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(54) **RADIOS CONFIGURED TO SPLIT POWER FOR A COMBINED SIGNAL, AND RELATED METHODS OF OPERATING RADIOS**

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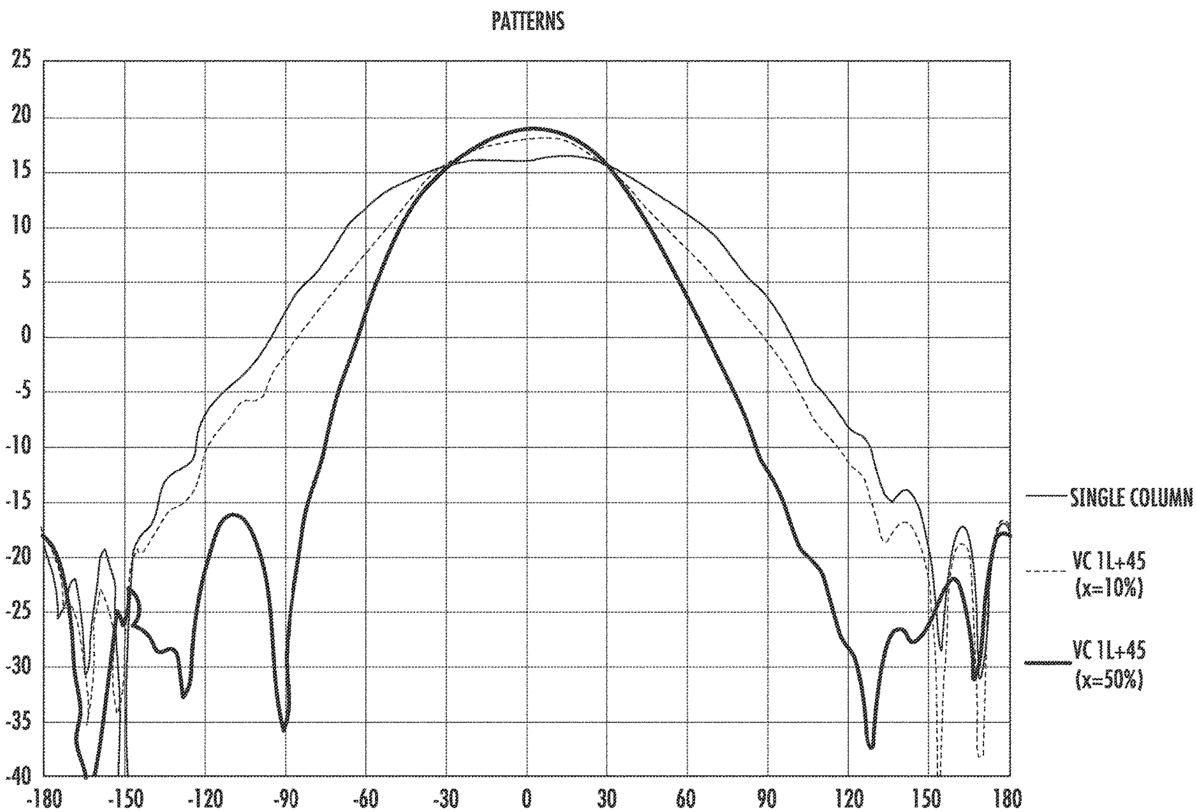
CPC ***H04B 7/06*** (2013.01); ***H01Q 21/24*** (2013.01); ***H03F 3/245*** (2013.01); *H03F 2200/451* (2013.01)

(57) **ABSTRACT**

Methods of operating radios are provided. A method of operating a radio that is coupled to an antenna having a plurality of columns of dual-polarized radiating elements may include splitting radio frequency power within each of a plurality of combinations of first and second data streams. Related radios are also provided.



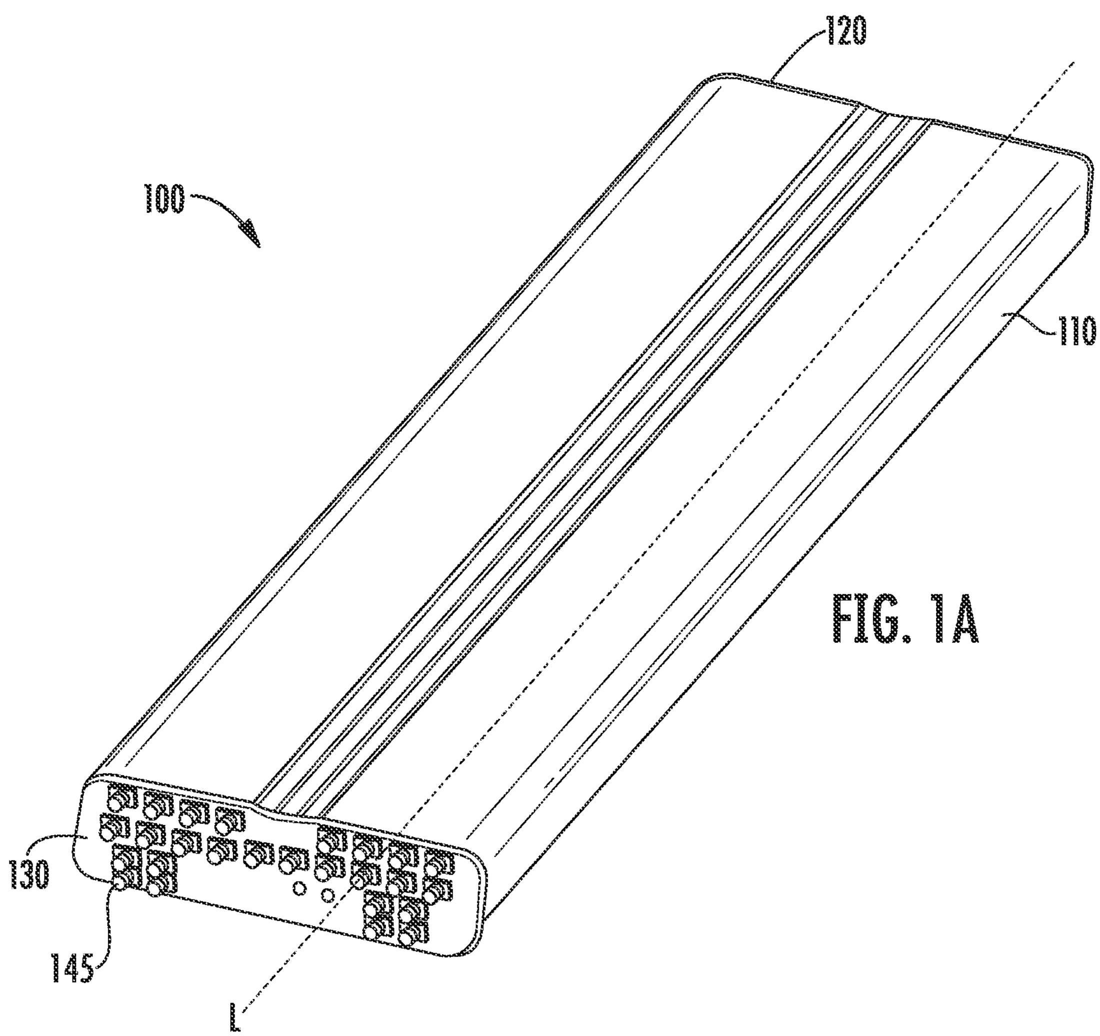


FIG. 1A

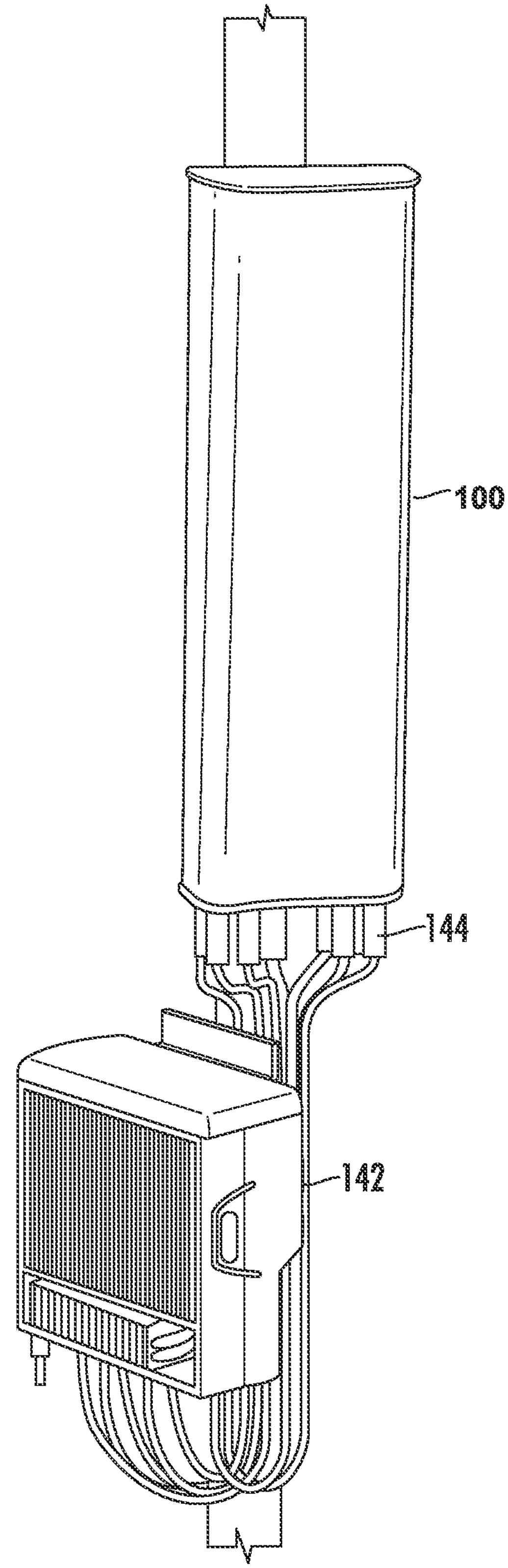
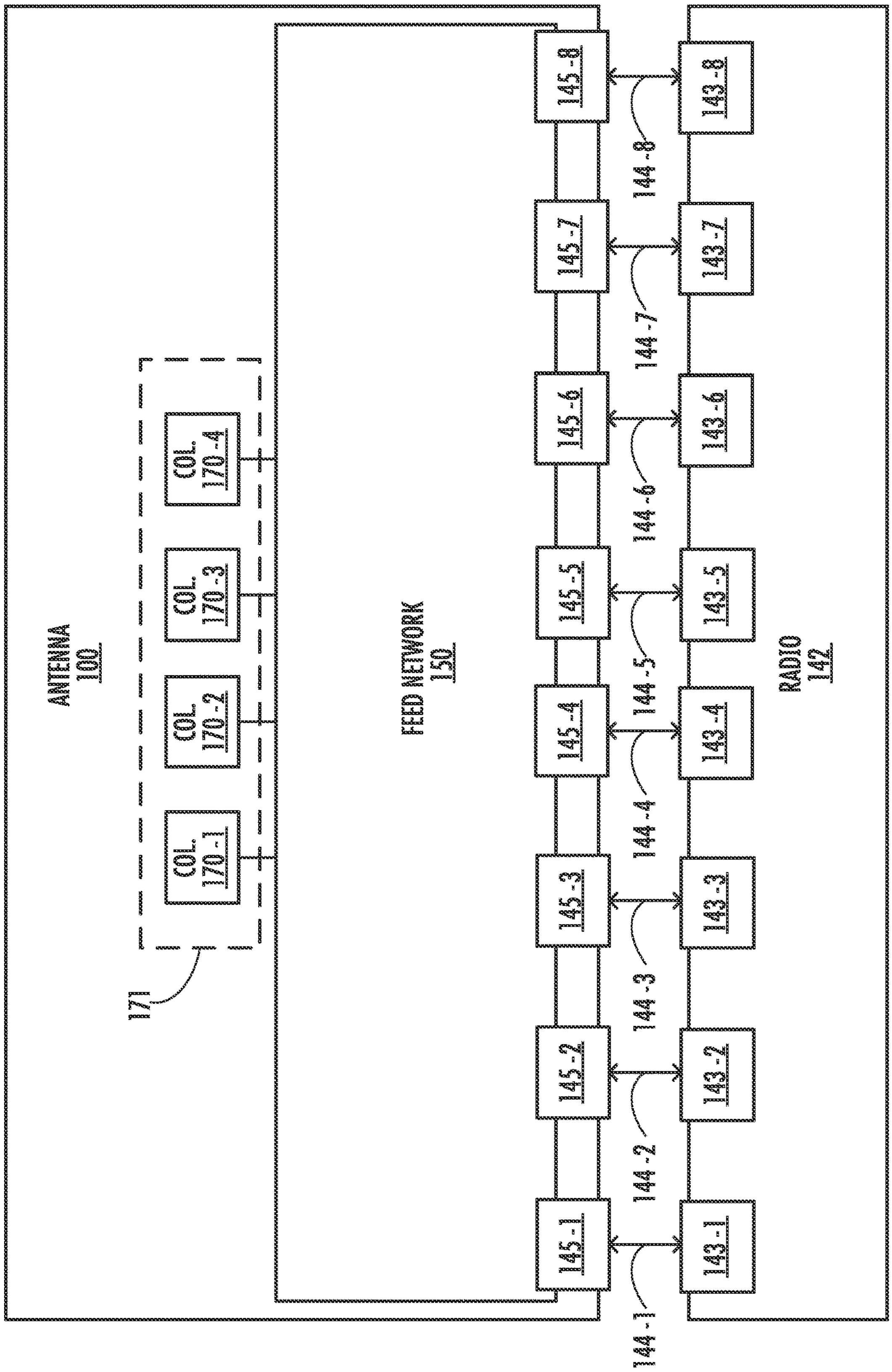
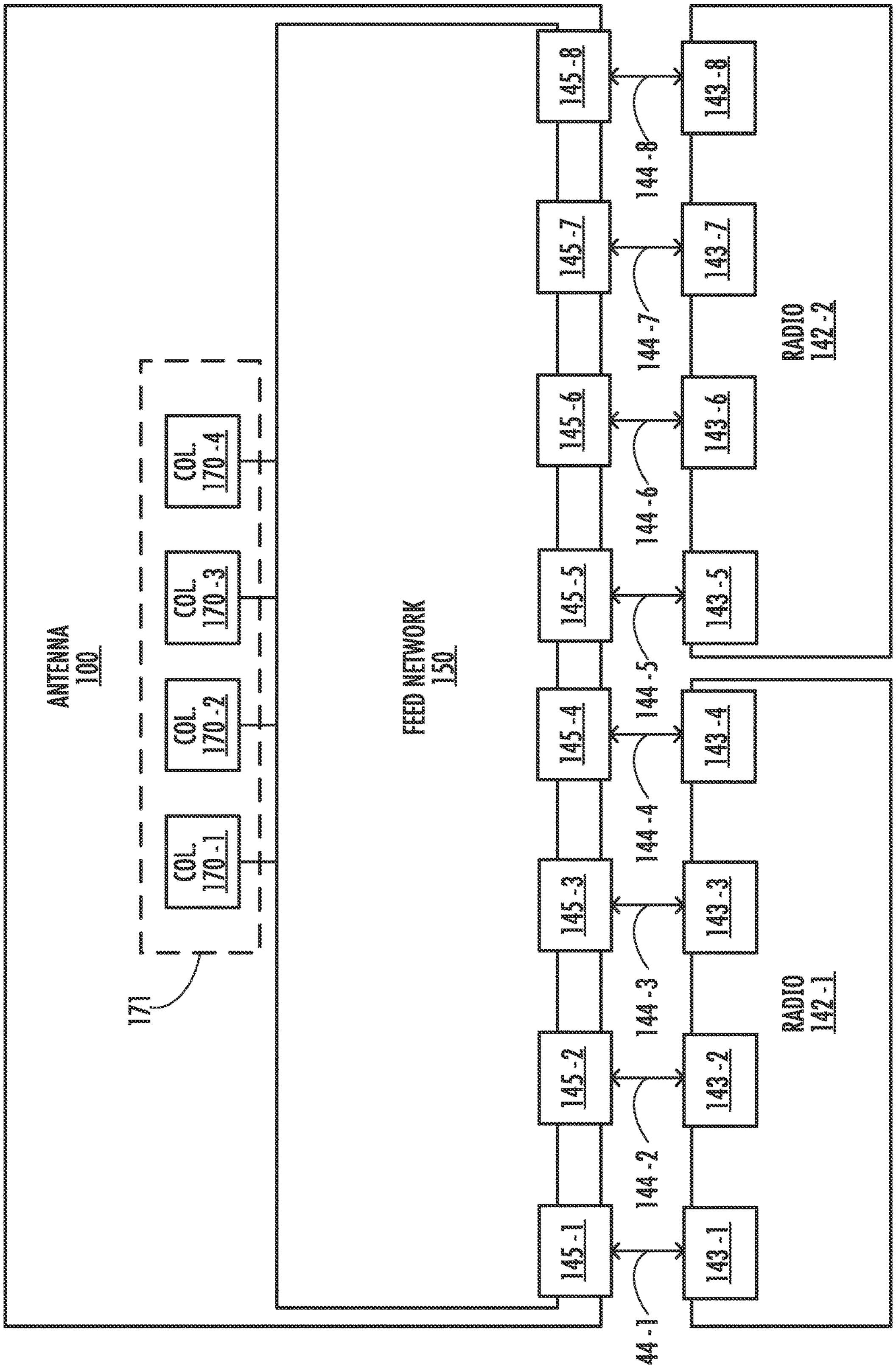


FIG. 1B

FIG. 1C


ANTENNA
100
171
COL.
170-1
COL.
170-2
COL.
170-3
COL.
170-4
FEED NETWORK
150
145-1
145-2
145-3
145-4
145-5
145-6
145-7
145-8
144-1
144-2
144-3
144-4
144-5
144-6
144-7
144-8
143-1
143-2
143-3
143-4
143-5
143-6
143-7
143-8
RADIO
142


ANTENNA
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FEED NETWORK
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COL.
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COL.
170-2
COL.
170-3
COL.
170-4
171
145-1
145-2
145-3
145-4
145-5
145-6
145-7
145-8
144-1
144-2
144-3
144-4
144-5
144-6
144-7
144-8
143-1
143-2
143-3
143-4
143-5
143-6
143-7
143-8
RADIO
142-1
RADIO
142-2

FIG. 1D

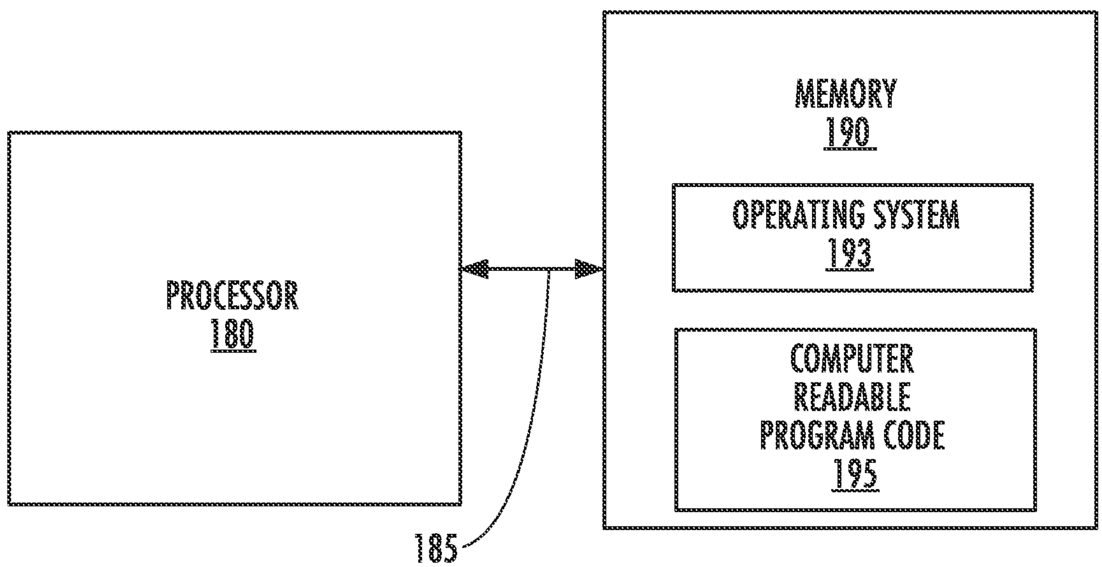

PROCESSOR
180
MEMORY
190
OPERATING SYSTEM
193
COMPUTER
READABLE
PROGRAM CODE
195
185

FIG. 1E

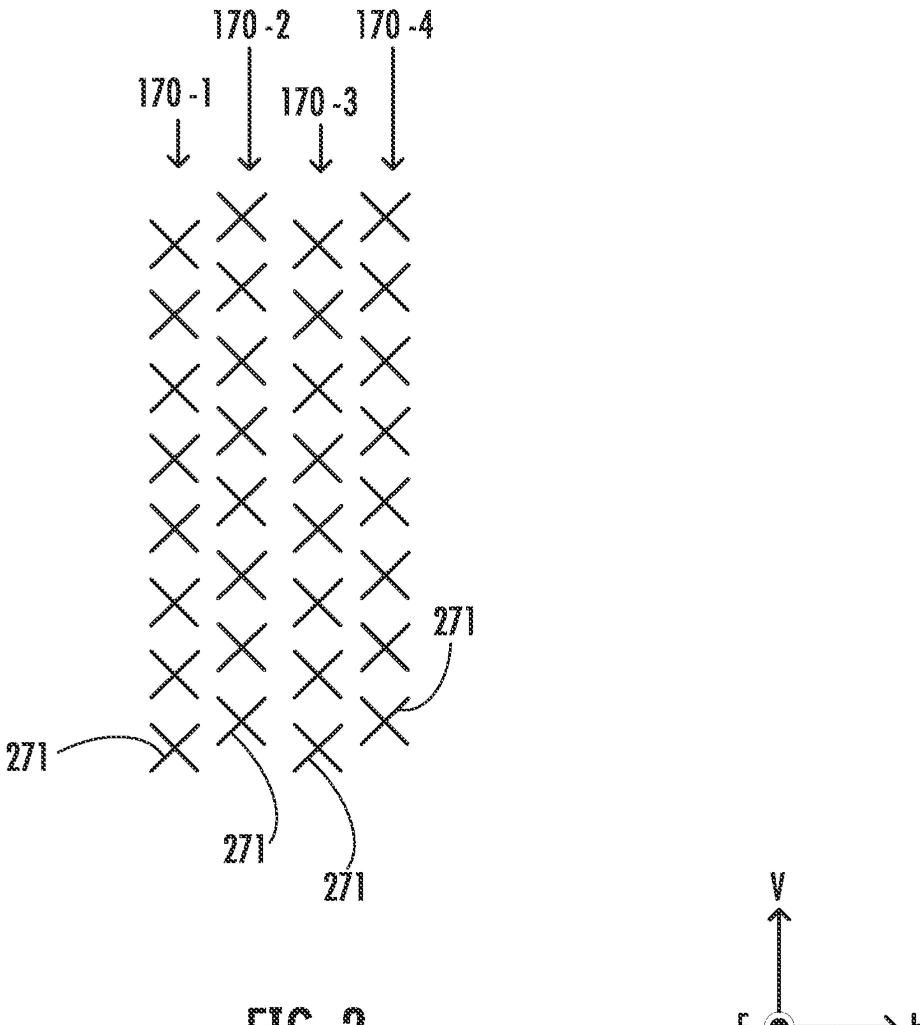


FIG. 2

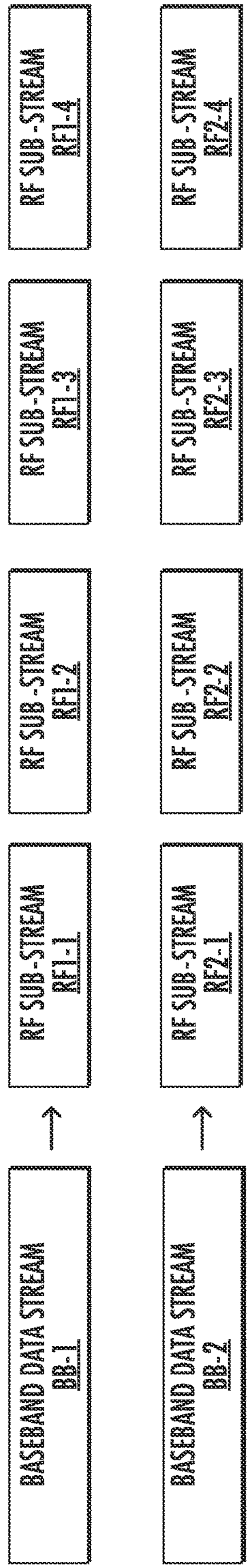
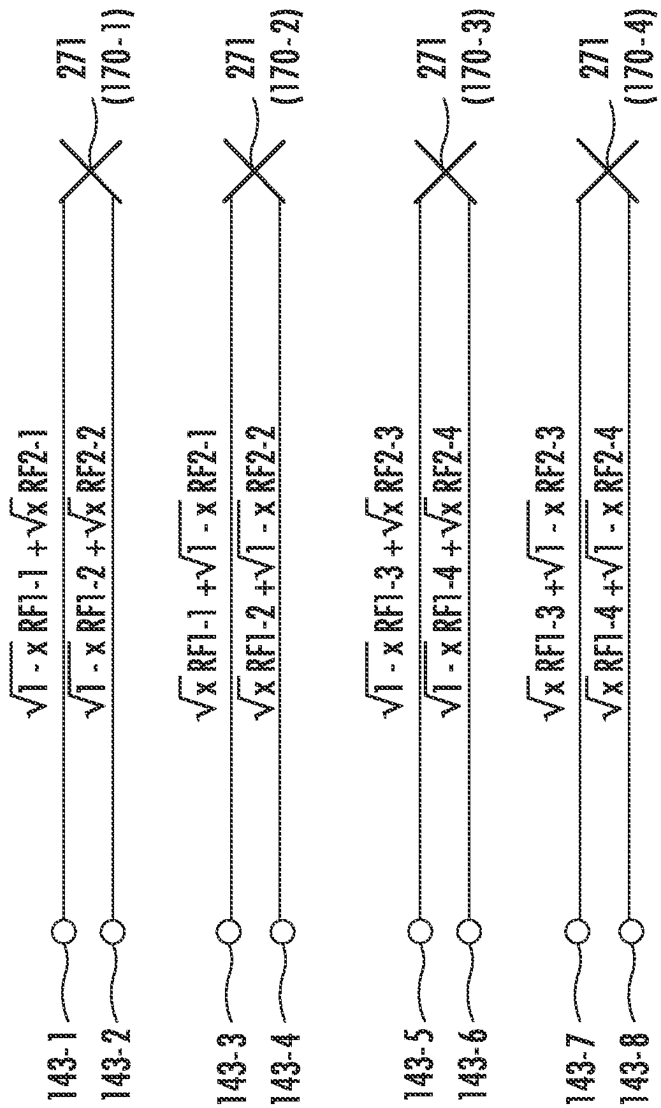

BASEBAND DATA STREAM BB-1
RF SUB-STREAM RF1-1
RF SUB-STREAM RF1-2
RF SUB-STREAM RF1-3
RF SUB-STREAM RF1-4
BASEBAND DATA STREAM BB-2
RF SUB-STREAM RF2-1
RF SUB-STREAM RF2-2
RF SUB-STREAM RF2-3
RF SUB-STREAM RF2-4

FIG. 3A



143-1
143-2
143-3
143-4
143-5
143-6
143-7
143-8
$\sqrt{1-x}$ RF1-1 + $\sqrt{x}$ RF2-1
$\sqrt{1-x}$ RF1-2 + $\sqrt{x}$ RF2-2
$\sqrt{x}$ RF1-1 + $\sqrt{1-x}$ RF2-1
$\sqrt{x}$ RF1-2 + $\sqrt{1-x}$ RF2-2
$\sqrt{1-x}$ RF1-3 + $\sqrt{x}$ RF2-3
$\sqrt{1-x}$ RF1-4 + $\sqrt{x}$ RF2-4
$\sqrt{x}$ RF1-3 + $\sqrt{1-x}$ RF2-3
$\sqrt{x}$ RF1-4 + $\sqrt{1-x}$ RF2-4
271 (170-1)
271 (170-2)
271 (170-3)
271 (170-4)

FIG. 3B

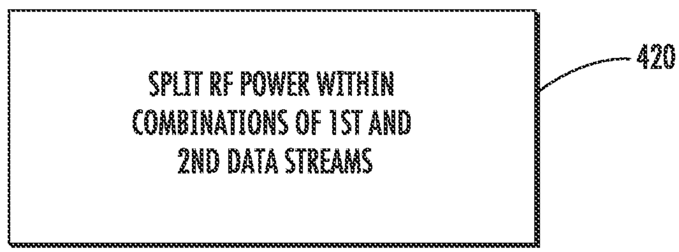

SPLIT RF POWER WITHIN COMBINATIONS OF 1ST AND 2ND DATA STREAMS
420

FIG. 4A

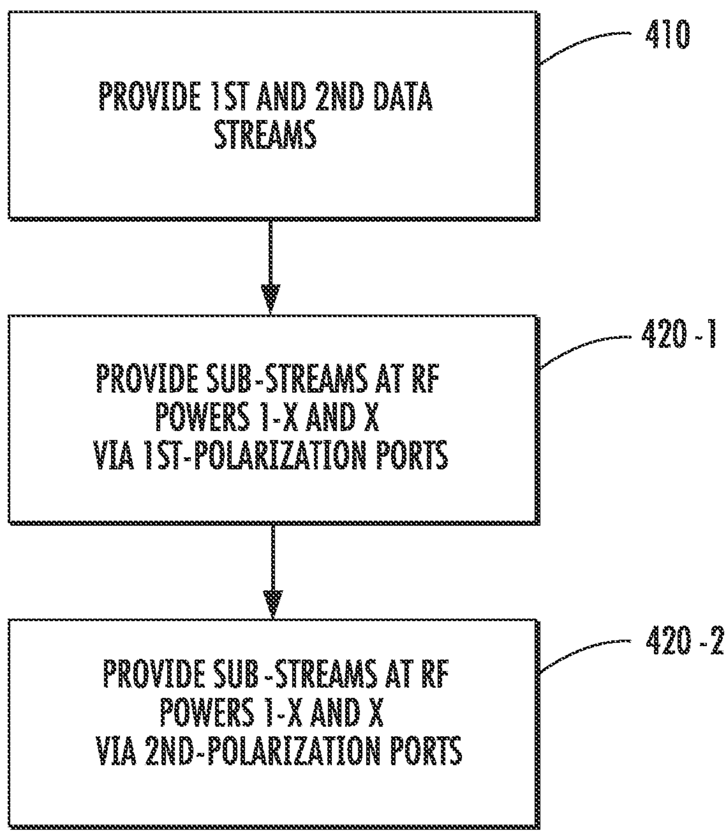

PROVIDE 1ST AND 2ND DATA STREAMS
410
PROVIDE SUB-STREAMS AT RF POWERS 1-X AND X VIA 1ST-POLARIZATION PORTS
420 -1
PROVIDE SUB -STREAMS AT RF POWERS 1-X AND X VIA 2ND-POLARIZATION PORTS
420 -2

FIG. 4B

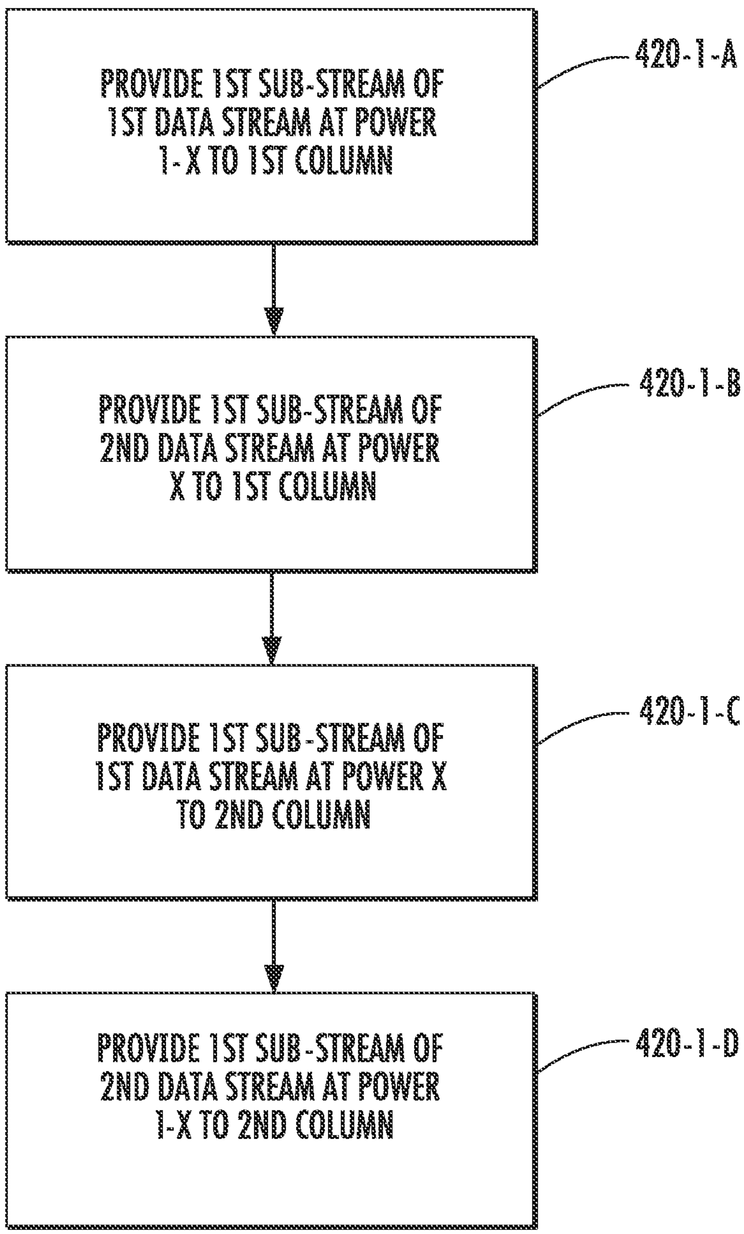

PROVIDE 1ST SUB-STREAM OF 1ST DATA STREAM AT POWER 1-X TO 1ST COLUMN
420-1-A
PROVIDE 1ST SUB-STREAM OF 2ND DATA STREAM AT POWER X TO 1ST COLUMN
420-1-B
PROVIDE 1ST SUB-STREAM OF 1ST DATA STREAM AT POWER X TO 2ND COLUMN
420-1-C
PROVIDE 1ST SUB-STREAM OF 2ND DATA STREAM AT POWER 1-X TO 2ND COLUMN
420-1-D

FIG. 4C

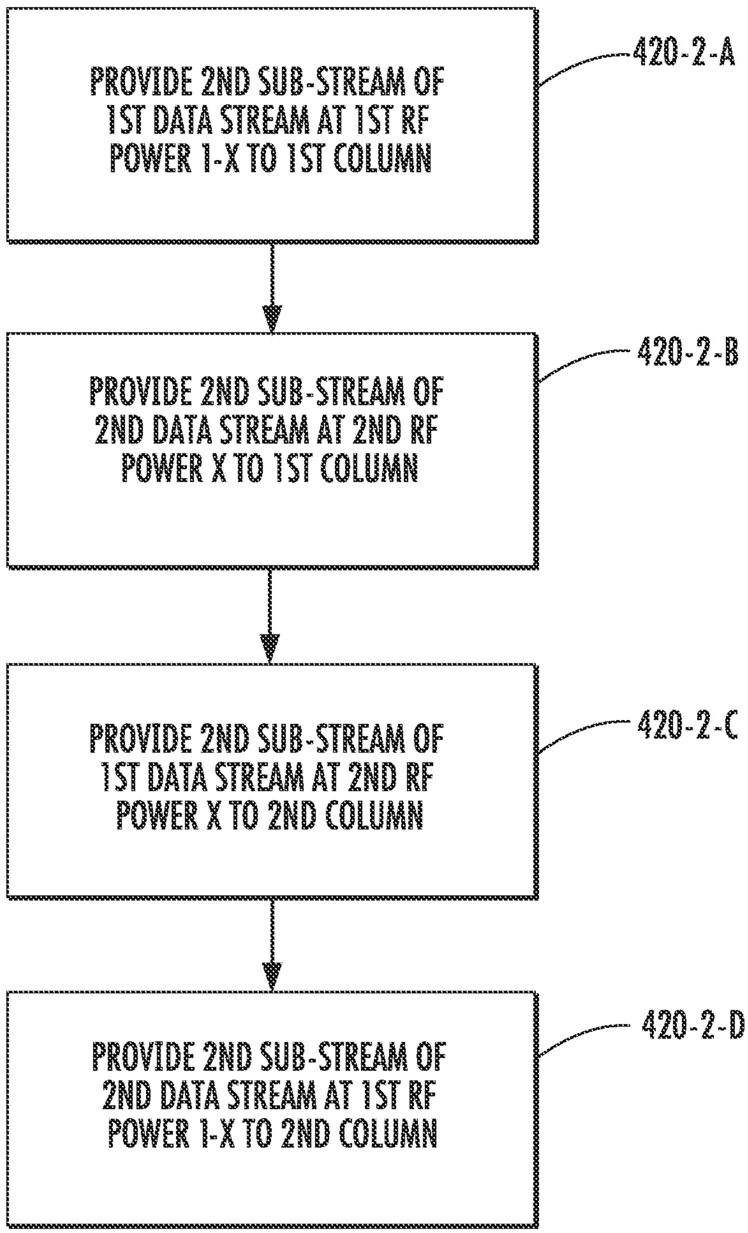

PROVIDE 2ND SUB-STREAM OF 1ST DATA STREAM AT 1ST RF POWER 1-X TO 1ST COLUMN
420-2-A
PROVIDE 2ND SUB-STREAM OF 2ND DATA STREAM AT 2ND RF POWER X TO 1ST COLUMN
420-2-B
PROVIDE 2ND SUB-STREAM OF 1ST DATA STREAM AT 2ND RF POWER X TO 2ND COLUMN
420-2-C
PROVIDE 2ND SUB-STREAM OF 2ND DATA STREAM AT 1ST RF POWER 1-X TO 2ND COLUMN
420-2-D

FIG. 4D

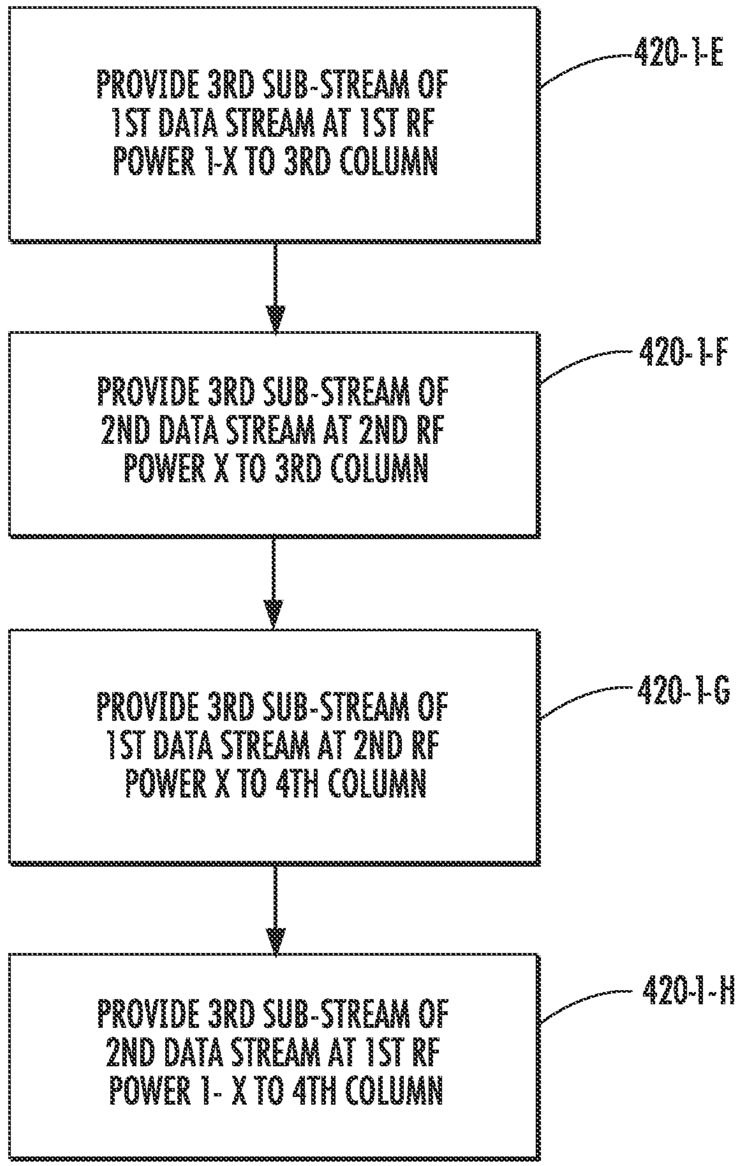

PROVIDE 3RD SUB-STREAM OF 1ST DATA STREAM AT 1ST RF POWER 1-X TO 3RD COLUMN
420-1-E
PROVIDE 3RD SUB-STREAM OF 2ND DATA STREAM AT 2ND RF POWER X TO 3RD COLUMN
420-1-F
PROVIDE 3RD SUB-STREAM OF 1ST DATA STREAM AT 2ND RF POWER X TO 4TH COLUMN
420-1-G
PROVIDE 3RD SUB-STREAM OF 2ND DATA STREAM AT 1ST RF POWER 1- X TO 4TH COLUMN
420-1-H

FIG. 4E

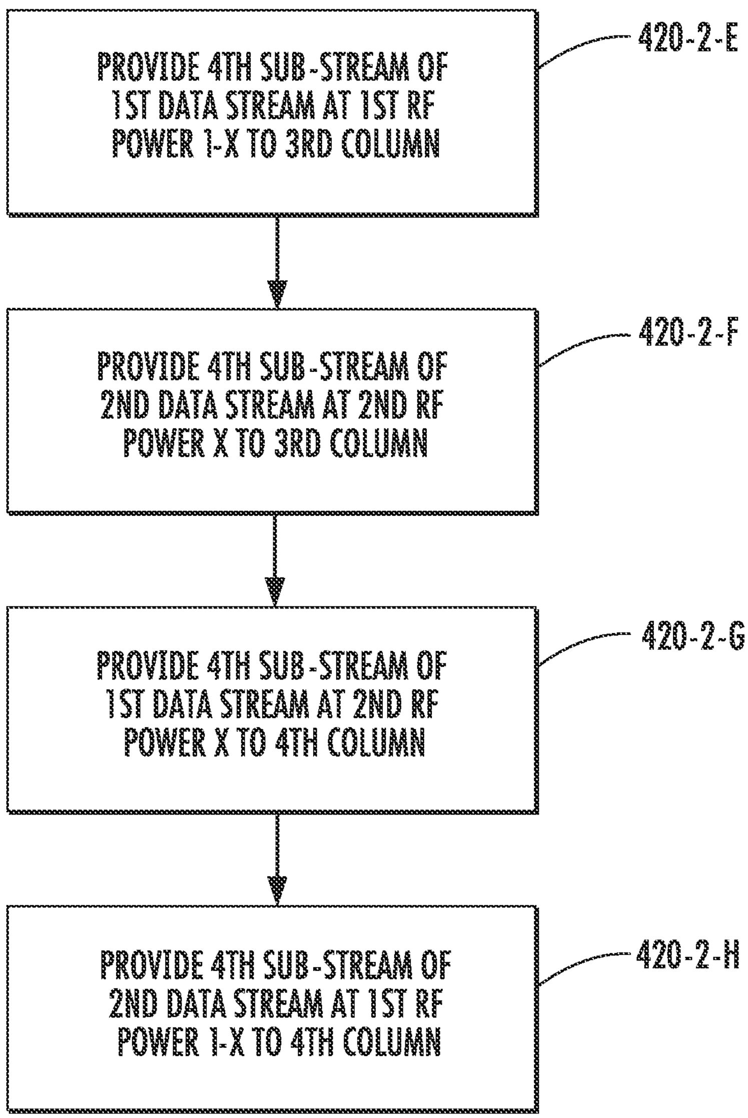

PROVIDE 4TH SUB-STREAM OF 1ST DATA STREAM AT 1ST RF POWER 1-X TO 3RD COLUMN
420-2-E
PROVIDE 4TH SUB-STREAM OF 2ND DATA STREAM AT 2ND RF POWER X TO 3RD COLUMN
420-2-F
PROVIDE 4TH SUB-STREAM OF 1ST DATA STREAM AT 2ND RF POWER X TO 4TH COLUMN
420-2-G
PROVIDE 4TH SUB-STREAM OF 2ND DATA STREAM AT 1ST RF POWER 1-X TO 4TH COLUMN
420-2-H

FIG. 4F

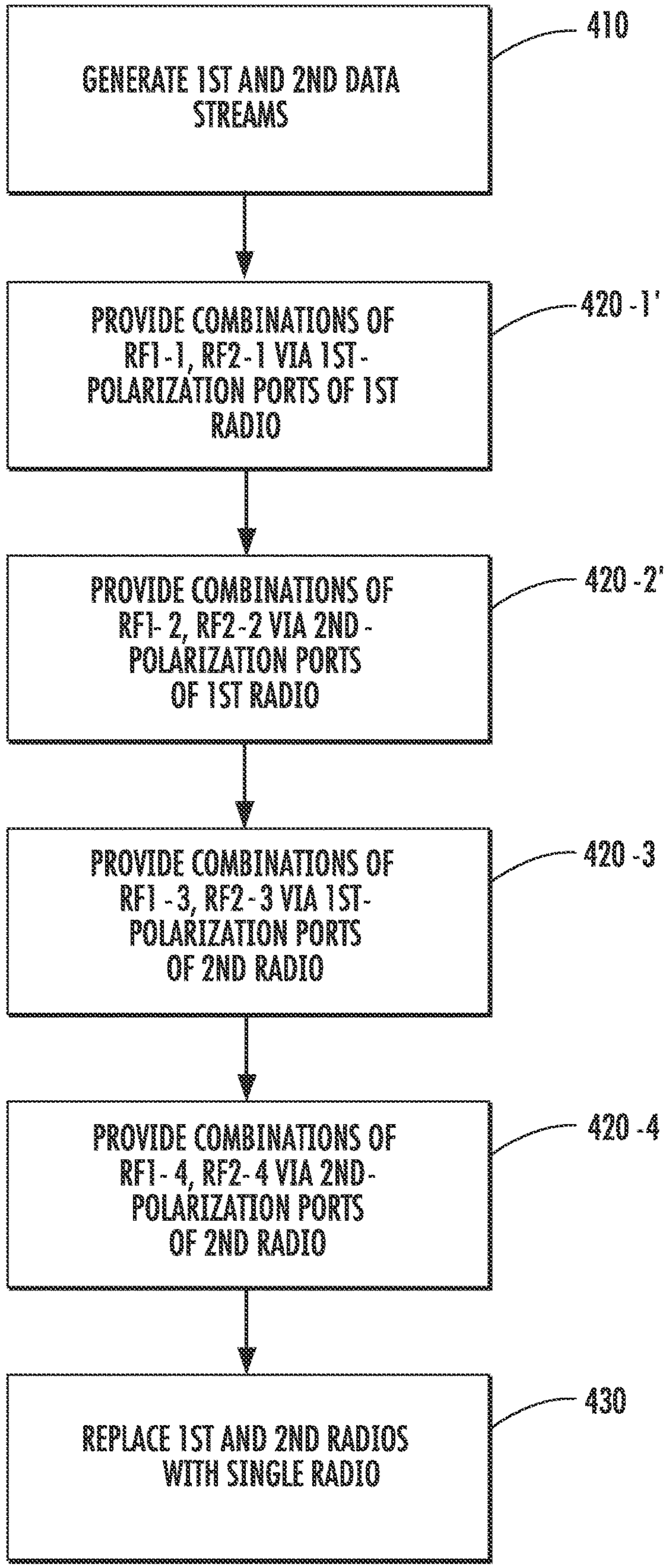

GENERATE 1ST AND 2ND DATA STREAMS
410
PROVIDE COMBINATIONS OF RF1-1, RF2-1 VIA 1ST-POLARIZATION PORTS OF 1ST RADIO
420-1'
PROVIDE COMBINATIONS OF RF1-2, RF2-2 VIA 2ND-POLARIZATION PORTS OF 1ST RADIO
420-2'
PROVIDE COMBINATIONS OF RF1-3, RF2-3 VIA 1ST-POLARIZATION PORTS OF 2ND RADIO
420-3
PROVIDE COMBINATIONS OF RF1-4, RF2-4 VIA 2ND-POLARIZATION PORTS OF 2ND RADIO
420-4
REPLACE 1ST AND 2ND RADIOS WITH SINGLE RADIO
430

FIG. 4G

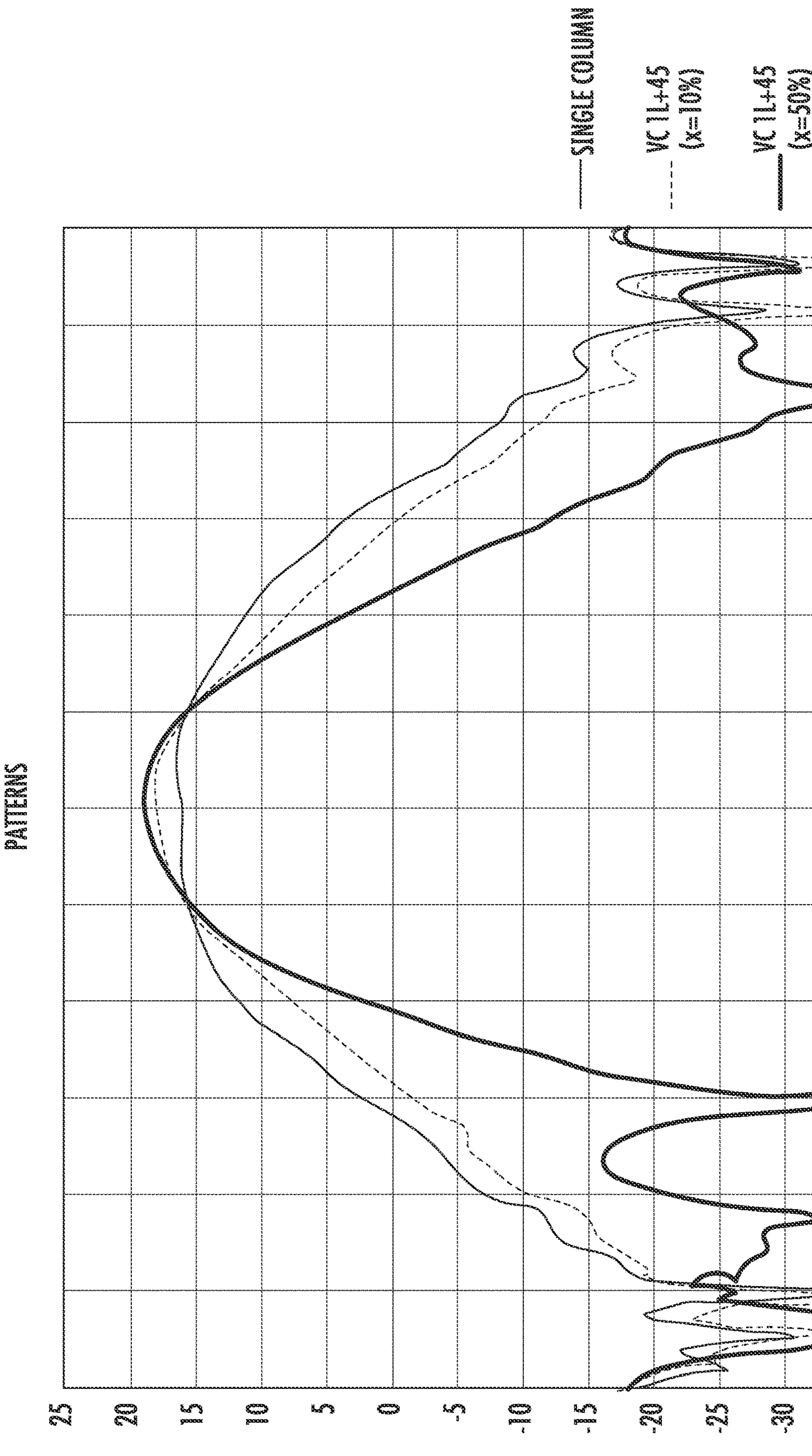

PATTERNS
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
SINGLE COLUMN
VC 1L+45
(x=10%)
VC 1L+45
(x=50%)

FIG. 5

RADIOS CONFIGURED TO SPLIT POWER FOR A COMBINED SIGNAL, AND RELATED METHODS OF OPERATING RADIOS

CROSS-REFERENCE TO PRIORITY APPLICATION

[0001] This application claims priority under 35 U.S.C. § 119 to U.S. Provisional Application No. 63/388,291, filed on Jul. 12, 2022, the disclosure of which is hereby incorporated by reference herein in its entirety.

FIELD

[0002] The present disclosure relates generally to communications systems and, in particular, to radios for cellular communications systems.

BACKGROUND

[0003] Cellular communications systems are well known in the art. In a cellular communications system, a geographic area is divided into a series of regions or "cells" that are served by respective base stations. Each base station may include one or more base station antennas that are configured to provide two-way radio frequency ("RF") communications with subscribers that are within the cell served by the base station. In many cases, each base station is divided into "sectors." In one common configuration, a hexagonally-shaped cell is divided into three 120° sectors in the azimuth plane, and each sector is served by one or more base station antennas that generate radiation patterns of "antenna beams" having azimuth Half Power Beamwidths ("HPBWs") of approximately 65°. Typically, the base station antennas are mounted on a tower or other raised structure, with the antenna beams that are generated by the base station antennas directed outwardly. Base station antennas are often implemented as linear arrays or planar phased arrays of radiating elements.

[0004] To increase capacity, base station antennas that include beamforming arrays and/or arrays that are configured to operate with massive multi-input-multi-output ("MIMO") radios have been introduced in recent years. A beamforming array refers to an antenna array that includes multiple columns of radiating elements. RF signals that are to be transmitted by the beamforming array are broken into sub-components that are transmitted through respective groups, or "sub-arrays," of one or more radiating elements. The amplitudes and phases of the sub-components are adjusted by the radio so that the beamforming array generates antenna beams having reduced (narrower) beamwidths in, for example, the horizontal or "azimuth" plane, which increases the directivity or "gain" of the antenna, thereby increasing the supportable throughput. MIMO refers to a communication technique in which a data stream is broken into pieces that are simultaneously transmitted using certain coding techniques over multiple relatively uncorrelated transmission paths between a transmitting station and a receiving station. Multi-column antenna arrays may be used for MIMO transmissions, where each column in the array may be connected to a port of a MIMO radio and used to transmit/receive one of the multiple data streams. In practice, as orthogonal polarizations tend to be highly uncorrelated, the radiating elements in a MIMO array are typically implemented as dual-polarized radiating elements, allowing each column in the MIMO array to be connected to two ports on the radio (where the first port is connected to the first-polarization radiators of the radiating elements in the column, and the second port is connected to the second-polarization radiators of the radiating elements in the column). This technique can effectively halve the number of columns of radiating elements required, as each physical column of the array contains two independent columns of radiators.

[0005] A beamforming 8-Transmit/8-Receive ("8T8R") antenna array (which is coupled to eight antenna ports), however, may have small spacing between its four physical columns of radiating elements. As a result, radiation patterns of individual columns of the beamforming 8T8R antenna array may have a larger azimuth HPBW (e.g., 90-100°) and a lower gain than a conventional sector antenna, which may have a 4-Transmit/4-Receive ("4T4R") antenna array (which is coupled to four antenna ports).

SUMMARY

[0006] A radio, according to some embodiments, may include a plurality of first-polarization RF ports that are configured to be coupled to respective first-polarization RF ports of an antenna that are coupled to a plurality of columns, respectively, of dual-polarized radiating elements of the antenna. Moreover, the radio may include a plurality of second-polarization RF ports that are configured to be coupled to respective second-polarization RF ports of the antenna that are coupled to the columns, respectively. The first polarization may be different from the second polarization. A first of the first-polarization RF ports of the radio may be configured to provide to a first of the columns: a first RF sub-stream of a first baseband data stream at a first RF power; and a first RF sub-stream of a second baseband data stream at a second RF power.

[0007] In some embodiments, the radio may be configured to generate the first RF sub-stream of the first baseband data stream and the first RF sub-stream of the second baseband data stream in first and second frequency bands, respectively, that are different from each other.

[0008] According to some embodiments, the first and second RF powers may collectively equal 100% of a total amplification power of a power amplifier coupled to the first of the first-polarization RF ports of the radio. Moreover, the first and second RF powers may be represented by $1-x$ and x, respectively, and x may be a positive non-zero value that is less than 1.

[0009] In some embodiments, a second of the first-polarization RF ports of the radio may be configured to provide to a second of the columns: the first RF sub-stream of the first baseband data stream at the second RF power; and the first RF sub-stream of the second baseband data stream at the first RF power. Moreover, first of the second-polarization RF ports of the radio may be configured to provide to the first of the columns: a second RF sub-stream of the first baseband data stream at the first RF power; and a second RF sub-stream of the second baseband data stream at the second RF power.

[0010] According to some embodiments, a second of the second-polarization RF ports of the radio may be configured to provide to the second of the columns: the second RF sub-stream of the first baseband data stream at the second RF power; and the second RF sub-stream of the second baseband data stream at the first RF power. Moreover, the radio may be configured to multiply each RF sub-stream of each of the first and second baseband data streams by a respective complex scalar representing magnitude and phase.

[0011] In some embodiments, the first and second of the columns may be consecutive columns. The first and second of the first-polarization RF ports of the antenna may be coupled to the first and second of the columns, respectively. The first and second of the second-polarization RF ports of the antenna may be coupled to the first and second of the columns, respectively. Moreover, the radio may be a first of a plurality of radios that are configured to be coupled to the antenna, and a second of the radios may be configured to provide to a third and a fourth of the columns: a third RF sub-stream of the first baseband data stream together with a third RF sub-stream of the second baseband data stream; and a fourth RF sub-stream of the first baseband data stream together with a fourth RF sub-stream of the second baseband data stream.

[0012] A method of operating a radio that is coupled to an antenna having a plurality of columns of dual-polarized radiating elements may be provided according to some embodiments. The method may include providing to a first of the columns via a first of a plurality of first-polarization ports of the radio: a first RF sub-stream of a first baseband data stream at a first RF power; and a first RF sub-stream of a second baseband data stream at a second RF power.

[0013] In some embodiments, the method may include generating the first RF sub-stream of the first baseband data stream and the first RF sub-stream of the second baseband data stream in first and second frequency bands, respectively, that are different from each other.

[0014] According to some embodiments, the first and second RF powers may collectively equal 100% of a total amplification power of a power amplifier coupled to the first of the first-polarization RF ports of the radio. Moreover, the first and second RF powers may be represented by $1-x$ and x, respectively, and x may be a positive non-zero value that is less than 1.

[0015] In some embodiments, the method may include providing to a second of the columns via a second of the first-polarization ports: the first RF sub-stream of the first baseband data stream at the second RF power; and the first RF sub-stream of the second baseband data stream at the first RF power. Moreover, the radio may multiply each RF sub-stream of each of the first and second baseband data streams by a respective complex scalar representing magnitude and phase.

[0016] According to some embodiments, the method may include providing to the first of the columns via a first of a plurality of second-polarization ports of the radio: a second RF sub-stream of the first baseband data stream at the first RF power; and a second RF sub-stream of the second baseband data stream at the second RF power. The second polarization may be different from the first polarization.

[0017] In some embodiments, the method may include providing to the second of the columns via a second of the second-polarization ports: the second RF sub-stream of the first baseband data stream at the second RF power; and the second RF sub-stream of the second baseband data stream at the first RF power. Moreover, the first and second of the columns may be consecutive columns.

[0018] According to some embodiments, the radio may be a first radio, and the method may include splitting, by a second radio, RF power by providing: a third RF sub-stream of the first baseband data stream together with a third RF sub-stream of the second baseband data stream; and a fourth RF sub-stream of the first baseband data stream together with a fourth RF sub-stream of the second baseband data stream. Moreover, the method may include replacing the first and second radios with a single radio that is coupled to the first through fourth of the columns.

[0019] In some embodiments, the radio may be a 4T4R radio.

[0020] A radio, according to some embodiments, may be configured to distribute a total amplification power for each of a plurality of RF ports of the radio among a plurality of RF sub-streams. For example, each of the RF ports may be configured to output together a first RF power and a second RF power that collectively equal 100% of the total amplification power.

[0021] In some embodiments, the radio may include first through fourth of the RF ports, the first and third of the RF ports may be configured to be coupled to consecutive first and second columns, respectively, of radiating elements of an antenna, and the RF sub-streams may include a plurality of RF sub-streams of a first baseband data stream and a plurality of RF sub-streams of a second baseband data stream. Moreover, distributing the total amplification power may include outputting: a first of the RF sub-streams of the first baseband data stream at the first RF power and a first of the RF sub-streams of the second baseband data stream at the second RF power, to the first column via the first of the RF ports; and the first of the RF sub-streams of the first baseband data stream at the second RF power and the first of the RF sub-streams of the second baseband data stream at the first RF power, to the second column via the third of the RF ports.

[0022] According to some embodiments, the radiating elements may be respective dual-polarized radiating elements, the first and third of the RF ports may have a first polarization, and the second and fourth of the RF ports may have a second polarization that is different from the first polarization. Moreover, the second and fourth of the RF ports may be configured to be coupled to the consecutive first and second columns, respectively.

[0023] In some embodiments, the radio may be configured to generate the first of the RF sub-streams of the first baseband data stream and the first of the RF sub-streams of the second baseband data stream in first and second frequency bands, respectively, that are different from each other.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] FIG. **1**A is a front perspective view of a base station antenna, according to embodiments of the present invention.

[0025] FIG. **1**B is a front perspective view of the base station antenna of FIG. **1**A electrically connected to a radio.

[0026] FIG. **1**C is a schematic block diagram of ports of the base station antenna of FIG. **1**A electrically connected to ports of the radio of FIG. **1**B.

[0027] FIG. **1**D is a schematic block diagram of ports of the base station antenna of FIG. **1**A electrically connected to ports of two radios.

[0028] FIG. **1**E is a block diagram that illustrates details of an example processor and memory that may be used in accordance with various embodiments.

[0029] FIG. **2** is an example schematic front view of the four-column beamforming array included in the antenna of FIG. **1**A.

[0030] FIG. **3**A is a schematic diagram of sub-streams of a plurality of data streams.

[0031] FIG. **3**B is a schematic diagram of combinations of the sub-streams of FIG. **3**A that are output through each of the radio ports of FIG. **1**C (or FIG. **1**D) to the columns of FIG. **2**.

[0032] FIGS. **4**A-**4**G are flowcharts illustrating operations of splitting RF power within each of the RF sub-stream combinations shown in FIG. **3**B.

[0033] FIG. **5** is a graph illustrating radiation patterns of columns of FIG. **2** according to different examples.

DETAILED DESCRIPTION

[0034] The use of MIMO transmission techniques can significantly increase the throughput supported by a base station antenna. Moreover, the greater the number of independent data streams, the greater the increase in throughput. Four-column arrays of dual polarized radiating element can support "8T8R" MIMO communication (where "8T" indicates eight separate sub-streams for transmissions from the base station antenna and "8R" means that the base station antenna can receive eight separate sub-streams).

[0035] Unfortunately, there are some cases where there are limitations on the effective isotropic radiated power ("EIRP") of the antenna beams generated by a base station antenna. Given the enhanced gain provided by the beamforming array and the eight ports on the radio (each of which has a separate power amplifier), the EIRP of an 8T8R array coupled to an 8T8R radio may be very large, and may exceed the EIRP constraints, thus precluding the use of the 8T8R radio in this situation.

[0036] While 8T8R radios are not currently configured to allow an operator to limit the maximum EIRP, it is quite possible that future 8T8R radios will include a software or hardware "fix" that allows an operator to specify a maximum EIRP. It is also possible that the EIRP constraints may be relaxed in the future.

[0037] If an operator believes that the EIRP constraints may be lifted in the future, or may be solved by a software fix to the 8T8R radio, it may make sense to use the 8T8R radio and the four-column array of radiating elements to support two 4T4R systems. This could be accomplished, for example, by using the left two columns of the array for the first 4T4R system and the right two columns of the array for the second 4T4R system. Two 4T4R radios could be used to support such a "dual 4T4R" approach, or a single 8T8R radio may be used that can be configured to operate either as an 8T8R radio or as two 4T4R radios (such radios are commercially available). However, when the dual 4T4R approach is used, the individual antenna beams generated by each column tend to have rather large azimuth HPBWs such as azimuth HPBWs of about 90°-100°. These wider antenna beams result in lower gain than would be achieved with conventional columns of radiating elements that are designed to have azimuth HPBWs of about 65°. The lower gain results in reduced system performance. The wider antenna beams will also extend outside of a 120° sector, creating interference with additional sectors.

[0038] There are also situations where an operator is not willing to deploy an 8T8R radio due to the current cost of such radios, and may instead deploy two 4T4R systems. The base station antennas used with such systems would include four linear arrays of radiating elements that are configured as sector arrays that each generate antenna beams having azimuth HPBWs of about 65°. If the operator later wants to upgrade to an 8T8R system, it will be necessary to not only replace the two 4T4R radios, but also to replace the base station antenna, since the 8T8R radio is designed to work with a four-column beamforming array that has four more closely spaced columns of (smaller) radiating elements, where each column generates individual antenna beams having an azimuth HPBW of about 90°-100°. It would be advantageous if 8T8R antenna arrays were available that could be used with 4T4R radios and provide suitable gain, as this would allow an operator to deploy base station antennas that had 8T8R antenna arrays. These antennas could initially be used with two 4T4R radios, and later could be used with an 8T8R radio. In other words, such radios would provide operators with greater flexibility and allow them to use the same base station antenna with different radio combinations.

[0039] Pursuant to embodiments of the present invention, radios are provided that can, in conjunction with a multi-column array of radiating elements, generate antenna beams having narrowed azimuth HPBW and/or increased gain. Moreover, 100% of the power generated by the radio may be used (thus achieving zero power loss) by distributing the total power (e.g., total power level) among two RF sub-streams that are output at a radio port. Thus, even though radiation patterns of an 8T8R antenna array typically have a larger HPBW (e.g., 90° or more) than radiation patterns of a conventional 4T4R antenna array (e.g., an HPBW of about 65°), radios according to embodiments of the present invention can narrow the HPBW of radiation patterns of an 8T8R antenna array to about 65° or smaller by outputting combinations of sub-streams at radio ports. As an example, the radios can achieve narrower HPBW by selectively applying respective power levels (e.g., by applying different digital amplitude weights) to the sub-streams of a combination. The radios can also increase gain (e.g., by more than 1 decibel ("dB")) by outputting the combinations of sub-streams.

[0040] Example embodiments of the present invention will be described in greater detail with reference to the attached figures.

[0041] FIG. **1**A is a front perspective view of a base station antenna **100**, according to embodiments of the present invention. The antenna **100** may be, for example, a cellular base station antenna at a macrocell base station or at a small cell base station. As shown in FIG. **1**A, the antenna **100** is an elongated structure and has a generally rectangular shape. The antenna **100** includes a radome **110**. In some embodiments, the antenna **100** further includes a top end cap **120** and/or a bottom end cap **130**. The bottom end cap **130** may include a plurality of RF connectors **145** mounted therein. The connectors **145**, which may also be referred to herein as RF "ports," are not limited, however, to being located on the bottom end cap **130**. Rather, one or more of the connectors **145** may be provided on, for example, the rear (i.e., back) side of the radome **110** that is opposite the front side of the radome **110**. The antenna **100** is typically mounted in a vertical configuration (i.e., the long side of the antenna **100** extends along a vertical axis L with respect to Earth).

[0042] FIG. **1**B is a front perspective view of the base station antenna **100** electrically connected to a radio **142** by RF transmission lines **144**, such as coaxial cables. For example, the radio **142** may be a cellular base station radio, and the antenna **100** and the radio **142** may be located at (e.g., may be components of) a cellular base station. In some cases, the radio **142** may be mounted on the back surface of the antenna **100** rather than below the antenna **100**. According to some embodiments, a single radio **142** may be coupled to the antenna **100**. In other embodiments, multiple radios **142** may be coupled to the antenna **100**. Moreover, each radio **142** may be a beamforming radio.

[0043] FIG. **1**C is a schematic block diagram of ports **145** of the base station antenna **100** electrically connected to respective ports **143** of the radio **142**. As shown in FIG. **1**C, ports **145-1** through **145-8** of the antenna **100** are electrically connected to ports **143-1** through **143-8**, respectively, of the radio **142** by respective RF transmission lines **144-1** through **144-8**, such as coaxial cables.

[0044] The antenna **100** may include arrays (e.g., vertical columns) **170-1** through **170-4** of radiating elements **271** (FIG. **2**) that are configured to transmit and/or receive RF signals. The four columns **170-1** through **170-4** may together constitute a beamforming array **171** that is suitable for use with an 8T8R radio. The antenna **100** may also include a feed network **150** that is coupled between the columns **170** and the radio **142**. For example, the columns **170** may be coupled to respective RF transmission paths (e.g., including one or more RF transmission lines) of the feed network **150**.

[0045] In some embodiments, the feed network **150** may include feed circuitry that is coupled between the ports **145** and the columns **170**. The feed circuitry can couple downlink RF signals from the radio **142** to radiating elements **271** that are in columns **170**. The feed circuitry may also couple uplink RF signals from radiating elements **271** that are in columns **170** to the radio **142**. For example, the feed circuitry may include power dividers, RF switches, RF couplers, and/or RF transmission lines.

[0046] Moreover, the antenna **100** may include phase shifters that are used to electronically adjust the tilt angle of the antenna beams generated by each column **170**. The phase shifters may be located at any appropriate location along the RF transmission paths that extend between the ports **145** and the columns **170**. Accordingly, though omitted from view in FIG. **1**C for simplicity of illustration, the feed network **150** may include phase shifters.

[0047] For simplicity of illustration, FIG. **1**C (and FIG. **1**D, discussed below) only illustrates the four columns **170-1** through **170-4** of radiating elements **271** that form the 8T8R beamforming array **171**. It will be appreciated that the base station antenna **100** may include additional arrays of radiating elements and additional RF ports that are not shown in FIG. **1**C.

[0048] FIG. **1**D is a schematic block diagram of ports **145** of the base station antenna **100** of FIG. **1**A electrically connected to ports **143** of first and second radios **142-1**, **142-2**. Each radio **142** may be a 4T4R radio. As shown in FIG. **1**D, the first radio **142-1** may have four ports **143-1** through **143-4** that are coupled to four ports **145-1** through **145-4**, respectively, of the antenna **100**. Moreover, the second radio **142-2** may have four ports **143-5** through **143-8** that are coupled to four ports **145-5** through **145-8**, respectively, of the antenna **100**.

[0049] FIG. **1**E is a block diagram that illustrates details of an example processor **180** and memory **190** that may be used in accordance with various embodiments. The processor **180** communicates with the memory **190** via an address/data bus **185**. The processor **180** may be, for example, a commercially available or custom microprocessor. Moreover, the processor **180** may include multiple processors. The memory **190** may be a non-transitory computer readable storage medium and may be representative of the overall hierarchy of memory devices containing the software and data used to implement various functions of a radio **142** (FIG. **1**B) as described herein. For example, the radio **142** may comprise the processor **180** and the memory **190**. The memory **190** may include, but is not limited to, the following types of devices: cache, ROM, PROM, EPROM, EEPROM, flash, static RAM ("SRAM"), and dynamic RAM ("DRAM").

[0050] As shown in FIG. **1**E, the memory **190** may hold various categories of software and data, such as computer readable program code **195** and/or an operating system **193**. The operating system **193** controls operations of the radio **142**. In some embodiments, the operating system **193** may manage the resources of the radio **142** and may coordinate execution of various programs by the processor **180**. For example, the computer readable program code **195**, when executed by a processor **180** of the radio **142**, may cause the processor **180** to perform any of the operations illustrated in the flowcharts of FIGS. **4**A-**4**F (as well as operations illustrated in Blocks **410** through **420-2'**, or Blocks **420-3** and **420-4**, of FIG. **4**G). Accordingly, the processor **180** may be coupled to, and configured to control, various RF hardware/circuitry of the radio **142**, such as one or more RF signal sources (e.g., one or more RF oscillators), one or more RF amplifiers, and/or one or more RF mixers/combiners. For simplicity of illustration, however, such hardware/circuitry is omitted from view in FIG. **1**E.

[0051] FIG. **2** is an example schematic front view of the 8T8R beamforming array **171** (FIGS. **1**C and **1**D) of the base station antenna **100** of FIG. **1**A. The beamforming array **171** includes four vertical columns **170-1** through **170-4** of radiating elements **271**. The four physical vertical columns are spaced apart from each other in a horizontal direction H. Each vertical column **170** of radiating elements **271** may extend in a vertical direction V from a lower portion of the antenna **100** to an upper portion of the antenna **100**. The vertical direction V may be, or may be parallel with, the longitudinal axis L (FIG. **1**A). The vertical direction V may also be perpendicular to the horizontal direction H and a forward direction F. As used herein, the term "vertical" does not necessarily require that something is exactly vertical (e.g., the antenna **100** may have a small mechanical downtilt).

[0052] The columns **170** are each configured to transmit and/or receive RF signals in one or more frequency bands, such as one or more bands comprising frequencies between 2,350 megahertz ("MHz") and 2,390 MHz. Though FIG. **2** illustrates four columns **170-1** through **170-4**, the antenna **100** may include more columns **170**. For example, in other embodiments, the techniques disclosed herein could be used with an eight-column array so that this array could be used with two 8T8R radios or one 16T16R radio. Moreover, the number of radiating elements **271** in a column **170** can be any quantity from two to twenty or more. For example, the four columns **170-1** through **170-4** shown in FIG. **2** may each have five to twenty radiating elements **271**. In some embodiments, the columns **170** may each have the same number (e.g., eight) of radiating elements **271**.

[0053] FIG. **3**A is a schematic diagram of sub-streams of two data streams. As shown in FIG. **3**A, first through fourth RF sub-streams RF**1-1** through RF**1-4** may be generated from a first baseband data stream BB-**1**. Similarly, first through fourth RF sub-streams RF**2-1** through RF**2-4** may be generated from a second baseband data stream BB-**2**. For example, a radio **142** (FIG. **1**B) may divide each of the first and second baseband data streams BB-**1**, BB-**2** into first through fourth baseband sub-streams, and then may convert the first through fourth baseband sub-streams of the first baseband data stream BB-**1** into the first through fourth RF sub-streams RF**1-1** through RF**1-4**, respectively, and convert the first through fourth baseband sub-streams of the second baseband data stream BB-**2** into the first through fourth RF sub-streams RF**2-1** through RF**2-4**. Each RF sub-stream may comprise a respective RF signal.

[0054] In some embodiments, a single radio **142** may provide both the first baseband data stream BB-**1** and the second baseband data stream BB-**2**. For example, an 8T8R radio may provide two 4T4R data streams. In other embodiments, the first baseband data stream BB-**1** can be generated by a first 4T4R radio and the second baseband data stream BB-**2** can be generated by a second 4T4R radio. Moreover, when two 4T4R radios are used, each 4T4R radio may provide half of the RF sub-streams of each baseband data stream. As an example, a first 4T4R radio may provide the four RF sub-streams RF**1-1**, RF**2-1**, RF**1-2**, and RF**2-2**, and a second 4T4R radio may provide the four RF sub-streams RF**1-3**, RF**2-3**, RF**1-4**, and RF**2-4**.

[0055] Embodiments of the present invention take advantage of the fact that the radio can be programmed to transmit each RF sub-stream through two of the columns **170** instead of through just a single column **170**. For example, RF sub-stream RF **1-1** may be transmitted through both the first column **170-1** and through the second column **170-2**. Since RF sub-stream RF **1-1** is transmitted through two horizontally spaced apart columns, the combined antenna beam corresponding to the portion of RF sub-stream RF **1-1** that is transmitted through the first column **170-1** and the portion of RF sub-stream RF **1-1** that is transmitted through the second column **170-2** will have a narrowed azimuth HPBW. Thus, the above-discussed problem of wide azimuth HPBWs that would result if two 4T4R radios are used with an 8T8R beamforming array such as array **171** is solved because the azimuth beamwidth of the antenna beams corresponding to each RF sub-stream are narrowed since the RF sub-stream is transmitted through two columns **170**.

[0056] Moreover, the four sub-streams RF**1-1** through RF**1-4** may operate in a frequency band different from that of the four sub-streams RF**2-1** through RF**2-4**. For example, the sub-streams RF**1-1** through RF**1-4** may operate in a first frequency band that includes all or a portion of 2,350-2,370 MHz, and the sub-streams RF**2-1** through RF**2-4** may operate in a second frequency band that includes all or a portion of 2,370-2,390 MHz. According to some embodiments, each radio **142** can provide both the first and second frequency bands. The use of these two different frequency bands can reduce interference.

[0057] Since beamforming array **171** is fed through a total of eight RF ports, and each RF sub-stream from the radio is coupled to two RF ports (to feed two columns **170**), it is necessary that the radio output portions of two different RF sub-streams at each radio port. However, since the RF sub-streams RF**1-1** through RF**1-4** are in a different frequency band than the RF sub-streams RF**2-1** through RF**2-4**, one of the RF sub-streams RF**1-1** through RF**1-4** and one of the RF sub-streams RF**2-1** through RF**2-4** may be fed to each RF port **145** without interference since the two RF sub-streams fed to each port **145** are in different frequency bands. Thus, by outputting at each radio port **143** (FIGS. **1**C, **1**D) a combination of one of RF sub-streams RF**1-1** through RF**1-4** and one of RF sub-streams RF**2-1** through RF**2-4**, it is possible to use the 8T8R beamforming array **171** with two 4T4R radios while generating higher gain antenna beams that fit within the sector.

[0058] FIG. **3**B is a schematic diagram illustrating the combinations of different RF sub-streams that are output through each of the radio ports **143** to the columns **170-1** through **170-4** of radiating elements **271** of FIG. **2** via the eight antenna ports **145-1** through **145-8** of FIG. **1**C (or FIG. **1**D). Eight RF signals can be provided to the four columns **170-1** through **170-4** of radiating elements because the radiating elements **271** are dual-polarized (e.g., slant −/+45° cross-dipole radiating elements) so that each column **170** actually includes two columns of dipole radiators and hence each column can be connected to a pair of radio ports (with the first port coupled to the dipole radiators that have the first polarization and the second radio port coupled to the dipole radiators having the second polarization). As an example, the ports **145-1**, **145-3**, **145-5**, and **145-7** may be first-polarization ports that are coupled to first-polarization radiators of the columns **170**, and the ports **145-2**, **145-4**, **145-6**, and **145-8** may be second-polarization ports that are coupled to second-polarization radiators of the columns **170**, where the second polarization (e.g., −45°) is different from (e.g., orthogonal to) the first polarization (+45°).

[0059] As shown in FIG. **3**B, each radio port **143** outputs an RF signal that is a combination of both a sub-stream generated from the first baseband data stream BB-**1** and a sub-stream generated from the second baseband data stream BB-**2**. The radio **142** may generate the eight combined RF signals shown in FIG. **3**B and may provide the eight combined RF signals to the eight antenna ports **145-1** through **145-8**, respectively.

[0060] For simplicity of illustration, only a single radiating element **271** per column **170** is shown in FIG. **3**B. Each column **170**, however, may (and typically will) include a plurality of radiating elements **271** that are each coupled to two ports **145** (one per polarization).

[0061] Each combined RF signal shown in FIG. **3**B will be amplified by a respective power amplifier of the radio **142** (the radio **142** includes eight power amplifiers that amplify the respective RF signals that are output through the eight radio ports **143**). The relative power of the two RF sub-streams output through each radio port **143** will determine how much each RF sub-stream is amplified. For example, as shown in FIG. **3**B, RF sub-streams RF**1-1** and RF**2-1** are output through the first radio port **143-1**. The magnitude of these RF sub-streams that are fed to the power amplifier associated with radio port **143-1** may be $\sqrt{1-x}$ RF**1-1** and $\sqrt{x}$ RF**2-1**, where "1−x" and "x" represent the powers of the two RF sub-streams. The power amplifier will apply 100% of its amplification power to the two RF sub-streams so that no power is lost. For example, if x is set to be 0.4, then 60% of the amplification power of the power amplifier will be applied to sub-stream RF**1-1** and the remaining 40% will be applied to RF sub-stream RF**2-1**. As described above, RF sub-streams RF **1-1** and RF**2-1** are also output from radio port **143-3** with the reverse power allocation corresponding to magnitudes $\sqrt{x}$ RF**1-1** and $\sqrt{1-x}$ RF**2-1**. The value of "x" may be selected to achieve a desired azimuth beamwidth for the combined antenna beams generated by the signals output through radio ports **143-1** and **143-3** to RF ports **145-1** and **145-3**. A value of x=0.5 results in equal power components of RF**1-1** and RF**2-1** being output through the first and second columns **170-1**, **170-2**, which will result in the greatest narrowing of the azimuth HPBW. As x moves away (in either direction) from the value of 0.5, the azimuth HPBW of the resulting antenna beams increases. In some embodiments, x may have a positive non-zero value that is less than 1.

[0062] According to some embodiments, the radio **142** may generate antenna beams by multiplying each RF sub-stream RF**1-1** through RF**1-4**, RF**2-1** through RF**2-4** by a respective complex scalar representing magnitude and phase. The eight combinations of RF sub-streams shown in FIG. **3**B may thus each have two complex scalars. For example, the radio **142** may digitally apply the magnitudes and phases in baseband (i.e., before converting to RF signals). For simplicity of illustration, however, the phases are omitted from view in FIG. **3**B.

[0063] FIGS. **4**A-**4**G are flowcharts illustrating operations of splitting RF power within each of the combinations of RF sub-streams shown in FIG. **3**B. As shown in FIG. **4**A, the operations may include splitting (Block **420**) RF power within each of a plurality of combinations of first and second RF sub-streams. For example, a radio **142** (FIG. **1**B) may combine RF sub-streams of the first and second baseband data streams BB-**1**, BB-**2** in the digital domain, where RF power is split for (i.e., distributed within) each RF sub-stream combination.

[0064] As shown in FIG. **4**B, the first and second baseband data streams BB-**1**, BB-**2**, respectively, may be provided (Block **410**). For example, the radio **142** or baseband equipment may generate the first and second baseband data streams BB-**1**, BB-**2**. The radio **142** may subsequently convert the first and second baseband data streams BB-**1**, BB-**2** into four RF sub-streams RF**1-1** through RF**1-4** (FIG. **3**A) and four RF sub-streams RF**2-1** through RF**2-4** (FIG. **3**A).

[0065] Moreover, operations of splitting (Block **420** of FIG. **4**A) RF power may include providing (Block **420-1**) the four sub-streams RF**1-1**, RF**2-1**, RF**1-3**, and RF**2-3** at the two RF powers 1−x and x (FIG. **3**B) via first-polarization radio ports **143-1**, **143-3**, **143-5**, **143-7** (FIG. **3**B) to first-polarization antenna ports **145-1**, **145-3**, **145-5**, **145-7** (FIG. **1**C), respectively. In some embodiments, the radio ports **143-1**, **143-3**, **143-5**, **143-7** are all part of a single radio **142**. In other embodiments, the radio ports **143-1**, **143-3** may be part of a first radio **142-1** (FIG. **1**D), and the radio ports **143-5**, **143-7** may be part of a second radio **142-2** (FIG. **1**D).

[0066] Operations of splitting (Block **420** of FIG. **4**A) RF power between the columns **170** may also include providing (Block **420-2**) the four sub-streams RF**1-2**, RF**2-2**, RF**1-4**, and RF**2-4** at the two RF powers 1−x and x (FIG. **3**B) via second-polarization radio ports **143-2**, **143-4**, **143-6**, **143-8** (FIG. **3**B) to second-polarization antenna ports **145-2**, **145-4**, **145-6**, **145-8** (FIG. **1**C), respectively. In some embodiments, the radio ports **143-2**, **143-4**, **143-6**, **143-8** are all part of a single radio **142**. In other embodiments, the radio ports **143-2**, **143-4** may be part of a first radio **142-1**, and the radio ports **143-6**, **143-8** may be part of a second radio **142-2**.

[0067] As shown in FIGS. **4**C and **3**B, operations of providing (Block **420-1** of FIG. **4**B) sub-streams via first-polarization radio ports **143-1**, **143-3**, **143-5**, **143-7** may include providing (Block **420-1**-A) the first RF sub-stream RF**1-1** of the first baseband data stream BB-**1** at the first RF power 1−x to the first column **170-1** via the first radio port **143-1**. The operations may also include providing (Block **420-1**-B) the first RF sub-stream RF**2-1** of the baseband second data stream BB-**2** at the second RF power x to the first column **170-1** via the first radio port **143-1**.

[0068] Operations of providing (Block **420-1** of FIG. **4**B) sub-streams via first-polarization radio ports **143-1**, **143-3**, **143-5**, **143-7** may also include providing (Block **420-1**-C) the first RF sub-stream RF**1-1** of the first baseband data stream BB-**1** at the second RF power x to the second column **170-2** via the third radio port **143-3**. The first and second columns **170-1**, **170-2** are consecutive columns **170**, and thus do not have another column **170** therebetween. Moreover, the operations may include providing (Block **420-1**-D) the first RF sub-stream RF**2-1** of the second baseband data stream BB-**2** at the first RF power 1−x to the second column **170-2** via the third radio port **143-3**.

[0069] According to some embodiments, the radio **142** may generate the RF sub-streams RF**1-1** through RF**1-4** and RF**2-1** through RF**2-4** separately/individually and add them in sub-stream pairs by superposition (e.g., while maintaining the total amplitude below a maximum possible level). For example, the radio **142** may comprise a weighted combiner in the digital domain. The weighted combiner can combine two sub-streams having respective amplitude weights (and thus respective powers). As an example, where the first power 1−x is 0.9 (i.e., 90%) and the second power x is 0.1 (i.e., 10%), the radio **142** may apply a first digital amplitude weight of 0.95 for each sub-stream having the first power 1−x and a second digital amplitude weight of 0.32 for each sub-stream having the second power x. The first and second digital amplitude weights may thus be different from each other.

[0070] For simplicity of illustration, the four Blocks **420-1**-A through **420-1**-D are shown sequentially in FIG. **4**C. In some embodiments, however, operation(s) of two or more of the four Blocks **420-1**-A through **420-1**-D may be performed concurrently. As an example, operation(s) of Block **420-1**-B may be performed concurrently with operation(s) of Block **420-1**-A and/or concurrently with operation(s) of Block **420-1**-C and/or Block **420-1**-D.

[0071] As shown in FIGS. **4**D and **3**B, operations of providing (Block **420-2** of FIG. **4**B) sub-streams via second-polarization radio ports **143-2**, **143-4**, **143-6**, **143-8** may include providing (Block **420-2**-A) the second RF sub-stream RF**1-2** of the first baseband data stream BB-**1** at the first RF power 1−x to the first column **170-1** via the second radio port **143-2**. The operations may also include providing (Block **420-2**-B) the second RF sub-stream RF**2-2** of the second baseband data stream BB-**2** at the second RF power x to the first column **170-1** via the second radio port **143-2**.

[0072] Operations of providing (Block **420-2** of FIG. **4**B) sub-streams via the radio ports **143-2**, **143-4**, **143-6**, **143-8** may also include providing (Block **420-2**-C) the second RF sub-stream RF**1-2** of the first baseband data stream BB-**1** at the second RF power x to the second column **170-2** via the fourth radio port **143-4**. Moreover, the operations may include providing (Block **420-2**-D) the second RF sub-stream RF**2-2** of the second baseband data stream BB-**2** at the first RF power 1−x to the second column **170-2** via the fourth radio port **143-4**.

[0073] For simplicity of illustration, the four Blocks **420-2**-A through **420-2**-D are shown sequentially in FIG. **4**D. In some embodiments, however, operation(s) of two or more of the four Blocks **420-2**-A through **420-2**-D may be performed concurrently. As an example, operation(s) of Block **420-2**-B may be performed concurrently with operation(s) of Block **420-2**-A and/or concurrently with operation(s) of Block **420-2**-C and/or Block **420-2**-D. Moreover, one or more of the four Blocks **420-2**-A through **420-2**-D may be performed concurrently with one or more of the four Blocks **420-1**-A through **420-1**-D of FIG. **4**C.

[0074] As shown in FIGS. **4**E and **3**B, operations of providing (Block **420-1** of FIG. **4**B) sub-streams via first-polarization radio ports **143-1**, **143-3**, **143-5**, **143-7** may further include providing (Block **420-1**-E) the third RF sub-stream RF**1-3** of the first baseband data stream BB-**1** at the first RF power 1−x to the third column **170-3** via the fifth radio port **143-5**. The operations may also include providing (Block **420-1**-F) the third RF sub-stream RF**2-3** of the second baseband data stream BB-**2** at the second RF power x to the third column **170-3** via the fifth radio port **143-5**.

[0075] Operations of providing (Block **420-1** of FIG. **4**B) sub-streams via the radio ports **143-1**, **143-3**, **143-5**, **143-7** may also include providing (Block **420-1**-G) the third RF sub-stream RF**1-3** of the first baseband data stream BB-**1** at the second RF power x to the fourth column **170-4** via the seventh radio port **143-7**. The third and fourth columns **170-3**, **170-4** are consecutive columns **170**, where the third column **170-3** is between the second and fourth columns **170-2**, **170-4**. Moreover, the operations may include providing (Block **420-1**-H) the third RF sub-stream RF**2-3** of the second baseband data stream BB-**2** at the first RF power 1−x to the fourth column **170-4** via the seventh radio port **143-7**.

[0076] For simplicity of illustration, the four Blocks **420-1**-E through **420-1**-H are shown sequentially in FIG. **4**E. In some embodiments, however, operation(s) of two or more of the four Blocks **420-1**-E through **420-1**-H may be performed concurrently. As an example, operation(s) of Block **420-1**-F may be performed concurrently with operation(s) of Block **420-1**-E and/or concurrently with operation(s) of Block **420-1**-G and/or Block **420-1**-H. Moreover, one or more of the four Blocks **420-1**-E through **420-1**-H may be performed concurrently with one or more of the four Blocks **420-1**-A through **420-1**-D of FIG. **4**C.

[0077] As shown in FIGS. **4**F and **3**B, operations of providing (Block **420-2** of FIG. **4**B) sub-streams via second-polarization radio ports **143-2**, **143-4**, **143-6**, **143-8** may further include providing (Block **420-2**-E) the fourth RF sub-stream RF**1-4** of the first baseband data stream BB-**1** at the first RF power 1−x to the third column **170-3** via the sixth radio port **143-6**. Moreover, the operations may include providing (Block **420-2**-F) the fourth RF sub-stream RF**2-4** of the second baseband data stream BB-**2** at the second RF power x to the third column **170-3** via the sixth radio port **143-6**.

[0078] Operations of providing (Block **420-2** of FIG. **4**B) sub-streams via radio ports **143-2**, **143-4**, **143-6**, **143-8** may also include providing (Block **420-2**-G) the fourth RF sub-stream RF**1-4** of the first baseband data stream BB-**1** at the second RF power x to the fourth column **170-4** via the eighth radio port **143-8**. Moreover, the operations may include providing (Block **420-2**-H) the fourth RF sub-stream RF**2-4** of the second baseband data stream BB-**2** at the first RF power 1−x to the fourth column **170-4** via the eighth radio port **143-8**.

[0079] For simplicity of illustration, the four Blocks **420-2**-E through **420-2**-H are shown sequentially in FIG. **4**F. In some embodiments, however, operation(s) of two or more of the four Blocks **420-2**-E through **420-2**-H may be performed concurrently. As an example, operation(s) of Block **420-2**-F may be performed concurrently with operation(s) of Block **420-2**-E and/or concurrently with operation(s) of Block **420-2**-G and/or Block **420-2**-H. Moreover, one or more of the four Blocks **420-2**-E through **420-2**-H may be performed concurrently with one or more of the four Blocks **420-2**-A through **420-2**-D of FIG. **4**D.

[0080] FIG. **4**G shows an example in which the eight radio ports **143-1** through **143-8** are distributed among multiple radios **142**. As illustrated in FIG. **4**G, combinations shown in FIG. **3**B of the sub-streams RF**1-1**, RF**2-1** may be provided (Block **420-1'**) by first-polarization radio ports **143-1**, **143-3** of a first radio **142-1** (FIG. **1**D). Moreover, the first radio **142-1** may provide (Block **420-2'**) combinations shown in FIG. **3**B of the sub-streams RF**1-2**, RF**2-2** via second-polarization radio ports **143-2**, **143-4**, respectively.

[0081] A second radio **142-2** (FIG. **1**D) may provide (Block **420-3**) combinations shown in FIG. **3**B of the sub-streams RF**1-3**, RF**2-3** via first-polarization radio ports **143-5**, **143-7**. Moreover, the second radio **142-2** may provide (Block **420-4**) combinations shown in FIG. **3**B of the sub-streams RF**1-4**, RF**2-4** via second-polarization radio ports **143-6**, **143-8**.

[0082] In some embodiments, after providing the eight RF sub-stream combinations shown in FIG. **3**B via the first and second radios **142-1**, **142-2** as shown in Blocks **420-1'** through **420-4**, the first and second radios **142-1**, **142-2** may be replaced (Block **430**) with a single radio **142**. For example, the single radio **142** may have eight ports **143-1** through **143-8** that are coupled to the eight antenna ports **145-1** through **145-8**, respectively.

[0083] FIG. **5** is a graph illustrating radiation patterns of columns **170** of FIG. **2** according to different examples. In the first example, a radiation pattern for a single physical column **170** may have the lowest gain (e.g., about 16.6 dB) and the widest azimuth HPBW (e.g., about 94°). In contrast, by distributing power for each RF sub-stream between first and second powers 1−x and x (FIG. **3**B) across different physical columns **170**, "virtual columns" can be provided that achieve higher gain and narrower azimuth HPBW. For example, the adjacent first and second physical columns **170-1**, **170-2** may together be implemented as a virtual column that provides the RF sub-stream RF**1-1**, where the RF sub-stream RF**1-1** having the first power 1−x applied thereto is provided to the first physical column **170-1** and where the RF sub-stream RF**1-1** having the second power x applied thereto is provided to the second physical column **170-2**. In embodiments where the value of x is 0.10, the gain for a virtual column may be higher (e.g., about 18.2 dB) than that for a single physical column **170** and the azimuth HPBW may be narrower (e.g., about 65°). Moreover, in embodiments where the value of x is 0.50, the gain for a virtual column may be even higher (e.g., about 19.1 dB) and the azimuth HPBW may be even narrower (e.g., about 57°).

[0084] Radios **142** (FIG. **1**B) according to embodiments of the present invention may provide a number of advantages. These advantages include generating, using two 4T4R radio systems in conjunction with a multi-column (e.g., 8T8R) beamforming array **171** (FIGS. **1**C and **1**D) of radiating elements **271** (FIG. **2**), antenna beams having narrowed azimuth HPBW and/or increased gain. Moreover, 100% of the power generated by the radios **142** may be used (thus achieving zero power loss) by distributing the total power among two RF sub-streams that are output at a radio port **143** (FIG. **3**B).

[0085] For example, by splitting power between two RF sub-streams that are provided to the same radio port **143** (FIG. **3**B), a 4T4R radio **142** may narrow HPBW to about 65° (e.g., when the first and second powers 1−x and x (FIG. **3**B) are 0.9 and 0.1, respectively) or about 57° (e.g., when the first and second powers 1−x and x are each 0.5). The 4T4R radio **142** can thus be used together with the 8T8R beamforming array **171** to provide radiation patterns resembling those of conventional 4T4R antenna arrays.

[0086] According to some embodiments, the first and second powers 1−x and x of the respective sub-streams output at a radio port **143** may collectively equal 100% of a total (e.g., maximum) amplification power of a power amplifier coupled to the radio port **143**, thus reducing/eliminating power loss by the radio **142**. The total amplification power for each radio port **143** of the radio **142** can be distributed in this manner. Moreover, the radio **142** may increase gain by about 1.6 dB (e.g., from about 16.6 dB to about 18.2 dB when the first and second powers 1−x and x are 0.9 and 0.1, respectively), or by about 2.5 dB (e.g., from about 16.6 dB to about 19.1 dB when the first and second powers 1−x and x are each 0.5).

[0087] In some embodiments, an 8T8R beamforming array **171** can initially be used with two 4T4R radios **142-1**, **142-2** (FIG. **1**D), and later can be used with a single 8T8R radio **142** (FIG. **1**C). Such radios **142** can thus provide operators with greater flexibility and allow them to use the same base station antenna with different radio **142** combinations.

[0088] The present invention has been described above with reference to the accompanying drawings. The present invention is not limited to the illustrated embodiments. Rather, these embodiments are intended to fully and completely disclose the present invention to those skilled in this art. In the drawings, like numbers refer to like elements throughout. Thicknesses and dimensions of some components may be exaggerated for clarity.

[0089] Spatially relative terms, such as "under," "below," "lower," "over," "upper," "top," "bottom," and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as "under" or "beneath" other elements or features would then be oriented "over" the other elements or features. Thus, the example term "under" can encompass both an orientation of over and under. The device may be otherwise oriented (rotated **90** degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0090] Herein, the terms "attached," "connected," "interconnected," "contacting," "mounted," "coupled," and the like can mean either direct or indirect attachment or coupling between elements, unless stated otherwise.

[0091] Well-known functions or constructions may not be described in detail for brevity and/or clarity. As used herein the expression "and/or" includes any and all combinations of one or more of the associated listed items.

[0092] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the present 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. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used in this specification, specify the presence of stated features, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, operations, elements, components, and/or groups thereof.

[0093] Example embodiments of the present inventive concepts may be embodied as devices (e.g., radios) and methods. Accordingly, example embodiments of present inventive concepts may be embodied in hardware and/or in software (including firmware, resident software, microcode, etc.). Furthermore, example embodiments of present inventive concepts may take the form of a computer program product comprising a non-transitory computer-usable or computer-readable storage medium having computer-usable or computer-readable program code embodied in the medium for use by or in connection with an instruction execution system. In the context of this document, a computer-usable or computer-readable medium may be any medium that can contain, store, communicate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device.

[0094] The computer-usable or computer-readable medium may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device. More specific examples (a non-exhaustive list) of the computer-readable medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, and a portable compact disc read-only memory (CD-ROM). Note that the computer-usable or computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via, for instance, optical scanning of the paper or other medium, then compiled, interpreted, or otherwise processed in a suitable manner, if necessary, and then stored in a computer memory.

[0095] Example embodiments of present inventive concepts are described herein with reference to flowchart and/or block diagram illustrations. It will be understood that each block of the flowchart and/or block diagram illustrations, and combinations of blocks in the flowchart and/or block diagram illustrations, may be implemented by computer program instructions and/or hardware operations. These computer program instructions may be provided to a processor of a general purpose computer, a special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create/use circuits for implementing the functions specified in the flowchart and/or block diagram block or blocks.

[0096] These computer program instructions may also be stored in a computer usable or computer-readable memory that may direct a computer or other programmable data processing apparatus to function in a particular manner, such that the instructions stored in the computer usable or computer-readable memory produce an article of manufacture including instructions that implement the functions specified in the flowchart and/or block diagram block or blocks.

[0097] The computer program instructions may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer implemented process such that the instructions that execute on the computer or other programmable apparatus provide steps for implementing the functions specified in the flowchart and/or block diagram block or blocks.

1. A radio, comprising:

a plurality of first-polarization radio frequency (RF) ports that are configured to be coupled to respective first-polarization RF ports of an antenna that are coupled to a plurality of columns, respectively, of dual-polarized radiating elements of the antenna; and

a plurality of second-polarization RF ports that are configured to be coupled to respective second-polarization RF ports of the antenna that are coupled to the columns, respectively,

wherein the first polarization is different from the second polarization, and

wherein a first of the first-polarization RF ports of the radio is configured to provide to a first of the columns:

a first RF sub-stream of a first baseband data stream at a first RF power; and

a first RF sub-stream of a second baseband data stream at a second RF power.

2. The radio of claim **1**, wherein the radio is configured to generate the first RF sub-stream of the first baseband data stream and the first RF sub-stream of the second baseband data stream in first and second frequency bands, respectively, that are different from each other.

3. The radio of claim **1**, wherein the first and second RF powers collectively equal 100% of a total amplification power of a power amplifier coupled to the first of the first-polarization RF ports of the radio.

4. The radio of claim **3**,

wherein the first and second RF powers are represented by 1−x and x, respectively, and wherein x is a positive non-zero value that is less than 1.

5. The radio of claim **1**, wherein a second of the first-polarization RF ports of the radio is configured to provide to a second of the columns:

the first RF sub-stream of the first baseband data stream at the second RF power; and

the first RF sub-stream of the second baseband data stream at the first RF power.

6. The radio of claim **5**, wherein a first of the second-polarization RF ports of the radio is configured to provide to the first of the columns:

a second RF sub-stream of the first baseband data stream at the first RF power; and

a second RF sub-stream of the second baseband data stream at the second RF power.

7. The radio of claim **6**, wherein a second of the second-polarization RF ports of the radio is configured to provide to the second of the columns:

the second RF sub-stream of the first baseband data stream at the second RF power; and

the second RF sub-stream of the second baseband data stream at the first RF power.

8. The radio of claim **7**, wherein the radio is configured to multiply each RF sub-stream of each of the first and second baseband data streams by a respective complex scalar representing magnitude and phase.

9. The radio of claim **7**,

wherein the first and second of the columns are consecutive columns,

wherein the first and second of the first-polarization RF ports of the antenna are coupled to the first and second of the columns, respectively, and

wherein the first and second of the second-polarization RF ports of the antenna are coupled to the first and second of the columns, respectively.

10. The radio of claim **9**,

wherein the radio is a first of a plurality of radios that are configured to be coupled to the antenna, and

wherein a second of the radios is configured to provide to a third and a fourth of the columns:

a third RF sub-stream of the first baseband data stream together with a third RF sub-stream of the second baseband data stream; and

a fourth RF sub-stream of the first baseband data stream together with a fourth RF sub-stream of the second baseband data stream.

11. A method of operating a radio that is coupled to an antenna comprising a plurality of columns of dual-polarized radiating elements, the method comprising:

providing to a first of the columns via a first of a plurality of first-polarization ports of the radio:

a first RF sub-stream of a first baseband data stream at a first radio frequency (RF) power; and

a first RF sub-stream of a second baseband data stream at a second RF power.

12. The method of claim **11**, further comprising generating the first RF sub-stream of the first baseband data stream and the first RF sub-stream of the second baseband data stream in first and second frequency bands, respectively, that are different from each other.

13. The method of claim **11**, further comprising:

providing to a second of the columns via a second of the first-polarization ports:

the first RF sub-stream of the first baseband data stream at the second RF power; and

the first RF sub-stream of the second baseband data stream at the first RF power, wherein the radio multiplies each RF sub-stream of each of the first and second baseband data streams by a respective complex scalar representing magnitude and phase.

14. The method of claim **13**, further comprising:

providing to the first of the columns via a first of a plurality of second-polarization ports of the radio:

a second RF sub-stream of the first baseband data stream at the first RF power; and

a second RF sub-stream of the second baseband data stream at the second RF power,

wherein the second polarization is different from the first polarization.

15. The method of claim **14**, further comprising:

providing to the second of the columns via a second of the second-polarization ports:

the second RF sub-stream of the first baseband data stream at the second RF power; and

the second RF sub-stream of the second baseband data stream at the first RF power.

16. The method of claim **15**, wherein the first and second of the columns comprise consecutive columns.

17. The method of claim **16**,

wherein the radio is a first radio, and

wherein the method further comprises splitting, by a second radio, RF power by providing:

a third RF sub-stream of the first baseband data stream together with a third RF sub-stream of the second baseband data stream; and

a fourth RF sub-stream of the first baseband data stream together with a fourth RF sub-stream of the second baseband data stream.

18. The method of claim **17**, further comprising replacing the first and second radios with a single radio that is coupled to the first through fourth of the columns.

19. A radio that is configured to distribute a total amplification power for each of a plurality of radio frequency (RF) ports of the radio among a plurality of RF sub-streams.

20. The radio of claim **19**,

wherein each of the RF ports is configured to output together a first RF power and a second RF power that collectively equal 100% of the total amplification power,

wherein the radio comprises first through fourth of the RF ports,

wherein the first and third of the RF ports are configured to be coupled to consecutive first and second columns, respectively, of radiating elements of an antenna,

wherein the RF sub-streams comprise a plurality of RF sub-streams of a first baseband data stream and a plurality of RF sub-streams of a second baseband data stream,

wherein distributing the total amplification power comprises outputting:

a first of the RF sub-streams of the first baseband data stream at the first RF power and a first of the RF sub-streams of the second baseband data stream at the second RF power, to the first column via the first of the RF ports; and

the first of the RF sub-streams of the first baseband data stream at the second RF power and the first of the RF sub-streams of the second baseband data stream at the first RF power, to the second column via the third of the RF ports.

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