comparator) **404***a*. Similarly, the COS outputs are communicated from the balanced phase detector **402** to the operational amplifier (or comparator) **404***b*.

[0058] Operational amplifiers (or comparators) are well known to those having ordinary skill in the art, and therefore will not be described herein. However, it should be understood that each of the operational amplifiers (or comparators) **404***a*, **404***b* compares the values of the signals received from the balanced phase detector **402**. Each of the operational amplifiers (or comparators) **404***a*, **404***b* also outputs an analog signal and communicates the same to the LPFs **406***a*, **406***b*, respectively. After performing filtering operations, the LPFs **406***a*, **406***b* forward the filtered analog signals to the ADCs **408***a*, **408***b*. The ADCs **408***a*, **408***b* convert the filtered analog signals to digital signals. The output of ADC **408***a* represents a real part I of a phase offset value. The output of ADC **408***b* represents an imaginary part Q of the phase offset value.

[0059] Referring now to FIG. **5**, there is provided a block diagram of the receive side **204** of FIG. **2** communicatively coupled to the RF equipment **104***a*, **104***b*, **104***c* of FIG. **1**. As shown in FIG. **5**, each of the RF equipment **104***a*, **104***b*, **104***c* further comprises a Radio Frequency (RF) translator **502***a*, **502***b*, **502***c*, a Low Noise Amplifier (LNA) **532***a*, **532***b*, **532***c*, and a portion of a closed loop operator **550***a*, **550***b*, **550***c*. The portion of a closed loop operator **550***a*, **550***b*, **550***c* includes a signal adder **530***a*, **530***b*, **530***c*. Each of the RF translators **502***a*, **502***b*, **502***c* performs signal frequency translation of received signals from a respective antenna element **106***a*, **106***b*, **106***c* in the respective RF equipment **104***a*, **104***b*, **104***c*. The translation function of the RF translators **502***a*, **502***b*, **502***c* generally converts the received signal at a respective antenna element **106***a*, **106***b*, **106***c* from an RF to an intermediate frequency (IF). The RF translators **502***a*, **502***b*, **502***c* communicate the IF signals to the signal adders **530***a*, **530***b*, **530***c*, respectively.

[0060] At the signal adders **530***a*, **530***b*, **530***c*, the IF signals are combined with a reference signal V_{ref} or a spread reference signal (not shown) generated using the reference signal V_{ref}. The reference signals V_{ref} can be generated by reference signal generators (not shown). The reference signal generator (not shown) will be described below in relation to FIGS. **8-13**. The combined signals (or spread spectrum signals) formed at the signal adders **530***a*, **530***b*, **530***c* are then communicated to the LNAs **532***a*, **532***b*, **532***c*, respectively. The LNAs **532***a*, **532***b*, **532***c* generally amplify the IF signals output from the RF translators **502***a*, **502***b*, **502***c*, respectively. Each of the LNAs **532***a*, **532***b*, **532***c* is communicatively coupled to the receive side **204** of the ACS **102**.

[0061] As shown in FIG. **5**, the receive side **204** comprises a plurality of filters **534***a*, **534***b*, **534***c*, portions of the closed loop operators **550***a*, **550***b*, **550***c*, a plurality of beamformers **508***a*, **508***b*, **508***c*, hardware entities **512***a*, **512***b*, **512***c*, **516**, and a signal combiner **514**. Embodiments of the present invention are not limited in this regard. For example, the receive side **204** can be absent of the filters **534***a,* **534***b,* **534***c* and hardware entities **512***a,* **512***b,* **512***c,* **516**.

[0062] As shown in FIG. **5**, the filters **534***a,* **534***b,* **534***c* are communicatively coupled between the LNAs **532***a,* **532***b,* **532***c* and beamformers **508***a,* **508***b,* **508***c*. Each of the beamformers **508***a,* **508***b,* **508***c* can generally include a down converter **506***a,* **506***b,* **506***c,* a filter **540***a,* **540***b,* **540***c,* and a combiner **510***a,* **510***b,* **510***c*. Embodiments of the present invention are not limited in this regard. For example, the beamformers **508***a,* **508***b,* **508***c* can be absent of the down converters **506***a,* **506***b,* **506***c* and filters **540***a,* **540***b,* **540***c*.

[0063] Each down converter **506***a,* **506***b,* **506***c* converts a digitized real signal centered at an IF to a baseband complex signal centered at zero (0) frequency. The down converters **506***a,* **506***b,* **506***c* share a common clock (not shown), and therefore receive the same clock (CLK) signal. The CLK signal can be generated within the receive side **204**, elsewhere in the ACS **102**, or external to the ACS **102**. The down converters **506***a,* **506***b,* **506***c* can be set to the same center frequency and bandwidth. The down converters **506***a,* **506***b,* **506***c* can also comprise local oscillators that are in-phase with each other. This in-phase feature of the down converters **506***a,* **506***b,* **506***c* ensures that the down converters **506***a,* **506***b,* **506***c* shift the phases of signals by the same amount. After converting the digitized real signals to baseband complex signals, the down converters **506***a,* **506***b,* **506***c* communicate the baseband complex signals to the filters **540***a,* **540***b,* **540***c,* respectively. The filters **540***a,* **540***b,* **540***c* filter the baseband complex signals and forward the same to the combiners **510***a,* **510***b,* **510***c*.

[0064] Each of the combiners **510***a,* **510***b,* **510***c* combines a baseband complex signal with a complex weight w_1, w_2, w_3 for a particular antenna element **106***a,* **106***b,* **106***c*. The complex weights w_1, w_2, w_3 are selected to combine the receive signals according to a particular radiation pattern **111**. That is, the complex weights w_1, w_2, w_3 are selected to provide a central beam **112**, side beams **114**, and nulls, as described above, so as to preferentially receive signals from one or more predefined directions. The values of the complex weights w_1, w_2, w_3 are controlled by closed loop operators **550***a,* **550***b,* **550***c*. The closed loop operators **550***a,* **550***b,* **550***c* will be described below.

[0065] The combiners **510***a,* **510***b,* **510***c* can include, but are not limited to, complex multipliers. Thereafter, the combiners **510***a,* **510***b,* **510***c* communicate the signals to the hardware entities **512***a,* **512***b,* **512***c,* respectively. The hardware entities **512***a,* **512***b,* **512***c* can further process the signals received from the beamformers **508***a,* **508***b,* **508***c*. The hardware entities **512***a,* **512***b,* **512***c* communicate the processed signals to the signal combiner **514**.

[0066] At the signal combiner **514**, the processed signals are combined to form a combined signal. The signal combiner **514** can include, but is not limited to, a signal adder as shown in FIG. **5**. Subsequent to forming the combined signal, the signal combiner **514** communicates the same to the hardware entities **516** for further processing. After processing the combined signal, the hardware entities **516** can communicate the same to a demodulator (not shown) for demodulation.

[0067] Each closed loop operator **550***a,* **550***b,* **550***c* is generally configured for controlling the phase and/or amplitude of receive signals so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102**, **104***a,* **104***b,* **104***c* of a communication system **100**. Accordingly, each closed loop operator **550***a,* **550***b,* **550***c* includes a signal adder **530***a,* **530***b,* **530***c,* a phase comparator **536***a,* **536***b,* **536***c,* and the phase/amplitude controller **328***a,* **328***b,* **328***c*. The phase comparator **536***a,* **536***b,* **536***c* is configured to receive a received signal from the respective LNA **532***a,* **532***b,* **532***c* and a reference signal V_{ref} from a reference signal generator (not shown) located at the RF equipment **104***a,* **104***b,* **104***c*. The reference signal generator (not shown) will be described below in relation to FIGS. **9**-**14**. Subsequent to receiving the signals, the phase comparator **536***a,* **536***b,* **536***c* performs a comparison operation to determine a phase offset between the signals. The phase offset can be represented in terms of an imaginary part Q and a real part I.

[0068] After determining the phase offset, the phase comparator **536***a,* **536***b,* **536***c* communicates the phase offset value(s) to the phase/amplitude controller **538***a,* **538***b,* **538***c*. The phase/amplitude controller **538***a,* **538***b,* **538***c* determines a complex weight w_1, w_2, w_3 that is to be used by a beamformer **508***a,* **508***b,* **508***c* to control the phase and/or amplitude of receive signals. The complex weight w_1, w_2, w_3 is determined using the received phase offset value(s) and a reference signal V_{ref} received from a reference signal generator (not shown). More particularly, the phase/amplitude controller **538***a,* **538***b,* **538***c* adjusts complex weights using the phase offset values. The reference signal generator (not shown) will be described below in relation to FIGS. **9**-**14**.

[0069] Referring now to FIGS. **6**A-**6**B, there are provided more detailed block diagrams of the communication system **100** that are useful for understanding the phase and/or amplitude adjustment functions thereof. The phase and/or amplitude adjustments functions of the transmit side **202** will be described below in relation to FIG. **6**A. The phase and/or amplitude adjustments functions of the receive side **204** will be described below in relation to FIG. **6**B. Notably, the antenna elements **106***b,* **106***c* and RF equipment **104***b,* **104***c* are not shown in FIGS. **6**A-**6**B to simplify the following discussion. However, it should be understood that the antenna elements **106***b,* **106***c* are the same as or substantially similar to the antenna element **106***a*. Similarly, the RF equipment **104***b,* **104***c* is the same as or substantially similar to the RF equipment **104***a*.

[0070] As shown in FIG. **6**A, the ACS **102** comprises a station frequency reference **602**, the TRSG **302**, hardware entities **304***a,* beamformers **308***a,* **395***a,* a power coupler **604**, the phase/amplitude controller **326***a,* the phase comparator **340***a,* and a reference signal generator **614***a*. As also shown in FIG. **6**A, the RF equipment **104***a* comprises hardware entities **328***a,* the HPA **330***a,* the phase comparator **332***a,* and a reference signal generator **614***b*. As further shown in FIG. **6**A, the MEAS **150** comprises a ½ transmit carrier frequency device **608**, an analog fiber modulator **610**, an optical fiber **616**, and a fiber mirror **628**.

[0071] The TRSG **302** of the ACS **102** can generate signals to be transmitted from the antenna elements **106***a,* **106***b* (not shown), **106***c* (not shown). The TRSG **302** is communicatively coupled to the station frequency reference **602** and the hardware entities **304***a*. The hardware entities **304***a* are communicatively coupled to the beamformer **308***a*.

[0072] As noted above in relation to FIG. **3**, the beamformer **308***a* can be utilized to control the phases and/or the amplitudes of transmit signals. Accordingly, the beamformer **308***a* combines a complex weight w_N with transmit signals to be provided to the RF equipment **904***a*, **904***b* (not shown), **904***c* (not shown). The beamformer **308***a* is communicatively coupled to power coupler **604**. The power coupler **604** is communicatively coupled to the closed loop operator **350***a*. The closed loop operator **350***a* will be described below. However, it should be understood that the closed loop operator **350***a* is generally configured to adjust the phase and/or amplitude of transmit signals. The closed loop operator **350***a* is also configured to communicate the phase and/or amplitude adjusted transit signals to the hardware entities **328***a* of the RF equipment **104***a*. The hardware entities **328***a* are communicatively coupled to the HPA **330***a*. The HPA **330***a* communicates processed signals to the antenna element **106***a* for transmission therefrom.

[0073] The closed loop operator **350***a* is generally configured for controlling the phases and/or amplitudes of transmit signals so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102** and **104***a* of the communication system **100**. Accordingly, the closed loop operator **350***a* includes phase comparators **340***a*, **332***a*, a phase/amplitude controller **326***a*, and a beamformer **395***a*.

[0074] The phase comparator **332***a* is configured to receive a transmit signal **624** from the antenna element **106***a* and a reference signal V_{ref-1} from a reference signal generator **614***b*. In this regard, it should be understood that the antenna element **106***a* has a transmit (Tx) signal probe **622** disposed on its reflector **620** for sensing the transmit signal **624**. In order to avoid the introduction of phase offsets into transmit signals, the communication path between the Tx signal probe **622** and the phase comparator **332***a* can be minimized. At the phase comparator **332***a*, the phase of the sensed transmit signal **624** is compared with the phase of the reference signal V_{ref-1} to determine a phase offset **626**. The phase offset **626** can be represented in terms of an imaginary part Q and a real part I. The phase offset **626** is then communicated from the phase comparator **332***a* to the phase/amplitude controller **326***a*.

[0075] The reference signal V_{ref-1} utilized by the phase comparator **332***a* is generated by the reference signal generator **614***b*. The reference signal generator **614***b* is configured to receive sensed signals V_f, V_r from one or more sensor devices (not shown) disposed on the optical fiber **616** at a first location. Additionally or alternatively, the reference signal generator **614***b* is configured to sense signals V_f, V_r propagated along the optical fiber **616**. The sensed signals V_f, V_r are used to determine the reference signal V_{ref-1}. The manner in which the reference signal V_{ref-1} is determined will be described below in relation to FIGS. **9**-**11**. The reference signal generator **614***b* can be the same as or substantially similar to any one of the reference signal generators described below in relation to FIGS. **12**-**14**.

[0076] The phase comparator **340***a* is configured to receive a transmit signal **618** from the power coupler **604** and a reference signal V_{ref-2} from a reference signal generator **614***a*. At the phase comparator **340***a*, the phase of the transmit signal **618** is compared with the phase of the reference signal V_{ref-2} to determine a phase offset **606**. The phase offset **606** can be represented in terms of an imaginary part Q and a real part I. The phase offset **606** is then communicated from the phase comparator **340***a* to the phase/amplitude controller **326***a*.

[0077] The reference signal V_{ref-2} utilized by the phase comparator **340***a* is generated by the reference signal generator **614***a*. The reference signal generator **614***a* is configured to receive sensed signals V_f, V_r from one or more sensor devices (not shown) disposed on the optical fiber **616** at a second location different from the first location. Additionally or alternatively, the reference signal generator **614***a* is configured to sense signals V_f, V_r propagated along the optical fiber **616**. The sensed signals V_f, V_r are used by the reference signal generator **614***a* to determine the reference signal V_{ref-2}. The manner in which the reference signal V_{ref-2} is determined is described below in relation to FIGS. **9**-**11**. The reference signal generator **614***a* can be the same as or substantially similar to any one of the reference signal generator described below in relation to FIGS. **12**-**14**. The reference signal generator **614***a* can also be the same as or substantially similar to the reference signal generator **614***b*.

[0078] The phase/amplitude controller **326***a* determines a phase and/or amplitude adjustment value Δw_N that is to be used by a beamformer **395***a* to adjust the phase and/or amplitude of transmit signals. The phase and/or amplitude adjustment value Δw_N is determined using the received phase offset **606**, **626** values received from the phase comparators **340***a*, **332***a*, respectively.

[0079] As shown in FIG. **6**B, the ACS **102** comprises a station frequency reference **652**, a receiver **670**, the hardware entities **516**, **512***a*, the signal adder **514**, the beamformer **508***a*, the filter **534***a*, a power coupler **654**, a despreader **672**, the phase/amplitude controller **538***a*, the phase comparator **536***a*, and a reference signal generator **654***a*. As also shown in FIG. **6**B, the RF equipment **104***a* comprises the LNA **532***a*, a reference signal generator **654***b*, and a spreader **676**. As further shown in FIG. **6**B, the MEAS **150** comprises a ½ transmit carrier frequency device **658**, an analog fiber modulator **660**, an optical fiber **656**, and a fiber mirror **668**.

[0080] During operation, the object of interest **108** communicates a signal to the MEAS **150**. The signal is received at the antenna element **106***a*. The antenna element **106***a* includes a reflector **620** with an Rx signal probe **652** disposed thereon. The Rx signal probe **652** transmits a spread reference signal **624** generated by a spreader **676**. The spreader **676** is provided to ensure that the reference signal V_{ref-1} does not interfere with receive signals. The spreader **676** can be, but is not limited to, a random number spreader or a pseudo-random number spreader. The spreader **676** can receive a reference signal V_{ref-1} from the reference signal generator **654***b* and utilize the reference signal V_{ref-1} to generate the spread reference signal **624**. More particularly, the spreader **676** can combine the reference signal V_{ref-1} with a random or pseudo-random number sequence to obtain the spread reference signal **624**. Embodiments of the present invention are not limited in this regard. For example, the MEAS **150** can be absent of the spreader **676**. In such a scenario, the MEAS **150** can alternatively include a frequency adjuster configured for offsetting the frequency of the reference signal V_{ref-1} by a desired amount. The desired amount can be selected for ensuring that the reference signal V_{ref-1} does not interfere with receive signals.

[0081] At the antenna element **106***a*, the received signal is combined with the spread reference signal **624** to form a spread spectrum signal. The spread spectrum signal is then communicated to the LNA **532***a* of the RF equipment **104***a*. The LNA **532***a* processes the spread spectrum signal and communicates the processed spread spectrum signal to the power coupler **654** of the ACS **102** or optional hardware entities **674**.

[0082] The reference signal V_{ref-1} utilized by the spreader **676** is generated by the reference signal generator **654***b*. The reference signal generator **654***b* is configured to receive sensed signals V_f, V_r from one or more sensor devices (not shown) disposed on the optical fiber **696** at a first location. Additionally or alternatively, the reference signal generator **654***b* is configured to sense signals V_f, V_r propagated along the optical fiber **696**. The sensed signals V_f, V_r are used to determine the reference signal V_{ref-1}. The manner in which the reference signal V_{ref-1} is determined will be described below in relation to FIGS. **9-11**. The reference signal generator **654***b* can be the same as or substantially similar to any one of the reference signal generators described below in relation to FIGS. **12-14**.

[0083] At the ACS **102**, the power coupler **654** receives the spread spectrum signal from the RF equipment **104***a* and processes the same. Thereafter, the power coupler **654** communicates the processed spread spectrum signal to the despreader **672** and the filter **534***a*. At the despreader **672**, operations are performed with a known despreading code sequence to despread the spread spectrum signal. The dispreading code sequence can be the same as the spread reference signal **624**. The despread signal is then communicated from the despreader **672** to the closed loop operator **550***a*.

[0084] The closed loop operator **550***a* is generally configured for controlling the phases and/or amplitudes of receive signals so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102** and **104***a* of the communication system **100**. Accordingly, the closed loop operator **550***a* includes a phase comparator **536***a* and a phase/amplitude controller **538***a*.

[0085] The phase comparator **536***a* is configured to receive a despread signal from the despreader **672** and a reference signal V_{ref-2} from a reference signal generator **654***a*. At the phase comparator **536***a*, the phase of the despread signal is compared with the phase of the reference signal V_{ref-2} to determine a phase offset **686**. The phase offset **686** can be represented in terms of an imaginary part Q and a real part I. The phase offset **686** is then communicated from the phase comparator **536***a* to the phase/amplitude controller **538***a*.

[0086] The reference signal V_{ref-2} utilized by the phase comparator **536***a* is generated by the reference signal generator **654***a*. The reference signal generator **654***a* is configured to receive sensed signals V_f, V_r from one or more sensor devices (not shown) disposed on the optical fiber **696** at a first location. Additionally or alternatively, the reference signal generator **654***a* is configured to sense signals V_f, V_r propagated along the optical fiber **696**. The sensed signals V_f, V_r are used to determine the reference signal V_{ref-2}. The manner in which the reference signal V_{ref-2} is determined will be described below in relation to FIGS. **9-11**. The reference signal generator **654***a* can be the same as or substantially similar to any one of the reference signal generator described below in relation to FIGS. **12-14**. The reference signal generator **654***a* can also be the same as or substantially similar to the reference signal generator **654***b* described above.

[0087] The phase/amplitude controller **538***a* determines the complex weight w_1 that is to be used by a beamformer **508***a* to control the phase and/or amplitude of receive signals. The complex weight w_1 is determined using the received phase offset **686** values received from the phase comparator **536***a*.

[0088] Referring now to FIG. **7**, there is provided a more detailed block diagram of the communication system **100** that is useful for understanding the phase and/or amplitude adjustment functions thereof. Notably, the antenna elements **106***b*, **106***c* and RF equipment **104***b*, **104***c* are not shown in FIG. **7** to simplify the following discussion. As shown in FIG. **7**, the ACS **102** comprises a station frequency reference **702**, the TRSG **302**, hardware entities **304***a*, beamformers **308***a*, **735**, and a phase/amplitude controller **726***a*. As also shown in FIG. **7**, the RF equipment **104***a* comprises hardware entities **328***a*, the HPA **330***a*, the phase comparator **732***a*, and a reference signal generator **714**. As further shown in FIG. **7**, the MEAS **150** comprises a ½ transmit carrier frequency device **708**, an analog fiber modulator **710**, an optical fiber **716**, and a fiber mirror **728**.

[0089] The TRSG **302** of the ACS **102** can generate signals to be transmitted from the antenna elements **106***a*, **106***b* (not shown), **106***c* (not shown). The TRSG **302** is communicatively coupled to the station frequency reference **702** and the hardware entities **304***a*. The hardware entities **304***a* are communicatively coupled to the beamformer **308***a*.

[0090] As noted above in relation to FIG. **3**, the beamformer **308***a* can be utilized to control the phases and/or the amplitudes of transmit signals. Accordingly, the beamformer **308***a* combines a complex weight w_N with transmit signals to be provided to the RF equipment **904***a*, **904***b* (not shown), **904***c* (not shown). The beamformer **308***a* is communicatively coupled to the closed loop operator **750***a*. The closed loop operator **750** will be described below. However, it should be understood that the closed loop operator **750***a* is generally configured to adjust the phase and/or amplitude of transmit signals. The closed loop operator **750***a* is also configured to communicate the phase and/or amplitude adjusted transmit signals to the hardware entities **328***a* of the RF equipment **104***a*. The hardware entities **328***a* are communicatively coupled to the HPA **330***a*. The HPA **330***a* communicates processed signals to the antenna element **106***a* for transmission therefrom.

[0091] The closed loop operator **750***a* is generally configured for controlling the phases and/or amplitudes of transmit signals so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102** and **104***a* of the communication system **100**. Accordingly, the closed loop operator **750***a* includes the phase comparator **732***a*, a phase/amplitude controller **726***a*, and a beamformer **735**.

[0092] The phase comparator **732***a* is configured to receive a transmit signal **724** from the antenna element **106***a* and a reference signal V_{ref-1} from a reference signal generator **714**. In this regard, it should be understood that the antenna element **106***a* has a transmit (Tx) signal probe **722** disposed on its reflector **720** for sensing the transmit signal **724**. At the phase comparator **732***a*, the phase of the sensed transmit signal **724** is compared with the phase of the reference signal V_{ref-1} to determine a phase offset **726**. The phase offset **726** can be represented in terms of an imaginary part Q and a real part I. The phase offset **726** is then communicated from the phase comparator **732***a* to the phase/amplitude controller **726***a*.

[0093] The reference signal V_{ref-1} utilized by the phase comparator **732***a* is generated by the reference signal generator **714**. The reference signal generator **714** is configured to receive sensed signals V_f, V_r from one or more sensor devices (not shown) disposed on the optical fiber **716** at a first location. Additionally or alternatively, the reference signal generator **714** is configured to sense signals V_f, V_r propagated along the optical fiber **716**. The sensed signals V_f, V_r are used to determine the reference signal $V_{ref\text{-}1}$. The manner in which the reference signal $V_{ref\text{-}1}$ is determined will be described below in relation to FIGS. **9-11**. The reference signal generator **714** can be the same as or substantially similar to any one of the reference signal generators described below in relation to FIGS. **12-14**.

[0094] The phase/amplitude controller **726***a* is configured for receiving phase offsets from each of the RF equipments **104***a*, **104***b* (not shown), **104***c* (not shown). The phase/amplitude controller **726***a* determines a phase and/or amplitude adjustment value Δw_N that is to be used by a beamformer **735** to adjust the phase and/or amplitude of transmit signals. The phase and/or amplitude adjustment value Δw_N is determined using the received phase offset **606** values received from the RF equipments **104***a*, **104***b* (not shown), **104***c* (not shown).

[0095] FIG. **8** is a schematic diagram of a computer system **800** for executing a set of instructions that, when executed, can cause the computer system to perform one or more of the methodologies and procedures described above. For example, a computer system **800** can be implemented to perform the various tasks of the transmit side **202** and/or the receive side **204** the ACS **102**. In some embodiments, the computer system **800** operates as a single standalone device. In other embodiments, the computer system **800** can be connected (e.g., using a network) to other computing devices to perform various tasks in a distributed fashion. In a networked deployment, the computer system **800** can operate in the capacity of a server or a client machine in server-client network environment, or as a peer machine in a peer-to-peer (or distributed) network environment.

[0096] The computer system **800** can comprise various types of computing systems and devices, including a server computer, a client user computer, a personal computer (PC), a tablet PC, a laptop computer, a desktop computer, a control system, a network router, switch or bridge, or any other device capable of executing a set of instructions (sequential or otherwise) that specifies actions to be taken by that device. It is to be understood that a device of the present disclosure also includes any electronic device that provides voice, video or data communication. Further, while a single computer is illustrated, the phrase "computer system" shall be understood to include any collection of computing devices that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein.

[0097] The computer system **800** can include a processor **802** (such as a central processing unit (CPU), a graphics processing unit (GPU, or both), a main memory **804** and a static memory **806**, which communicate with each other via a bus **808**. The computer system **800** can further include a display unit **810**, such as a video display (e.g., a liquid crystal display or LCD), a flat panel, a solid state display, or a cathode ray tube (CRT)). The computer system **800** can include an input device **812** (e.g., a keyboard), a cursor control device **814** (e.g., a mouse), a disk drive unit **816**, a signal generation device **818** (e.g., a speaker or remote control) and a network interface device **820**.

[0098] The disk drive unit **816** can include a computer-readable storage medium **822** on which is stored one or more sets of instructions **824** (e.g., software code) configured to implement one or more of the methodologies, procedures, or functions described herein. The instructions **824** can also reside, completely or at least partially, within the main memory **804**, the static memory **806**, and/or within the processor **802** during execution thereof by the computer system **800**. The main memory **804** and the processor **802** also can constitute machine-readable media.

[0099] Dedicated hardware implementations including, but not limited to, application-specific integrated circuits, programmable logic arrays, and other hardware devices can likewise be constructed to implement the methods described herein. Applications that can include the apparatus and systems of various embodiments broadly include a variety of electronic and computer systems. Some embodiments implement functions in two or more specific interconnected hardware modules or devices with related control and data signals communicated between and through the modules, or as portions of an application-specific integrated circuit. Thus, the exemplary system is applicable to software, firmware, and hardware implementations.

[0100] In accordance with various embodiments of the present disclosure, the methods described herein can be stored as software programs in a computer-readable storage medium and can be configured for running on a computer processor. Furthermore, software implementations can include, but are not limited to, distributed processing, component/object distributed processing, parallel processing, virtual machine processing, which can also be constructed to implement the methods described herein.

[0101] The present disclosure contemplates a computer-readable storage medium containing instructions **824** or that receives and executes instructions **824** from a propagated signal so that a device connected to a network environment **826** can send or receive data, and that can communicate over the network **826** using the instructions **824**. The instructions **824** can further be transmitted or received over a network **826** via the network interface device **820**.

[0102] While the computer-readable storage medium **822** is shown in an exemplary embodiment to be a single storage medium, the term "computer-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "computer-readable storage medium" shall also be taken to include any medium that is capable of storing, encoding or carrying a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present disclosure.

[0103] The term "computer-readable medium" shall accordingly be taken to include, but not be limited to, solid-state memories such as a memory card or other package that houses one or more read-only (non-volatile) memories, random access memories, or other re-writable (volatile) memories; magneto-optical or optical medium such as a disk or tape; as well as carrier wave signals such as a signal embodying computer instructions in a transmission medium; and/or a digital file attachment to e-mail or other self-contained information archive or set of archives considered to be a distribution medium equivalent to a tangible storage medium. Accordingly, the disclosure is considered to include any one or more of a computer-readable medium or a distribution medium, as listed herein and to include recognized equivalents and successor media, in which the software implementations herein are stored.

[0104] Although the present specification describes components and functions implemented in the embodiments with reference to particular standards and protocols, the disclosure is not limited to such standards and protocols. Each of the standards for Internet and other packet switched network transmission (e.g., TCP/IP, UDP/IP, HTML, and HTTP) represent examples of the state of the art. Such standards are periodically superseded by faster or more efficient equivalents having essentially the same functions. Accordingly, replacement standards and protocols having the same functions are considered equivalents.

[0105] As noted above, the cable assemblies **110***a,* **110***b,* **110***c* and the communication links **118***a,* **118***b,* **118***c* (or **119***a,* **119***b,* **119***c*) of the communication system **100** delay signals between the ACS **102** and the antenna elements **106***a,* **106***b,* **106***c*. In effect, the phases of the signals are shifted thereby resulting in phasing errors. Such phasing errors are exacerbated by the spacing between the antenna elements **106***a,* **106***b,* **106***c*. Phasing errors also occur as a result of environmental effects on the hardware components **102**, **104***a,* **104***b,* **104***c* of the communication system **100**. Phasing errors further occur as a result of operation delays between the beamformers **308***a,* **308***b,* **308***c* or operation delays between beamformers **408***a,* **408***b,* **408***c*. The accumulated phasing errors inhibit desirable or adequate beam formation, i.e., the accumulated phasing errors can result in the steering of the radiated central beam **112** in a direction other than the direction **116** of the object of interest **108**.

[0106] Accordingly, the communication system **100** implements a method for adjusting the phases and/or amplitudes of signals transmitted from and received at each antenna element **106***a,* **106***b,* **106***c*. The phases and/or amplitudes of the transmit and receive signals are adjusted using a plurality of reference signals V_{ref}. The reference signals V_{ref} generally represent transmitted signals absent of phase shifts. A first one of the reference signals V_{ref} is compared with a signal having phase shifts for determining a phase offset between the same. The phase offset and a second one of the reference signals V_{ref} are then used to control the phase and/or amplitude of a transmit and/or receive signal so as to counteract phasing errors due to cable delay effects, wide antenna spacing effects, and environmental effects on hardware components **102**, **104***a,* **104***b,* **104***c* of a communication system **100**. More particularly, the phase offset and a second one of the reference signals V_{ref} are used to determine the complex weights w_1, w_2, w_3 that are subsequently combined with transmit and/or receive signals. Systems and methods for determining the reference signals V_{ref} will now be described in relation to FIGS. **9**-**14**.

Systems and Methods for Determining Reference Signals V_{ref}

[0107] Referring now to FIG. **9**, there is provided a block diagram of a communication system **900** that is useful for understanding how a reference signal V_{ref} is determined. As shown in FIG. **9**, the communication system **900** can comprise a signal source **902**, a sensor **916**, a reflective termination **914**, and a non-reflective termination **904**. Each of these components **902**, **904**, **914**, **916** is well known to those having ordinary skill in the art, and therefore will not be described in detail herein. However it should be understood that in order to determine a reference signal V_{ref}, a forward propagated signal V_f and a reverse propagated signal V_r need to be sensed at a location "z" along the transmission media **908**. As such, the signal source **902** generally transmits a signal V_f to the reflective termination **914**. A reflected version of the transmitted signal V_r is communicated from the reflective termination **914** to the non-reflective termination **904**. The sensor **916** senses the presence of a forward propagated signal V_f and a reverse propagated signal V_r on the transmission media **908**. The sensor **916** may also adjust the gain of the signals V_f, V_r so that they have equal arbitrarily defined amplitudes "a". This gain adjustment can involve performing Automatic Gain Control (AGC) operations which are well known to those having ordinary skill in the art. Thereafter, the sensor **916** outputs signals representing the forward propagated signal V_f and the reverse propagated signal V_r. These output signals can subsequently be used to compute the reference signal V_{ref}.

[0108] A conceptual diagram of a first exemplary process **1000** for determining the reference signal V_{ref} is provided in FIG. **10**. As shown in FIG. **10**, the process **1000** begins by (**1002**, **1004**) sensing a forward propagated signal V_f and a reverse propagated signal V_r. It should be appreciated that the sensing processes (**1002**, **1004**) can involve gain adjustments as necessary so that the resulting signals have an arbitrarily defined amplitude a. The gain adjustments can involve performing AGC operations. The forward propagated signal V_f can be defined by the following mathematical equation (1). Similarly, the reverse propagated signal V_r, for the exemplary case of a short circuit reflection, can be defined by the following mathematical equation (2).

$$V_f=ae^{j(\omega t+\phi-\beta z)} \tag{1}$$

$$V_r=ae^{j(\omega t+\phi+\beta z)} \tag{2}$$

where a is signal amplitude. j is the square root of minus one ($j=(-1)^{1/2}$). ω is a radian frequency. ϕ is a phase angle. β is a wave number that is equal to 2π/λ, where λ is a wavelength. z is a location along a transmission media.

[0109] Thereafter, a signal combination operation **1006** is performed where the signals V_f, V_r are combined to obtain a Sum signal (S). This signal combination operation **1006** generally involves adding the signals V_f, V_r together. The signal combination operation **1006** can be defined by the following mathematical equation (3).

$$S=ae^{j(\omega t+\phi-\beta z)}-ae^{j(\omega t+\phi+\beta z)}=-2aje^{j(\omega t+\phi)}[\sin(\beta z)] \tag{3}$$

As evident from mathematical equation (3), the Sum signal S is a sine signal that depends on the location "z" at which the sensor **916** is placed along the transmission media **908**.

[0110] The process **1000** also involves performing a subtraction operation **1008**. The subtraction operation **1008** generally involves subtracting the reverse propagated signal V_r from the forward propagated signal V_f to obtain a Difference signal (D). The subtraction operation **1008** can be defined by the following mathematical equation (4).

$$D=ae^{j(\omega t+\phi-\beta z)}+ae^{j(\omega t+\phi+\beta z)}=2ae^{j(\omega t+\phi)}[\cos(\beta z)] \tag{4}$$

As evident from mathematical equation (4), the Difference signal D is a cosine signal that depends on the location "z" at which the sensor **916** is placed along the transmission media **908**.

[0111] After determining the Sum signal S and the Difference signal D, the process **1000** continues with a plurality of multiplication operations **1010**, **1012**. A first one of the multiplication operations **1010** generally involves multiplying the Sum signal S by itself to obtain a first Exponentiation signal E_S. The first multiplication operation **1010** can generally be defined by the following mathematical equation (5).

$$E_S = S \cdot S = S^2 \tag{5}$$

where E_S is the first Exponentiation signal. S is the Sum signal. S^2 is the Sum signal S raised to the second power.

[0112] A second one of the multiplication operations **1012** generally involves multiplying the Difference signal D by itself to obtain a second Exponentiation signal E_D. The second multiplication operation **1012** can generally be defined by the following mathematical equation (6).

$$E_D = D \cdot D = D^2 \tag{6}$$

where E_D is the second Exponentiation signal. D is the Difference signal. D^2 is the Difference signal D raised to the second power.

[0113] Subsequent to determining the first and second Exponentiation signals, the process continues with a subtraction operation **1014**. The subtraction operation **1014** generally involves subtracting the first Exponentiation signal E_S from the second Exponentiation signal E_D. The subtraction operation **1014** can be defined by the following mathematical equation (7).

$$V_{doubled} = D^2 - S^2 = 4a^2 e^{j2(\omega t+\phi)}[\sin^2(\beta z)+\cos^2(\beta z)] = 4a^2 e^{j2(\omega t+\phi)} \tag{7}$$

where $V_{doubled}$ represents the signal obtained as a result of performing the subtraction operation **1014**. As evident from mathematical equation (7), the resulting signal $V_{doubled}$ does not depend on the location "z" at which the sensor **916** is placed along the transmission media **908**. The resulting signal $V_{doubled}$ has twice the frequency relative to that of each propagated signal V_f, V_r. As such, the resulting signal $V_{doubled}$ is further processed to increase its frequency to a desired value or reduce its frequency to a desired value (i.e., the value of the frequency of a propagated signal V_f, V_r). If the frequency of the resulting signal $V_{doubled}$ is to be increased to the desired value, then a multiplication operation (not shown) can be performed. If the frequency of the resulting signal $V_{doubled}$ is to be reduced to the desired value, then a frequency reduction operation **1016** can be performed.

[0114] The frequency reduction operation **1016** can generally involve performing a phase locked loop operation and a frequency division operation. Phase locked loop operations are well known to those having ordinary skill in the art, and therefore will not be described herein. The frequency division operation can involve dividing the frequency of the resulting signal $V_{doubled}$ by two (2). The output signal from the frequency reduction operation is the reference signal V_{ref}. The reference signal V_{ref} can be defined by the following mathematical equation (8):

$$V_{ref} = \pm e^{j(\omega t+\phi)} \tag{8}$$

for any line position "z". As evident from mathematical equation (8), the reference signal V_{ref} is a signal that does not depend on the location "z" at which the sensor **916** is placed along the transmission media **908**. As such, the reference signal V_{ref} can be determined at one or more locations along a transmission media. This location "z" independence is a significant and highly desirable result.

[0115] Embodiments of the present invention are not limited to the process **1000** described above in relation to FIG. **10**. For example, if the frequency of each propagated signal V_f, V_r is reduced by exactly half, then the frequency reduction operation **916** need not be performed. A conceptual diagram of a process **1100** for determining the reference signal V_{ref} absent of the frequency reduction operation **1016** is provided in FIG. **11**. The propagated signals with half the frequency of the signals V_f, V_r is referred to herein as V'_f, V'_r, respectively.

[0116] As shown in FIG. **11**, the process **1100** generally involves performing sensing operations **1102**, **1104** to sense propagated signals V'_f, V'_r, a signal combination operation **1106**, a subtraction operations **1108**, **1114**, and multiplication operations **1110**, **1112**. These listed operations **1102**, **1104**, . . . , **1114** are the same as or substantially similar to the operations **1002**, **1004**, . . . , **1014** of FIG. **10**, respectively. As such, the operations **1102**, **1104**, . . . , **1114** of process **1100** will not be described herein.

[0117] Referring now to FIG. **12**, there is provided a block diagram of a first exemplary system **1200** implementing a method for determining a reference signal V_{ref}, V'_{ref}. As shown in FIG. **12**, the system **1200** comprises a sensing device **1202**, a signal adder **1206**, signal subtractors **1208**, **1214**, and signal multipliers **1210**, **1212**. The system **1200** can also comprise an optional phase lock loop **1216** and an optional frequency divider **1218**. The sensing device **1202** is generally configured for sensing the presence of a forward propagated signal V_f or V'_f and a reverse propagated signal V_r or V'_r on the transmission media **908**. The sensing device **1202** may also adjust the gain of the signals V_f or V'_f, V_r or V'_r so that they have equal arbitrarily defined amplitudes "a". This gain adjustment can involve performing AGC operations. The sensing device **1202** can also generate output signals representing the forward propagated signal V_f or V'_f and the reverse propagated signal V_r or V'_r. These output signals can subsequently be used to compute the signal $V_{doubled}$ and/or the reference signal V_{ref}. As such, the sensing device **1202** can further communicate the signals representing the forward propagated signal V_f or V'_f and the reverse propagated signal V_r or V'_r to the following components **1206**, **1208**.

[0118] The signal adder **1206** is generally configured for performing a signal combination operation **1006**, **1106** to obtain a Sum signal S or S'. The signal subtractor **1208** is generally configured for performing a subtraction operation **1008**, **1108** to obtain a Difference signal D or D'. The output signals of the components **1206**, **1208** are forwarded to the signal multipliers **1210**, **1212**. Each of the multipliers **1210**, **1212** is configured to perform a multiplication operation **1010**, **1012**, **1110**, **1112** to obtain a respective Exponentiation signal E_S, E'_S, E_D, E'_D. The Exponentiation signals E_S and E_D or E'_S and E'_D are then communicated to the signal subtractor **1214**. At the signal subtractor **1214**, a subtraction operation **1014**, **1114** is performed to obtain a signal $V_{doubled}$ or a reference signal V_{ref}.

[0119] If the result of the subtraction operation is a signal $V_{doubled}$, then the signal $V_{doubled}$ can be further processed to reduce the value of its frequency. In such a scenario, the signal $V_{doubled}$ is forwarded to an optional phase lock loop **1216** and an optional frequency divider **1218**. The components **1216**, **1218** collectively act to reduce the frequency of the signal $V_{doubled}$ to a desired value (i.e., the value of the frequency of a propagated signal V_f, V_r). The output of the frequency divider **1218** is the reference signal V_{ref}.

[0120] Referring now to FIG. **13**, there is provided a block diagram of a second exemplary system **1300** implementing a method for determining a reference signal V_{ref}. As shown in FIG. **13**, the system **1300** comprises a sensing device **1304** disposed along a transmission media **1302** and a reference signal generator **1350**. The reference signal generator **1350**

comprises a sum-diff hybrid circuit **1308**, multipliers **1310**, **1312**, a signal subtractor **1314**, a phase lock loop (PLL) **1316**, and a frequency divider **1318**. Embodiments of the present invention are not limited to the configuration shown in FIG. **13**. For example, the reference signal generator **1350** can be absent of the PLL **1316** and the frequency divider **1318**.

[0121] The sensing device **1304** is generally configured for sensing the presence of a forward propagated signal V_f and a reverse propagated signal V_r on the transmission media **1302**. The sensing device **1304** may also adjust the gain of the signals V_f, V_r so that they have equal arbitrarily defined amplitudes “a”. This gain adjustment can involve performing AGC operations. The sensing device **1304** can also generate output signals representing the forward propagated signal V_f and the reverse propagated signal V_r. These output signals can subsequently be used to compute the reference signal V_{ref}. As such, the sensing device **1302** can further communicate the signals representing the forward propagated signal V_f and the reverse propagated signal V_r to the sum-diff hybrid circuit **1308**.

[0122] The sum-diff hybrid circuit **1308** is generally configured for performing a signal combination operation **1006** to obtain a Sum signal S and a subtraction operation **1008** to obtain a Difference signal D. Subsequent to completing the signal combination operation and subtraction operation, the sum-diff hybrid circuit **1308** communicates the signals S and D to the multipliers **1310**, **1312**, respectively. Each of the multipliers **1310**, **1312** is configured to perform a multiplication operation **1010**, **1012** to obtain a respective Exponentiation signal E_S, E_D. The Exponentiation signals E_S, E_D are then communicated to the signal subtractor **1314**. At the signal subtractor **1314**, a subtraction operation **1014** is performed to obtain a signal $V_{doubled}$. The signal $V_{doubled}$ is then processed by the PLL **1316** and frequency divider **1318** to reduce the frequency of the signal $V_{doubled}$ to a desired value (i.e., the value of the frequency of a propagated signal V_f, V_r). The output of the frequency divider **1318** is the reference signal V_{ref}.

[0123] Referring now to FIG. **14**, there is provided a block diagram of a third system embodiment **1400** implementing the method of FIG. **10**. As shown in FIG. **14**, the system **1400** comprises transducers **1404**, **1420** and a reference signal generator **1450**. Transducers are well known to those having ordinary skill in the art, and therefore will not be described herein. However, it should be understood that each of the transducers **1404**, **1420** is configured to communicate a signal representing a signal V_f, V_r propagated on the transmission media **1402** to the reference signal generator **1450**.

[0124] As also shown in FIG. **14**, the reference signal generator **1450** comprises 180 degree hybrid couplers **1406**, **1414**, input square devices **1408***a*, **1408***b*, a PLL **1416**, and a frequency divider **1418**. Embodiments of the present invention are not limited to the configuration shown in FIG. **14**. For example, the reference signal generator **1450** can be absent of the PLL **1416** and the frequency divider **1418**.

[0125] Hybrid couplers **1406** are well known to those having ordinary skill in the art, and therefore will not be described herein. However, it should be understood that the hybrid coupler **1406** generates signals representing the Sum signal S and the Difference signal D. The generated signals S and D are then communicated from the hybrid coupler **1406** to the input square devices **1408***a*, **1408***b*, respectively. Each of the input square devices **1408***a*, **1408***b* generates a respective Exponentiation signal E_S, E_D. The Exponentiation signals E_S, E_D are communicated from the input square devices **1308***a*, **1408***b* to the hybrid coupler **1414**. The hybrid coupler **1414** performs a subtraction operation **1014** to obtain a signal $V_{doubled}$.

[0126] Next, the signal $V_{doubled}$ is further processed to reduce the value of its frequency. Accordingly, the signal $V_{doubled}$ is forwarded from the hybrid coupler **1414** to the PLL **1416** and the frequency divider **1418**. The components **1416**, **1418** collectively act to reduce the frequency of the signal $V_{doubled}$ to a desired value (i.e., the value of the frequency of a propagated signal V_f, V_r).

[0127] In light of the forgoing description of the invention, it should be recognized that the present invention can be realized in hardware, software, or a combination of hardware and software. A method for determining a reference signal V_{ref} according to the present invention can be realized in a centralized fashion in one processing system, or in a distributed fashion where different elements are spread across several interconnected processing systems. Any kind of computer system, or other apparatus adapted for carrying out the methods described herein, is suited. A typical combination of hardware and software could be a general purpose computer processor, with a computer program that, when being loaded and executed, controls the computer processor such that it carries out the methods described herein. Of course, an application specific integrated circuit (ASIC), and/or a field programmable gate array (FPGA) could also be used to achieve a similar result.

[0128] Applicants present certain theoretical aspects above that are believed to be accurate that appear to explain observations made regarding embodiments of the invention. However, embodiments of the invention may be practiced without the theoretical aspects presented. Moreover, the theoretical aspects are presented with the understanding that Applicants do not seek to be bound by the theory presented.

[0129] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not limitation. Numerous changes to the disclosed embodiments can be made in accordance with the disclosure herein without departing from the spirit or scope of the invention. Thus, the breadth and scope of the present invention should not be limited by any of the above described embodiments. Rather, the scope of the invention should be defined in accordance with the following claims and their equivalents.

[0130] Although the invention has been illustrated and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In addition, while a particular feature of the invention may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application.

[0131] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. Furthermore, to the extent that the terms “including”, “includes”, “having”, “has”, “with”, or variants thereof are used in either the detailed description and/or the claims, such terms are intended to be inclusive in a manner similar to the term "comprising."

[0132] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

We claim:

1. A method for compensating for phase shifts of a communication signal, comprising:
- determining a first reference signal at a first location along a transmission path and a second reference signal at a second location along the transmission path, the second reference signal having the same phase as the first reference signal;
- determining at the first location a first phase offset using the first reference signal and a first communication signal;
- determining at the second location a second phase offset using the second reference signal and a second communication signal; and
- adjusting at the second location a phase of a third communication signal using the first and second phase offsets to obtain a modified communication signal;
- wherein the first, second, and third communication signals are the same communication signal obtained at different locations along the transmission path.

2. The method according to claim **1**, wherein the first phase offset is determined by comparing at the first location a first phase of the first communications signal by a second phase of the first reference signal and the second phase offset is determined by comparing at the second location a third phase of the second communications signal by a fourth phase of the second reference signal.

3. The method according to claim **1**, wherein the adjusting step comprises determining a phase adjustment value for reducing a difference between the first and second phase offsets.

4. The method according to claim **1**, wherein the adjusting step comprises computing a correction weight at the second location using the first and second phase offsets and combining the correction weight with the third communication signal to obtain the modified communication signal.

5. The method according to claim **1**, further comprising filtering the first communications signal prior to determining the first phase offset.

6. The method according to claim **1**, wherein the step of determining the first reference signal comprises
- sensing at the first location a transmit signal propagated over a transmission media in a forward direction and a reverse signal propagated over the transmission media in a reverse direction opposed from the forward direction, the reverse signal being a reflected version of the transmit signal;
- computing a first sum signal by adding the transmit and reverse signals together and a first difference signal by subtracting the reverse signal from the transmit signal;
- computing a first exponentiation signal using the first sum signal and a second exponentiation signal using the first difference signal; and
- subtracting the first exponentiation signal from the second exponentiation signal to obtain the first reference signal.

7. The method according to claim **6**, wherein the first reference signal has a first frequency equal to a second frequency of the transmit signal.

8. The method according to claim **6**, wherein the first reference signal has a first frequency different than a second frequency of the transmit signal.

9. The method according to claim **8**, further comprising processing the first reference signal to obtain an adjusted reference signal with a third frequency equal to the second frequency of the transmit signal.

10. The method according to claim **6**, wherein the step of determining the second reference signal comprises
- sensing at the second location the transmit and reverse signals; and
- computing the second reference signal using the transmit and reverse signals sensed at the second location.

11. The method according to claim **10**, wherein the second reference signal is further determined by
- computing a second sum signal by adding the transmit and reverse signals sensed at the second location together and a second difference signal by subtracting the reverse signal sensed at the second location from the transit signal sensed at the second location;
- computing a third exponentiation signal using the second sum signal and a fourth exponentiation signal using the second difference signal; and
- subtracting the third exponentiation signal from the fourth exponentiation signal to obtain the second reference signal.

12. The method according to claim **1**, further comprising transmitting the modified communication signal to an object of interest.

13. A method for compensating for phase shifts of a communication signal, comprising:
- determining a first reference signal at a first location along a transmission path and a second reference signal at a second location along the transmission path, the second reference signal has the same phase as the first reference signal;
- combining at the first location the communication signal with the first reference signal to obtain a modified communication signal;
- determining at the second location a phase offset using the modified communication signal and the second reference signal; and
- adjusting at the second location a phase of a modified communication signal using the phase offset to obtain a phase adjusted communication signal.

14. The method according to claim **13**, further comprising modifying a frequency of the first reference signal prior to combining the first reference signal with the communication signal.

15. The method according to claim **13**, further comprising combining the first reference signal with a random or pseudo-random number sequence prior to combining the first reference signal with the communication signal.

16. A system, comprising:
- at least one reference signal generator configured for determining a first reference signal at a first location along a transmission path and a second reference signal at a

second location along the transmission path, the second reference signal has the same phase the first reference signal; and

at least one closed loop operator communicatively coupled to the reference signal generator and configured for determining at the first location a first phase offset using the first reference signal and a first communication signal, determining at the second location a second phase offset using the second reference signal and a second communication signal, and adjusting at the second location a phase of a third communication signal using the first and second phase offsets to obtain a modified communication signal;

wherein the first, second, and third communication signals are the same communication signal obtained at different locations along the transmission path.

17. The system according to claim **16**, wherein the closed loop operator is further configured for determining a phase adjustment value for reducing the first and second phase offsets.

18. The system according to claim **16**, wherein the closed loop operator is further configured for computing a weight at the second location using the first and second phase offsets and combining the weight with the third communication signal to obtain the modified communication signal.

19. The system according to claim **16**, further comprising:

at least one sensing device configured for sensing at the first location a transmit signal propagated over a transmission media in a forward direction and a reverse signal propagated over the transmission media in a reverse direction opposed from the forward direction, the reverse signal being a reflected version of the transmit signal; and

a first reference signal generator communicatively coupled to the sensing device and configured for computing a sum signal by adding the transmit and reverse signals together, computing a difference signal by subtracting the reverse signal from the transmit signal, computing a first exponentiation signal using the sum signal, computing a second exponentiation signal using the difference signal, and subtracting the first exponentiation signal from the second exponentiation signal to obtain the first reference signal.

20. The system according to claim **17**, wherein the first reference signal has a first frequency equal to a second frequency of the transmit signal.

21. The system according to claim **17**, wherein the first reference signal has a first frequency different than a second frequency of the transmit signal.

22. The system according to claim **21**, wherein the first reference signal generator is further configured for processing the first reference signal to obtain an adjusted reference signal with a third frequency equal to the second frequency of the transmit signal.

23. The system according to claim **16**, further comprising

at least one sensing device configured for sensing at the second location the transmit and receive signals; and

a second reference signal generator communicatively coupled to the sensing device and configured for computing the second reference signal using the transmit and reverse signals sensed at the second location.

24. The system according to claim **23**, wherein the second reference signal generator is further configured for

computing a sum signal by adding the transmit and reverse signals sensed at the second location together and a difference signal by subtracting the reverse signal sensed at the second location from the transmit signal sensed at the second location;

computing a first exponentiation signal using the sum signal and a second exponentiation signal using the difference signal; and

subtracting the first exponentiation signal from the second exponentiation signal to obtain the second reference signal.

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