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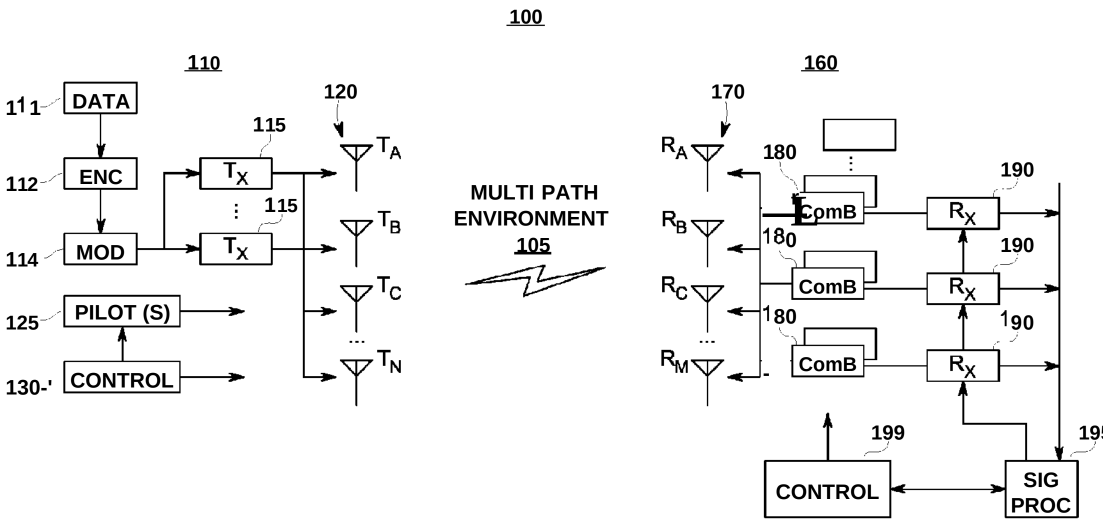

FIG. 1

(57) Abstract: A Multiple Input Multiple Output (MIMO) antenna system and operating method that provides spatial- and temporal multiplexing with polarization independent operating modes.

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DIRECTIONAL MIMO ANTENNA

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to a co-pending U.S. Provisional Patent Application entitled "Directional MIMO Antenna", Serial Number 62/463,076 filed February 24, 2017, the entire contents of which are hereby incorporated by reference herein.

BACKGROUND

Multiple-input and multiple-output (MFMO) is a method for increasing the capacity of a radio link using multiple transmit and receive antennas to exploit multipath propagation. MIMO techniques are now in use for many wireless communication standards including IEEE 802.1 In (Wi-Fi), IEEE 802.1 lac (Wi-Fi), HSPA+ (3G), WiMAX (4G), and Long Term Evolution (LTE) (4G). MIMO methods have also been applied and proposed to other uses where multipath is possible, such as power-line communication as per the ITU G.hn standard, the HomePlug AV2 specification and certain Bluetooth environments.

SUMMARY

A MIMO system provides spatial- and time-multiplexing with polarization independent operating modes through the use of channel estimation, coherent processing in an operating mode, and beamforming networks.

BRIEF DESCRIPTION OF THE DRAWINGS

The description below refers to the accompanying drawings, of which:

Fig. 1 illustrates a MIMO system in a multipath environment; and

Fig. 2 illustrates regions of coherence for signals emitted from a first antenna and a second antenna B that can be used to develop spatial- and time-multiplexing.

Fig. 3A is a schematic diagram of a directional antenna provided by a pair of crossed bowtie radiators.

Fig. 3B is a combining circuit used with the antenna of Fig. 3A to provide left-hand and right-hand polarized outputs.

Figs. 4A and 4B illustrate another type of directional antenna that uses four pairs of crossed dipoles arranged in a cylindrical pattern.

Fig. 4C is another type of directional antenna uses four crossed dipoles arranged in a common plane.

Fig. 4D is an example polarization combining network that can be used with the antennas of Fig. 4A, 4B and 4C to provide vertical, horizontal, left-hand and right-hand polarization modes.

Fig. 5A is a more detailed view of the crossed dipole antenna of Fig. 4A and a switched feed to provide further vertical, horizontal, directional and directional finding operating modes.

Fig. 5B is a combining circuit that may be used with Fig. 5A.

Fig. 6A is another combining circuit used with a crossed dipole antenna to provide receive azimuth and elevation angle estimates.

Fig. 6B shows a loop antenna disposed adjacent a crossed dipole element.

Fig. 6C is an example combining circuit may be used with the antenna of Fig. 6B.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

Fig. 1 illustrates a MIMO system 100 that may be used in a multipath environment 105. The components of a transmitter 110 subsystem (shown on the left hand side) include one or more transmit data sources 111, one or more encoders 112, one or more modulators 114 and/or transmitters 115, and multiple transmit antennas 120 (TA, TB, TC, .. TN) . A controller 130, such as microprocessor, manages the operation of the transmitter components. The controller 130 operates the system in a training mode, where pilot signals 125 are transmitted via the antennas 120, and an operating mode, where the encoded data is transmitted via the antennas 120. The number of active transmitters 115 may or may not be the same as the number of antennas 120, depending upon the state of the system.

The receiver subsystem 160 components, including two or more receive antennas 270 (RA, RB, RC, .. RM) , one or more receivers 190 (which may include demodulators), and receive signal processor 195. A controller 199, such as a microprocessor, is also used on the receiver side. In some embodiments, at least one combining circuit 180 is associated with each antenna 170 to provide polarization diversity, or to estimate an elevation and angle of arrival, or both.

In some implementations such as for mobile telephone, the transmitter 110 is located in a base station and the receiver 160 is in a mobile phone; however it should be understood that the transmitter 110 may also be in the mobile phone and the receiver in a base station 160, or in other implementations, a transmitter 110 and receiver 160 are located in each wireless device. Thus it should be understood that the transmitter and receiver may each be implemented in a base station or a mobile phone, and that other types of wireless communication networks may utilize the systame components in a tablet computer, a laptop computer, a smart watch, an Internet of Things (IoT) device, or any other wireless device.

The MIMO system 100 operates in a multipath environment 105 such that a signal radiated by the transmit antenna(s) 120 may follow multiple paths before arriving at one or more of the receive antenna(s) 170.

Spatial multiplexing using MIMO with multiple antennas at both the transmitter 110 and the receiver 160 can take advantage of the extra degrees of freedom provided by the independent propagation paths present in a multipath environment. In particular, such spatial multiplexing allows sending independent streams of information at the same time over the same frequencies.

An effective way to leverage this situation to provide a multiplex operating mode is to obtain an estimate of channel state information between the transmit and receive antennas by sending orthogonal pilot sequences 125 in a training mode. For this to work the correlation between the temporal frequency transfer functions of the different propagation paths should be low enough to create independent channels.

In the training mode, the controller 130 on the transmit side sets up the transmitter 110 to at first radiate using only one of the antennas, such as antenna TA. The receiver 160 is placed by its controller 199 in a scanning mode, looking for the pilot signal, and to note an angle of arrival (AOA) and time of arrival (TOA) for the pilot signal received from antenna TA. Next, the controller activates only antenna TB for radiation, and the receiver is again placed in a scanning mode, to note an AOA and TOA for the pilot signal received from antenna TB. The process is repeated for other transmit antennas, Tc through TN. More details regarding one way to estimate AOA are described below. TOA can be estimated with time stamps added to the signals, or with an estimate of phase, as also described below.

Due to spatial coherence, optimum gains from spatial multiplexing alone may not be realized, in that propagation is not random as a function of angle of arrival, but exhibits local maxima.

The resulting information regarding spatial frequency (angle of arrival) and temporal frequency (time of arrival) may be used to form a 3-D processing domain as represented in Fig. 2. The x-axis represents elevation angle of arrival (ϕ) and the y-axis represents the azimuthal angle (ϕ) angle arrival. The z-axis represents time of arrival. A region of coherence for signals emitted from antenna TA is formed around angle (ϕ_A, Φ_A) at height (time) ti; similarly, a region of coherence for signals emitted from antenna TB is formed around angle (φ_B, Φ_B) at time t_2.

In an operating mode, it is then possible to optimize the performance over a wide range of coherence conditions where two or more of the transmit antennas are activated. In particular, the observed responses to the pilot sequences are used to devise transfer functions in spatial and temporal frequency domains. These transfer functions are the used by the signal processor 195 for coherent receiver processing during the operating mode. In particular, the signal processor 195 may implement one or more matched filters or receiver correlators in the operating mode. Thus during normal operation two or more antennas TA,... TN may be active on the transmit side to provide the spatial and/or temporal multiplex modes). Time of arrival (TOA) can be estimated using a correlation peak output from the matched filters.

As also shown in Fig. 2, in a multi antenna base station/multi beam cell phone MIMO configuration, two of the scanning receive antennas (on the receive side) will converge on the two dominant plane waves. Spatial frequency processing enables a matched filter which can discriminate against interfering signals and use the coherent plane waves to increase signal power. It can also be expected that the transfer functions associated with the two beams are uncorrelated.

Also, another multiplex dimension can be added by utilizing polarization diversity in the system 100. For example, modulator 114 or transmitter 115 circuits may be utilized to provide left hand / right hand circular and/or vertical/horizontal polarization in each transmit beam. More particularly, polarization dependent operating modes can then be provided with the use of directional receive antennas 170 and one or more corresponding combining networks 180.

In one implementation, the receive antennas 170 may each be a crossed bowtie type antenna 300, as shown in Fig. 3A. One such bowtie antenna 300 uses four generally triangular radiators 310 (or segments) arranged with their apexes adjacent a center point 330. Four feedlines A,B,C, D are connected to a respective one of each of the four triangular radiators 310, typically near the center point. Fig. 3B shows a polarization combining network 180-1 that may be used with the crossed bowtie of Fig. 3A. The four feedpoints are coupled to a pair of 180 degree hybrid combiners 301-1, 301-2 feeding a 90 degree hybrid combiner 302. This combining network 180-1 provides Left Hand (LH) 305-L and Right Hand (RH) 305-H circularly polarized (C-POL) feed points.

It should be understood that other types of combining networks can be used to produce other types of directional and/or polarized signals. For example, a monopole pattern may be derived from the directional elements by feeding the sum ports of the 180 hybrids 301-1, 301-2 into another combiner (not shown). A switch controlled by the controller 199 and decision logic (also in the controller 199) can permit selection of one of these directional operating modes, such as for example, by selecting the mode that produces the highest received power at a given time.

In other embodiments, depending on the desired frequency of operation, the hybrids of FIG. 3B can be replaced by ferrite baluns. In particular, a different technique replaces the ombining network 180-1 with orthogonal transmission line baluns. One balun is connected between feed points A and C and another balun is connected between feed points B and D. More details of this configuration are provided in U.S. Patent 9, 118,1 16 hereby incorporated by reference.

Still other types of directional antennas 170 may be used. Figs. 4Aand 4B is an example of a cylindrical form factor directional antenna 170. The cylindrical form factor has a given height and a diameter; the radiators or antenna segments are provided by metalizing the surface of a cylindrical substrate formed of a dielectric. The cylinder is further divided into four quadrants (North (N), East €, South (S) and West(W)); each quadrant in turn contains four radiating antenna elements similar to a crossed bowtie (in other words, there are a total of 16 radiating elements).

Fig. 4C is another implementation of a four quadrant, four element directional antenna. Here the four "quadrants" or "North, East, South and West" components are actually planar radiating patches or segments disposed on the same planar substrate (over a cavity), rather than on the sides of a hollow cylindrical substrate. As with the Fig. 4A configuration, each quadrant 401-N, 401-E, 401-S, 401-W includes a set of four planar patch elements 420 (only one labelled for clarity) which serve as the two "crossed bowtie" radiators This type of directional antenna is further described in our co-pending U.S. Patent Application Serial Number 15/861,749 filed on January 1, 2018, entitled "Low Profile Antenna - Conformal", which is hereby incorporated by reference in its entirety.

Fig. 4D is a detailed circuit diagram for a second type of combiner 180-2 that may be used with the directional antennas of Figs. 4A, 4B and 4C. The diagram shows the interconnection of the four A,B,C,D feeds from each of the N,E,S,W quadrants. A Single Pole Four Throw (SP4T) switch associated with each of the feed points enables selection of an open, omnidirectional, directional, or short connection for respective feed points. These switch outputs are then fed to 4:1 combiners 910-1, 910-2 to provide vertical and horizontal omnidirectional modes, respectively. A 90° hybrid combiner 912 couples through a Single Pole Six Throw (SP6T) switch providing selection of the respective vertical omni or vertical directional mode for each of the N,E,S,W quadrants, or an open circuit. A similar connection is provided on another port (port 2) of the hybrid 912 from the horizontal oriented elements. By connecting the output to a Single Pole Two Throw (SP2T) switch, and feeding the vertical directional/omni, right-hand directional/omni, left-hand directional/omni and the horizontal directional/omni points, the outputs from these various modes can then be selectively activated.

Fig. 5A shows more detail of the combiner 180-2 how a given quadrant of the cylindrical implementation of Fig. 4A, or a segment of the embodiment of Fig. 4C) provides a vertical and a horizontal feed point. Here, two ports, that is radiating triangular elements 3 and 4, feed into a tapered balun 710 to provide the vertical polarization output (V). SP4T switch 1010 thus provides multiple output options including open, vertical, omnidirectional, vertical directional, or short for each of the corresponding one of the available face directions (N,E,S,W).

Similar switching is provided to the horizontal feed point of the example side or quadrant where the two ports (that is, elements 1 and 2) feed into a tapered balun to provide the horizontally polarized output (H). The SP4T switch 1010 provides four options again - open circuit, horizontal omni, horizontal directional, or short.

Fig. 5B shows the 90° hybrid combiner connections in more detail. Here the Vout terminal on the second leg is provided through a SP6T switch providing multiple options (vertical omni, vertical North South East or West, directional and open). The $H_{o}ut$ terminal provides the corresponding six vertical polarized outputs. The second leg and its corresponding SP6T switch also has six corresponding options. See our issued U.S. Patent 9,013,360 incorporated by reference herein for more information.

Fig. 6A is another types of Radio Frequency (RF) combining network 180-3 that may be used in the MIMO system 100 provide an estimate of direction of arrival for both azimuth and elevation. It can be used to produce an orientation independent response from any of the directional antennas 400 previously mentioned such as the crossed bowtie antennas. A combiner 180-3 would typically be provided for each directional antenna element 400.

In this arrangement, a first hybrid combiner 401 produces a signal VΣ representing the sum of signals at the four radiating elements A,B, C, D and, with the suppression of the horizontal component, represents only (or mostly) the vertical component. A second hybrid power combiner 402, which is a difference, or 180° combiner provides an output signal

$$\boldsymbol{D} - \boldsymbol{B} = \boldsymbol{v}\,\sin(\varphi)$$

and a third 180° hybrid 403 provides and output signal

$$\boldsymbol{A} - \boldsymbol{C} = \boldsymbol{v}\,\cos(\varphi)$$

The outputs of combiners 402, 403 then feed a 90° quadrature hybrid 404 to produce a signal,

$$\mathrm{V} = \boldsymbol{v}\,\boldsymbol{e}^{\boldsymbol{j}\varphi}$$

which is proportional to the azimuthal angle.

A phase detector 406 can determine a phase difference 406 between signals VΣ and V thus provides the azimuthal angle, ϕ. A hybrid divider 407 determines the ratio between them, to produce an output proportional to the elevation angle Θ.

Another implementation of the directional antenna element 401 shown in in Fig. 6B can be used where both horizontal and vertical polarized signals are present. A circular wire loop 320 is disposed above the cylindrical radiating element 300.

Fig. 6C shows another combining circuit that may be used with the antenna of Fig. 6B. Here, the output of the wire loop 320 can be combined with other signals to produce a signal proportional to the horizontal component

$$H \cos \Theta$$

Hybrid combiners 602, 604 are 180° combiners that provide both a sum and difference output from radiators A, B, C, D. The 180° hybrid combiners 602, 604, quadrature combiner 606, and combiner 608, arranged as shown, produce signals:

$$V \cos \theta$$

$$V \sin \varphi$$

$$H \cos \phi$$

$$-H \sin \varphi$$

$$V e^{j\varphi}$$

and

$$H e^{i\varphi}$$

The resulting signals from the hybrid combiners can be further processed by the signal processor 195 to obtain signals representative of both the azimuth and elevation that are independent of any horizontal component and vertical component. For example, Analog-to-Digital Converter(s) (ADCs) may process the outputs of the hybrid combiners and be fed to one or more Digital Signal Processors (DSPs) to thereby obtain an azimuth and elevation. More information about this approach to determining azimuth and elevation angles can be found in U.S. Patent Application Serial No. 15/861,739 filed January 4, 2018 entitled "Indoor Positioning System Utilizing Beamforming with Orientation and Polarization Independent Antennas", the entire contents of which are hereby incorporated by reference. As mentioned above, the same signal processor 195 may also implement the matched filter based on the channel estimate made during the training mode; time of arrival (TOA) is then estimated, in one implementation, using a correlation peak derived from that matched filter output.

What is claimed is:

CLAIMS

1. A multiplexing method for operating a Multiple Input Multiple Output (MIMO) system in a multipath environment, the MIMO system comprising a transmit subsystem comprising two or more transmit antennas and a receive subsystem comprising two or more receive antennas, the multiplexing method comprising:

in a training mode,

activating a first transmit antenna to transmit a predetermined pilot signal, determining a first angle of arrival (AOA) and a first time of arrival (TOA) from one or more signals received at the receive subsystem;

activating a second transmit antenna to transmit a predetermined pilot signal, and determining a second angle of arrival (AOA) and a second time of arrival (TOA) from one or more signals received at the receive subsystem;

deriving a spatial frequency and temporal frequency transfer function from the signals received at the receive subsystem;

in an operating mode,

using the spatial and temporal transfer function to discriminate signals received at the receive subsystem.

2. The multiplexing method of claim 1 additionally wherein two or more of the receive antennas are directional receiving antennas.

3. The multiplexing method of claim 2 wherein the angles of arrival include an elevational angle and an azimuth angle.

4. The multiplexing method of claim 2 wherein the directional receiving antennas are crossed dipole antennas.

5. The multiplexing method of claim 2 wherein each directional receiving antenna further comprises a structure having sets of antenna elements, with each set of antenna elements including four radiating segments, and further comprising the step of:

combining the outputs of two or more radiating segments in each set of elements, to provide two or more of a horizontal, vertical, left hand or right hand polarization mode.

6. The multiplexing method of claim 2 additionally wherein the directional receiving antennas further comprises four quadrant elements, with each quadrant element further comprising:

a conductive cylinder side section and a feed point;

a first pair of the four quadrant elements positioned opposite to one another along a major axis;

a second pair of the four quadrant elements positioned opposite to one another along the major axis; and

a combining circuit for selectively combining the feed points provided by respective quadrant elements.

7. An apparatus comprising:

a plurality of directional receiving antennas, arranged to receive multiple signals from an array of transmitting antennas;

a plurality of combining circuits, with each combining circuit connected to a respective one of the directional receiving antennas,

to produce a first angle signal indicative of a first angle of arrival (AOA) for one or more signals received when a first transmit antenna is active;

to produce a second angle signal indicative of a second angle of arrival (AOA) when a second transmit antenna is active;

a signal processor,

for deriving a spatial frequency and temporal frequency transfer function from the signals received at the receive subsystem; and in an operating mode, for using the spatial and temporal transfer function to discriminate signals received at the receive subsystem.

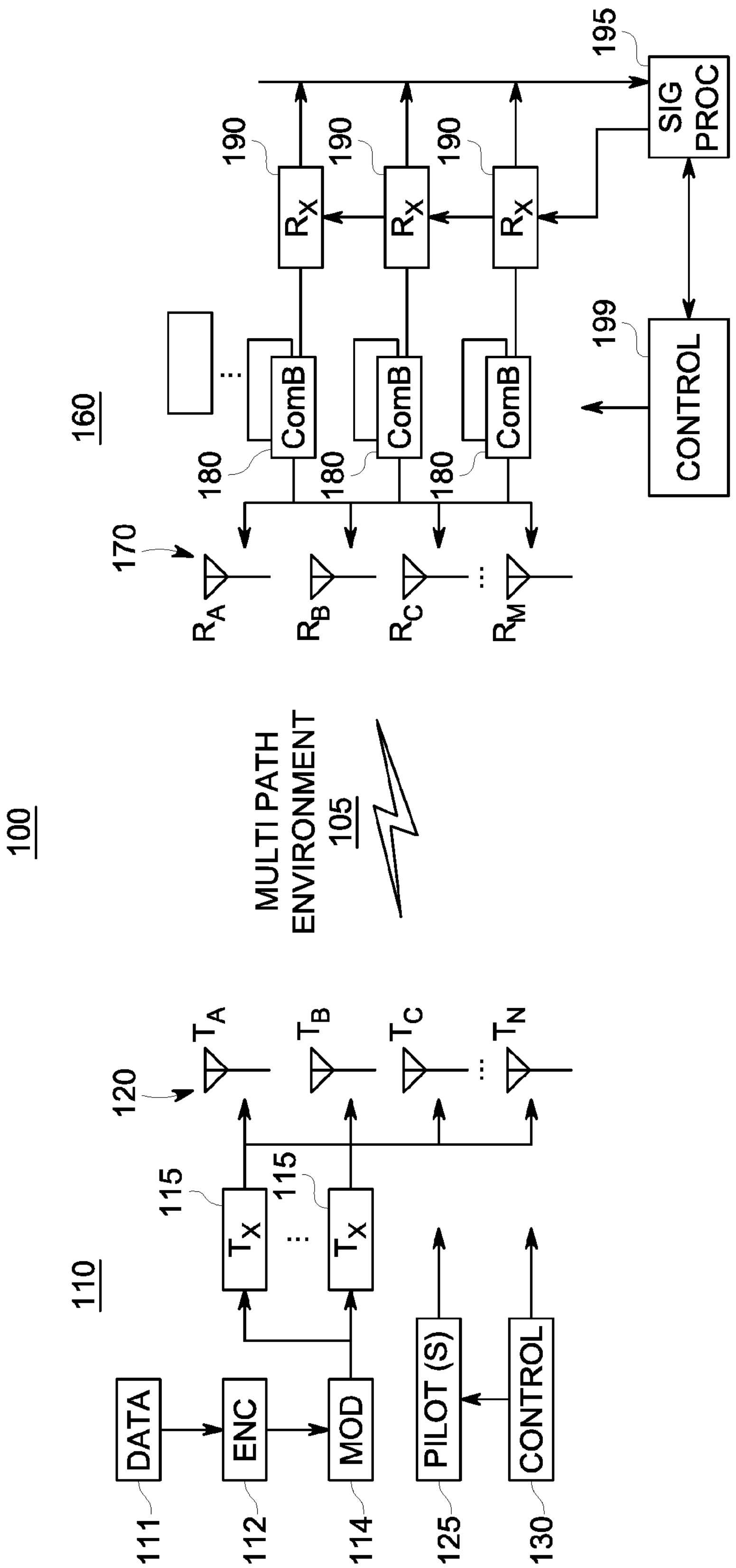

100
110
DATA
ENC
MOD
PILOT (S)
CONTROL
111
112
114
125
130
Tx
115
120
TA
TB
TC
TN
MULTI PATH ENVIRONMENT
105
160
170
RA
RB
RC
RM
ComB
180
Rx
190
SIG PROC
195
CONTROL
199

FIG. 1

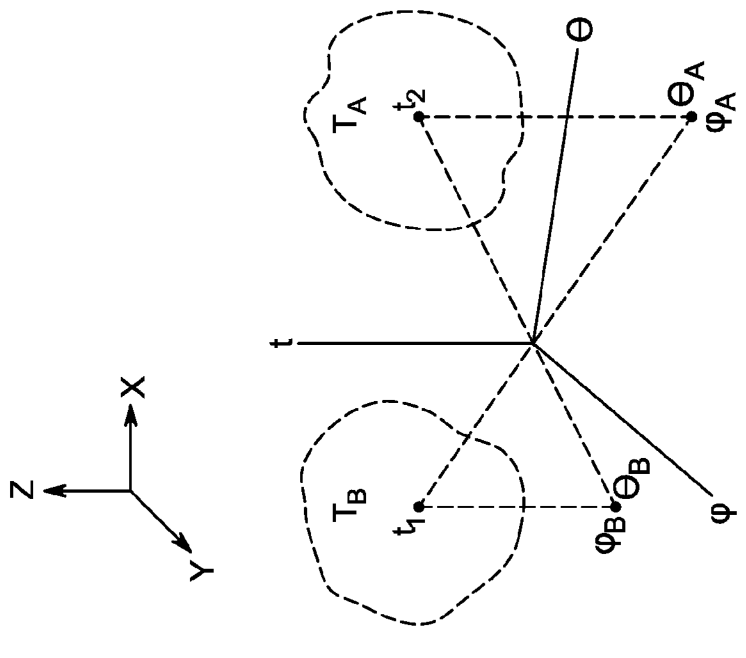


FIG. 2

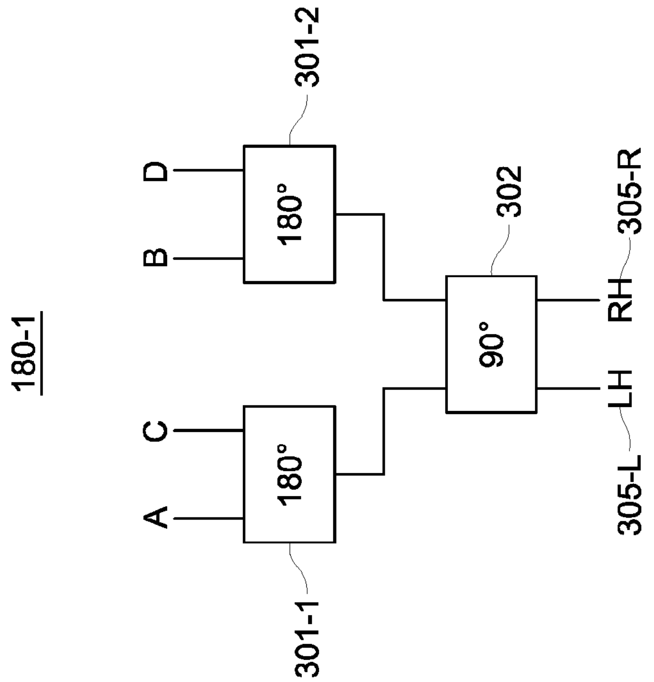

180-1
A
C
B
D
180°
180°
90°
301-1
301-2
302
LH
RH
305-L
305-R

FIG. 3B

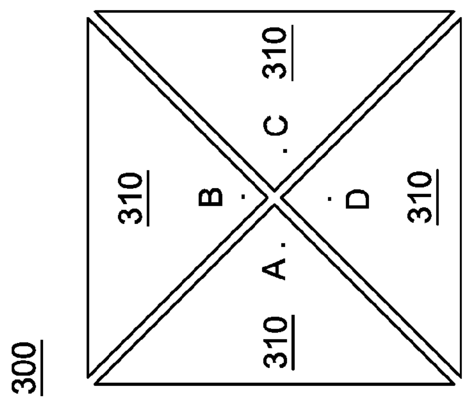

300
310
310
310
310
A
B
C
D

FIG. 3A

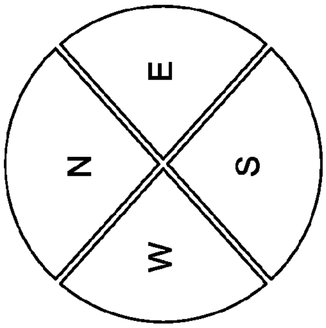


FIG. 4B

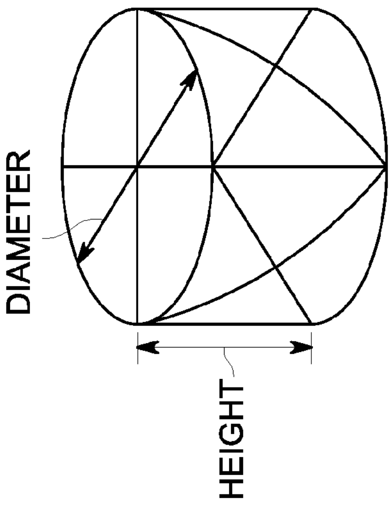


FIG. 4A

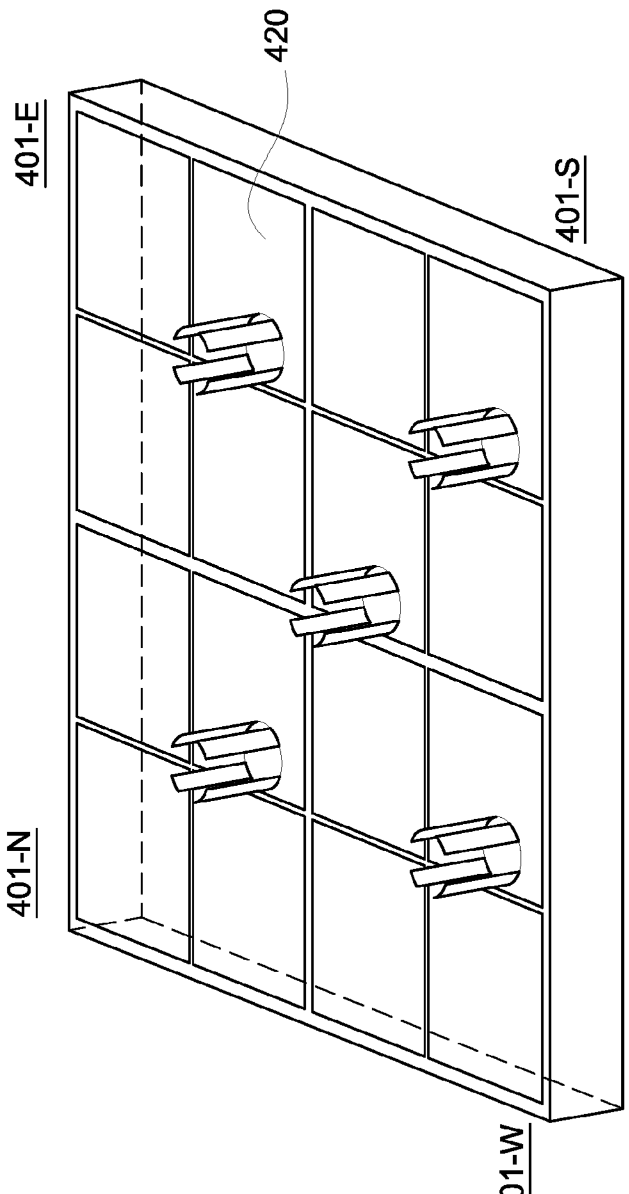
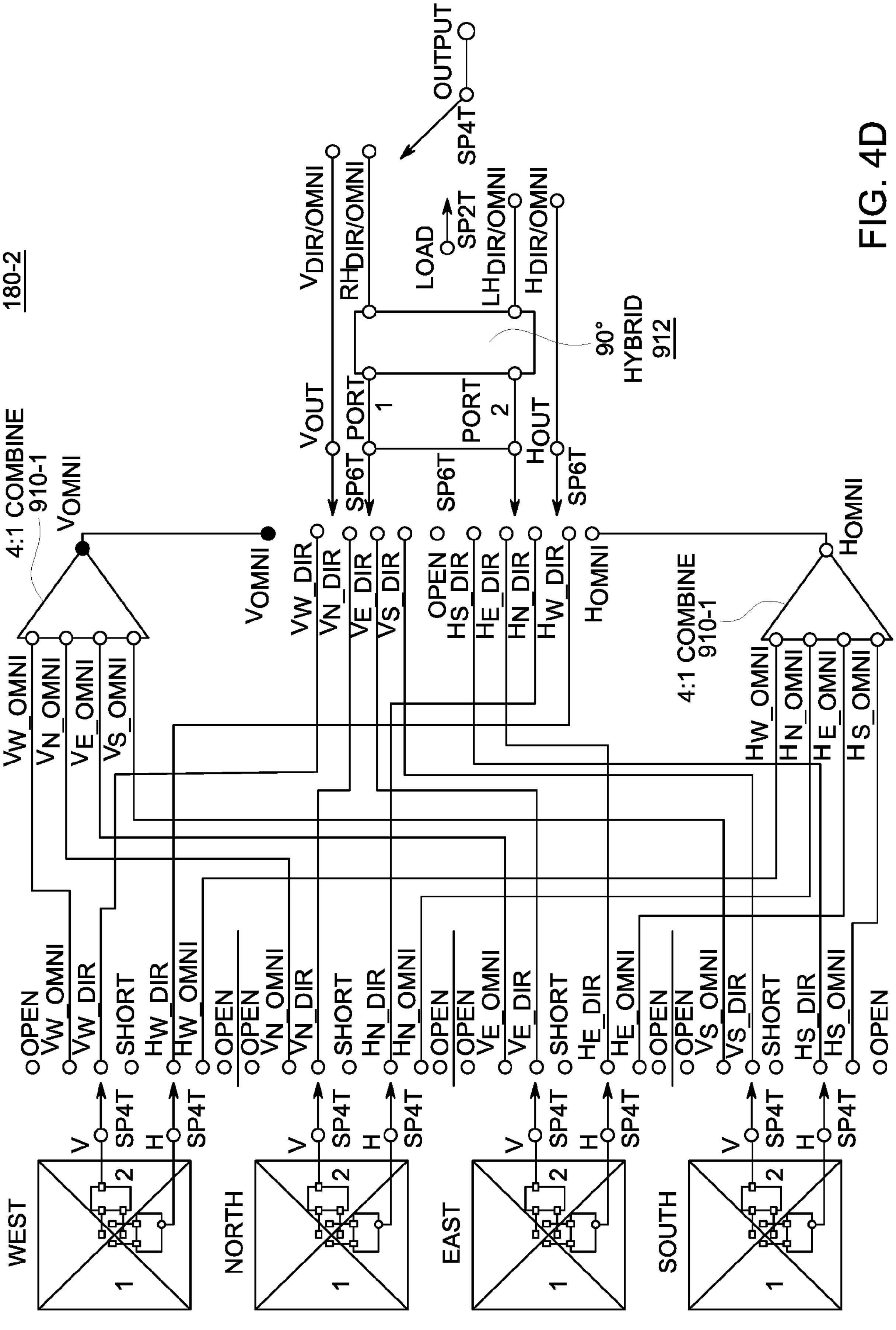


FIG. 4C


180-2
OUTPUT
SP4T
VDIR/OMNI
RHDIR/OMNI
LOAD
SP2T
LHDIR/OMNI
HDIR/OMNI
90°
HYBRID
912
VOUT
PORT 1
PORT 2
HOUT
SP6T
4:1 COMBINE
910-1
VOMNI
VW_DIR
VN_DIR
VE_DIR
VS_DIR
OPEN
HS_DIR
HE_DIR
HN_DIR
HW_DIR
HOMNI
VW_OMNI
VN_OMNI
VE_OMNI
VS_OMNI
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HE_OMNI
HS_OMNI
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WEST
NORTH
EAST
SOUTH
V
H
1
2

FIG. 4D

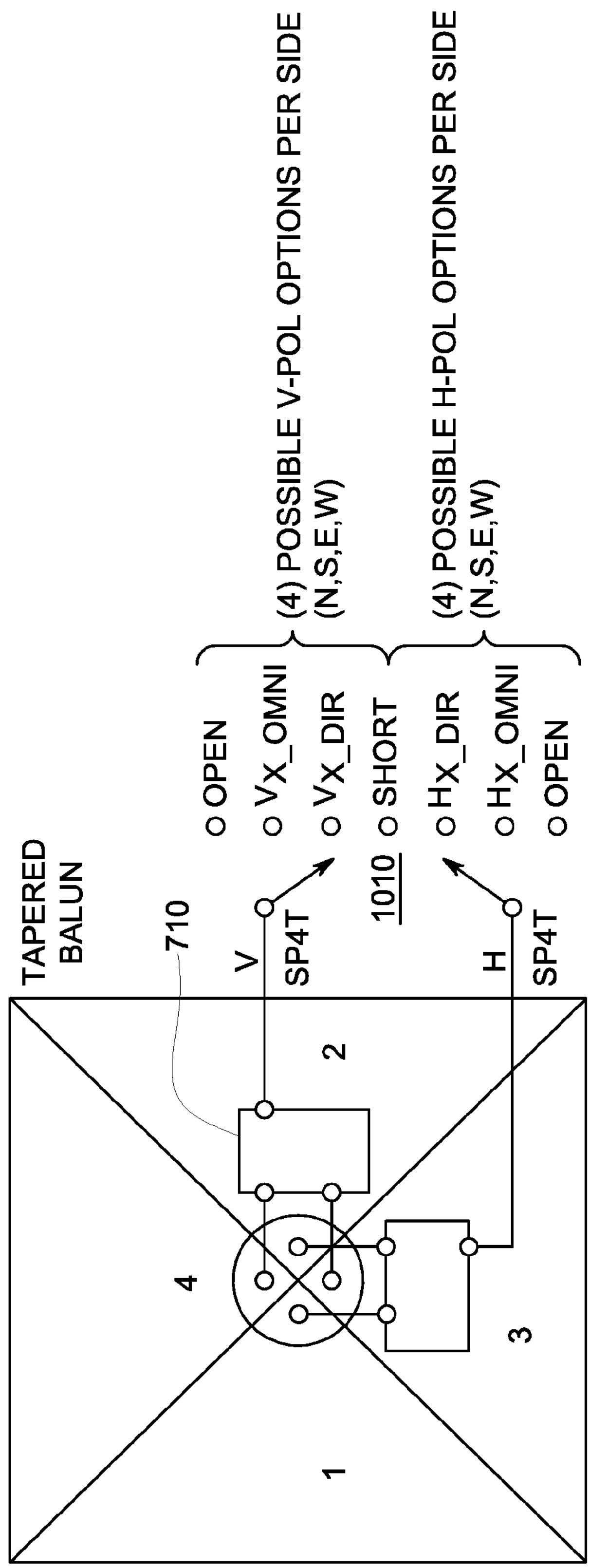
TAPERED BALUN
710
V
SP4T
1010
H
SP4T
1
2
3
4
OPEN
V_X_OMNI
V_X_DIR
SHORT
H_X_DIR
H_X_OMNI
OPEN
(4) POSSIBLE V-POL OPTIONS PER SIDE (N,S,E,W)
(4) POSSIBLE H-POL OPTIONS PER SIDE (N,S,E,W)

FIG. 5A

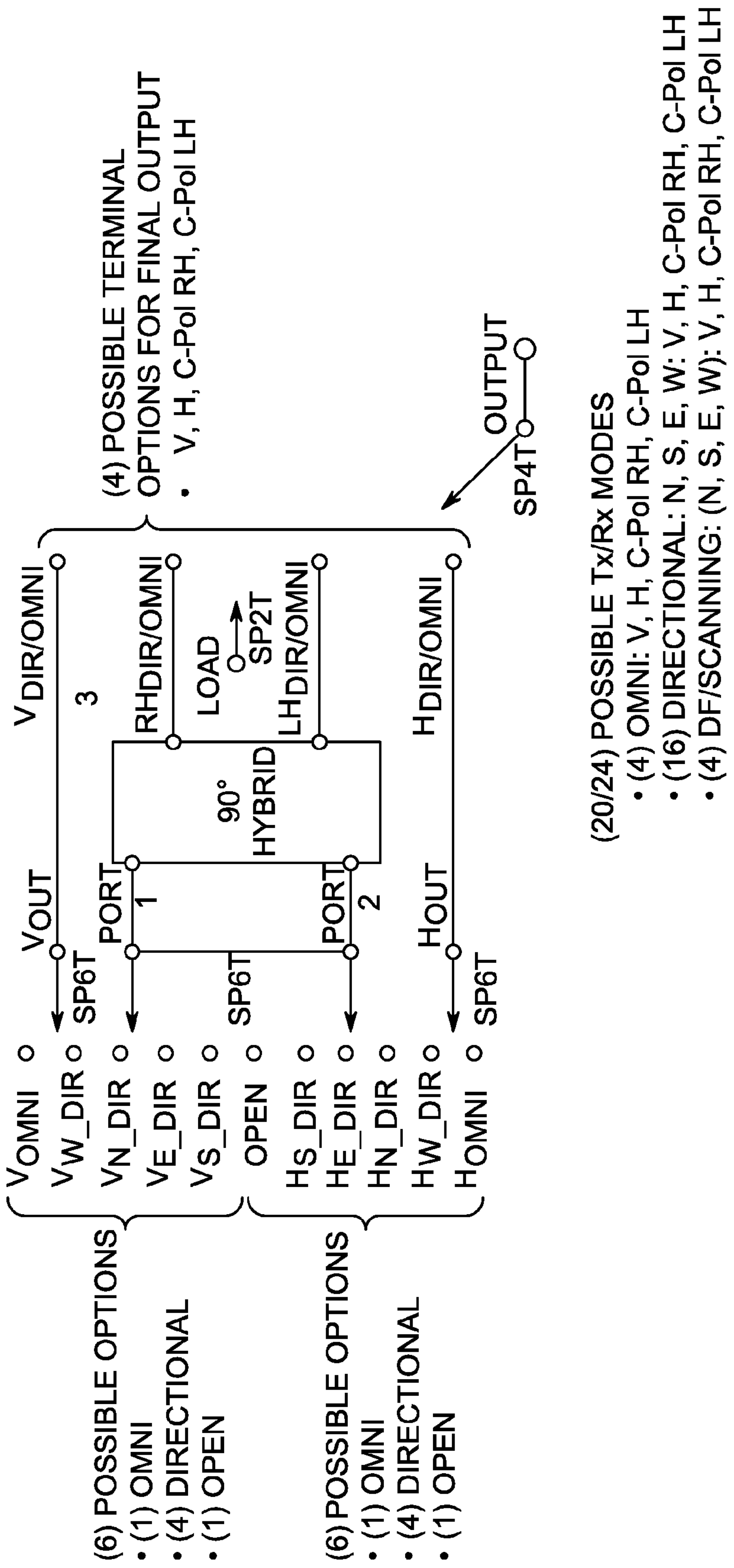
(4) POSSIBLE TERMINAL OPTIONS FOR FINAL OUTPUT
• V, H, C-Pol RH, C-Pol LH
OUTPUT
SP4T
V DIR/OMNI
3
RH DIR/OMNI
LOAD
SP2T
LH DIR/OMNI
H DIR/OMNI
90° HYBRID
V OUT
PORT 1
PORT 2
H OUT
SP6T
SP6T
SP6T
V OMNI
V W_DIR
V N_DIR
V E_DIR
V S_DIR
OPEN
H S_DIR
H E_DIR
H N_DIR
H W_DIR
H OMNI
(6) POSSIBLE OPTIONS
• (1) OMNI
• (4) DIRECTIONAL
• (1) OPEN
(6) POSSIBLE OPTIONS
• (1) OMNI
• (4) DIRECTIONAL
• (1) OPEN
(20/24) POSSIBLE Tx/Rx MODES
• (4) OMNI: V, H, C-Pol RH, C-Pol LH
• (16) DIRECTIONAL: N, S, E, W: V, H, C-Pol RH, C-Pol LH
• (4) DF/SCANNING: (N, S, E, W): V, H, C-Pol RH, C-Pol LH

FIG. 5B

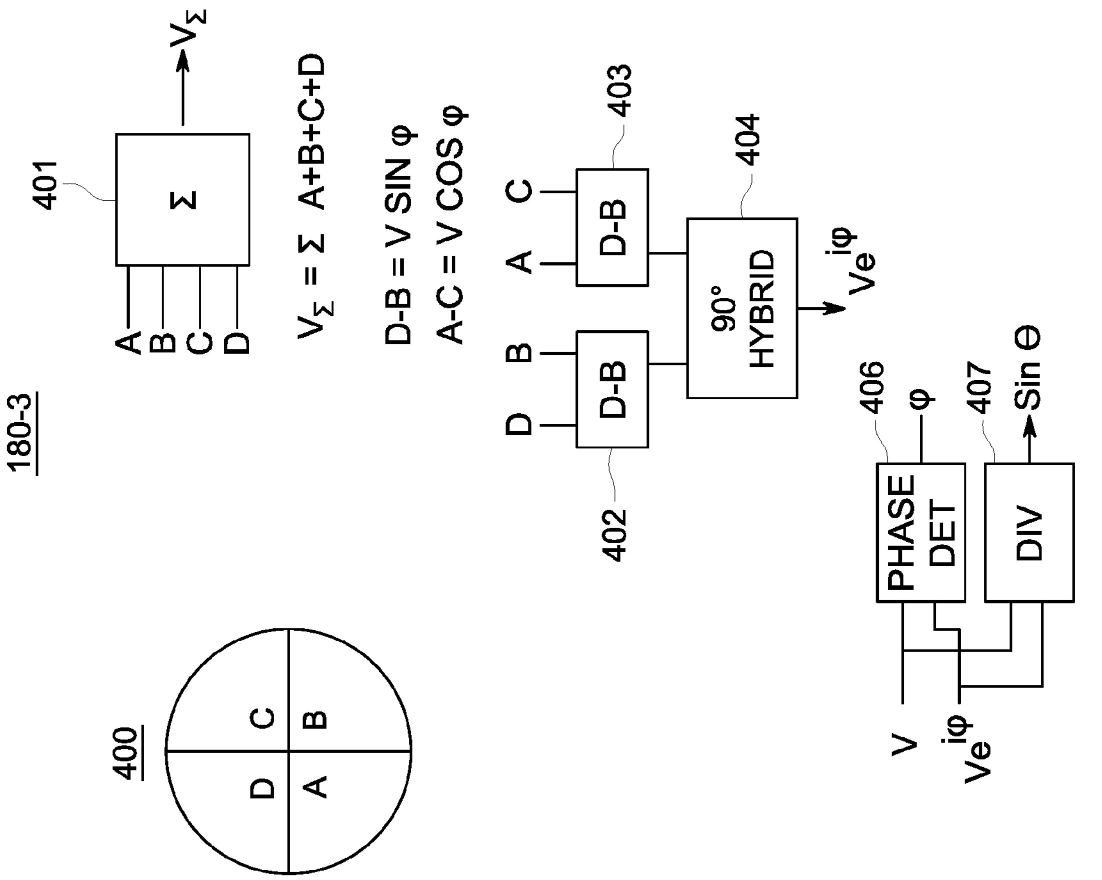
180-3
400
D
A
C
B
401
Σ
A
B
C
D
VΣ
VΣ = Σ A+B+C+D
D-B = V SIN φ
A-C = V COS φ
D
B
A
C
D-B
D-B
402
403
404
90°
HYBRID
Veiφ
406
PHASE
DET
φ
407
DIV
Sin Θ
V
Veiφ

FIG. 6A

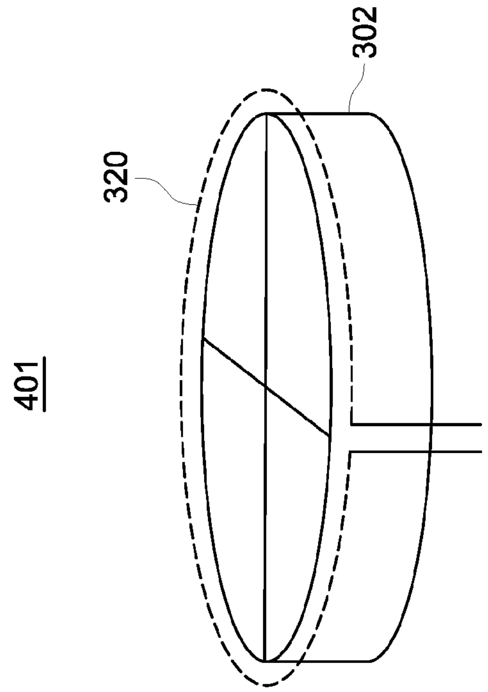

FIG. 6B

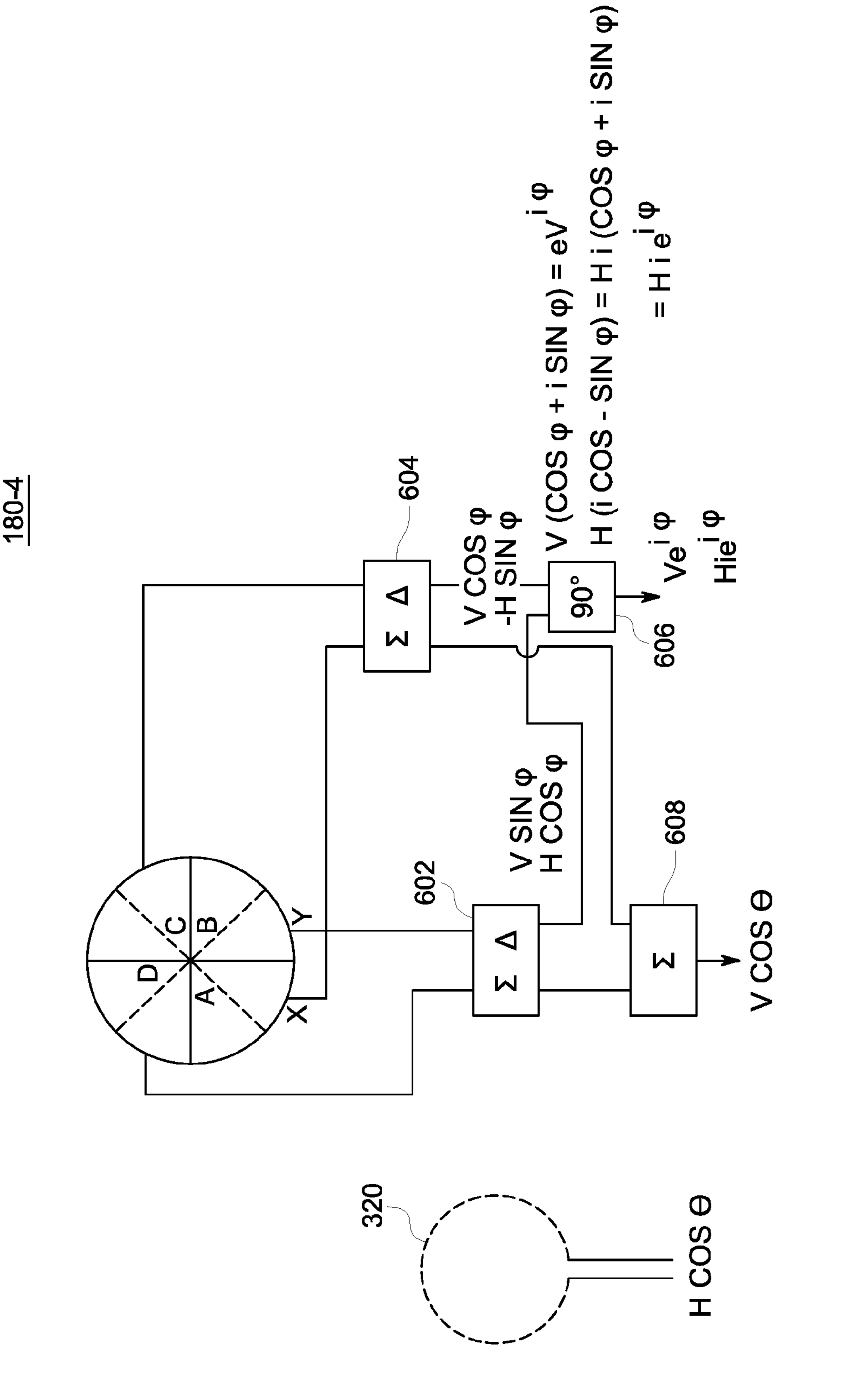
180-4
604
Σ Δ
V COS φ
-H SIN φ
90°
606
$Ve^{i\varphi}$
$Hie^{i\varphi}$
V (COS φ + i SIN φ) = $eV^{i\varphi}$
H (i COS - SIN φ) = H i (COS φ + i SIN φ)
= H i $e^{i\varphi}$
A
B
C
D
X
Y
602
Σ Δ
V SIN φ
H COS φ
608
Σ
V COS Θ
320
H COS Θ

FIG. 6C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 18/19317

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H04L 5/06; H04B 7/04; H04B 7/0413 (2018.01)
CPC - H04L 5/0048; H04B 7/0697; H04B 7/0669; H04L 25/0204, H04L 25/022; H04B 7/0417

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History Document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008/0080631 A1 (Forenza et al.) 03 April 2008 (03.04.2008); entire document, especially, abstract, FIG.. 1,2, 9, 21, 26, para [0091], [0098], [0101], [0139], [0251], [0274],	1-7
A	US 2004/0136349 A1 (Walton et al.) 15 July 2004 (15.07.2004) entire document, especially, abstract, FIG.3, para [0125], [0159], [0163], [0170], [0190]	1-7
A	US 9,088,447 B1 (Mitsubishi Electric Research Laboratories Inc.,) 21 July 2015 (21.07.2015); entire document, especially, abstract, FIG.1, col.3, ln 5-9, ln 33-36, ln 63-65	1-7
A	US 6,144,711 A (Raleigh et al.) 07 November 2000 (07.11.2000); entire document	1-7
A	US 2006/0023803 A1 (Periman et al.) 02 February 2006 (02.02.2006); entire document	1-7

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 May 2018	**20 JUN 2018**

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