US 20240337744A1

(19) **United States**

(12) **Patent Application Publication**

DUAN et al.

(10) **Pub. No.: US 2024/0337744 A1**

(43) **Pub. Date: Oct. 10, 2024**

(54) **ENHANCED DOPPLER DIVISION MULTIPLEXING (DDM) MULTIPLE-INPUT AND MULTIPLE-OUTPUT (MIMO) SENSING BASED ON DOPPLER SPECTRUM PUNCTURING**

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(21) Appl. No.: **18/297,483**

(22) Filed: **Apr. 7, 2023**

Publication Classification

(51) **Int. Cl.**

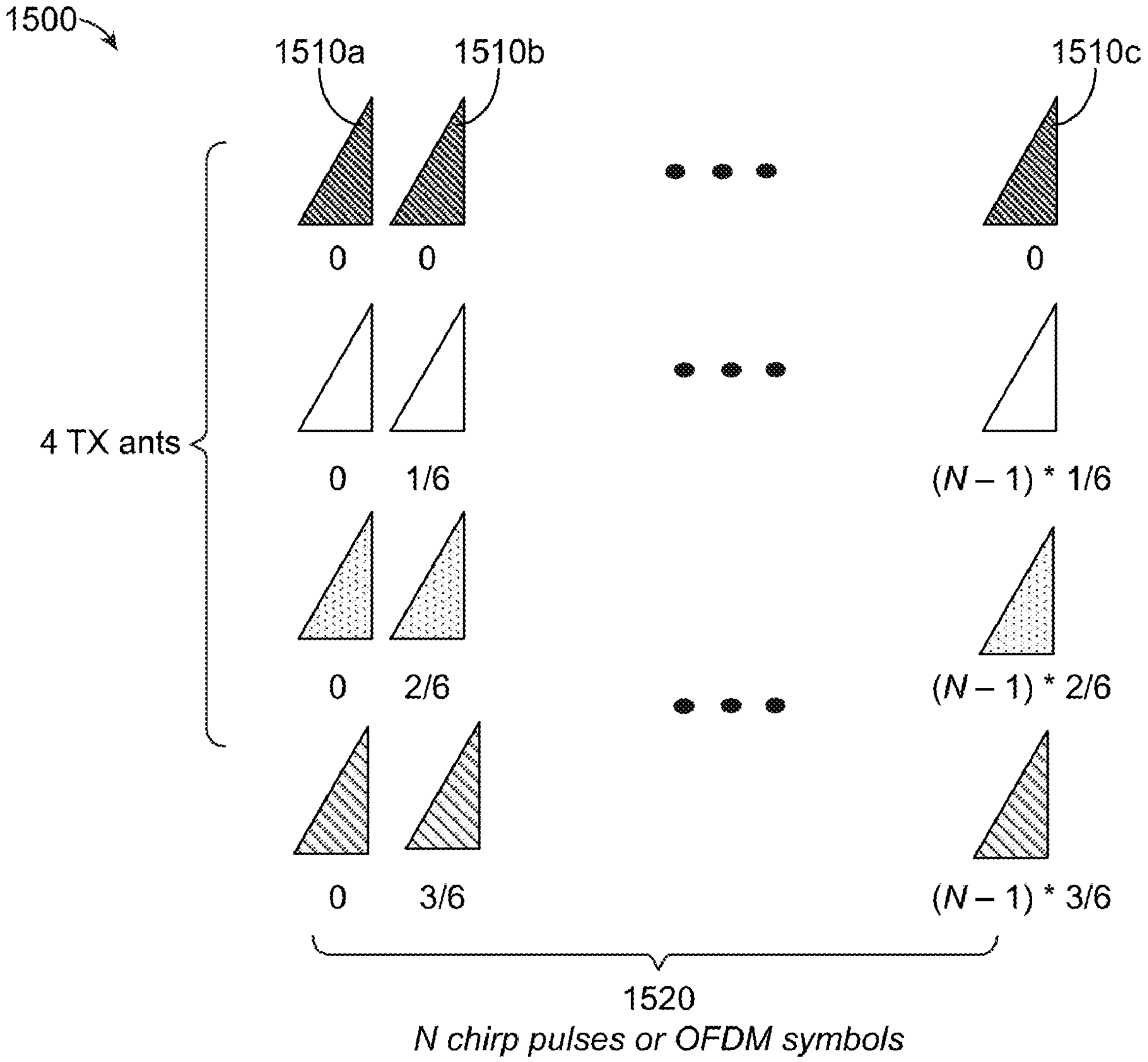
G01S 13/58	(2006.01)
G01S 7/41	(2006.01)
G01S 13/28	(2006.01)
G01S 13/34	(2006.01)

(52) **U.S. Cl.**

CPC ***G01S 13/584*** (2013.01); ***G01S 7/414*** (2013.01); ***G01S 13/288*** (2013.01); ***G01S 13/34*** (2013.01)

(57) **ABSTRACT**

Disclosed are systems and techniques for wireless communications. For example, a network device can transmit a sensing signal for sensing one or more targets. The transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices includes one or more phase codes and a same frequency modulated carrier wave (FMCW). Each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns. The network device can receive at least one echo signal from the one or more targets. The network device can mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.



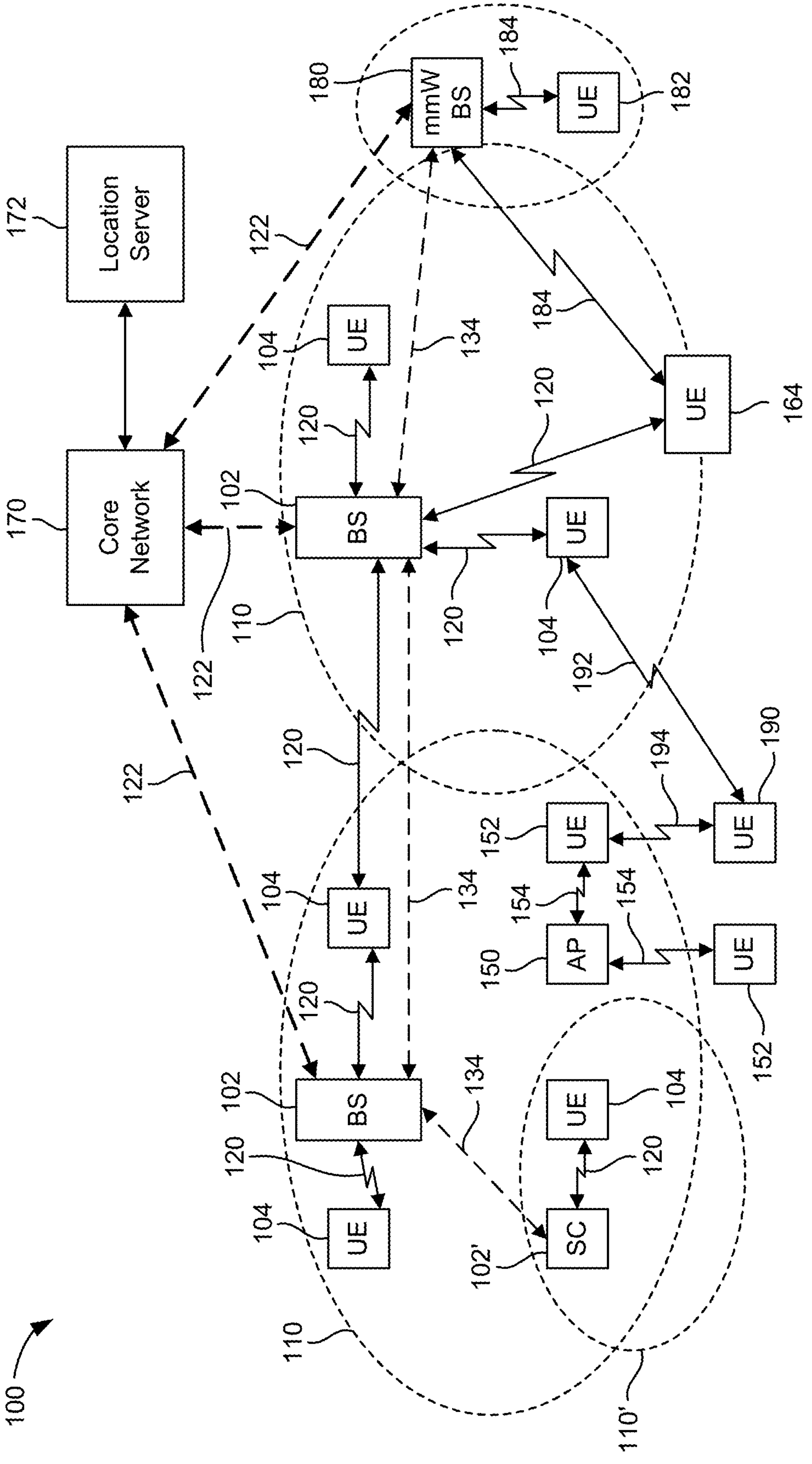

100
Location Server
172
Core Network
170
122
122
122
mmW BS
180
184
UE
182
184
UE
164
BS
102
UE
104
134
120
120
120
110
UE
104
192
UE
190
194
UE
152
154
AP
150
154
UE
152
120
UE
104
134
BS
102
120
UE
104
134
UE
104
120
SC
102'
110
110'

FIG. 1

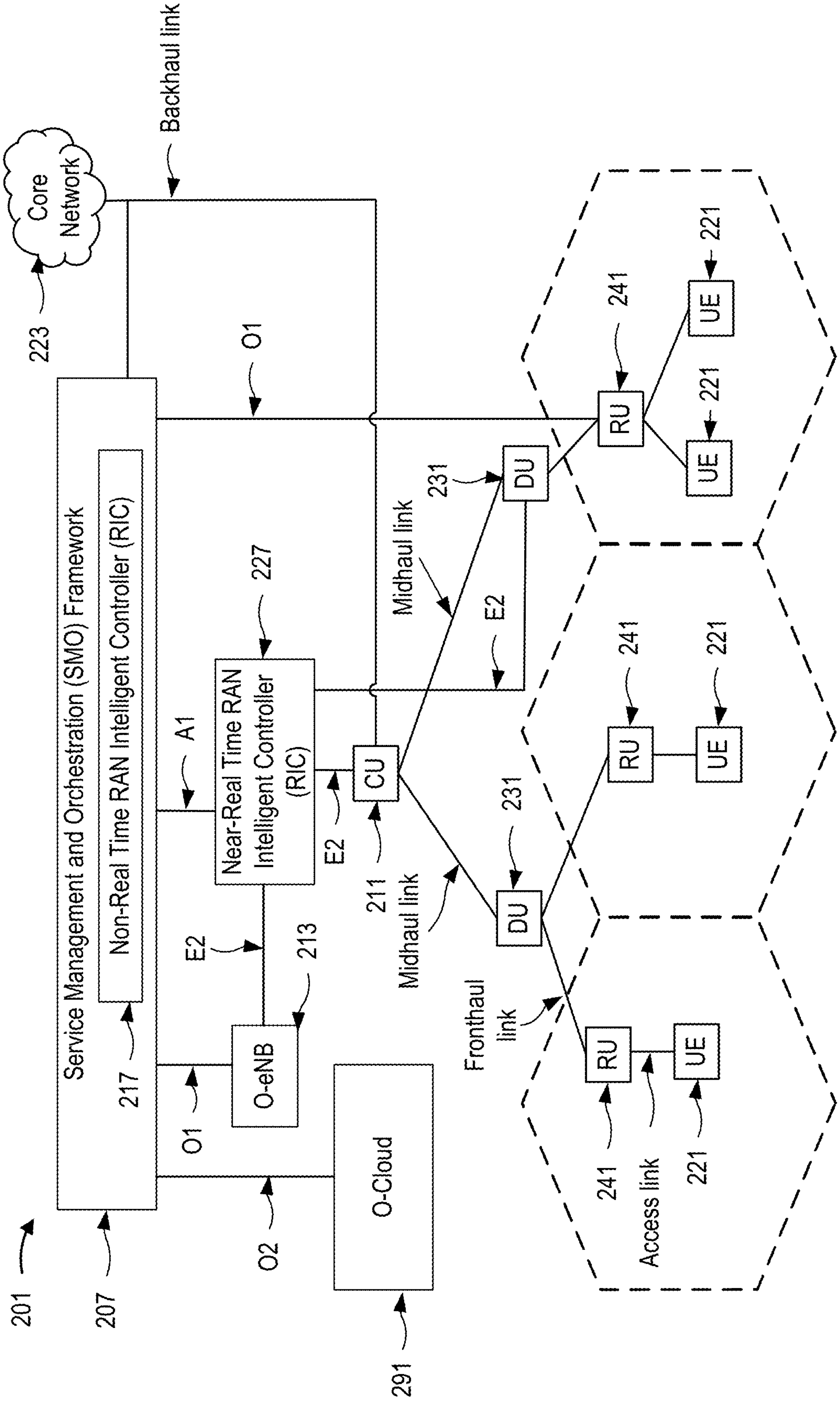

201
207
Service Management and Orchestration (SMO) Framework
Non-Real Time RAN Intelligent Controller (RIC)
217
223
Core Network
Backhaul link
O1
O1
O2
A1
E2
E2
E2
E2
Near-Real Time RAN Intelligent Controller (RIC)
227
O-eNB
213
O-Cloud
291
CU
211
Midhaul link
Midhaul link
DU
DU
231
231
Fronthaul link
RU
RU
RU
241
241
241
UE
UE
UE
UE
221
221
221
221
Access link

FIG. 2

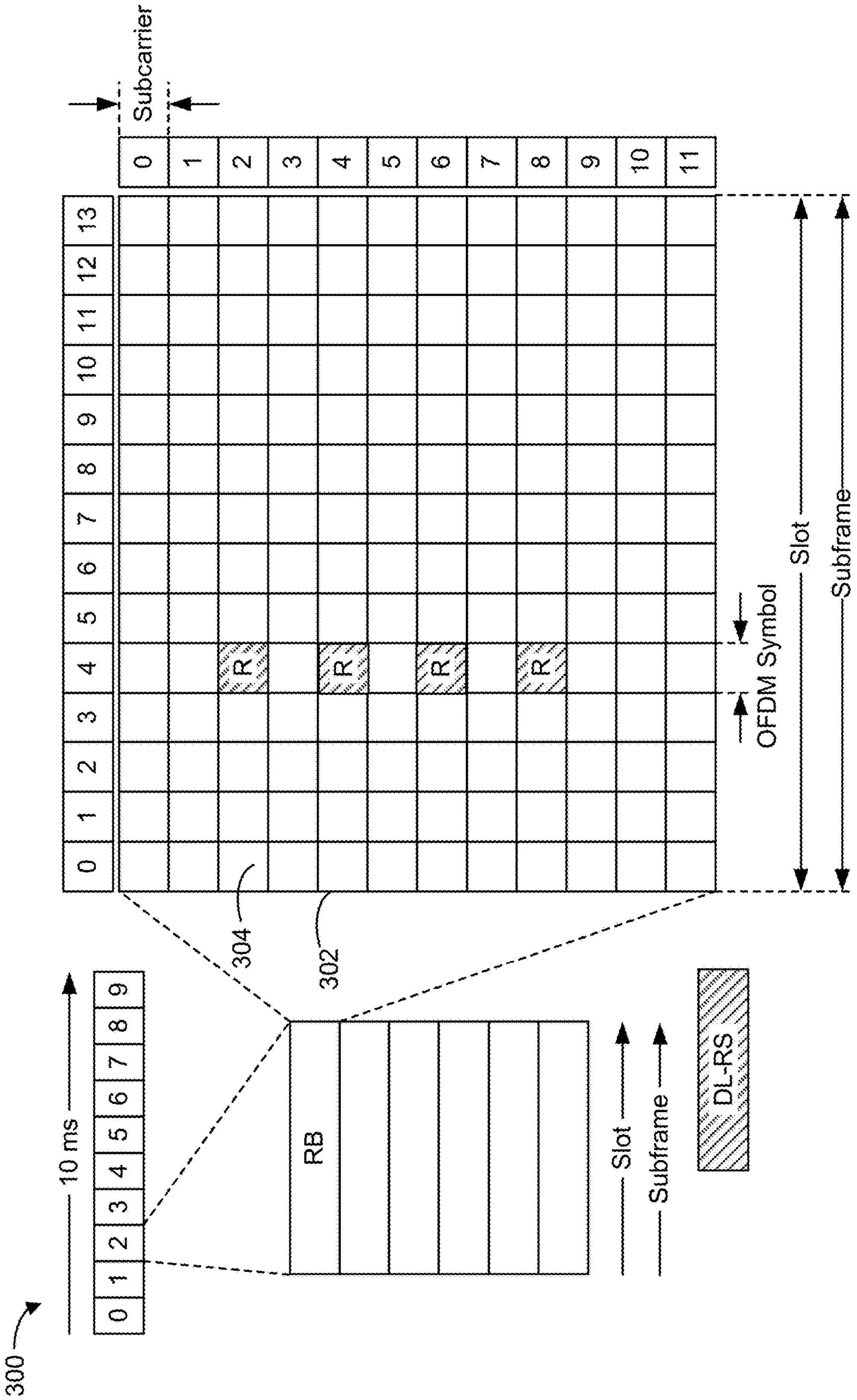

300
10 ms
0
1
2
3
4
5
6
7
8
9
RB
Slot
Subframe
DL-RS
304
302
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Subcarrier
0
1
2
3
4
5
6
7
8
9
10
11
R
R
R
R
OFDM Symbol
Slot
Subframe

FIG. 3

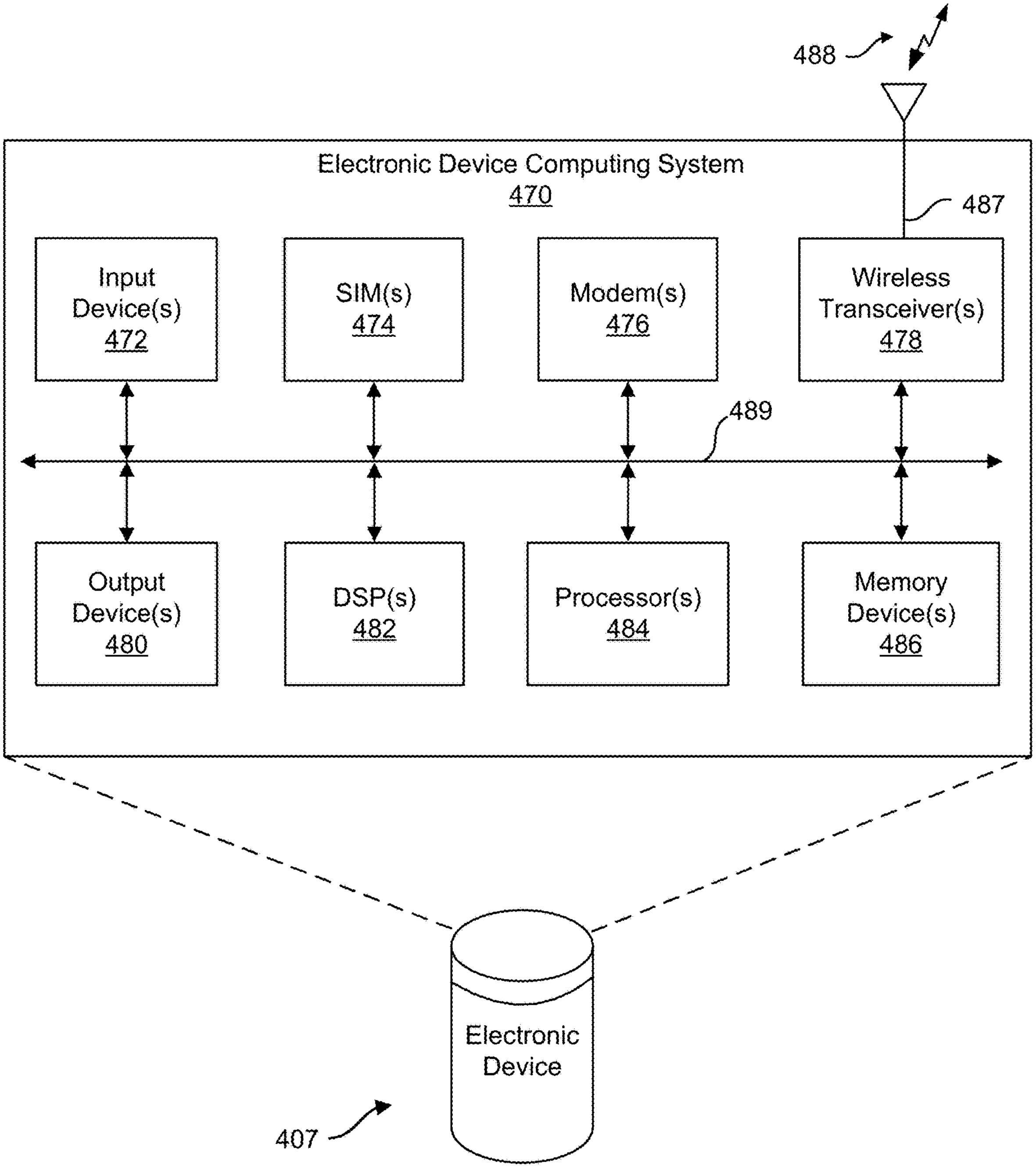

488
Electronic Device Computing System
470
487
Input Device(s)
472
SIM(s)
474
Modem(s)
476
Wireless Transceiver(s)
478
489
Output Device(s)
480
DSP(s)
482
Processor(s)
484
Memory Device(s)
486
Electronic Device
407

FIG. 4

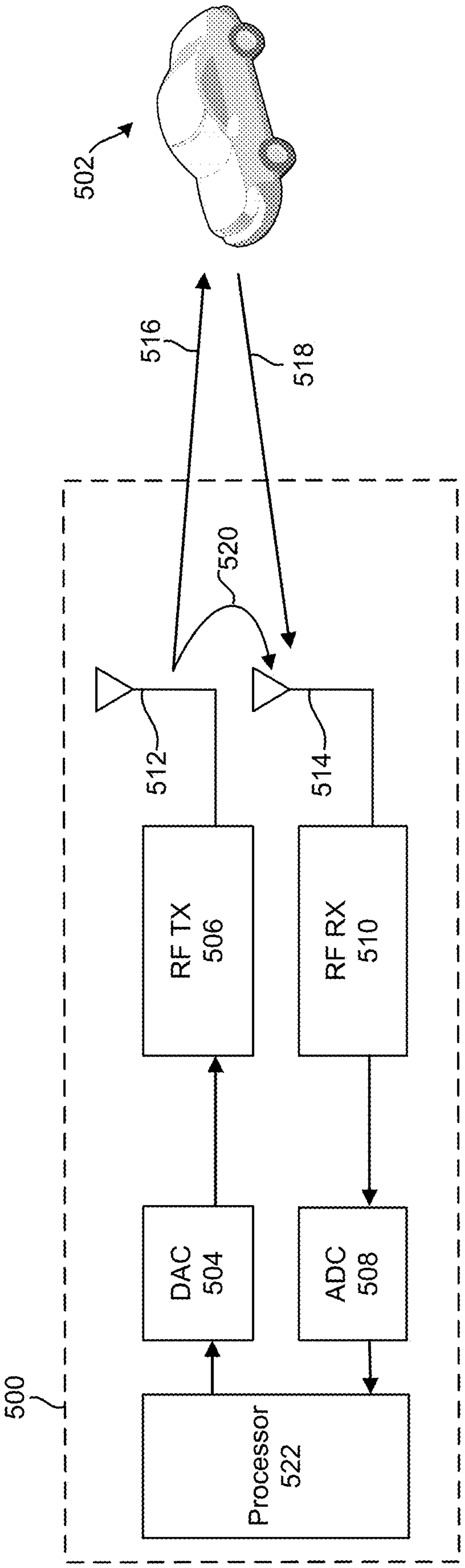

502
516
518
520
512
514
RF TX
506
RF RX
510
DAC
504
ADC
508
Processor
522
500

FIG. 5

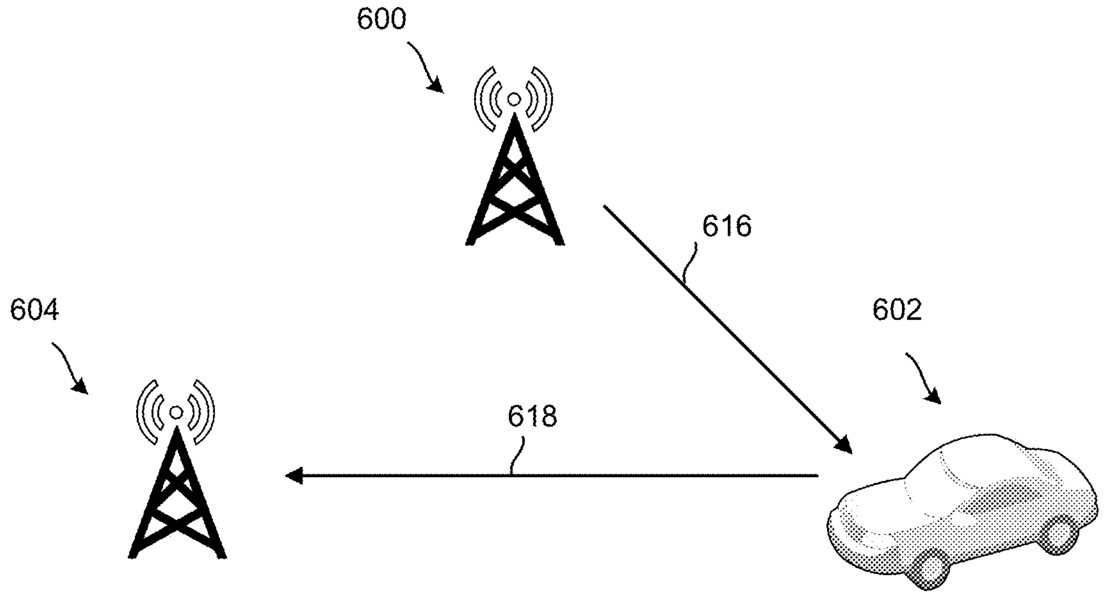


FIG. 6

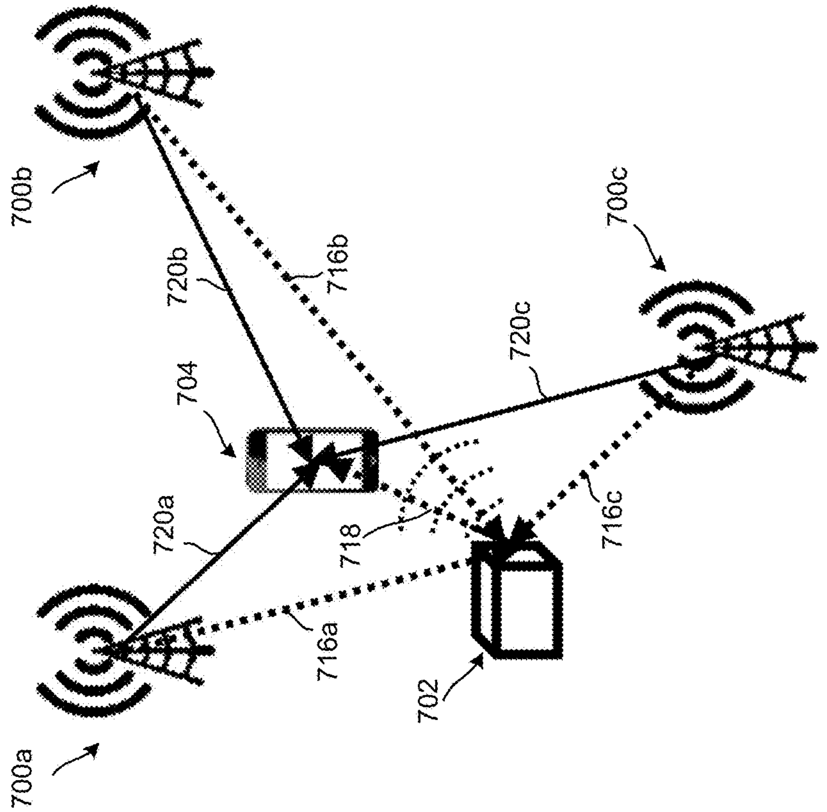


FIG. 7

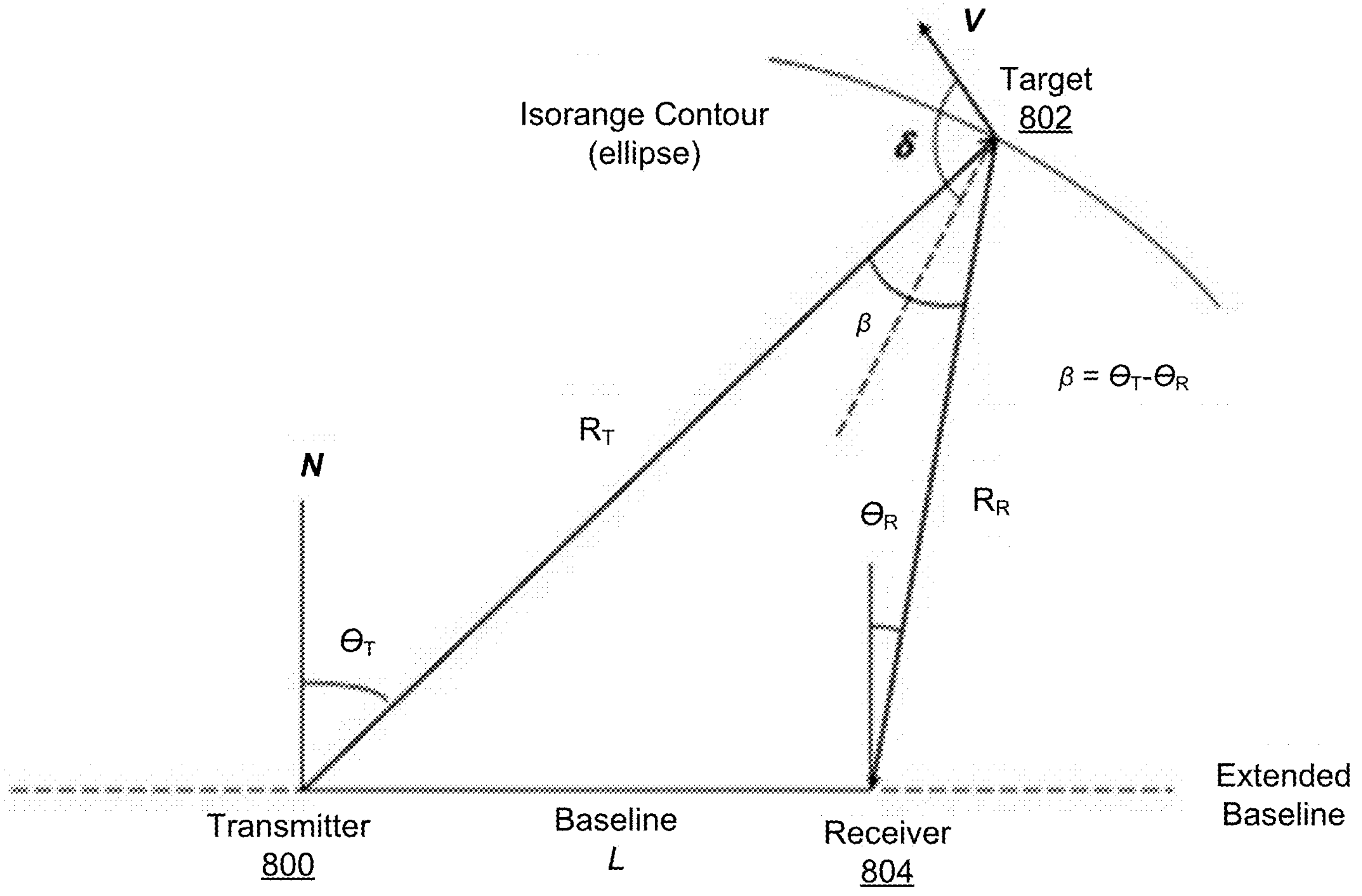

V
Target
802
Isorange Contour
(ellipse)
δ
β
$\beta = \Theta_T - \Theta_R$
R_T
N
Θ_R
R_R
Θ_T
Extended
Baseline
Transmitter
800
Baseline
L
Receiver
804

FIG. 8

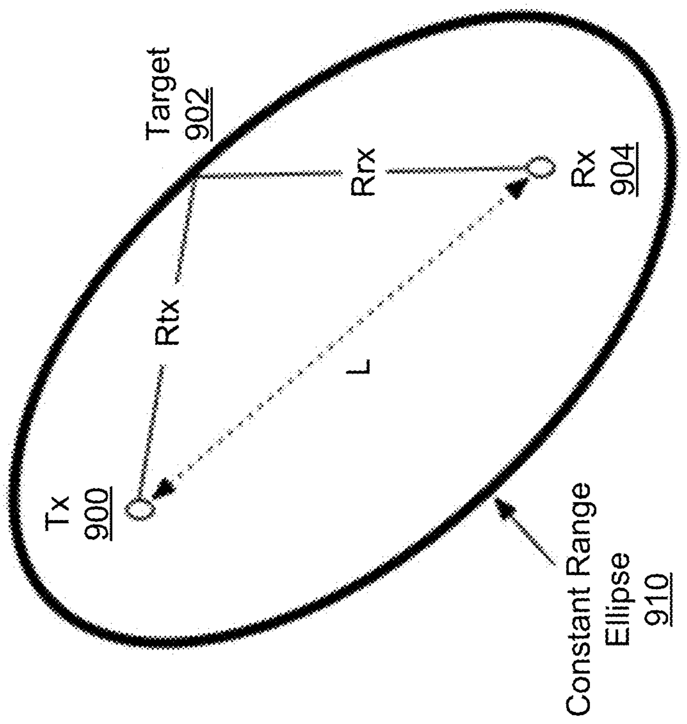


FIG. 9

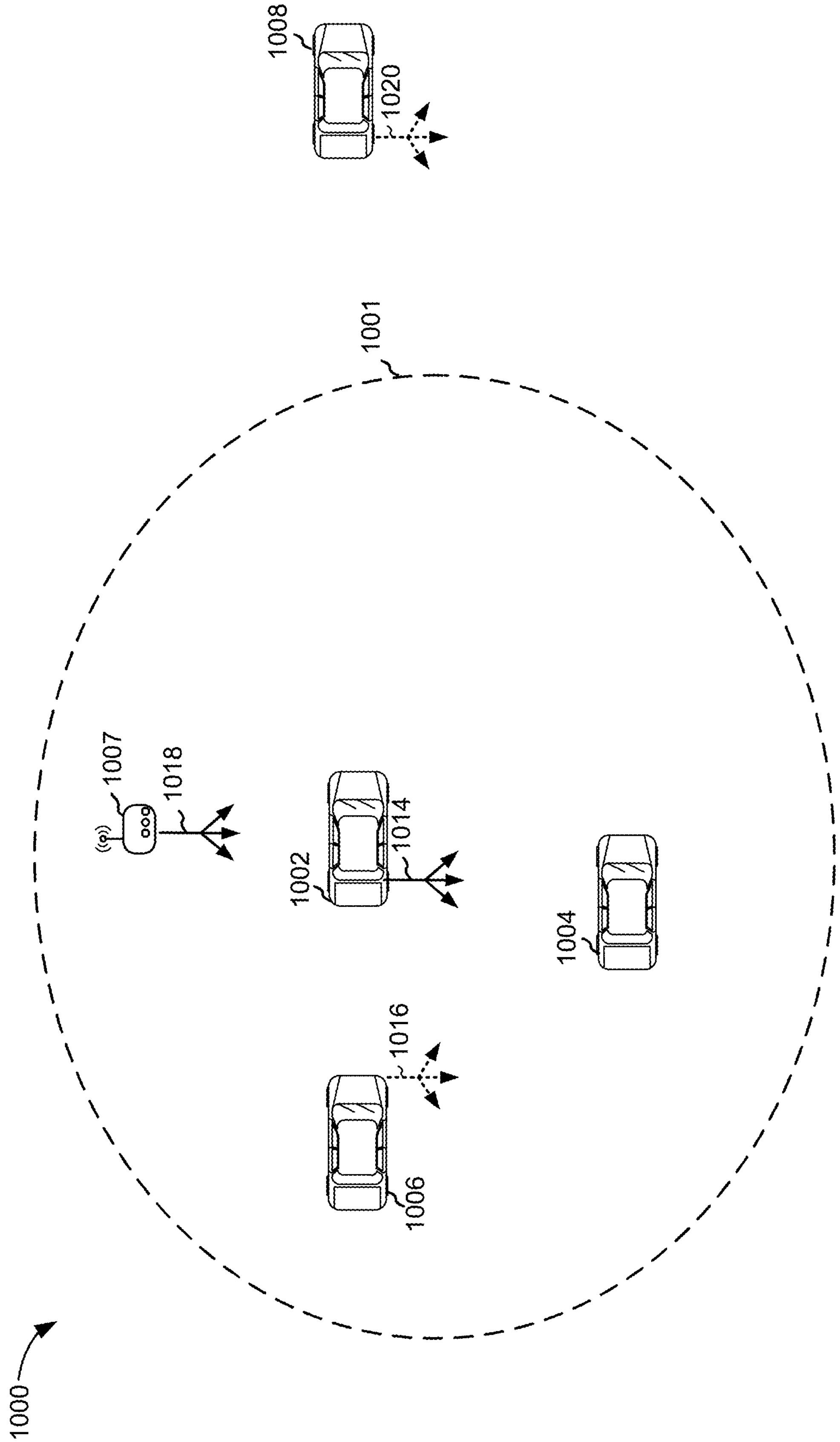


FIG. 10

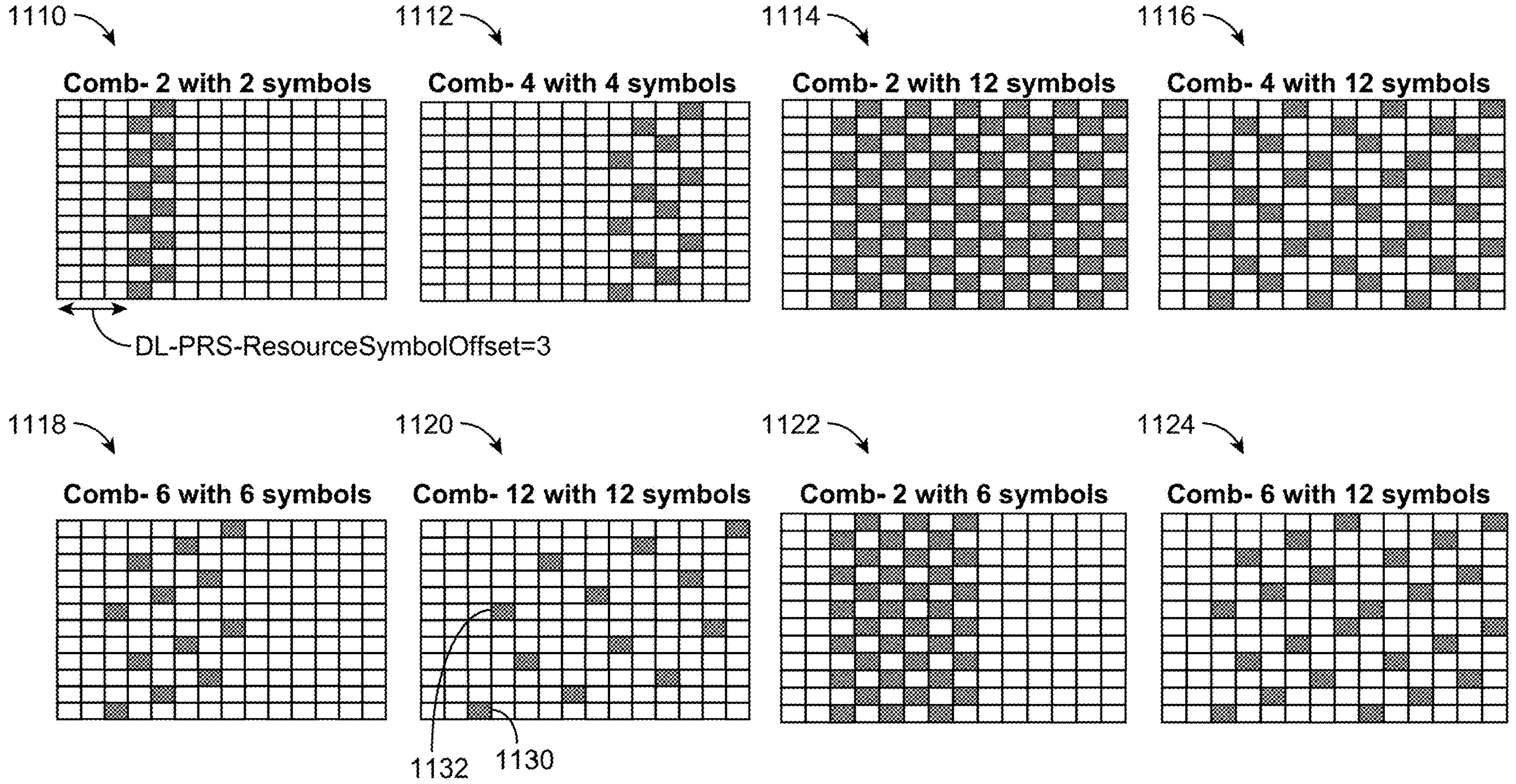

1110
Comb- 2 with 2 symbols
DL-PRS-ResourceSymbolOffset=3
1112
Comb- 4 with 4 symbols
1114
Comb- 2 with 12 symbols
1116
Comb- 4 with 12 symbols
1118
Comb- 6 with 6 symbols
1120
Comb- 12 with 12 symbols
1132
1130
1122
Comb- 2 with 6 symbols
1124
Comb- 6 with 12 symbols

FIG. 11

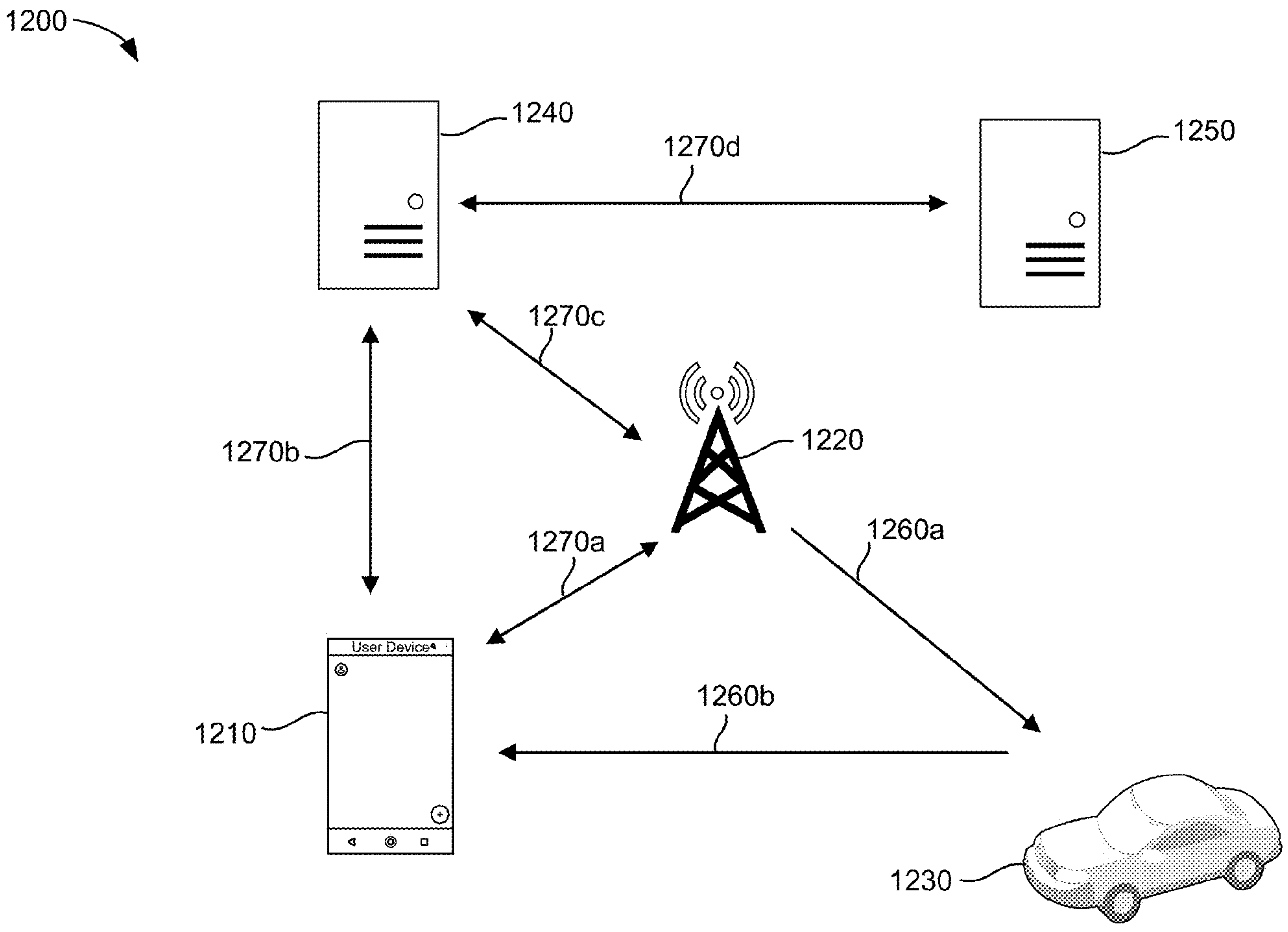

1200
1240
1270d
1250
1270c
1270b
1220
1270a
1260a
User Device
1210
1260b
1230

FIG. 12

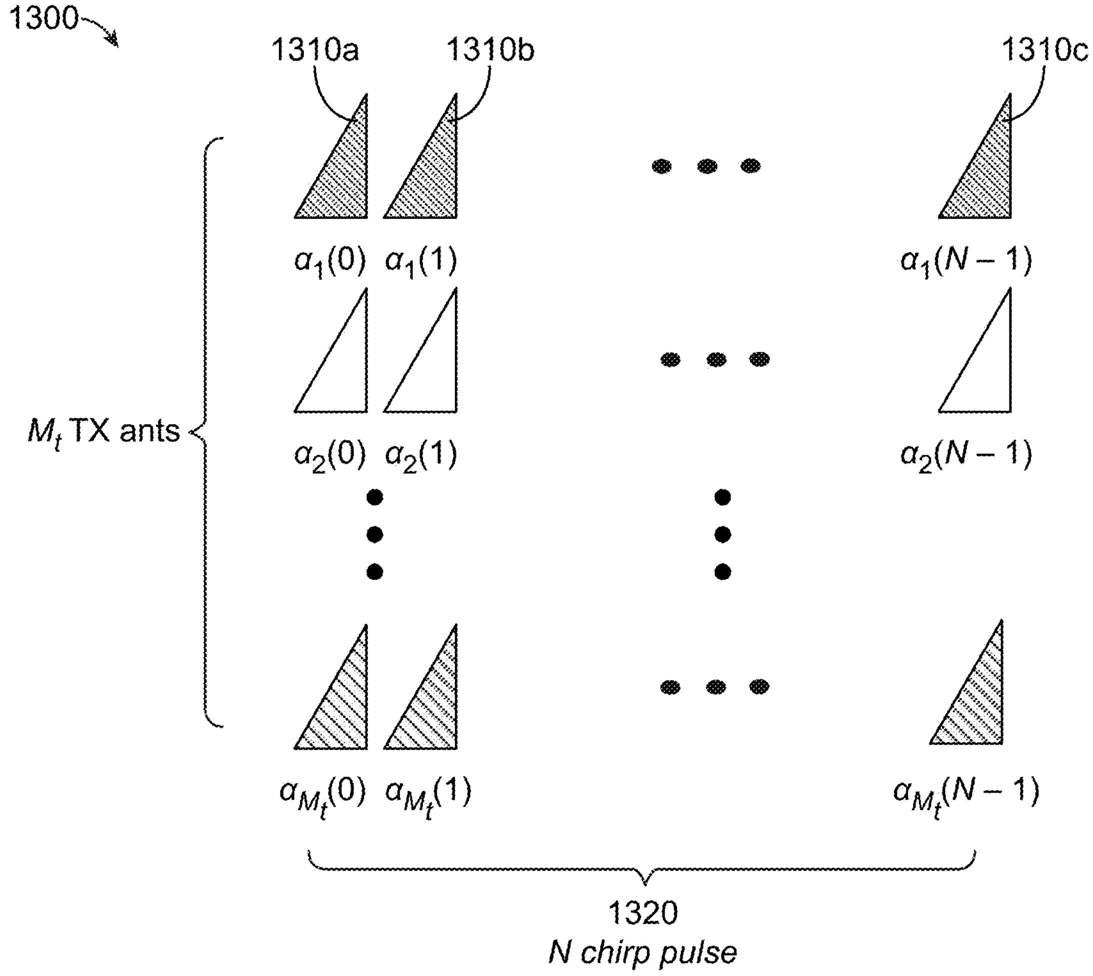

1300
1310a
1310b
1310c
M_t TX ants
$\alpha_1(0)$
$\alpha_1(1)$
$\alpha_1(N-1)$
$\alpha_2(0)$
$\alpha_2(1)$
$\alpha_2(N-1)$
$\alpha_{M_t}(0)$
$\alpha_{M_t}(1)$
$\alpha_{M_t}(N-1)$
1320
N chirp pulse

FIG. 13

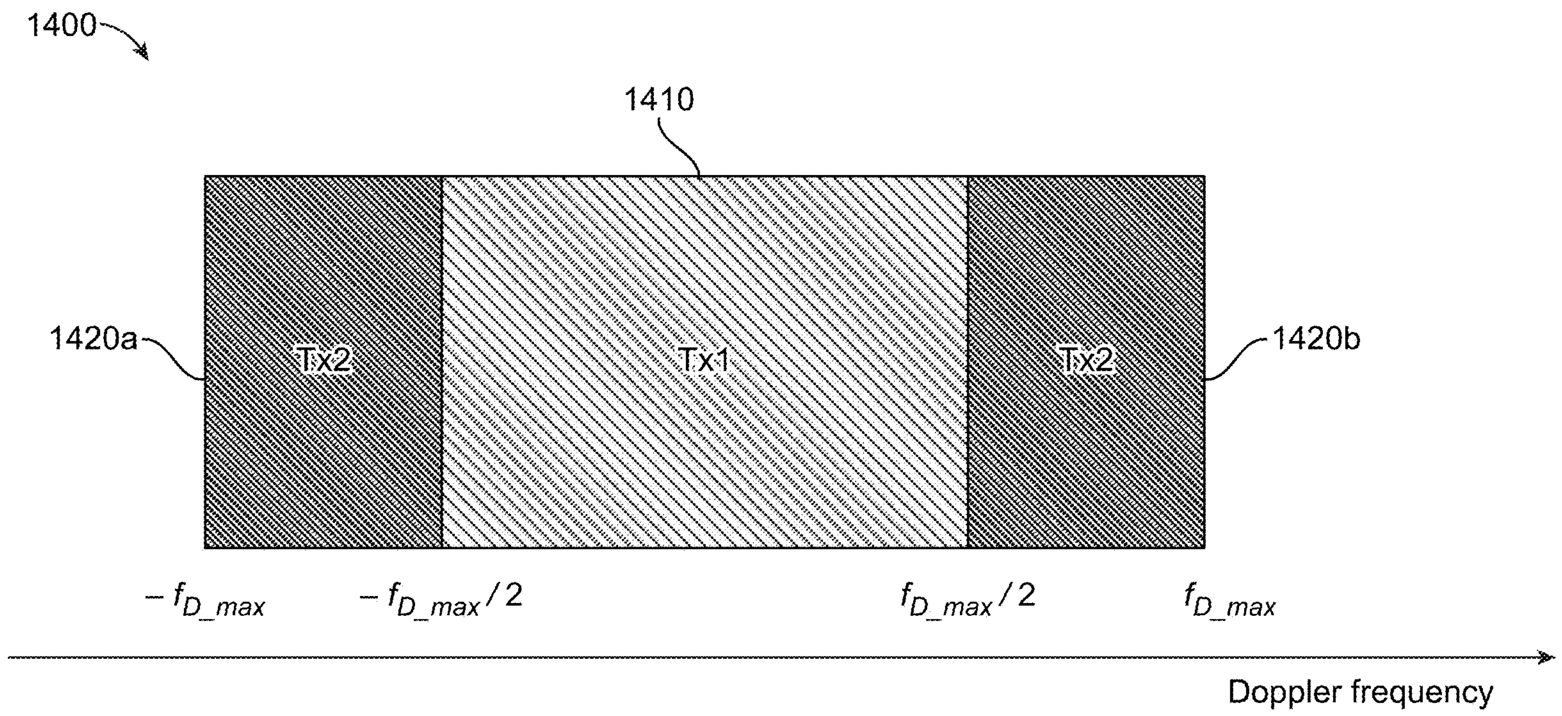
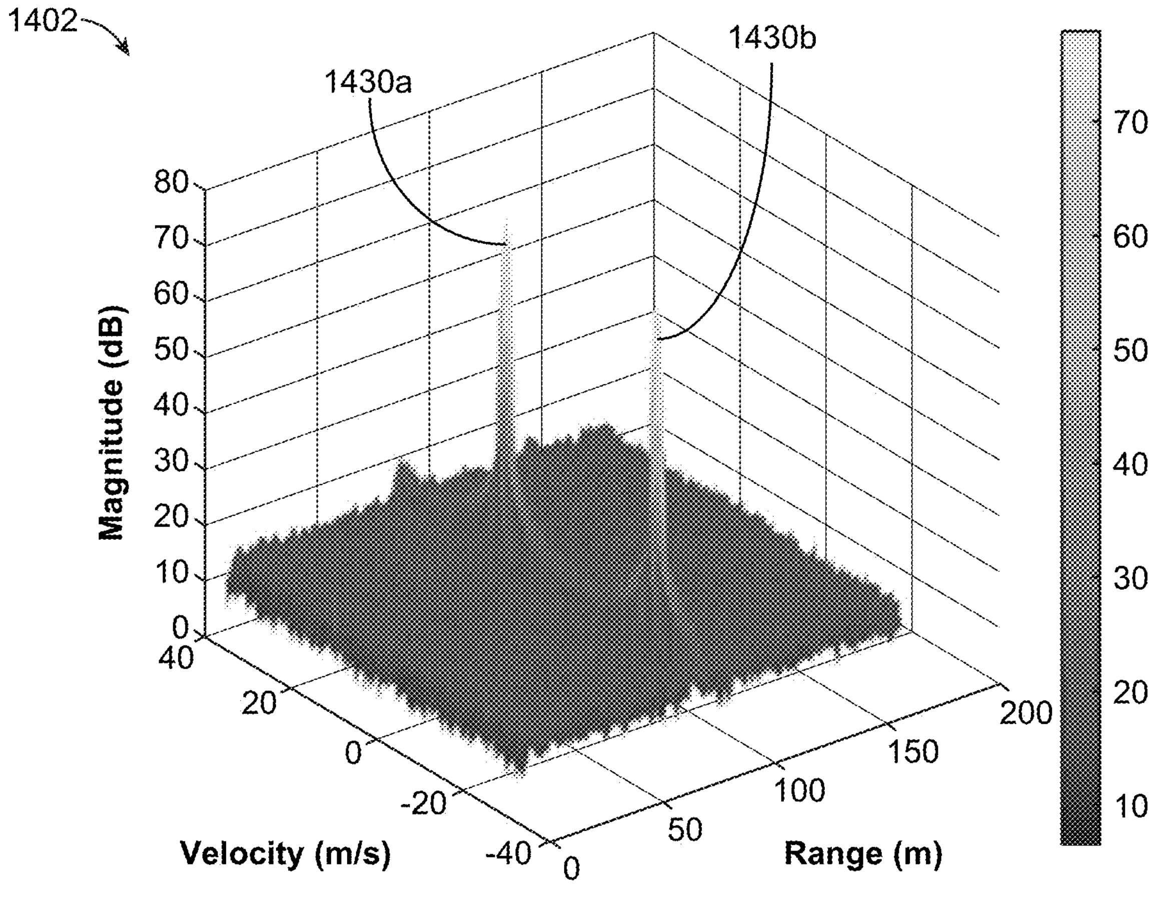

1400
1410
1420a
1420b
Tx2
Tx1
Tx2
$-f_{D\_max}$
$-f_{D\_max}/2$
$f_{D\_max}/2$
f_{D_max}
Doppler frequency

FIG. 14A


1402
1430a
1430b
Magnitude (dB)
80
70
60
50
40
30
20
10
0
40
20
0
-20
-40
Velocity (m/s)
0
50
100
150
200
Range (m)
70
60
50
40
30
20
10

(a)

FIG. 14B

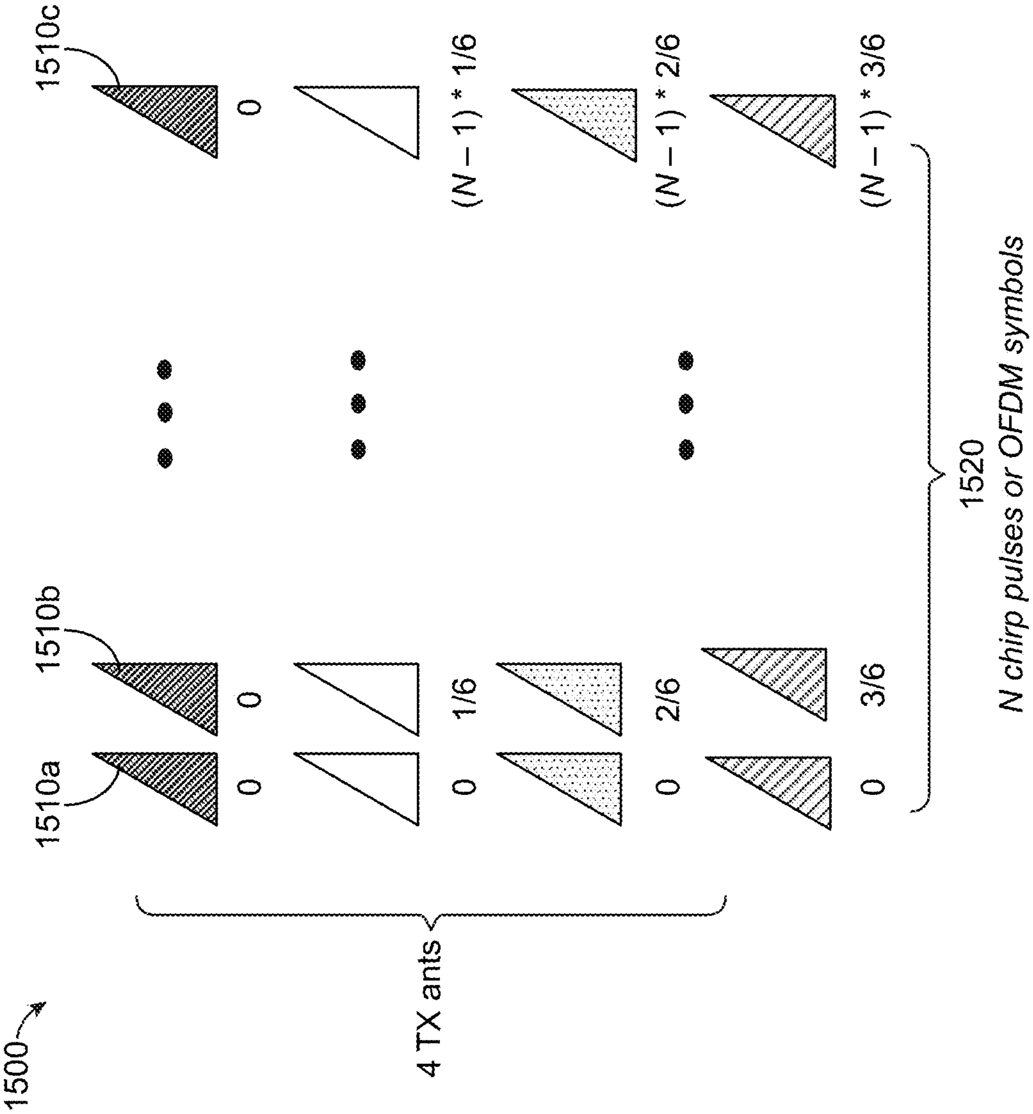

1500
4 TX ants
1510a
1510b
1510c
0
0
0
0
0
1/6
2/6
3/6
0
(N – 1) * 1/6
(N – 1) * 2/6
(N – 1) * 3/6
1520
N chirp pulses or OFDM symbols

FIG. 15A

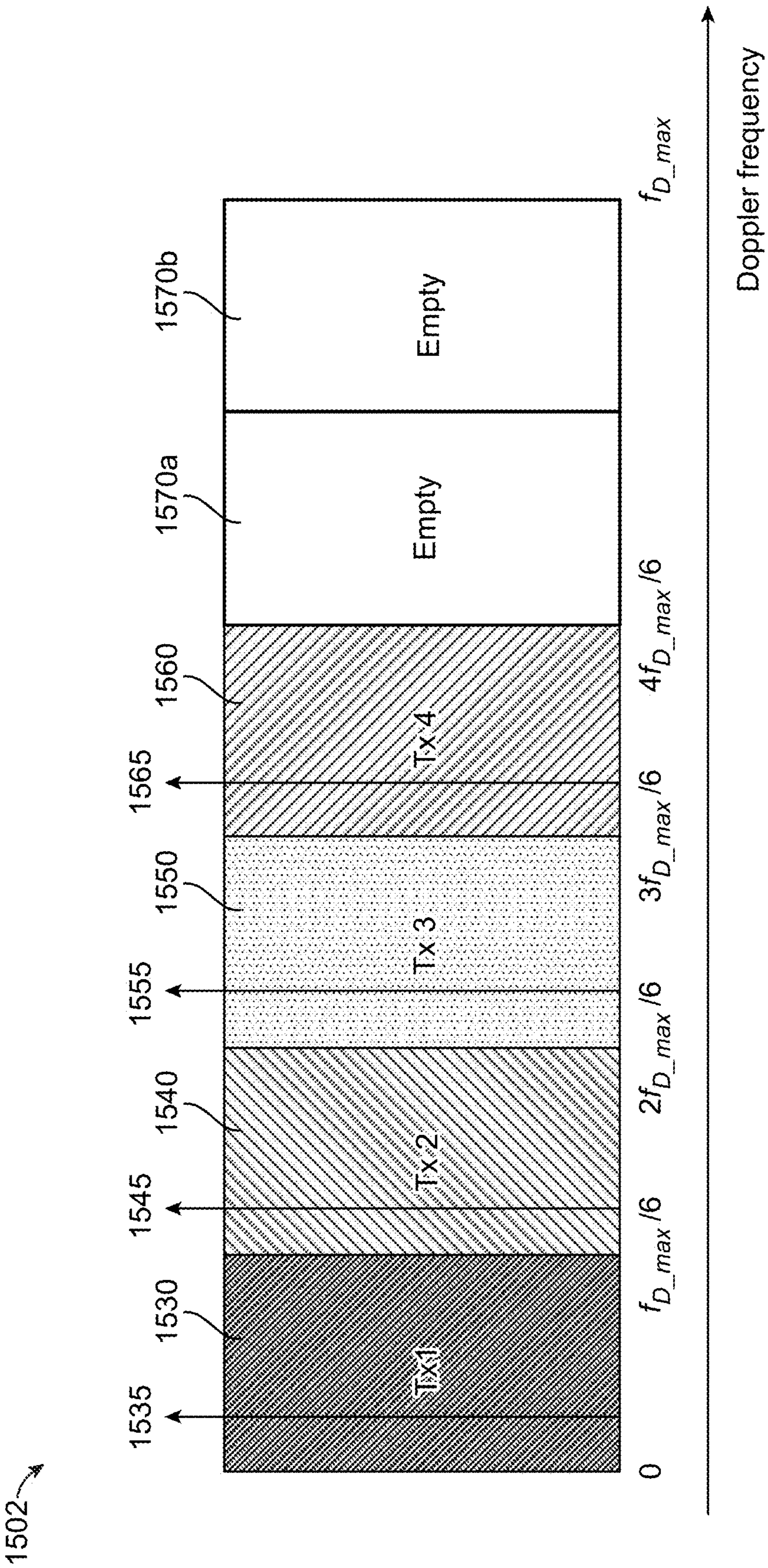
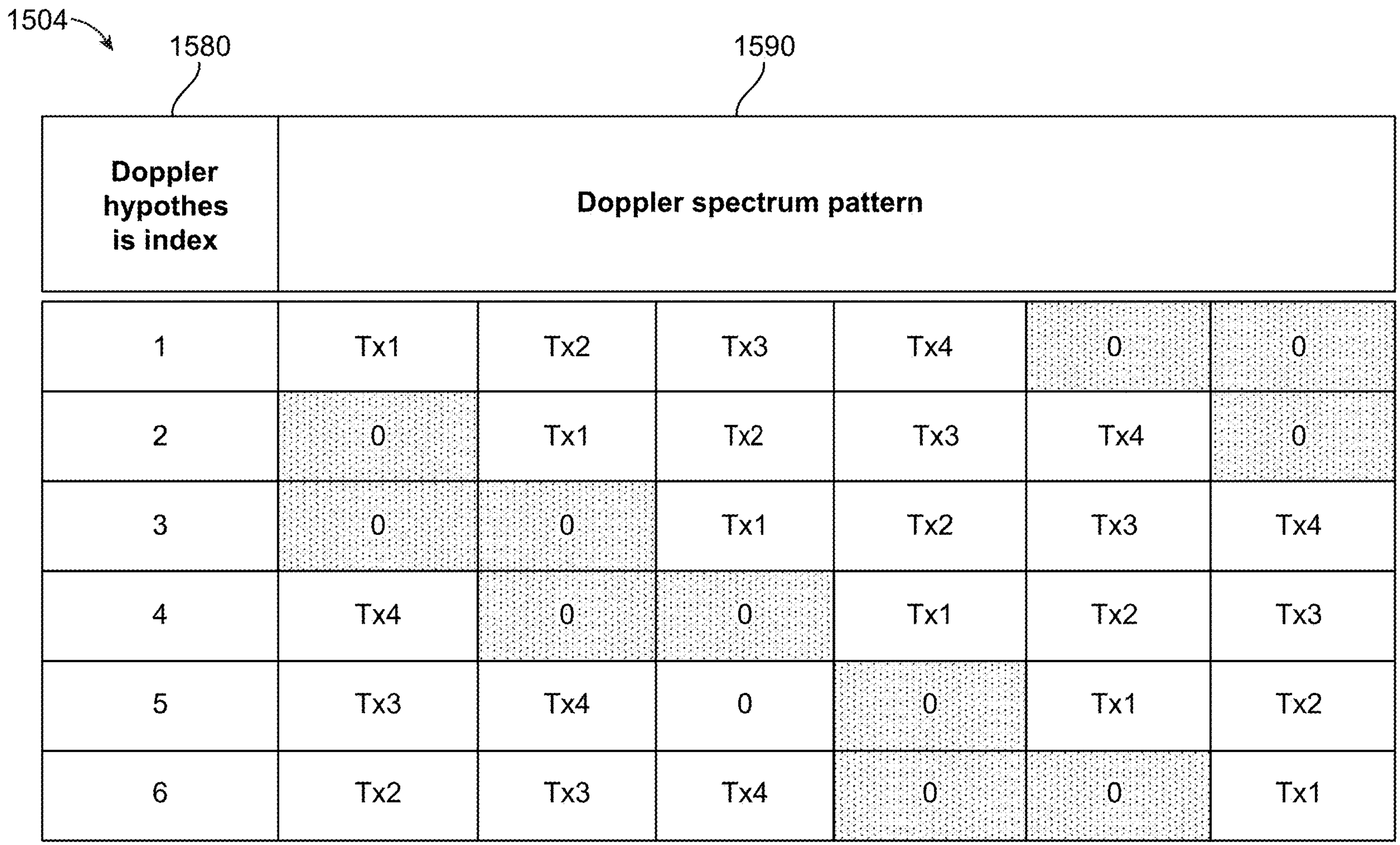

1502
1535
1530
Tx1
1545
1540
Tx 2
1555
1550
Tx 3
1565
1560
Tx 4
1570a
Empty
1570b
Empty
0
$f_{D\_max}/6$
$2f_{D\_max}/6$
$3f_{D\_max}/6$
$4f_{D\_max}/6$
f_{D_max}
Doppler frequency

FIG. 15B



Doppler hypothes is index	Doppler spectrum pattern					
1	Tx1	Tx2	Tx3	Tx4	0	0
2	0	Tx1	Tx2	Tx3	Tx4	0
3	0	0	Tx1	Tx2	Tx3	Tx4
4	Tx4	0	0	Tx1	Tx2	Tx3
5	Tx3	Tx4	0	0	Tx1	Tx2
6	Tx2	Tx3	Tx4	0	0	Tx1

FIG. 15C

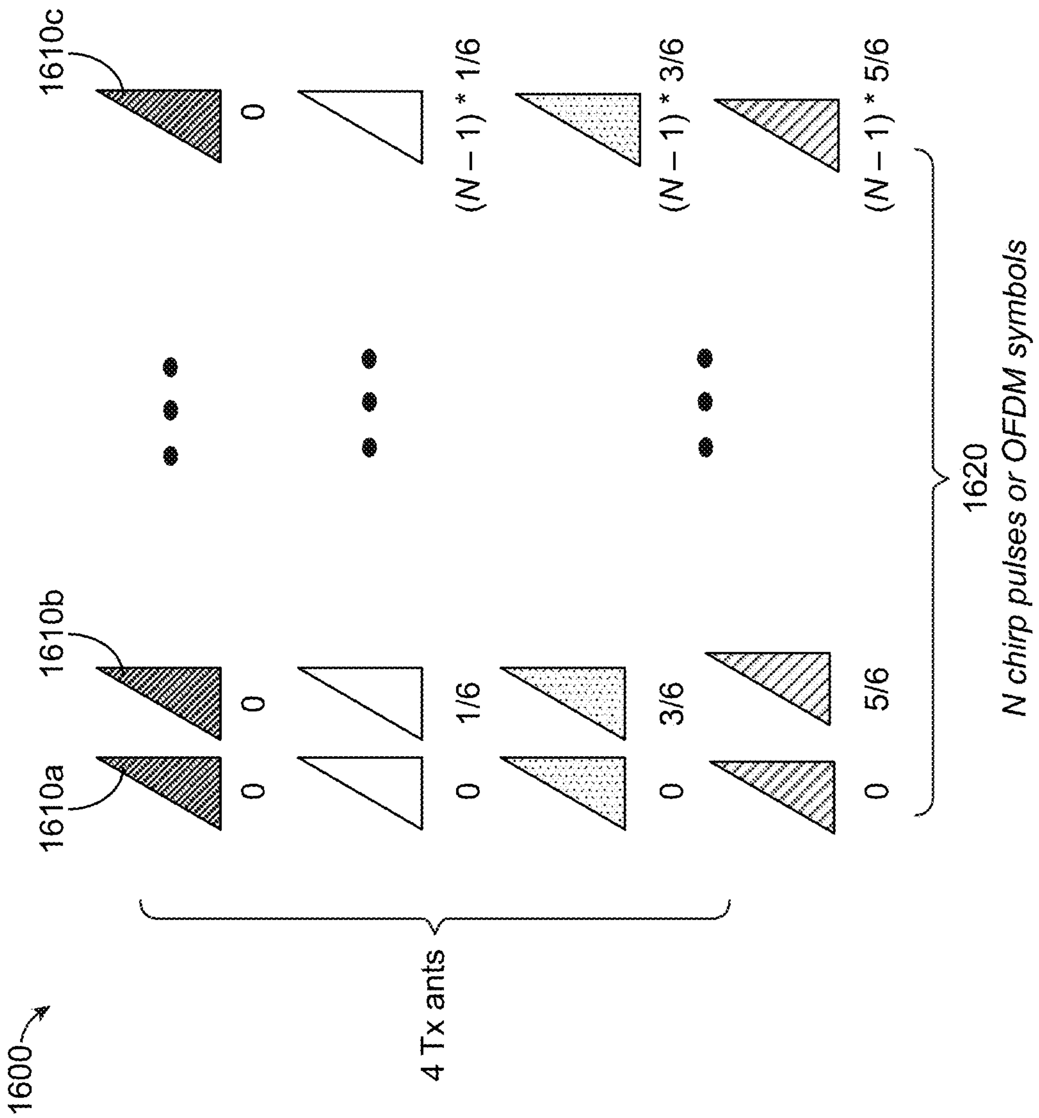

1600
4 Tx ants
1610a
1610b
1610c
0
0
0
0
0
1/6
(N − 1) * 1/6
0
3/6
(N − 1) * 3/6
0
5/6
(N − 1) * 5/6
1620
N chirp pulses or OFDM symbols

FIG. 16A

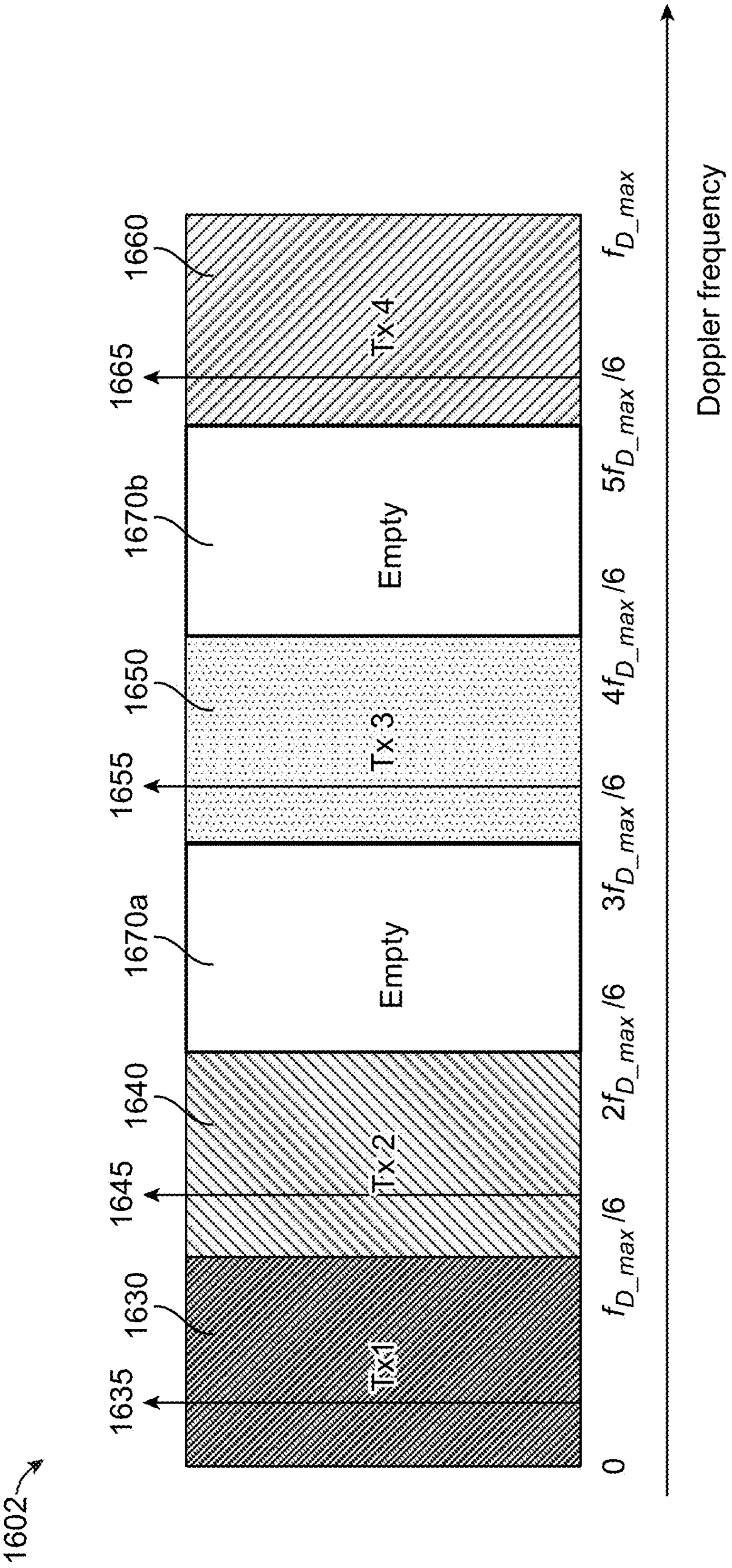
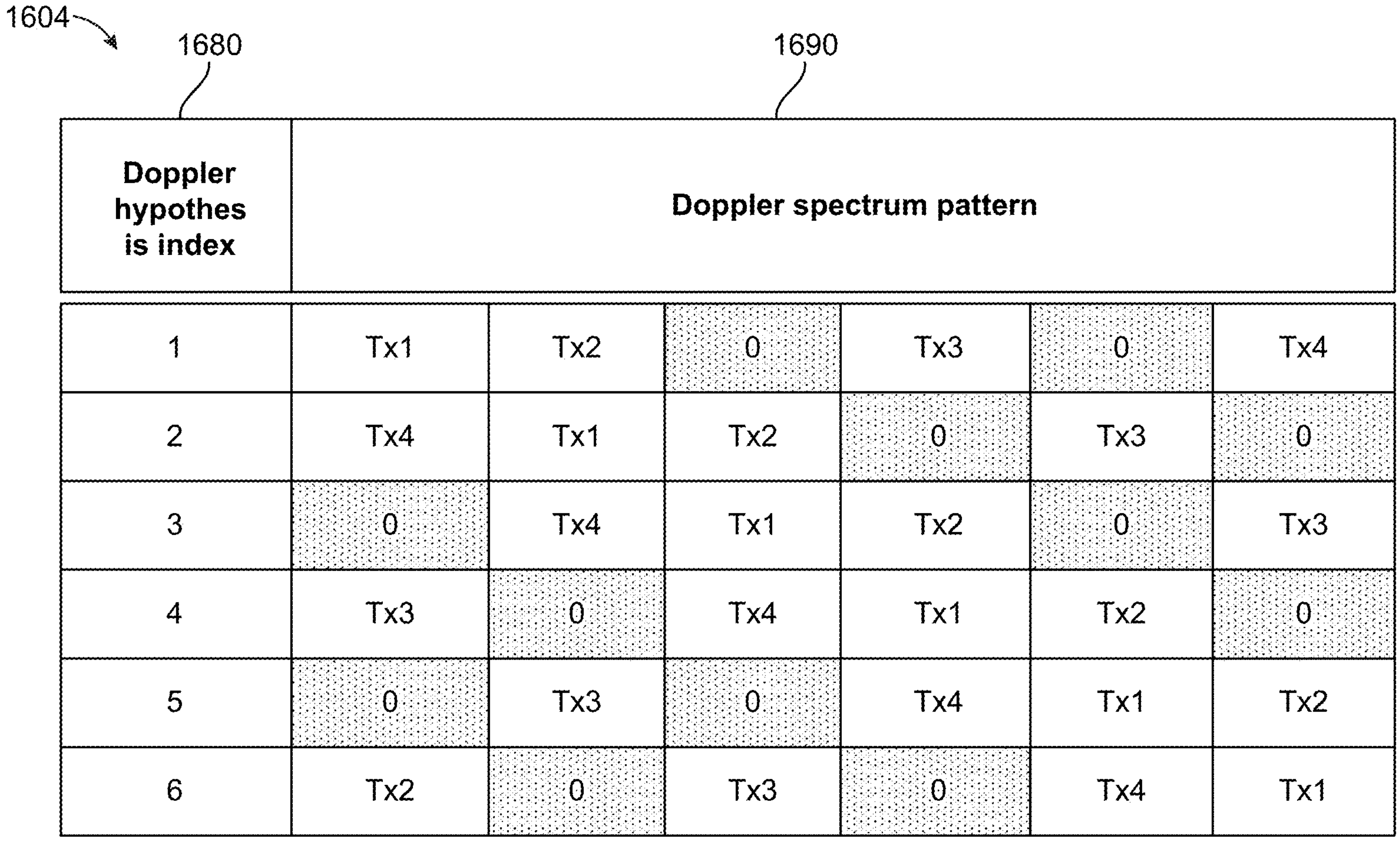

1602
1635
1630
1645
1640
1670a
1655
1650
1670b
1665
1660
Tx1
Tx 2
Empty
Tx 3
Empty
Tx 4
0
$f_{D\_max}/6$
$2f_{D\_max}/6$
$3f_{D\_max}/6$
$4f_{D\_max}/6$
$5f_{D\_max}/6$
f_{D_max}
Doppler frequency

FIG. 16B



Doppler hypothes is index	Doppler spectrum pattern					
1	Tx1	Tx2	0	Tx3	0	Tx4
2	Tx4	Tx1	Tx2	0	Tx3	0
3	0	Tx4	Tx1	Tx2	0	Tx3
4	Tx3	0	Tx4	Tx1	Tx2	0
5	0	Tx3	0	Tx4	Tx1	Tx2
6	Tx2	0	Tx3	0	Tx4	Tx1

FIG. 16C

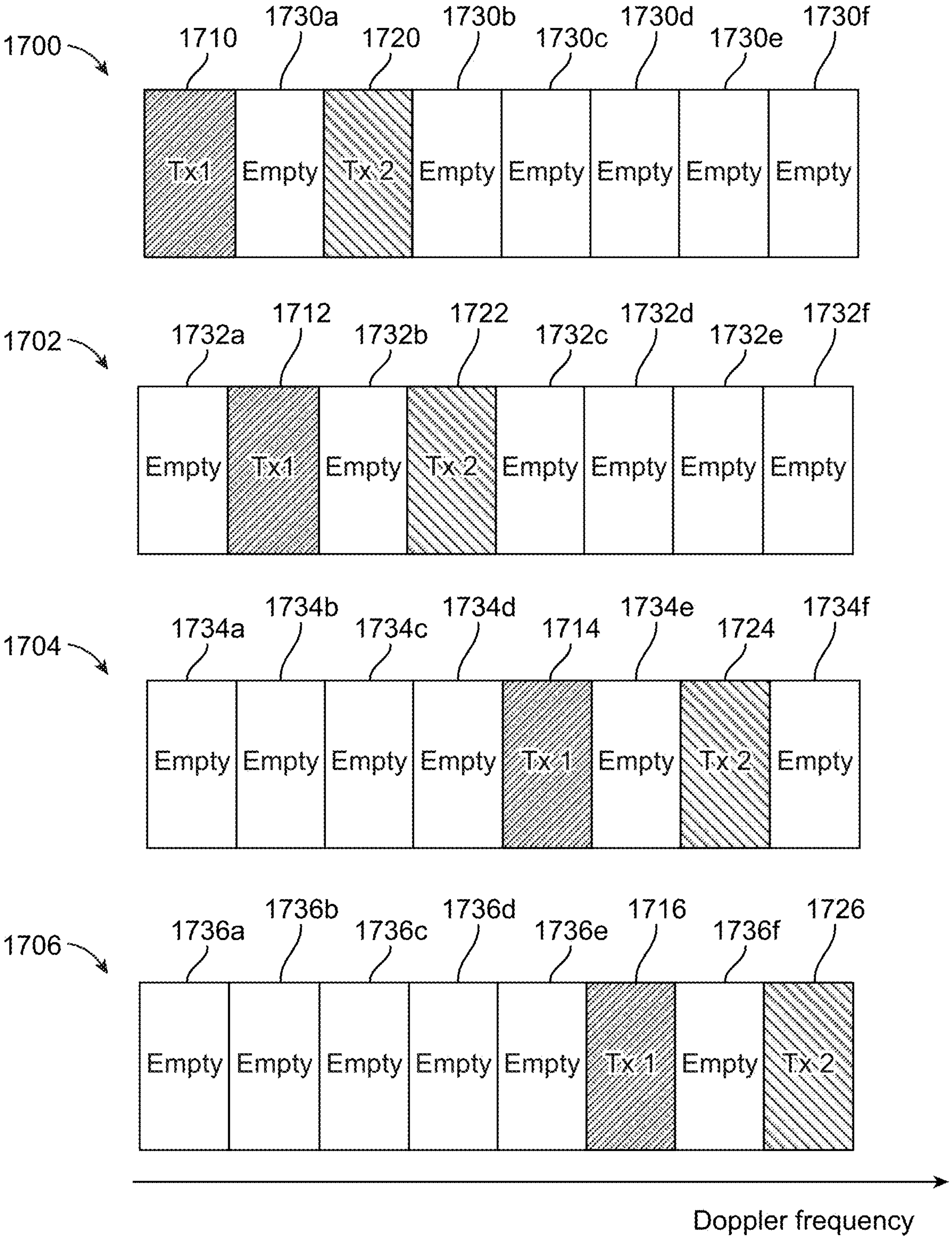

1700
1710
1730a
1720
1730b
1730c
1730d
1730e
1730f
Tx1
Empty
Tx 2
Empty
Empty
Empty
Empty
Empty
1702
1732a
1712
1732b
1722
1732c
1732d
1732e
1732f
Empty
Tx1
Empty
Tx 2
Empty
Empty
Empty
Empty
1704
1734a
1734b
1734c
1734d
1714
1734e
1724
1734f
Empty
Empty
Empty
Empty
Tx 1
Empty
Tx 2
Empty
1706
1736a
1736b
1736c
1736d
1736e
1716
1736f
1726
Empty
Empty
Empty
Empty
Empty
Tx 1
Empty
Tx 2
Doppler frequency

FIG. 17

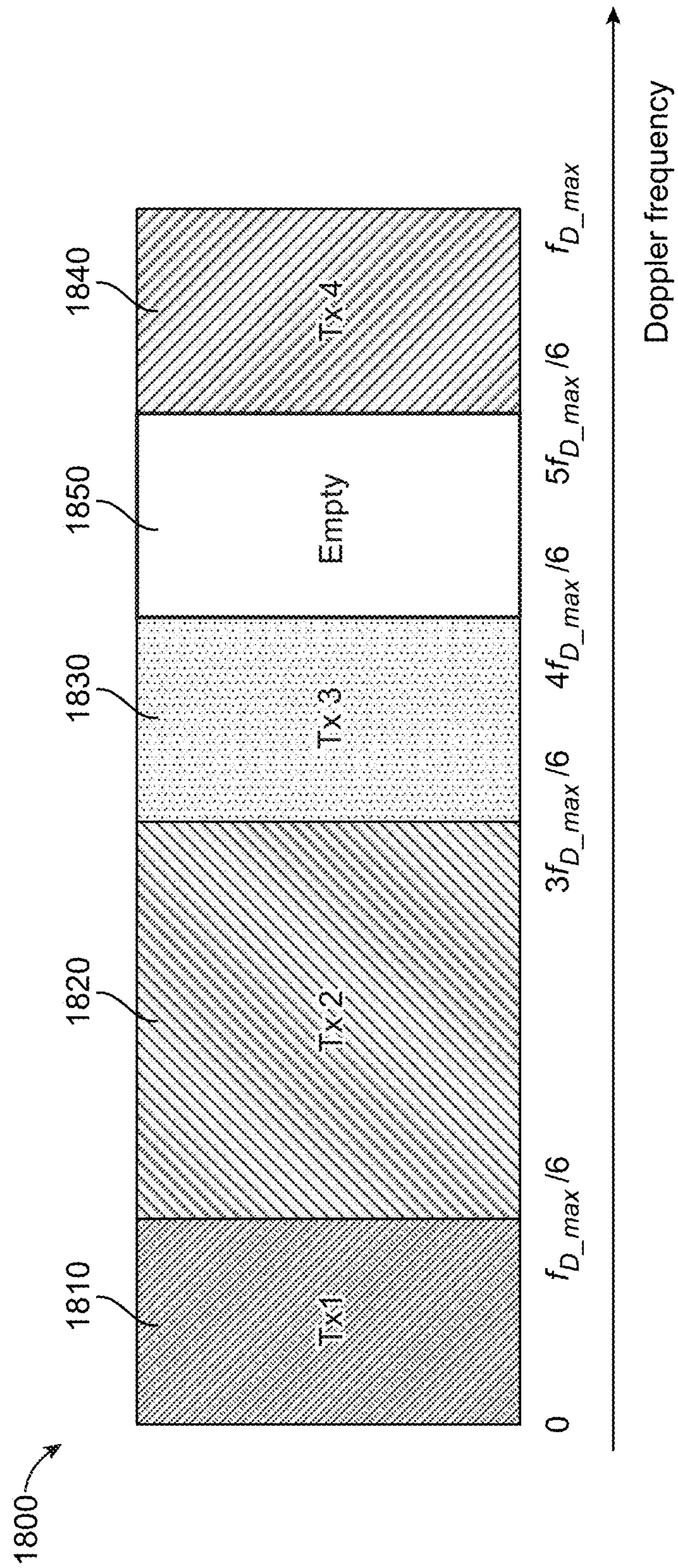

1800
1810
1820
1830
1850
1840
Tx 1
Tx 2
Tx 3
Empty
Tx 4
0
$f_{D\_max}/6$
$3f_{D\_max}/6$
$4f_{D\_max}/6$
$5f_{D\_max}/6$
f_{D_max}
Doppler frequency

FIG. 18

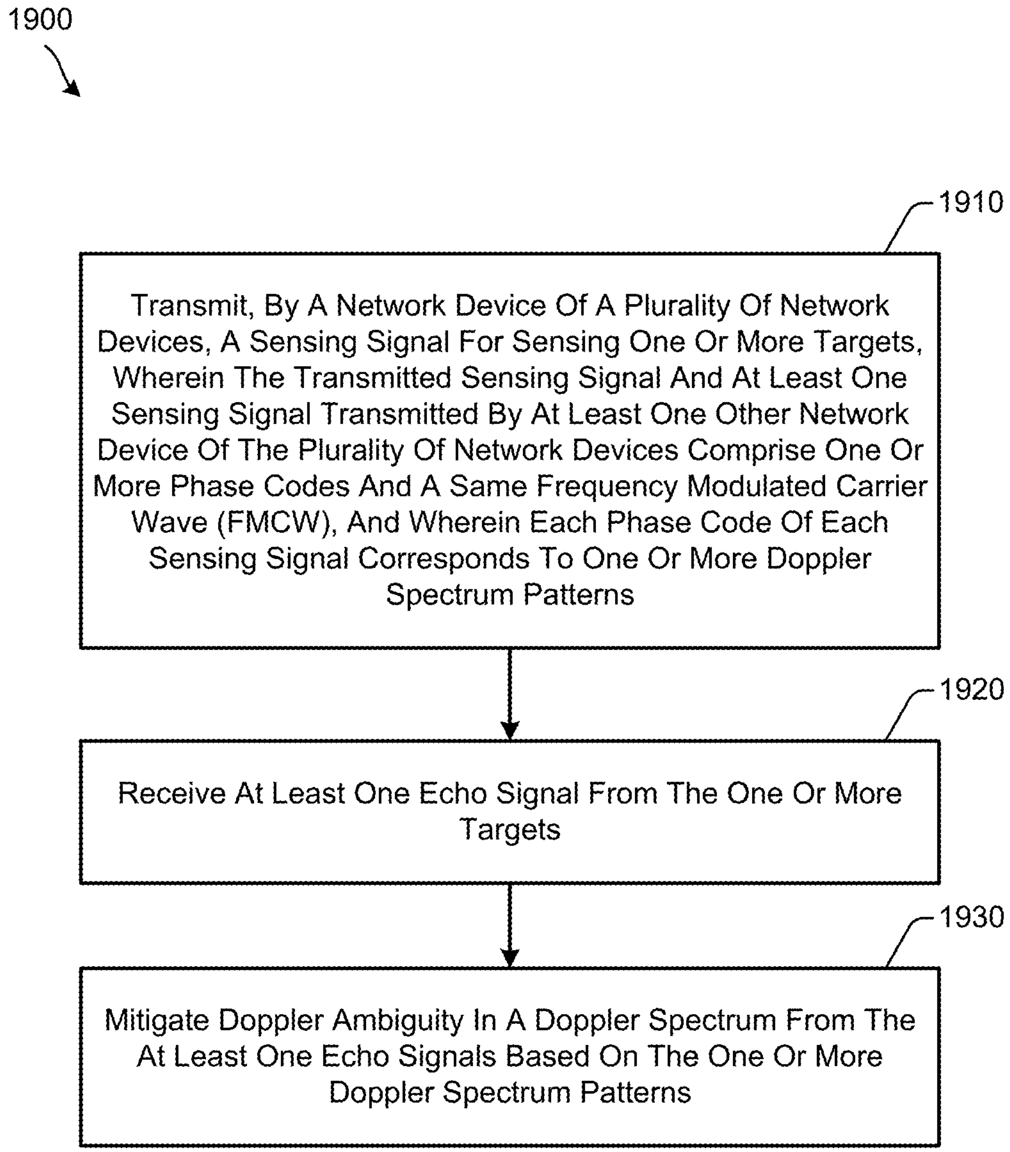

1900
1910
Transmit, By A Network Device Of A Plurality Of Network Devices, A Sensing Signal For Sensing One Or More Targets, Wherein The Transmitted Sensing Signal And At Least One Sensing Signal Transmitted By At Least One Other Network Device Of The Plurality Of Network Devices Comprise One Or More Phase Codes And A Same Frequency Modulated Carrier Wave (FMCW), And Wherein Each Phase Code Of Each Sensing Signal Corresponds To One Or More Doppler Spectrum Patterns
1920
Receive At Least One Echo Signal From The One Or More Targets
1930
Mitigate Doppler Ambiguity In A Doppler Spectrum From The At Least One Echo Signals Based On The One Or More Doppler Spectrum Patterns

FIG. 19

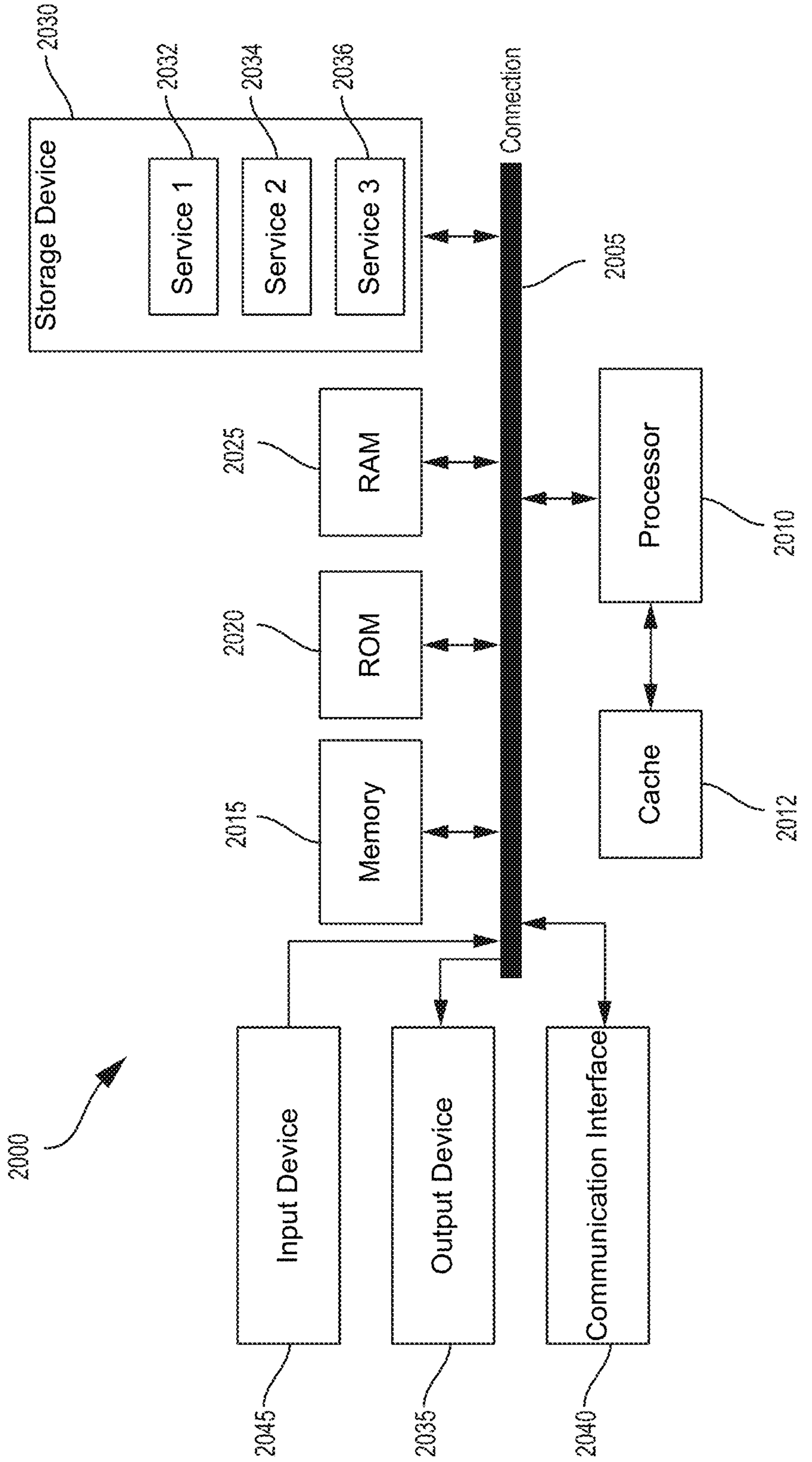

2000
2030
Storage Device
2032
Service 1
2034
Service 2
2036
Service 3
Connection
2005
2025
RAM
2020
ROM
2015
Memory
Processor
2010
Cache
2012
Input Device
Output Device
Communication Interface
2045
2035
2040

FIG. 20

ENHANCED DOPPLER DIVISION MULTIPLEXING (DDM) MULTIPLE-INPUT AND MULTIPLE-OUTPUT (MIMO) SENSING BASED ON DOPPLER SPECTRUM PUNCTURING

FIELD OF THE DISCLOSURE

[0001] The present disclosure generally relates to scheduling and/or processing sensing and communication signals for joint communications and sensing. For example, aspects of the present disclosure relate to providing enhancements for Doppler division multiplexing (DDM) multiple-input and multiple-output (MIMO) sensing based on Doppler spectrum puncturing.

BACKGROUND OF THE DISCLOSURE

[0002] Wireless communications systems are widely deployed to provide various types of communication content, such as voice, video, packet data, messaging, and broadcast. These systems may be capable of supporting communication with multiple users by sharing the available system resources (e.g., time, frequency, and power). Examples of such multiple-access systems include fourth generation (4G) systems such as Long Term Evolution (LTE) systems, LTE-Advanced (LTE-A) systems, or LTE-A Pro systems, and fifth generation (5G) systems which may be referred to as New Radio (NR) systems. These systems may employ technologies such as code division multiple access (CDMA), time division multiple access (TDMA), frequency division multiple access (FDMA), orthogonal FDMA (OFDMA), or discrete Fourier transform spread orthogonal frequency division multiplexing (DFT-S-OFDM). A wireless multiple-access communications system may include one or more base stations or one or more network access nodes, each simultaneously supporting communication for multiple communication devices, which may be otherwise known as user equipment (UE). Some wireless communications systems may support communications between UEs, which may involve direct transmissions between two or more UEs.

[0003] Due to larger bandwidths being allocated for wireless cellular communications systems (e.g., including 5G and 5G beyond) and more use cases being introduced into the cellular communications systems, Doppler division multiplexing (DDM) multiple-input and multiple-output (MIMO) sensing can be an essential feature for existing or future wireless communication systems, such as to enhance the overall spectral efficiency of the wireless communication networks.

SUMMARY

[0004] The following presents a simplified summary relating to one or more aspects disclosed herein. Thus, the following summary should not be considered an extensive overview relating to all contemplated aspects, nor should the following summary be considered to identify key or critical elements relating to all contemplated aspects or to delineate the scope associated with any particular aspect. Accordingly, the following summary has the sole purpose to present certain concepts relating to one or more aspects relating to the mechanisms disclosed herein in a simplified form to precede the detailed description presented below.

[0005] Systems and techniques are described for wireless communications. According to at least one example, a network device of a plurality of network devices for wireless communications is provided. The network device includes at least one memory and at least one processor coupled to the at least one memory and configured to: output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receive at least one echo signal from the one or more targets; and mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0006] In another illustrative example, a method is provided for wireless communications at a network device. The method includes: transmitting, by the network device, a sensing signal for sensing one or more targets, wherein the transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receiving, by the network device, at least one echo signal from the one or more targets; and mitigating, by the network device, Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0007] In another illustrative example, a non-transitory computer-readable medium of a network device of a plurality of network devices is provided. The non-transitory computer-readable medium has stored thereon instructions that, when executed by at least one processor, cause the at least one processor to: output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receive at least one echo signal from the one or more targets; and mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0008] In another illustrative example, a network device of a plurality of network devices for wireless communications is provided. The apparatus includes: means for transmitting a sensing signal for sensing one or more targets, wherein the transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; means for receiving at least one echo signal from the one or more targets; and means for mitigating Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0009] In some aspects, one or more of the network devices, apparatus, or other devices described herein is, is part of, and/or includes a user equipment (UE), a base station (e.g., a gNodeB (gNB), an eNodeB (eNB), etc.), or a portion of a base station (e.g., one or more of a central unit (CU), a distributed unit (DU), a radio unit (RU), a Near-Real Time (Near-RT) RAN Intelligent Controller (RIC), or a Non-Real Time (Non-RT) RIC of the base station). The UE may be a wearable device, an extended reality (XR) device (e.g., a virtual reality (VR) device, an augmented reality (AR) device, or a mixed reality (MR) device), a head-mounted display (HMD) device, a wireless communication device, a mobile device (e.g., a mobile telephone and/or mobile handset and/or so-called "smart phone" or other mobile device), a camera, a personal computer, a laptop computer, a server computer, a vehicle or a computing device or component of a vehicle, another device, or a combination thereof. In some aspects, the one or more of the network devices, apparatus, or other devices may include a camera or multiple cameras for capturing one or more images. In some examples, the one or more of the network devices, apparatus, or other devices may further include a display for displaying one or more images, notifications, and/or other displayable data. In some cases, the one or more of the network devices, apparatus, or other devices may include one or more receivers, transmitters, or transceivers for receiving and/or transmitting wireless communications.

[0010] This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this patent, any or all drawings, and each claim.

[0011] The foregoing, together with other features and aspects, will become more apparent upon referring to the following specification, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The accompanying drawings are presented to aid in the description of various aspects of the disclosure and are provided solely for illustration of the aspects and not limitation thereof.

[0013] FIG. **1** is a diagram illustrating an example wireless communications system, which may be employed by the disclosed systems and techniques for enhancements on Doppler division multiplexing (DDM) multiple-input and multiple-output (MIMO) sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

[0014] FIG. **2** is a diagram illustrating an example of a disaggregated base station architecture, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

[0015] FIG. **3** is a diagram illustrating an example of a frame structure, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

[0016] FIG. **4** is a block diagram illustrating an example of a computing system of an electronic device that may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

[0017] FIG. **5** is a diagram illustrating an example of a wireless device utilizing radio frequency (RF) monostatic sensing techniques, which may be employed by the disclosed systems and techniques described herein to determine one or more characteristics of a target object, in accordance with some aspects of the present disclosure.

[0018] FIG. **6** is a diagram illustrating an example of a receiver utilizing RF bistatic sensing techniques with one transmitter, which may be employed by the disclosed systems and techniques described herein to determine one or more characteristics of a target object, in accordance with some aspects of the present disclosure.

[0019] FIG. **7** is a diagram illustrating an example of a receiver utilizing RF bistatic sensing techniques with multiple transmitters, which may be employed by the disclosed systems and techniques described herein to determine one or more characteristics of a target object, in accordance with some aspects of the present disclosure.

[0020] FIG. **8** is a diagram illustrating an example geometry for bistatic (or monostatic) sensing, in accordance with some aspects of the present disclosure.

[0021] FIG. **9** is a diagram illustrating a bistatic range of bistatic sensing, in accordance with some aspects of the present disclosure.

[0022] FIG. **10** is a diagram illustrating an example of devices involved in wireless communications (e.g., sidelink communications), in accordance with some aspects of the present disclosure.

[0023] FIG. **11** is a diagram illustrating examples of existing comb structures for reference signals.

[0024] FIG. **12** is a diagram illustrating an example of a system for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, where the system is performing bistatic sensing of a target, in accordance with some aspects of the present disclosure.

[0025] FIG. **13** is a diagram illustrating an example of chirps being transmitted by a plurality of antennas, in accordance with some aspects of the present disclosure.

[0026] FIG. **14**A is a diagram illustrating an example of Doppler frequency of transmissions from two antennas, in accordance with some aspects of the present disclosure.

[0027] FIG. **14**B is a graph illustrating an example of a range-velocity profile for a DDM MIMO radar with two transmitting antennas, in accordance with some aspects of the present disclosure.

[0028] FIG. **15**A is a diagram illustrating an example of chirps being transmitted by four antennas, in accordance with some aspects of the present disclosure.

[0029] FIG. **15**B is a diagram illustrating an example of Doppler frequency of transmissions from four antennas, where the empty sub-bands are consecutive, in accordance with some aspects of the present disclosure.

[0030] FIG. **15**C is a table illustrating examples of Doppler spectrum patterns, where the empty sub-bands are consecutive, in accordance with some aspects of the present disclosure.

[0031] FIG. **16**A is a diagram illustrating an example of chirps being transmitted by four antennas, in accordance with some aspects of the present disclosure.

[0032] FIG. **16**B is a diagram illustrating an example of Doppler frequency of transmissions from four antennas, where the empty sub-bands are non-consecutive, in accordance with some aspects of the present disclosure.

[0033] FIG. **16**C is a table illustrating examples of Doppler spectrum patterns, where the empty sub-bands are non-consecutive, in accordance with some aspects of the present disclosure.

[0034] FIG. **17** is a diagram illustrating examples of Doppler frequency of transmissions for MIMO sensing with four different users, in accordance with some aspects of the present disclosure.

[0035] FIG. **18** is a diagram illustrating an example of Doppler frequency of transmissions from four antennas, where the periodicity of one sub-band is doubled, in accordance with some aspects of the present disclosure.

[0036] FIG. **19** is a flow chart illustrating an example of a process for wireless communications utilizing methods for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

[0037] FIG. **20** is a block diagram illustrating an example of a computing system, which may be employed by the disclosed systems and for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, in accordance with some aspects of the present disclosure.

DETAILED DESCRIPTION

[0038] Certain aspects of this disclosure are provided below for illustration purposes. Alternate aspects may be devised without departing from the scope of the disclosure. Additionally, well-known elements of the disclosure will not be described in detail or will be omitted so as not to obscure the relevant details of the disclosure. Some of the aspects described herein may be applied independently and some of them may be applied in combination as would be apparent to those of skill in the art. In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of aspects of the application. However, it will be apparent that various aspects may be practiced without these specific details. The figures and description are not intended to be restrictive.

[0039] The ensuing description provides example aspects, and is not intended to limit the scope, applicability, or configuration of the disclosure. Rather, the ensuing description of the example aspects will provide those skilled in the art with an enabling description for implementing an example aspect. It should be understood that various changes may be made in the function and arrangement of elements without departing from the scope of the application as set forth in the appended claims.

[0040] Radar sensing systems use radio frequency (RF) waveforms to perform RF sensing to determine or estimate one or more characteristics of a target object, such as the distance, angle, and/or velocity of the target object. A target object may include a vehicle, an obstruction, a user, a building, or other object. A typical radar system includes at least one transmitter, at least one receiver, and at least one processor. A radar sensing system may perform monostatic sensing when one receiver is employed that is co-located with a transmitter. A radar system may perform bistatic sensing when one receiver of a first device is employed that is located remote from a transmitter of a second device. Similarly, a radar system may perform multi-static sensing when multiple receivers of multiple devices are employed that are all located remotely from at least one transmitter of at least one device.

[0041] During operation of a radar sensing system, a transmitter transmits an electromagnetic (EM) signal in the RF domain towards a target object. The signal reflects off of the target object to produce one or more reflection signals, which provides information or properties regarding the target, such as target object's location and speed. At least one receiver receives the one or more reflection signals and at least one processor, which may be associated with at least one receiver, utilizes the information from the one or more reflection signals to determine information or properties of the target object. A target object can also be referred herein as a target.

[0042] Generally, RF sensing involves monitoring moving targets with different motions (e.g., a moving car or pedestrian, a body motion of a person, such as breathing, and/or other micro-motions related to a target). Doppler, which measures the phase variation in a signal and is indicative of motion, is an important characteristic for sensing of a target.

[0043] In some cases, the radar sensing signals, which can be referred to as radar reference signals (RSS), such as sensing reference signals (S-RS), may be designed for and used for sensing purposes. Radar RSs are typically designed solely for sensing purposes (e.g., not for communications purposes). Conversely, communication RSs, such as demodulation reference signals (DMRSs), are typically designed for and solely used for communications purposes, such as estimating channel parameters for communications.

[0044] Cellular communications systems are designed to transmit communication signals on designated communication frequency bands (e.g., 23 gigahertz (GHz), 3.5 GHz, etc. for 5G/NR, 2.2 GHz for LTE, among others). RF sensing systems are designed to transmit RF sensing signals on designated radar RF frequency bands (e.g., 77 GHz for autonomous driving). Future cellular communications systems are likely to use a common spectrum for both communications and sensing, in which case the communications and sensing should be jointly considered.

[0045] MIMO is a multi-antenna spectrum-efficient technique, and has become a leading driver of next-generation antenna technology for cellular networks. A MIMO system may transmit more than one signal over the same channel, providing for an increase in spectral efficiency and overall throughput. By taking advantage of spatial separation, the antennas of a MIMO system are spaced at specific distances and angles for various purposes, such as to reduce the correlation between different sub-channels, to achieve precoding/beamforming purposes, etc. A MIMO system can provide a robust wireless communication mechanism to address fading and shadowing caused by multiple transmission paths and long distances. In a MIMO system, various streams of data can be transmitted at the same time, which can provide for multiplexing gains and an improvement in the overall throughput. For at least these reasons, MIMO has been recently employed in cellular wireless communications technology and is included in various next-generation wireless projects and standards, including 5G NR.

[0046] A simple form of MIMO is point-to-point MIMO. In point-to-point MIMO, two systems (e.g., a base station and a UE) each employ multiple antennas to communicate with each other. The use of multiple antennas provides for an increase in the capacity of the air interface. However, point-to-point MIMO employs a multi-antenna configuration that requires additional hardware at both the base station and the end-user device (e.g., in the UE). The requirement of additional hardware at both the base station and the user device is a disadvantage to point-to-point MIMO because it increases the overall system complexity. In some cases, end-user equipment (e.g., UE) of a mobile communications system may not be able to support multiple antennas, such as due to its small physical size and/or the low-cost requirements of the UE devices.

[0047] A feature of point-to-point MIMO is single-user MIMO (SU-MIMO), which provides for an increase in the data rate by transmitting multiple data streams to a specific user device (e.g., specific UE). Similar to point-to-point MIMO, SU-MIMO has the drawback of requiring the user device (e.g., UE) to support multiple antennas.

[0048] Conversely to point-to-point MIMO and SU-MIMO, multiple-user MIMO (MU-MIMO) does not have the disadvantage of requiring the user device to support multiple antennas. In MU-MIMO, multiple users share the same time and frequency resources, while each base station (e.g., a next generation node B (gNB), evolved node B (cNB), or portion thereof such as a central unit (CU), a distributed unit (DU), a radio unit (RU), a Near-Real Time (Near-RT) RAN Intelligent Controller (RIC), or a Non-Real Time (Non-RT) RIC) is equipped with multiple antennas (e.g., antenna arrays) and serves many users (e.g., UEs) simultaneously. Each end-user device (e.g., UE) can employ a single antenna or multiple antennas. In cases where a single antenna is used by an end-user device, complex hardware may only be needed at the base station side. The cost and complexity of the antenna system are significantly reduced for a MU-MIMO system because low-cost single antennas (e.g., dipole antennas) may be employed for the end-user devices (e.g., UEs), and the more expensive, complex hardware may be utilized only at the base station side.

[0049] Due to the variety in the distance, angle, and quality of the signals of the multiple users in MU-MIMO systems, the performance of MU-MIMO systems is generally less affected by the transmission environment as compared to point-to-point MIMO. This advantage is achieved by MU-MIMO systems employing selective beamforming and power control to cancel interference. MU-MIMO systems offer high reliability and throughput and, as such, have become an integral part of wireless communication systems, including Wi-Fi, LTE, and 5G networks.

[0050] Massive MIMO (mMIMO) is a form a MU-MIMO that employs a larger number of antennas at the base stations than MU-MIMO and, as such, the number of users (e.g., UEs) served can be increased significantly over MU-MIMO systems (e.g., in mMIMO, a single base station with many antennas can serve a large number of users). With a large number of antennas in each base station, the channel vectors between users (e.g., UEs) and the base station are per pair almost rectangular and, as such, can provide for exceptional linear transmissions. In mMIMO, a large throughput can be achieved due to multiplexing gain, diversity gain, and array gain. The large number of antennas at the base stations, in mMIMO, may serve hundreds of users with the same frequency resource by taking advantage of antenna beamforming techniques.

[0051] In mMIMO, the more antennas employed for each base station, the more robust the communications operation. Theoretically, mMIMO may employ an infinite number of antennas at each of the base stations. But, usually (e.g., in 5G networks), 64 to 128 (e.g., 64 receive antennas and 64 transmit antennas) antennas have been utilized practically in mMIMO base stations. One advantage of mMIMO is that sophisticated hardware may only be needed at the base stations, not at the user devices (e.g., UEs), which each may use a single antenna and a simple antenna design. Another advantage of mMIMO is that it has an extensible architecture that can be easily scaled up to serve more users by only needing to upgrade the antenna systems on the base stations.

[0052] Currently, some radar (e.g., automotive radar) transmit signals with frequency modulated continuous wave (FMCW) waveforms. An FMCW waveform, also referred to as a chirp or a pulse, is a complex sinusoid whose frequency increases linearly with time. FMCW radar transmit chirps (e.g., chirps **1310***a*, **1310***b*, **1310***c* of FIG. **13**) in a periodic fashion, with a period referred to as a pulse repetition interval (PRI). A target echo at the radar receiver can contain a delayed and attenuated copy of the transmitted chirp. The received signal is mixed with the transmitted chirp, which results a complex sinusoid known as the beat signal.

[0053] The process of obtaining the beat signal can be implemented in the RF domain by using a mixer, followed by a bandpass filter (BPF) to remove signals with frequencies outside of the band of interest, which also places a limit on the maximum detectable range. The estimation of the beat frequency can be implemented in the digital domain, after the sampling of the beat signal. In many scenarios (e.g., automotive scenarios), the beat frequency is much smaller than the signal bandwidth and, as such, a low-speed analog-to-digital converter (ADC), which is low cost, can be used to sample the beat signal. FMCW waveforms are commonly used within the radar industry for their high performance-to-cost ratio, which is at least in part provided by the implementation of a low cost ADC. The time during one period or chirp is typically referred to as the "fast time." while the time across multiple periods or chirps is typically referred to as the "slow time." For example, if a beat signal is sampled and the samples of each chirp are placed within columns of a matrix, the row indices of that matrix correspond to the fast time and the column indices correspond to the slow time. By applying a Fast Fourier Transform (FFT) on the sampled beat signal along the fast time, the range frequency can be determined. A second FFT can be applied along the slow time to determine the Doppler frequency. The application of these two FFTs is equivalent to a two-dimensional (2D) FFT of the beat signal in the fast and slow times. The result of this 2D FFT operation produces a 2D range-Doppler spectrum (e.g., graph **1402** of FIG. **14**B).

[0054] The 2D FFT operation used for beat-frequency estimation can be computed with low-cost digital signal processors (DSPs) or field-programmable gate arrays (FPGAs). The range resolution depends on the beat-frequency resolution. The low hardware cost (e.g., a low cost ADC) coupled with a high range resolution that may be achieved, make the use of FMCW radar very desirable for various different radar applications, including automotive radar applications.

[0055] In some scenarios, MIMO radar can be employed to transmit FMCW sequences. For these cases, transmit antennas of the MIMO radar may transmit the FMCW sequences in a way that guarantees their orthogonality. At each receive antenna (e.g., of the MIMO radar), the contribution of each transmit antenna can be extracted by exploiting waveform orthogonality. Various different techniques may be used to achieve waveform orthogonality while transmitting FMCW including, but not limited to, Doppler division multiplexing (DDM).

[0056] For achieving waveform orthogonality while transmitting FMCW by using DDM, a total of N number of chirps (i.e., pulses) should be transmitted sequentially with pulse-repetition interval T_{PRI}. All transmit antennas should simultaneously transmit the same FMCW waveform after multiplying the FMCW waveform with a phase code that is different for each antenna and changes between pulses, where the transmitted waveform is: $x_m(n)=e^{j2\pi\alpha_m}(n)$, where $m=1, 2, \ldots, m_t$, and $n=0, 1, 2, \ldots, N-1$. To separate the h^{th} transmit signal at the l^{th} receiver, after performing the range FFT, a slow-time Doppler demodulation can be applied to all range bins corresponding to the same chirp. The Doppler demodulated outputs of N number of chirps can be assembled into a vector s_l^h. The Doppler FFT can then be applied on the vector s_l^h.

[0057] In one or more examples, to separate the transmit signals in the Doppler domain, phase codes can be employed to shift the Doppler FFT of the interference $e^{j2\pi(\alpha_m(n)-\alpha_n(n))}$ to a frequency that is higher than the maximum detectable Doppler frequency f_{D_max}. A low-pass filter (LPF) can then be applied to remove the interference. An example of a phase code is $\alpha_m(n)=\alpha_m n$, where $m=1, 2, \ldots, m_t$, and $n=0, 1, 2, \ldots, N-1$, and where the starting phase α_m is linear across different transmit antennas, such that $\alpha_m=m\alpha_0$. With this approach, the radar pulse repetition frequency f_{PRF} should be larger than $M_t f_{D\_max}$. As such, if the f_{PFR} remains unchanged, the maximum detectable unambiguous Doppler frequency is reduced by a factor of M_t. A Doppler unfolding, or de-aliasing, algorithm with different f_{PRF} in different looks to mitigate Doppler ambiguity could be very beneficial.

[0058] In some aspects of the present disclosure, systems, apparatuses, methods (also referred to as processes), and computer-readable media (collectively referred to herein as "systems and techniques") are described herein that provide solutions for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. The systems and techniques provide solutions that remove or mitigate Doppler ambiguity, which may be caused by aliasing issues.

[0059] The systems and techniques described herein provide various advantages over existing systems including, but not limited to, increasing RF sensing performance, decreasing hardware costs, and increasing efficiency of communications, among other benefits.

[0060] Additional aspects of the present disclosure are described in more detail below.

[0061] As used herein, the terms "user equipment" (UE) and "network entity" are not intended to be specific or otherwise limited to any particular radio access technology (RAT), unless otherwise noted. In general, a UE may be any wireless communication device (e.g., a mobile phone, router, tablet computer, laptop computer, and/or tracking device, etc.), wearable (e.g., smartwatch, smart-glasses, wearable ring, and/or an extended reality (XR) device such as a virtual reality (VR) headset, an augmented reality (AR) headset or glasses, or a mixed reality (MR) headset), vehicle (e.g., automobile, motorcycle, bicycle, etc.), and/or Internet of Things (IoT) device, etc., used by a user to communicate over a wireless communications network. A UE may be mobile or may (e.g., at certain times) be stationary, and may communicate with a radio access network (RAN). As used herein, the term "UE" may be referred to interchangeably as an "access terminal" or "AT," a "client device," a "wireless device," a "subscriber device," a "subscriber terminal," a "subscriber station," a "user terminal" or "UT," a "mobile device," a "mobile terminal," a "mobile station," or variations thereof. Generally, UEs can communicate with a core network via a RAN, and through the core network the UEs can be connected with external networks such as the Internet and with other UEs. Of course, other mechanisms of connecting to the core network and/or the Internet are also possible for the UEs, such as over wired access networks, wireless local area network (WLAN) networks (e.g., based on IEEE 802.11 communication standards, etc.) and so on.

[0062] A network entity can be implemented in an aggregated or monolithic base station architecture, or alternatively, in a disaggregated base station architecture, and may include one or more of a central unit (CU), a distributed unit (DU), a radio unit (RU), a Near-Real Time (Near-RT) RAN Intelligent Controller (RIC), or a Non-Real Time (Non-RT) RIC. A base station (e.g., with an aggregated/monolithic base station architecture or disaggregated base station architecture) may operate according to one of several RATs in communication with UEs depending on the network in which it is deployed, and may be alternatively referred to as an access point (AP), a network node, a NodeB (NB), an evolved NodeB (eNB), a next generation eNB (ng-eNB), a New Radio (NR) Node B (also referred to as a gNB or gNodeB), etc. A base station may be used primarily to support wireless access by UEs, including supporting data, voice, and/or signaling connections for the supported UEs. In some systems, a base station may provide edge node signaling functions while in other systems it may provide additional control and/or network management functions. A communication link through which UEs can send signals to a base station is called an uplink (UL) channel (e.g., a reverse traffic channel, a reverse control channel, an access channel, etc.). A communication link through which the base station can send signals to UEs is called a downlink (DL) or forward link channel (e.g., a paging channel, a control channel, a broadcast channel, or a forward traffic channel, etc.). The term traffic channel (TCH), as used herein, can refer to either an uplink, reverse or downlink, and/or a forward traffic channel.

[0063] The term "network entity" or "base station" (e.g., with an aggregated/monolithic base station architecture or disaggregated base station architecture) may refer to a single physical Transmission-Reception Point (TRP) or to multiple physical Transmission-Reception Points (TRPs) that may or may not be co-located. For example, where the term "network entity" or "base station" refers to a single physical TRP, the physical TRP may be an antenna of the base station corresponding to a cell (or several cell sectors) of the base station. Where the term "network entity" or "base station" refers to multiple co-located physical TRPs, the physical TRPs may be an array of antennas (e.g., as in a multiple-input multiple-output (MIMO) system or where the base station employs beamforming) of the base station. Where the term "base station" refers to multiple non-co-located physical TRPs, the physical TRPs may be a distributed antenna system (DAS) (a network of spatially separated antennas connected to a common source via a transport medium) or a remote radio head (RRH) (a remote base station connected to a serving base station). Alternatively, the non-co-located physical TRPs may be the serving base station receiving the measurement report from the UE and a neighbor base station whose reference radio frequency (RF) signals (or simply "reference signals") the UE is measuring. Because a TRP is the point from which a base station transmits and receives wireless signals, as used herein, references to transmission from or reception at a base station are to be understood as referring to a particular TRP of the base station.

[0064] In some implementations that support positioning of UEs, a network entity or base station may not support wireless access by UEs (e.g., may not support data, voice, and/or signaling connections for UEs), but may instead transmit reference signals to UEs to be measured by the UEs, and/or may receive and measure signals transmitted by the UEs. Such a base station may be referred to as a positioning beacon (e.g., when transmitting signals to UEs) and/or as a location measurement unit (e.g., when receiving and measuring signals from UEs).

[0065] An RF signal includes an electromagnetic wave of a given frequency that transports information through the space between a transmitter and a receiver. As used herein, a transmitter may transmit a single "RF signal" or multiple "RF signals" to a receiver. However, the receiver may receive multiple "RF signals" corresponding to each transmitted RF signal due to the propagation characteristics of RF signals through multipath channels. The same transmitted RF signal on different paths between the transmitter and receiver may be referred to as a "multipath" RF signal. As used herein, an RF signal may also be referred to as a "wireless signal" or simply a "signal" where it is clear from the context that the term "signal" refers to a wireless signal or an RF signal.

[0066] According to various aspects, FIG. **1** illustrates an exemplary wireless communications system **100**, which may be employed by the disclosed systems and techniques described herein for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. The wireless communications system **100** (which may also be referred to as a wireless wide area network (WWAN)) can include various base stations **102** and various UEs **104**. In some aspects, the base stations **102** may also be referred to as "network entities" or "network nodes." One or more of the base stations **102** can be implemented in an aggregated or monolithic base station architecture. Additionally or alternatively, one or more of the base stations **102** can be implemented in a disaggregated base station architecture, and may include one or more of a central unit (CU), a distributed unit (DU), a radio unit (RU), a Near-Real Time (Near-RT) RAN Intelligent Controller (RIC), or a Non-Real Time (Non-RT) RIC. The base stations **102** can include macro cell base stations (high power cellular base stations) and/or small cell base stations (low power cellular base stations). In an aspect, the macro cell base station may include eNBs and/or ng-eNBs where the wireless communications system **100** corresponds to a long term evolution (LTE) network, or gNBs where the wireless communications system **100** corresponds to a NR network, or a combination of both, and the small cell base stations may include femtocells, picocells, microcells, etc.

[0067] The base stations **102** may collectively form a RAN and interface with a core network **170** (e.g., an evolved packet core (EPC) or a 5G core (5GC)) through backhaul links **122**, and through the core network **170** to one or more location servers **172** (which may be part of core network **170** or may be external to core network **170**). In addition to other functions, the base stations **102** may perform functions that relate to one or more of transferring user data, radio channel ciphering and deciphering, integrity protection, header compression, mobility control functions (e.g., handover, dual connectivity), inter-cell interference coordination, connection setup and release, load balancing, distribution for non-access stratum (NAS) messages, NAS node selection, synchronization, RAN sharing, multimedia broadcast multicast service (MBMS), subscriber and equipment trace, RAN information management (RIM), paging, positioning, and delivery of warning messages. The base stations **102** may communicate with each other directly or indirectly (e.g., through the EPC or 5GC) over backhaul links **134**, which may be wired and/or wireless.

[0068] The base stations **102** may wirelessly communicate with the UEs **104**. Each of the base stations **102** may provide communication coverage for a respective geographic coverage area **110**. In an aspect, one or more cells may be supported by a base station **102** in each coverage area **110**. A "cell" is a logical communication entity used for communication with a base station (e.g., over some frequency resource, referred to as a carrier frequency, component carrier, carrier, band, or the like), and may be associated with an identifier (e.g., a physical cell identifier (PCI), a virtual cell identifier (VCI), a cell global identifier (CGI)) for distinguishing cells operating via the same or a different carrier frequency. In some cases, different cells may be configured according to different protocol types (e.g., machine-type communication (MTC), narrowband IoT (NB-IoT), enhanced mobile broadband (eMBB), or others) that may provide access for different types of UEs. Because a cell is supported by a specific base station, the term "cell" may refer to either or both of the logical communication entity and the base station that supports it, depending on the context. In addition, because a TRP is typically the physical transmission point of a cell, the terms "cell" and "TRP" may be used interchangeably. In some cases, the term "cell" may also refer to a geographic coverage area of a base station (e.g., a sector), insofar as a carrier frequency can be detected and used for communication within some portion of geographic coverage areas **110**.

[0069] While neighboring macro cell base station **102** geographic coverage areas **110** may partially overlap (e.g., in a handover region), some of the geographic coverage areas **110** may be substantially overlapped by a larger geographic coverage area **110**. For example, a small cell base station **102'** may have a coverage area **110'** that substantially overlaps with the coverage area **110** of one or more macro cell base stations **102**. A network that includes both small cell and macro cell base stations may be known as a heterogeneous network. A heterogeneous network may also include home eNBs (HeNBs), which may provide service to a restricted group known as a closed subscriber group (CSG).

[0070] The communication links **120** between the base stations **102** and the UEs **104** may include uplink (also referred to as reverse link) transmissions from a UE **104** to a base station **102** and/or downlink (also referred to as forward link) transmissions from a base station **102** to a UE **104**. The communication links **120** may use MIMO antenna technology, including spatial multiplexing, beamforming, and/or transmit diversity. The communication links **120** may be through one or more carrier frequencies. Allocation of carriers may be asymmetric with respect to downlink and uplink (e.g., more or less carriers may be allocated for downlink than for uplink).

[0071] The wireless communications system **100** may further include a WLAN AP **150** in communication with WLAN stations (STAs) **152** via communication links **154** in an unlicensed frequency spectrum (e.g., 5 Gigahertz (GHz)). When communicating in an unlicensed frequency spectrum, the WLAN STAs **152** and/or the WLAN AP **150** may perform a clear channel assessment (CCA) or listen before talk (LBT) procedure prior to communicating in order to determine whether the channel is available. In some examples, the wireless communications system **100** can include devices (e.g., UEs, etc.) that communicate with one or more UEs **104**, base stations **102**, APs **150**, etc. utilizing the ultra-wideband (UWB) spectrum. The UWB spectrum can range from 3.1 to 10.5 GHZ.

[0072] The small cell base station **102'** may operate in a licensed and/or an unlicensed frequency spectrum. When operating in an unlicensed frequency spectrum, the small cell base station **102'** may employ LTE or NR technology and use the same 5 GHz unlicensed frequency spectrum as used by the WLAN AP **150**. The small cell base station **102'**, employing LTE and/or 5G in an unlicensed frequency spectrum, may boost coverage to and/or increase capacity of the access network. NR in unlicensed spectrum may be referred to as NR-U. LTE in an unlicensed spectrum may be referred to as LTE-U, licensed assisted access (LAA), or MulteFire.

[0073] The wireless communications system **100** may further include a millimeter wave (mmW) base station **180** that may operate in mmW frequencies and/or near mmW frequencies in communication with a UE **182**. The mmW base station **180** may be implemented in an aggregated or monolithic base station architecture, or alternatively, in a disaggregated base station architecture (e.g., including one or more of a CU, a DU, a RU, a Near-RT RIC, or a Non-RT RIC). Extremely high frequency (EHF) is part of the RF in the electromagnetic spectrum. EHF has a range of 30 GHz to 300 GHZ and a wavelength between 1 millimeter and 10 millimeters. Radio waves in this band may be referred to as a millimeter wave. Near mmW may extend down to a frequency of 3 GHZ with a wavelength of 100 millimeters. The super high frequency (SHF) band extends between 3 GHZ and 30 GHZ, also referred to as centimeter wave. Communications using the mmW and/or near mmW radio frequency band have high path loss and a relatively short range. The mmW base station **180** and the UE **182** may utilize beamforming (transmit and/or receive) over an mmW communication link **184** to compensate for the extremely high path loss and short range. Further, it will be appreciated that in alternative configurations, one or more base stations **102** may also transmit using mmW or near mmW and beamforming. Accordingly, it will be appreciated that the foregoing illustrations are merely examples and should not be construed to limit the various aspects disclosed herein.

[0074] Transmit beamforming is a technique for focusing an RF signal in a specific direction. Traditionally, when a network node or entity (e.g., a base station) broadcasts an RF signal, it broadcasts the signal in all directions (omni-directionally). With transmit beamforming, the network node determines where a given target device (e.g., a UE) is located (relative to the transmitting network node) and projects a stronger downlink RF signal in that specific direction, thereby providing a faster (in terms of data rate) and stronger RF signal for the receiving device(s). To change the directionality of the RF signal when transmitting, a network node can control the phase and relative amplitude of the RF signal at each of the one or more transmitters that are broadcasting the RF signal. For example, a network node may use an array of antennas (referred to as a "phased array" or an "antenna array") that creates a beam of RF waves that can be "steered" to point in different directions, without actually moving the antennas. Specifically, the RF current from the transmitter is fed to the individual antennas with the correct phase relationship so that the radio waves from the separate antennas add together to increase the radiation in a desired direction, while canceling to suppress radiation in undesired directions.

[0075] Transmit beams may be quasi-collocated, meaning that they appear to the receiver (e.g., a UE) as having the same parameters, regardless of whether or not the transmitting antennas of the network node themselves are physically collocated. In NR, there are four types of quasi-collocation (QCL) relations. Specifically, a QCL relation of a given type means that certain parameters about a second reference RF signal on a second beam can be derived from information about a source reference RF signal on a source beam. Thus, if the source reference RF signal is QCL Type A, the receiver can use the source reference RF signal to estimate the Doppler shift, Doppler spread, average delay, and delay spread of a second reference RF signal transmitted on the same channel. If the source reference RF signal is QCL Type B, the receiver can use the source reference RF signal to estimate the Doppler shift and Doppler spread of a second reference RF signal transmitted on the same channel. If the source reference RF signal is QCL Type C, the receiver can use the source reference RF signal to estimate the Doppler shift and average delay of a second reference RF signal transmitted on the same channel. If the source reference RF signal is QCL Type D, the receiver can use the source reference RF signal to estimate the spatial receive parameter of a second reference RF signal transmitted on the same channel.

[0076] In receiving beamforming, the receiver uses a receive beam to amplify RF signals detected on a given channel. For example, the receiver can increase the gain setting and/or adjust the phase setting of an array of antennas in a particular direction to amplify (e.g., to increase the gain level of) the RF signals received from that direction. Thus, when a receiver is said to beamform in a certain direction, it means the beam gain in that direction is high relative to the beam gain along other directions, or the beam gain in that direction is the highest compared to the beam gain of other beams available to the receiver. This results in a stronger received signal strength (e.g., reference signal received power (RSRP), reference signal received quality (RSRQ), signal-to-interference-plus-noise ratio (SINR), etc.) of the RF signals received from that direction.

[0077] Receive beams may be spatially related. A spatial relation means that parameters for a transmit beam for a second reference signal can be derived from information about a receive beam for a first reference signal. For example, a UE may use a particular receive beam to receive one or more reference downlink reference signals (e.g., positioning reference signals (PRS), tracking reference signals (TRS), phase tracking reference signal (PTRS), cell-specific reference signals (CRS), channel state information reference signals (CSI-RS), primary synchronization signals

(PSS), secondary synchronization signals (SSS), synchronization signal blocks (SSBs), etc.) from a network node or entity (e.g., a base station). The UE can then form a transmit beam for sending one or more uplink reference signals (e.g., uplink positioning reference signals (UL-PRS), sounding reference signal (SRS), demodulation reference signals (DMRS), PTRS, etc.) to that network node or entity (e.g., a base station) based on the parameters of the receive beam.

[0078] Note that a "downlink" beam may be either a transmit beam or a receive beam, depending on the entity forming it. For example, if a network node or entity (e.g., a base station) is forming the downlink beam to transmit a reference signal to a UE, the downlink beam is a transmit beam. If the UE is forming the downlink beam, however, it is a receive beam to receive the downlink reference signal. Similarly, an "uplink" beam may be either a transmit beam or a receive beam, depending on the entity forming it. For example, if a network node or entity (e.g., a base station) is forming the uplink beam, it is an uplink receive beam, and if a UE is forming the uplink beam, it is an uplink transmit beam.

[0079] In 5G, the frequency spectrum in which wireless network nodes or entities (e.g., base stations **102**/**180**, UEs **104**/**182**) operate is divided into multiple frequency ranges, FR1 (from 450 to 6000 Megahertz (MHz)), FR2 (from 24250 to 52600 MHZ), FR3 (above 52600 MHZ), and FR4 (between FR1 and FR2). In a multi-carrier system, such as 5G, one of the carrier frequencies is referred to as the "primary carrier" or "anchor carrier" or "primary serving cell" or "PCell," and the remaining carrier frequencies are referred to as "secondary carriers" or "secondary serving cells" or "SCells." In carrier aggregation, the anchor carrier is the carrier operating on the primary frequency (e.g., FR1) utilized by a UE **104**/**182** and the cell in which the UE **104**/**182** either performs the initial radio resource control (RRC) connection establishment procedure or initiates the RRC connection re-establishment procedure. The primary carrier carries all common and UE-specific control channels, and may be a carrier in a licensed frequency (however, this is not always the case). A secondary carrier is a carrier operating on a second frequency (e.g., FR2) that may be configured once the RRC connection is established between the UE **104** and the anchor carrier and that may be used to provide additional radio resources. In some cases, the secondary carrier may be a carrier in an unlicensed frequency. The secondary carrier may contain only necessary signaling information and signals, for example, those that are UE-specific may not be present in the secondary carrier, since both primary uplink and downlink carriers are typically UE-specific. This means that different UEs **104**/**182** in a cell may have different downlink primary carriers. The same is true for the uplink primary carriers. The network is able to change the primary carrier of any UE **104**/**182** at any time. This is done, for example, to balance the load on different carriers. Because a "serving cell" (whether a PCell or an SCell) corresponds to a carrier frequency and/or component carrier over which some base station is communicating, the term "cell," "serving cell," "component carrier," "carrier frequency," and the like can be used interchangeably.

[0080] For example, still referring to FIG. **1**, one of the frequencies utilized by the macro cell base stations **102** may be an anchor carrier (or "PCell") and other frequencies utilized by the macro cell base stations **102** and/or the mmW base station **180** may be secondary carriers ("SCells"). In carrier aggregation, the base stations **102** and/or the UEs **104** may use spectrum up to Y MHZ (e.g., 5, 10, 15, 20, 100 MHZ) bandwidth per carrier up to a total of Yx MHZ (x component carriers) for transmission in each direction. The component carriers may or may not be adjacent to each other on the frequency spectrum. Allocation of carriers may be asymmetric with respect to the downlink and uplink (e.g., more or less carriers may be allocated for downlink than for uplink). The simultaneous transmission and/or reception of multiple carriers enables the UE **104**/**182** to significantly increase its data transmission and/or reception rates. For example, two 20 MHZ aggregated carriers in a multi-carrier system would theoretically lead to a two-fold increase in data rate (i.e., 40 MHZ), compared to that attained by a single 20 MHz carrier.

[0081] In order to operate on multiple carrier frequencies, a base station **102** and/or a UE **104** is equipped with multiple receivers and/or transmitters. For example, a UE **104** may have two receivers, "Receiver **1**" and "Receiver **2**," where "Receiver **1**" is a multi-band receiver that can be tuned to band (i.e., carrier frequency) 'X' or band 'Y,' and "Receiver **2**" is a one-band receiver tuneable to band 'Z' only. In this example, if the UE **104** is being served in band 'X,' band 'X' would be referred to as the PCell or the active carrier frequency, and "Receiver **1**" would need to tune from band 'X' to band 'Y' (an SCell) in order to measure band 'Y' (and vice versa). In contrast, whether the UE **104** is being served in band 'X' or band 'Y,' because of the separate "Receiver **2**," the UE **104** can measure band 'Z' without interrupting the service on band 'X' or band 'Y.'

[0082] The wireless communications system **100** may further include a UE **164** that may communicate with a macro cell base station **102** over a communication link **120** and/or the mmW base station **180** over an mmW communication link **184**. For example, the macro cell base station **102** may support a PCell and one or more SCells for the UE **164** and the mmW base station **180** may support one or more SCells for the UE **164**.

[0083] The wireless communications system **100** may further include one or more UEs, such as UE **190**, that connects indirectly to one or more communication networks via one or more device-to-device (D2D) peer-to-peer (P2P) links (referred to as "sidelinks"). In the example of FIG. **1**, UE **190** has a D2D P2P link **192** with one of the UEs **104** connected to one of the base stations **102** (e.g., through which UE **190** may indirectly obtain cellular connectivity) and a D2D P2P link **194** with WLAN STA **152** connected to the WLAN AP **150** (through which UE **190** may indirectly obtain WLAN-based Internet connectivity). In an example, the D2D P2P links **192** and **194** may be supported with any well-known D2D RAT, such as LTE Direct (LTE-D), Wi-Fi Direct (Wi-Fi-D). Bluetooth®, and so on. As noted above, UE **104** and UE **190** can be configured to communicate using sidelink communications. In some cases, a sidelink transmission can include a request for feedback (e.g., a hybrid automatic repeat request (HARQ)) from the receiving UE.

[0084] FIG. **2** is a diagram illustrating an example of a disaggregated base station architecture, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. Deployment of communication systems, such as 5G NR systems, may be arranged in multiple manners with various components or constituent parts. In a

5G NR system, or network, a network node, a network entity, a mobility element of a network, a radio access network (RAN) node, a core network node, a network element, or a network equipment, such as a base station (BS), or one or more units (or one or more components) performing base station functionality, may be implemented in an aggregated or disaggregated architecture. For example, a BS (such as a Node B (NB), evolved NB (eNB), NR BS, 5G NB. AP, a transmit receive point (TRP), or a cell, etc.) may be implemented as an aggregated base station (also known as a standalone BS or a monolithic BS) or a disaggregated base station.

[0085] An aggregated base station may be configured to utilize a radio protocol stack that is physically or logically integrated within a single RAN node. A disaggregated base station may be configured to utilize a protocol stack that is physically or logically distributed among two or more units (such as one or more central or centralized units (CUs), one or more distributed units (DUs), or one or more radio units (RUS)). In some aspects, a CU may be implemented within a RAN node, and one or more DUs may be co-located with the CU, or alternatively, may be geographically or virtually distributed throughout one or multiple other RAN nodes. The DUs may be implemented to communicate with one or more RUs. Each of the CU, DU and RU also can be implemented as virtual units, i.e., a virtual central unit (VCU), a virtual distributed unit (VDU), or a virtual radio unit (VRU).

[0086] Base station-type operation or network design may consider aggregation characteristics of base station functionality. For example, disaggregated base stations may be utilized in an integrated access backhaul (IAB) network, an open radio access network (O-RAN (such as the network configuration sponsored by the O-RAN Alliance)), or a virtualized radio access network (vRAN, also known as a cloud radio access network (C-RAN)). Disaggregation may include distributing functionality across two or more units at various physical locations, as well as distributing functionality for at least one unit virtually, which can enable flexibility in network design. The various units of the disaggregated base station, or disaggregated RAN architecture, can be configured for wired or wireless communication with at least one other unit.

[0087] As previously mentioned, FIG. **2** shows a diagram illustrating an example disaggregated base station **201** architecture. The disaggregated base station **201** architecture may include one or more central units (CUs) **211** that can communicate directly with a core network **223** via a backhaul link, or indirectly with the core network **223** through one or more disaggregated base station units (such as a Near-Real Time (Near-RT) RAN Intelligent Controller (RIC) **227** via an E2 link, or a Non-Real Time (Non-RT) RIC **217** associated with a Service Management and Orchestration (SMO) Framework **207**, or both). A CU **211** may communicate with one or more distributed units (DUs) **231** via respective midhaul links, such as an F1 interface. The DUs **231** may communicate with one or more radio units (RUs) **241** via respective fronthaul links. The RUs **241** may communicate with respective UEs **221** via one or more RF access links. In some implementations, the UE **221** may be simultaneously served by multiple RUs **241**.

[0088] Each of the units, i.e., the CUS **211**, the DUs **231**, the RUs **241**, as well as the Near-RT RICs **227**, the Non-RT RICs **217** and the SMO Framework **207**, may include one or more interfaces or be coupled to one or more interfaces configured to receive or transmit signals, data, or information (collectively, signals) via a wired or wireless transmission medium. Each of the units, or an associated processor or controller providing instructions to the communication interfaces of the units, can be configured to communicate with one or more of the other units via the transmission medium. For example, the units can include a wired interface configured to receive or transmit signals over a wired transmission medium to one or more of the other units. Additionally, the units can include a wireless interface, which may include a receiver, a transmitter or transceiver (such as an RF transceiver), configured to receive or transmit signals, or both, over a wireless transmission medium to one or more of the other units.

[0089] In some aspects, the CU **211** may host one or more higher layer control functions. Such control functions can include radio resource control (RRC), packet data convergence protocol (PDCP), service data adaptation protocol (SDAP), or the like. Each control function can be implemented with an interface configured to communicate signals with other control functions hosted by the CU **211**. The CU **211** may be configured to handle user plane functionality (i.e., Central Unit-User Plane (CU-UP)), control plane functionality (i.e., Central Unit-Control Plane (CU-CP)), or a combination thereof. In some implementations, the CU **211** can be logically split into one or more CU-UP units and one or more CU-CP units. The CU-UP unit can communicate bidirectionally with the CU-CP unit via an interface, such as the E1 interface when implemented in an O-RAN configuration. The CU **211** can be implemented to communicate with the DU **231**, as necessary, for network control and signaling.

[0090] The DU **231** may correspond to a logical unit that includes one or more base station functions to control the operation of one or more RUs **241**. In some aspects, the DU **231** may host one or more of a radio link control (RLC) layer, a medium access control (MAC) layer, and one or more high physical (PHY) layers (such as modules for forward error correction (FEC) encoding and decoding, scrambling, modulation and demodulation, or the like) depending, at least in part, on a functional split, such as those defined by the 3rd Generation Partnership Project (3GPP). In some aspects, the DU **231** may further host one or more low PHY layers. Each layer (or module) can be implemented with an interface configured to communicate signals with other layers (and modules) hosted by the DU **231**, or with the control functions hosted by the CU **211**.

[0091] Lower-layer functionality can be implemented by one or more RUs **241**. In some deployments, an RU **241**, controlled by a DU **231**, may correspond to a logical node that hosts RF processing functions, or low-PHY layer functions (such as performing fast Fourier transform (FFT), inverse FFT (IFFT), digital beamforming, physical random access channel (PRACH) extraction and filtering, or the like), or both, based at least in part on the functional split, such as a lower layer functional split. In such an architecture, the RU(s) **241** can be implemented to handle over the air (OTA) communication with one or more UEs **221**. In some implementations, real-time and non-real-time aspects of control and user plane communication with the RU(s) **241** can be controlled by the corresponding DU **231**. In some scenarios, this configuration can enable the DU(s) **231** and the CU **211** to be implemented in a cloud-based RAN architecture, such as a vRAN architecture.

[0092] The SMO Framework **207** may be configured to support RAN deployment and provisioning of non-virtualized and virtualized network elements. For non-virtualized network elements, the SMO Framework **207** may be configured to support the deployment of dedicated physical resources for RAN coverage requirements which may be managed via an operations and maintenance interface (such as an O1 interface). For virtualized network elements, the SMO Framework **207** may be configured to interact with a cloud computing platform (such as an open cloud (O-Cloud) **291**) to perform network element life cycle management (such as to instantiate virtualized network elements) via a cloud computing platform interface (such as an O2 interface). Such virtualized network elements can include, but are not limited to, CUs **211**, DUs **231**, RUS **241** and Near-RT RICs **227**. In some implementations, the SMO Framework **207** can communicate with a hardware aspect of a 4G RAN, such as an open eNB (O-eNB) **213**, via an O1 interface. Additionally, in some implementations, the SMO Framework **207** can communicate directly with one or more RUs **241** via an O1 interface. The SMO Framework **207** also may include a Non-RT RIC **217** configured to support functionality of the SMO Framework **207**.

[0093] The Non-RT RIC **217** may be configured to include a logical function that enables non-real-time control and optimization of RAN elements and resources, Artificial Intelligence/Machine Learning (AI/ML) workflows including model training and updates, or policy-based guidance of applications/features in the Near-RT RIC **227**. The Non-RT RIC **217** may be coupled to or communicate with (such as via an A1 interface) the Near-RT RIC **227**. The Near-RT RIC **227** may be configured to include a logical function that enables near-real-time control and optimization of RAN elements and resources via data collection and actions over an interface (such as via an E2 interface) connecting one or more CUs **211**, one or more DUs **231**, or both, as well as an O-eNB **213**, with the Near-RT RIC **227**.

[0094] In some implementations, to generate AI/ML models to be deployed in the Near-RT RIC **227**, the Non-RT RIC **217** may receive parameters or external enrichment information from external servers. Such information may be utilized by the Near-RT RIC **227** and may be received at the SMO Framework **207** or the Non-RT RIC **217** from non-network data sources or from network functions. In some examples, the Non-RT RIC **217** or the Near-RT RIC **227** may be configured to tune RAN behavior or performance. For example, the Non-RT RIC **217** may monitor long-term trends and patterns for performance and employ AI/ML models to perform corrective actions through the SMO Framework **207** (such as reconfiguration via O1) or via creation of RAN management policies (such as A1 policies).

[0095] Various radio frame structures may be used to support downlink, uplink, and sidelink transmissions between network nodes (e.g., base stations and UEs). FIG. **3** is a diagram **300** illustrating an example of a frame structure, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. Other wireless communications technologies may have different frame structures and/or different channels.

[0096] NR (and LTE) utilizes OFDM on the downlink and single-carrier frequency division multiplexing (SC-FDM) on the uplink. Unlike LTE, however, NR has an option to use OFDM on the uplink as well. OFDM and SC-FDM partition the system bandwidth into multiple (K) orthogonal subcarriers, which are also commonly referred to as tones, bins, etc. Each subcarrier may be modulated with data. In general, modulation symbols are sent in the frequency domain with OFDM and in the time domain with SC-FDM. The spacing between adjacent subcarriers may be fixed, and the total number of subcarriers (K) may be dependent on the system bandwidth. For example, the spacing of the subcarriers may be 15 kHz and the minimum resource allocation (resource block) may be 12 subcarriers (or 180 kHz). Consequently, the nominal fast Fourier transform (FFT) size may be equal to 128, 256, 512, 1024, or 2048 for system bandwidth of 1.25, 2.5, 5, 10, or 20 megahertz (MHz), respectively. The system bandwidth may also be partitioned into subbands. For example, a subband may cover 1.08 MHZ (i.e., **6** resource blocks), and there may be 1, 2, 4, 8, or 16 subbands for system bandwidth of 1.25, 2.5, 5, 10, or 20 MHz, respectively.

[0097] LTE supports a single numerology (subcarrier spacing, symbol length, etc.). In contrast, NR may support multiple numerologies (u). For example, subcarrier spacing (SCS) of 15 kHz, 30 kHz, 60 kHz, 120 kHz, and 240 kHz or greater may be available. Table 1 provided below lists some various parameters for different NR numerologies.

TABLE 1

	SCS (kHz)	Symbols/ Sot	Slots/ Subframe	Slots/ Frame	Slot Duration (ms)	Symbol Duration (μs)	Max. nominal system BW (MHz) with 4K FFT size
0	15	14	1	10	1	66.7	50
1	30	14	2	20	0.5	33.3	100
2	60	14	4	40	0.25	16.7	100
3	120	14	8	80	0.125	8.33	400
4	240	14	16	160	0.0625	4.17	800

[0098] In one example, a numerology of 15 kHz is used. Thus, in the time domain, a 10 millisecond (ms) frame is divided into 10 equally sized subframes of 1 ms each, and each subframe includes one time slot. In FIG. **3**, time is represented horizontally (e.g., on the X axis) with time increasing from left to right, while frequency is represented vertically (e.g., on the Y axis) with frequency increasing (or decreasing) from bottom to top.

[0099] A resource grid may be used to represent time slots, each time slot including one or more time-concurrent resource blocks (RBs) (also referred to as physical RBs (PRBs)) in the frequency domain. FIG. **3** illustrates an example of a resource block (RB) **302**. Data or information for joint communications and sensing may be included in one or more RBs **302**. The RB **302** is arranged with the time domain on the horizontal (or x-) axis and the frequency domain on the vertical (or y-) axis. As shown, the RB **302** may be 180 kilohertz (kHz) wide in frequency and one slot long in time (with a slot being 1 milliseconds (ms) in time). In some cases, the slot may include fourteen symbols (e.g., in a slot configuration 0). The RB **302** includes twelve subcarriers (along the y-axis) and fourteen symbols (along the x-axis).

[0100] An intersection of a symbol and subcarrier can be referred to as a resource element (RE) **304** or tone. The RB **302** of FIG. **3** includes multiple REs, including the resource element (RE) **304**. For instance, a RE **304** is 1 subcarrier×1 symbol (e.g., OFDM symbol), and is the smallest discrete part of the subframe. A RE **304** includes a single complex value representing data from a physical channel or signal. The number of bits carried by each RE **304** depends on the modulation scheme.

[0101] In some aspects, some REs **304** can be used to transmit downlink reference (pilot) signals (DL-RS). The DL-RS can include Positioning Reference Signal (PRS), Tracking Reference Signal (TRS), Phase Tracking Reference Signal (PTRS), Channel State Information Reference Signal (CSI-RS), Demodulation Reference Signal (DMRS), Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), etc. The resource grid if FIG. **3** illustrates exemplary locations of REs **304** used to transmit DL-RS (labeled "R").

[0102] FIG. **4** is a block diagram illustrating an example of a computing system **470** of an electronic device **407**, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. The electronic device **407** is an example of a device that can include hardware and software for the purpose of connecting and exchanging data with other devices and systems using a communications network (e.g., a 3rd Generation Partnership network, such as a 5th Generation (5G)/New Radio (NR) network, a 4th Generation (4G)/Long Term Evolution (LTE) network, a WiFi network, or other communications network). For example, the electronic device **407** can include, or be a part of, a mobile device (e.g., a mobile telephone), a wearable device (e.g., a network-connected or smart watch), an extended reality device (e.g., a virtual reality (VR) device, an augmented reality (AR) device, or a mixed reality (MR) device), a personal computer, a laptop computer, a tablet computer, an Internet-of-Things (IoT) device, a wireless access point, a router, a vehicle or component of a vehicle, a server computer, a robotics device, and/or other device used by a user to communicate over a wireless communications network. In some cases, the device **407** can be referred to as user equipment (UE), such as when referring to a device configured to communicate using 5G/NR, 4G/LTE, or other telecommunication standard. In some cases, the device can be referred to as a station (STA), such as when referring to a device configured to communicate using the Wi-Fi standard.

[0103] The computing system **470** includes software and hardware components that can be electrically or communicatively coupled via a bus **489** (or may otherwise be in communication, as appropriate). For example, the computing system **470** includes one or more processors **484**. The one or more processors **484** can include one or more CPUs, ASICS, FPGAs, APs, GPUs, VPUs, NSPs, microcontrollers, dedicated hardware, any combination thereof, and/or other processing device/s and/or system/s. The bus **489** can be used by the one or more processors **484** to communicate between cores and/or with the one or more memory devices **486**.

[0104] The computing system **470** may also include one or more memory devices **486**, one or more digital signal processors (DSPs) **482**, one or more subscriber identity modules (SIMs) **474**, one or more modems **476**, one or more wireless transceivers **478**, one or more antennas **487**, one or more input devices **472** (e.g., a camera, a mouse, a keyboard, a touch sensitive screen, a touch pad, a keypad, a microphone or a microphone array, and/or the like), and one or more output devices **480** (e.g., a display, a speaker, a printer, and/or the like).

[0105] The one or more wireless transceivers **478** can receive wireless signals (e.g., signal **488**) via antenna **487** from one or more other devices, such as other user devices, network devices (e.g., base stations such as evolved Node Bs (eNBs) and/or gNodeBs (gNBs), WiFi access points (APs) such as routers, range extenders or the like, etc.), cloud networks, and/or the like. In some examples, the computing system **470** can include multiple antennas or an antenna array that can facilitate simultaneous transmit and receive functionality. Antenna **487** can be an omnidirectional antenna such that RF signals can be received from and transmitted in all directions. The wireless signal **488** may be transmitted via a wireless network. The wireless network may be any wireless network, such as a cellular or telecommunications network (e.g., 3G, 4G, 5G, etc.), wireless local area network (e.g., a WiFi network), a Bluetooth™ network, and/or other network. In some examples, the one or more wireless transceivers **478** may include an RF front end including one or more components, such as an amplifier, a mixer (also referred to as a signal multiplier) for signal down conversion, a frequency synthesizer (also referred to as an oscillator) that provides signals to the mixer, a baseband filter, an analog-to-digital converter (ADC), one or more power amplifiers, among other components. The RF front-end can generally handle selection and conversion of the wireless signals **488** into a baseband or intermediate frequency and can convert the RF signals to the digital domain.

[0106] In some cases, the computing system **470** can include a coding-decoding device (or CODEC) configured to encode and/or decode data transmitted and/or received using the one or more wireless transceivers **478**. In some cases, the computing system **470** can include an encryption-decryption device or component configured to encrypt and/or decrypt data (e.g., according to the Advanced Encryption Standard (AES) and/or Data Encryption Standard (DES) standard) transmitted and/or received by the one or more wireless transceivers **478**.

[0107] The one or more SIMs **474** can each securely store an international mobile subscriber identity (IMSI) number and related key assigned to the user of the electronic device **407**. The IMSI and key can be used to identify and authenticate the subscriber when accessing a network provided by a network service provider or operator associated with the one or more SIMs **474**. The one or more modems **476** can modulate one or more signals to encode information for transmission using the one or more wireless transceivers **478**. The one or more modems **476** can also demodulate signals received by the one or more wireless transceivers **478** in order to decode the transmitted information. In some examples, the one or more modems **476** can include a WiFi modem, a 4G (or LTE) modem, a 5G (or NR) modem, and/or other types of modems. The one or more modems **476** and the one or more wireless transceivers **478** can be used for communicating data for the one or more SIMs **474**.

[0108] The computing system **470** can also include (and/or be in communication with) one or more non-transitory machine-readable storage media or storage devices (e.g., one or more memory devices **486**), which can include, without limitation, local and/or network accessible storage, a disk drive, a drive array, an optical storage device, a solid-state storage device such as a RAM and/or a ROM, which can be programmable, flash-updateable and/or the like. Such storage devices may be configured to implement any appropriate data storage, including without limitation, various file systems, database structures, and/or the like.

[0109] In various aspects, functions may be stored as one or more computer-program products (e.g., instructions or code) in memory device(s) **486** and executed by the one or more processor(s) **484** and/or the one or more DSPs **482**. The computing system **470** can also include software elements (e.g., located within the one or more memory devices **486**), including, for example, an operating system, device drivers, executable libraries, and/or other code, such as one or more application programs, which may comprise computer programs implementing the functions provided by various aspects, and/or may be designed to implement methods and/or configure systems, as described herein.

[0110] In some aspects, the electronic device **407** can include means for performing operations described herein. The means can include one or more of the components of the computing system **470**. For example, the means for performing operations described herein may include one or more of input device(s) **472**, SIM(s) **474**, modems(s) **476**, wireless transceiver(s) **478**, output device(s) **480**, DSP(s) **482**, processors **484**, memory device(s) **486**, and/or antenna (s) **487**.

[0111] In some aspects, the electronic device **407** can include means for providing joint communications and sensing as well as a means for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing, for example, when multiplexing sensing and communication signals for joint communications and sensing (JCS). In some examples, any or all of these means can include the one or more wireless transceivers **478**, the one or more modems **476**, the one or more processors **484**, the one or more DSPs **482**, the one or more memory devices **486**, any combination thereof, or other component(s) of the electronic device **407**.

[0112] FIG. **5** is a diagram illustrating an example of a wireless device **500** utilizing RF monostatic sensing technique for determining one or more characteristics (e.g., location, speed or velocity, heading, etc.) of a target **502** object. In particular, FIG. **5** is a diagram illustrating an example of a wireless device **500** (e.g., a transmit/receive sensing node) that utilizes RF sensing techniques (e.g., monostatic sensing) to perform one or more functions, such as detecting a presence and location of a target **502** (e.g., an object, user, or vehicle), which in this figure is illustrated in the form of a vehicle.

[0113] In some examples, the wireless device **500** can be a mobile phone, a tablet computer, a wearable device, a vehicle, an extending reality (XR) device, a computing device or component of a vehicle, or other device (e.g., device **407** of FIG. **4**) that includes at least one RF interface. In some examples, the wireless device **500** can be a device that provides connectivity for a user device (e.g., for electronic device **407** of FIG. **4**), such as a base station (e.g., a gNB, eNB, etc.), a wireless access point (AP), or other device that includes at least one RF interface.

[0114] In some aspects, wireless device **500** can include one or more components for transmitting an RF signal. The wireless device **500** can include at least one processor **522** for generating a digital signal or waveform. The wireless device **500** can also include a digital-to-analog converter (DAC) **504** that is capable of receiving the digital signal or waveform from the processor(s) **522** (e.g., a microprocessor), and converting the digital signal or waveform to an analog waveform. The analog signal that is the output of the DAC **504** can be provided to RF transmitter **506** for transmission. The RF transmitter **506** can be a Wi-Fi transmitter, a 5G/NR transmitter, a Bluetooth™ transmitter, or any other transmitter capable of transmitting an RF signal.

[0115] RF transmitter **506** can be coupled to one or more transmitting antennas such as Tx antenna **512**. In some examples, transmit (Tx) antenna **512** can be an omnidirectional antenna that is capable of transmitting an RF signal in all directions. For example, Tx antenna **512** can be an omnidirectional Wi-Fi antenna that can radiate Wi-Fi signals (e.g., 2.4 GHz, 5 GHZ, 6 GHZ, etc.) in a 360-degree radiation pattern. In another example, Tx antenna **512** can be a directional antenna that transmits an RF signal in a particular direction.

[0116] In some examples, wireless device **500** can also include one or more components for receiving an RF signal. For example, the receiver lineup in wireless device **500** can include one or more receiving antennas such as a receive (Rx) antenna **514**. In some examples, Rx antenna **514** can be an omnidirectional antenna capable of receiving RF signals from multiple directions. In other examples, Rx antenna **514** can be a directional antenna that is configured to receive signals from a particular direction. In further examples, the Tx antenna **512** and/or the Rx antenna **514** can include multiple antennas (e.g., elements) configured as an antenna array (e.g., a phase antenna array).

[0117] Wireless device **500** can also include an RF receiver **510** that is coupled to Rx antenna **514**. RF receiver **510** can include one or more hardware components for receiving an RF waveform such as a Wi-Fi signal, a Bluetooth™ signal, a 5G/NR signal, or any other RF signal. The output of RF receiver **510** can be coupled to an analog-to-digital converter (ADC) **508**. ADC **508** can be configured to convert the received analog RF waveform into a digital waveform. The digital waveform that is the output of the ADC **508** can be provided to the processor(s) **522** for processing. The processor(s) **522** (e.g., a digital signal processor (DSP)) can be configured for processing the digital waveform.

[0118] In one example, wireless device **500** can implement RF sensing techniques, for example monostatic sensing techniques, by causing a Tx waveform **516** to be transmitted from Tx antenna **512**. Although Tx waveform **516** is illustrated as a single line, in some cases, Tx waveform **516** can be transmitted in all directions by an omnidirectional Tx antenna **512**. In one example, Tx waveform **516** can be a Wi-Fi waveform that is transmitted by a Wi-Fi transmitter in wireless device **500**. In some cases, Tx waveform **516** can correspond to a Wi-Fi waveform that is transmitted at or near the same time as a Wi-Fi data communication signal or a Wi-Fi control function signal (e.g., a beacon transmission). In some examples, Tx waveform **516** can be transmitted using the same or a similar frequency resource as a Wi-Fi data communication signal or a Wi-Fi control function signal (e.g., a beacon transmission). In some aspects, Tx waveform **516** can correspond to a Wi-Fi waveform that is transmitted separately from a Wi-Fi data communication signal and/or a Wi-Fi control signal (e.g., Tx waveform **516** can be transmitted at different times and/or using a different frequency resource).

[0119] In some examples, Tx waveform **516** can correspond to a 5G NR waveform that is transmitted at or near the same time as a 5G NR data communication signal or a 5G NR control function signal. In some examples, Tx waveform **516** can be transmitted using the same or a similar frequency resource as a 5G NR data communication signal or a 5G NR control function signal. In some aspects, Tx waveform **516** can correspond to a 5G NR waveform that is transmitted separately from a 5G NR data communication signal and/or a 5G NR control signal (e.g., Tx waveform **516** can be transmitted at different times and/or using a different frequency resource).

[0120] In some aspects, one or more parameters associated with Tx waveform **516** can be modified that may be used to increase or decrease RF sensing resolution. The parameters may include frequency, bandwidth, number of spatial streams, the number of antennas configured to transmit Tx waveform **516**, the number of antennas configured to receive a reflected RF signal (e.g., Rx waveform **518**) corresponding to Tx waveform **516**, the number of spatial links (e.g., number of spatial streams multiplied by number of antennas configured to receive an RF signal), the sampling rate, or any combination thereof. The transmitted waveform (e.g., Tx waveform **516**) and the received waveform (e.g., Rx waveform **518**) can include one or more RF sensing signals, which are also referred to as radar reference signals (RSs).

[0121] In further examples, Tx waveform **516** can be implemented to have a sequence that has perfect or almost perfect autocorrelation properties. For instance, Tx waveform **516** can include single carrier Zadoff sequences or can include symbols that are similar to orthogonal frequency-division multiplexing (OFDM) Long Training Field (LTF) symbols. In some cases, Tx waveform **516** can include a chirp signal, as used, for example, in a Frequency-Modulated Continuous-Wave (FM-CW) radar system. In some configurations, the chirp signal can include a signal in which the signal frequency increases and/or decreases periodically in a linear and/or an exponential manner.

[0122] In some aspects, wireless device **500** can implement RF sensing techniques by performing alternating transmit and receive functions (e.g., performing a half-duplex operation). For example, wireless device **500** can alternately enable its RF transmitter **506** to transmit the Tx waveform **516** when the RF receiver **510** is not enabled to receive (i.e. not receiving), and enable its RF receiver **510** to receive the Rx waveform **518** when the RF transmitter **506** is not enabled to transmit (i.e. not transmitting). When the wireless device **500** is performing a half-duplex operation, the wireless device **500** may transmit Tx waveform **516**, which may be a radar RS (e.g., sensing signal).

[0123] In other aspects, wireless device **500** can implement RF sensing techniques by performing concurrent transmit and receive functions (e.g., performing a sub-band or full-band full-duplex operation). For example, wireless device **500** can enable its RF receiver **510** to receive at or near the same time as it enables RF transmitter **506** to transmit Tx waveform **516**. When the wireless device **500** is performing a full-duplex operation (e.g., either sub-band full-duplex or full-band full-duplex), the wireless device **500** may transmit Tx waveform **516**, which may be a radar RS (e.g., sensing signal).

[0124] In some examples, transmission of a sequence or pattern that is included in Tx waveform **516** can be repeated continuously such that the sequence is transmitted a certain number of times or for a certain duration of time. In some examples, repeating a pattern in the transmission of Tx waveform **516** can be used to avoid missing the reception of any reflected signals if RF receiver **510** is enabled after RF transmitter **506**. In one example implementation, Tx waveform **516** can include a sequence having a sequence length L that is transmitted two or more times, which can allow RF receiver **510** to be enabled at a time less than or equal to L in order to receive reflections corresponding to the entire sequence without missing any information.

[0125] By implementing alternating or simultaneous transmit and receive functionality (e.g. half-duplex or full-duplex operation), wireless device **500** can receive signals that correspond to Tx waveform **516**. For example, wireless device **500** can receive signals that are reflected from objects or people that are within range of Tx waveform **516**, such as Rx waveform **518** reflected from target **502**. Wireless device **500** can also receive leakage signals (e.g., Tx leakage signal **520**) that are coupled directly from Tx antenna **512** to Rx antenna **514** without reflecting from any objects. For example, leakage signals can include signals that are transferred from a transmitter antenna (e.g., Tx antenna **512**) on a wireless device to a receive antenna (e.g., Rx antenna **514**) on the wireless device without reflecting from any objects. In some cases, Rx waveform **518** can include multiple sequences that correspond to multiple copies of a sequence that are included in Tx waveform **516**. In some examples, wireless device **500** can combine the multiple sequences that are received by RF receiver **510** to improve the signal to noise ratio (SNR).

[0126] Wireless device **500** can further implement RF sensing techniques by obtaining RF sensing data associated with each of the received signals corresponding to Tx waveform **516**. In some examples, the RF sensing data can include channel state information (CSI) data relating to the direct paths (e.g., leakage signal **520**) of Tx waveform **516** together with data relating to the reflected paths (e.g., Rx waveform **518**) that correspond to Tx waveform **516**.

[0127] In some aspects, RF sensing data (e.g., CSI data) can include information that can be used to determine the manner in which an RF signal (e.g., Tx waveform **516**) propagates from RF transmitter **506** to RF receiver **510**. RF sensing data can include data that corresponds to the effects on the transmitted RF signal due to scattering, fading, and/or power decay with distance, or any combination thereof. In some examples, RF sensing data can include imaginary data and real data (e.g., I/Q components) corresponding to each tone in the frequency domain over a particular bandwidth.

[0128] In some examples, RF sensing data can be used by the processor(s) **522** to calculate distances and angles of arrival that correspond to reflected waveforms, such as Rx waveform **518**. In further examples, RF sensing data can also be used to detect motion, determine location, detect changes in location or motion patterns, or any combination thereof. In some cases, the distance and angle of arrival of the reflected signals can be used to identify the size, position, movement, and/or orientation of targets (e.g., target **502**) in the surrounding environment in order to detect target presence/proximity.

[0129] The processor(s) **522** of the wireless device **500** can calculate distances and angles of arrival corresponding to reflected waveforms (e.g., the distance and angle of arrival corresponding to Rx waveform **518**) by utilizing signal processing, machine learning algorithms, any other suitable technique, or any combination thereof. In other examples, wireless device **500** can transmit or send the RF sensing data to at least one processor of another computing device, such as a server or base station, that can perform the calculations to obtain the distance and angle of arrival corresponding to Rx waveform **518** or other reflected waveforms.

[0130] In one example, the distance of Rx waveform **518** can be calculated by measuring the difference in time from reception of the leakage signal to the reception of the reflected signals. For example, wireless device **500** can determine a baseline distance of zero that is based on the difference from the time the wireless device **500** transmits Tx waveform **516** to the time it receives leakage signal **520** (e.g., propagation delay). The processor(s) **522** of the wireless device **500** can then determine a distance associated with Rx waveform **518** based on the difference from the time the wireless device **500** transmits Tx waveform **516** to the time it receives Rx waveform **518** (e.g., time of flight, which is also referred to as round trip time (RTT)), which can then be adjusted according to the propagation delay associated with leakage signal **520**. In doing so, the processor(s) **522** of the wireless device **500** can determine the distance traveled by Rx waveform **518** which can be used to determine the presence and movement of a target (e.g., target **502**) that caused the reflection.

[0131] In further examples, the angle of arrival of Rx waveform **518** can be calculated by the processor(s) **522** by measuring the time difference of arrival of Rx waveform **518** between individual elements of a receive antenna array, such as antenna **514**. In some examples, the time difference of arrival can be calculated by measuring the difference in received phase at each element in the receive antenna array.

[0132] In some cases, the distance and the angle of arrival of Rx waveform **518** can be used by processor(s) **522** to determine the distance between wireless device **500** and target **502** as well as the position of the target **502** relative to the wireless device **500**. The distance and the angle of arrival of Rx waveform **518** can also be used to determine presence, movement, proximity, identity, or any combination thereof, of target **502**. For example, the processor(s) **522** of the wireless device **500** can utilize the calculated distance and angle of arrival corresponding to Rx waveform **518** to determine that the target **502** is moving towards wireless device **500**.

[0133] As noted above, wireless device **500** can include mobile devices (e.g., IoT devices, smartphones, laptops, tablets, etc.) or other types of devices. In some examples, wireless device **500** can be configured to obtain device location data and device orientation data together with the RF sensing data. In some instances, device location data and device orientation data can be used to determine or adjust the distance and angle of arrival of a reflected signal such as Rx waveform **518**. For example, wireless device **500** may be set on the ground facing the sky as a target **502** (e.g., a vehicle) moves towards it during the RF sensing process. In this instance, wireless device **500** can use its location data and orientation data together with the RF sensing data to determine the direction that the target **502** is moving.

[0134] In some examples, device position data can be gathered by wireless device **500** using techniques that include RTT measurements, time of arrival (TOA) measurements, time difference of arrival (TDOA) measurements, passive positioning measurements, angle of arrival (AOA) measurements, angle of departure (AoD) measurements, received signal strength indicator (RSSI) measurements, CSI data, using any other suitable technique, or any combination thereof. In further examples, device orientation data can be obtained from electronic sensors on the wireless device **500**, such as a gyroscope, an accelerometer, a compass, a magnetometer, a barometer, any other suitable sensor, or any combination thereof.

[0135] FIG. **6** is a diagram illustrating an example of a receiver **604** utilizing RF bistatic sensing techniques with one transmitter **600** for determining one or more characteristics (e.g., location, speed or velocity, heading, etc.) of a target **602** object. For example, the receiver **604** can use the RF bistatic sensing to detect a presence and location of a target **602** (e.g., an object, user, or vehicle), which is illustrated in the form of a vehicle in FIG. **6**. In one example, the receiver **604** may be in the form of a base station, such as a gNB.

[0136] The bistatic radar system of FIG. **6** includes a transmitter **600** (e.g., a transmit sensing node), which in this figure is depicted to be in the form of a base station (e.g., gNB), and a receiver **604** (e.g., a receive sensing node) that are separated by a distance comparable to the expected target distance. As compared to the monostatic system of FIG. **5**, the transmitter **600** and the receiver **604** of the bistatic radar system of FIG. **6** are located remote from one another. Conversely, monostatic radar is a radar system (e.g., the system of FIG. **5**) comprising a transmitter (e.g., the RF transmitter **506** of wireless device **500** of FIG. **5**) and a receiver (e.g., the RF receiver **510** of wireless device **500** of FIG. **5**) that are co-located with one another.

[0137] An advantage of bistatic radar (or more generally, multistatic radar, which has more than one receiver) over monostatic radar is the ability to collect radar returns reflected from a scene at angles different than that of a transmitted pulse. This can be of interest to some applications (e.g., vehicle applications, scenes with multiple objects, military applications, etc.) where targets may reflect the transmitted energy in many directions (e.g., where targets are specifically designed to reflect in many directions), which can minimize the energy that is reflected back to the transmitter. It should be noted that, in one or more examples, a monostatic system can coexist with a multistatic radar system, such as when the transmitter also has a co-located receiver.

[0138] In some examples, the transmitter **600** and/or the receiver **604** of FIG. **6** can be a mobile phone, a tablet computer, a wearable device, a vehicle, or other device (e.g., device **407** of FIG. **4**) that includes at least one RF interface. In some examples, the transmitter **600** and/or the receiver **604** can be a device that provides connectivity for a user device (e.g., for IoT device **407** of FIG. **4**), such as a base station (e.g., a gNB, eNB, etc.), a wireless access point (AP), or other device that includes at least one RF interface.

[0139] In some aspects, transmitter **600** can include one or more components for transmitting an RF signal. The transmitter **600** can include at least one processor (e.g., the at least one processor **522** of FIG. **5**) that is capable of determining signals (e.g., determining the waveforms for the signals) to be transmitted. The transmitter **600** can also include an RF transmitter (e.g., the RF transmitter **506** of FIG. **5**) for transmission of a Tx signal comprising Tx waveform **616**. The RF transmitter can be a transmitter configured to transmit cellular or telecommunication signals (e.g., a transmitter configured to transmit 5G/NR signals, 4G/LTE signals, or other cellular/telecommunication signals, etc.), a Wi-Fi transmitter, a Bluetooth™ transmitter, any combination thereof, or any other transmitter capable of transmitting an RF signal.

[0140] The RF transmitter can be coupled to one or more transmitting antennas, such as a Tx antenna (e.g., the TX antenna **512** of FIG. **5**). In some examples, a Tx antenna can be an omnidirectional antenna that is capable of transmitting an RF signal in all directions, or a directional antenna that transmits an RF signal in a particular direction. In some examples, the Tx antenna may include multiple antennas (e.g., elements) configured as an antenna array.

[0141] The receiver **604** can include one or more components for receiving an RF signal. For example, the receiver **604** may include one or more receiving antennas, such as an Rx antenna (e.g., the Rx antenna **514** of FIG. **5**). In some examples, an Rx antenna can be an omnidirectional antenna capable of receiving RF signals from multiple directions, or a directional antenna that is configured to receive signals from a particular direction. In further examples, the Rx antenna can include multiple antennas (e.g., elements) configured as an antenna array.

[0142] The receiver **604** may also include an RF receiver (e.g., RF receiver **510** of FIG. **5**) coupled to the Rx antenna. The RF receiver may include one or more hardware components for receiving an RF waveform such as a Wi-Fi signal, a Bluetooth™ signal, a 5G/NR signal, or any other RF signal. The output of the RF receiver can be coupled to at least one processor (e.g., the at least one processor **522** of FIG. **5**). The processor(s) may be configured to process a received waveform (e.g., Rx waveform **618**).

[0143] In one or more examples, transmitter **600** can implement RF sensing techniques, for example bistatic sensing techniques, by causing a Tx waveform **616** to be transmitted from a Tx antenna. It should be noted that although the Tx waveform **616** is illustrated as a single line, in some cases, the Tx waveform **616** can be transmitted in all directions by an omnidirectional Tx antenna.

[0144] In one or more aspects, one or more parameters associated with the Tx waveform **616** may be used to increase or decrease RF sensing resolution. The parameters may include frequency, bandwidth, number of spatial streams, the number of antennas configured to transmit Tx waveform **616**, the number of antennas configured to receive a reflected RF signal (e.g., Rx waveform **618**) corresponding to the Tx waveform **616**, the number of spatial links (e.g., number of spatial streams multiplied by number of antennas configured to receive an RF signal), the sampling rate, or any combination thereof. The transmitted waveform (e.g., Tx waveform **616**) and the received waveform (e.g., the Rx waveform **618**) can include one or more radar RF sensing signals (also referred to as RF sensing RSs).

[0145] During operation, the receiver **604** (e.g., which operates as a receive sensing node) can receive signals that correspond to Tx waveform **616**, which is transmitted by the transmitter **600** (e.g., which operates as a transmit sensing node). For example, the receiver **604** can receive signals that are reflected from objects or people that are within range of the Tx waveform **616**, such as Rx waveform **618** reflected from target **602**. In some cases, the Rx waveform **618** can include multiple sequences that correspond to multiple copies of a sequence that are included in the Tx waveform **616**. In some examples, the receiver **604** may combine the multiple sequences that are received to improve the SNR.

[0146] In some examples, RF sensing data can be used by at least one processor within the receiver **604** to calculate distances, angles of arrival, or other characteristics that correspond to reflected waveforms, such as the Rx waveform **618**. In other examples, RF sensing data can also be used to detect motion, determine location, detect changes in location or motion patterns, or any combination thereof. In some cases, the distance and angle of arrival of the reflected signals can be used to identify the size, position, movement, and/or orientation of targets (e.g., target **602**) in the surrounding environment in order to detect target presence/proximity.

[0147] The processor(s) of the receiver **604** can calculate distances and angles of arrival corresponding to reflected waveforms (e.g., the distance and angle of arrival corresponding to the Rx waveform **618**) by using signal processing, machine learning algorithms, any other suitable technique, or any combination thereof. In other examples, the receiver **604** can transmit or send the RF sensing data to at least one processor of another computing device, such as a server, that can perform the calculations to obtain the distance and angle of arrival corresponding to the Rx waveform **618** or other reflected waveforms.

[0148] In one or more examples, the angle of arrival of the Rx waveform **618** can be calculated by a processor(s) of the receiver **604** by measuring the time difference of arrival of the Rx waveform **618** between individual elements of a receive antenna array of the receiver **604**. In some examples, the time difference of arrival can be calculated by measuring the difference in received phase at each element in the receive antenna array.

[0149] In some cases, the distance and the angle of arrival of the Rx waveform **618** can be used by the processor(s) of the receiver **604** to determine the distance between the receiver **604** and the target **602** as well as the position of target **602** relative to the receiver **604**. The distance and the angle of arrival of the Rx waveform **618** can also be used to determine presence, movement, proximity, identity, or any combination thereof, of the target **602**. For example, the processor(s) of the receiver **604** may use the calculated distance and angle of arrival corresponding to the Rx waveform **618** to determine that the target **602** is moving towards the receiver **604**.

[0150] FIG. **7** is a diagram illustrating an example of a receiver **704**, in the form of a smart phone, utilizing RF bistatic sensing techniques with multiple transmitters (including a transmitter **700***a*, a transmitter **700***b*, and a transmitter **700***c*), which may be employed to determine one or more characteristics (e.g., location, velocity or speed, heading, etc.) of a target **702** object. For example, the receiver

704 may use RF bistatic sensing to detect a presence and location of a target **702** (e.g., an object, user, or vehicle). The target **702** is depicted in FIG. **7** in the form of an object that does not have communications capabilities (which can be referred to as a device-free object), such as a person, a vehicle (e.g., a vehicle without the ability to transmit and receive messages, such as using C-V2X or DSRC protocols), or other device-free object. The bistatic radar system of FIG. **7** is similar to the bistatic radar system of FIG. **6**, except that the bistatic radar system of FIG. **7** has multiple transmitters **700***a*, **700***b*, **700***c*, while the bistatic radar system of FIG. **6** has only one transmitter **600**.

[0151] The bistatic radar system of FIG. **7** includes multiple transmitters **700***a*, **700***b*, **700***c* (e.g., transmit sensing nodes), which are illustrated to be in the form of base stations. The bistatic radar system of FIG. **7** also includes a receiver **704** (e.g., a receive sensing node), which is depicted in the form of a smart phone. The each of the transmitters **700***a*, **700***b*, **700***c* is separated from the receiver **704** by a distance comparable to the expected distance from the target **702**. Similar to the bistatic system of FIG. **6**, the transmitters **700***a*, **700***b*, **700***c* and the receiver **704** of the bistatic radar system of FIG. **7** are located remote from one another.

[0152] In one or more examples, the transmitters **700***a*, **700***b*, **700***c* and/or the receiver **704** may each be a mobile phone, a tablet computer, a wearable device, a vehicle (e.g., a vehicle configured to transmit and receive communications according to C-V2X, DSRC, or other communication protocol), or other device (e.g., device **407** of FIG. **4**) that includes at least one RF interface. In some examples, the transmitters **700***a*, **700***b*, **700***c* and/or the receiver **704** may each be a device that provides connectivity for a user device (e.g., for IoT device **407** of FIG. **4**), such as a base station (e.g., a gNB, eNB, etc.), a wireless access point (AP), or other device that includes at least one RF interface.

[0153] The transmitters **700***a*, **700***b*, **700***c* may include one or more components for transmitting an RF signal. Each of the transmitters **700***a*, **700***b*, **700***c* may include at least one processor (e.g., the processor(s) **522** of FIG. **5**) that is capable of determining signals (e.g., determining the waveforms for the signals) to be transmitted. Each of the transmitters **700***a*, **700***b*, **700***c* can also include an RF transmitter (e.g., the RF transmitter **506** of FIG. **5**) for transmission of Tx signals comprising Tx waveforms **716***a*, **716***b*, **716***c*. **720***a*, **720***b*, **720***c*. In one or more examples, Tx waveforms **716***a*, **716***b*, **716***c* are RF sensing signals, and Tx waveforms **720***a*, **720***b*, **720***c* are communications signals. In one or more examples, the Tx waveforms **720***a*, **720***b*, **720***c* are communications signals that may be used for scheduling transmitters (e.g., transmitters **700***a*, **700***b*, **700***c*) and receivers (e.g., receiver **704**) for performing RF sensing of a target (e.g., target **702**) to obtain location information regarding the target. The RF transmitter can be a transmitter configured to transmit cellular or telecommunication signals (e.g., a transmitter configured to transmit 5G/NR signals, 4G/LTE signals, or other cellular/telecommunication signals, etc.), a Wi-Fi transmitter, a Bluetooth™ transmitter, any combination thereof, or any other transmitter capable of transmitting an RF signal.

[0154] The RF transmitter may be coupled to one or more transmitting antennas, such as a Tx antenna (e.g., the TX antenna **512** of FIG. **5**). In one or more examples, a Tx antenna can be an omnidirectional antenna that is capable of transmitting an RF signal in all directions, or a directional antenna that transmits an RF signal in a particular direction. The Tx antenna may include multiple antennas (e.g., elements) configured as an antenna array.

[0155] The receiver **704** of FIG. **7** may include one or more components for receiving an RF signal. For example, the receiver **704** can include one or more receiving antennas, such as an Rx antenna (e.g., the Rx antenna **514** of FIG. **5**). In one or more examples, an Rx antenna can be an omnidirectional antenna capable of receiving RF signals from multiple directions, or a directional antenna that is configured to receive signals from a particular direction. In some examples, the Rx antenna may include multiple antennas (e.g., elements) configured as an antenna array (e.g., a phase antenna array).

[0156] The receiver **704** can also include an RF receiver (e.g., RF receiver **510** of FIG. **5**) coupled to the Rx antenna. The RF receiver may include one or more hardware components for receiving an RF waveform such as a Wi-Fi signal, a Bluetooth™ signal, a 5G/NR signal, or any other RF signal. The output of the RF receiver can be coupled to at least one processor (e.g., the processor(s) **522** of FIG. **5**). The processor(s) may be configured to process a received waveform (e.g., Rx waveform **718**, which is a reflection (ccho) RF sensing signal).

[0157] In some examples, the transmitters **700***a*, **700***b*, **700***c* can implement RF sensing techniques, for example bistatic sensing techniques, by causing Tx waveforms **716***a*, **716***b*, **716***c* (e.g., radar sensing signals) to be transmitted from a Tx antenna associated with each of the transmitters **700***a*, **700***b*, **700***c*. Although the Tx waveforms **716***a*, **716***b*, **716***c* are illustrated as single lines, in some cases, the Tx waveforms **716***a*, **716***b*, **716***c* may be transmitted in all directions (e.g., by an omnidirectional Tx antenna associated with each of the transmitters **700***a*, **700***b*, **700***c*).

[0158] In one or more aspects, one or more parameters associated with the Tx waveforms **716***a*, **716***b*, **716***c* may be used to increase or decrease RF sensing resolution. The parameters can include, but are not limited to, frequency, bandwidth, number of spatial streams, the number of antennas configured to transmit Tx waveforms **716***a*, **716***b*, **716***c*, the number of antennas configured to receive a reflected (echo) RF signal (e.g., Rx waveform **718**) corresponding to each of the Tx waveforms **716***a*, **716***b*, **716***c*, the number of spatial links (e.g., number of spatial streams multiplied by number of antennas configured to receive an RF signal), the sampling rate, or any combination thereof. The transmitted waveforms (e.g., Tx waveforms **716***a*, **716***b*, **716***c*) and the received waveforms (e.g., the Rx waveform **718**) may include one or more radar RF sensing signals (also referred to as RF sensing RSs). It should be noted that although only one reflected sensing signal (e.g., Rx waveform **718**) is shown in FIG. **7**, it is understood that a separate reflection (echo) sensing signal will be generated by each sensing signal (e.g., Tx waveforms **716***a*. **716***b*, **716***c*) reflecting off of the target **702**.

[0159] During operation of the system of FIG. **7**, the receiver **704** (e.g., which operates as a receive sensing node) can receive signals that correspond to Tx waveforms **716***a*, **716***b*, **716***c*, which are transmitted by the transmitters **700***a*, **700***b*, **700***c* (e.g., which each operate as a transmit sensing node). The receiver **704** can receive signals that are reflected from objects or people that are within range of the Tx waveforms **716***a*, **716***b*, **716***c*, such as Rx waveform **718** reflected from the target **702**. In one or more examples, the

Rx waveform **718** may include multiple sequences that correspond to multiple copies of a sequence that are included in its corresponding Tx waveform **716***a*, **716***b*, **716***c*. In some examples, the receiver **704** may combine the multiple sequences that are received to improve the SNR.

[0160] In some examples, RF sensing data can be used by at least one processor within the receiver **704** to calculate distances, angles of arrival (AOA), TDOA, angle of departure (AoD), or other characteristics that correspond to reflected waveforms (e.g., Rx waveform **718**). In further examples, RF sensing data can also be used to detect motion, determine location, detect changes in location or motion patterns, or any combination thereof. In one or more examples, the distance and angle of arrival of the reflected signals can be used to identify the size, position, movement, and/or orientation of targets (e.g., target **702**) in order to detect target presence/proximity.

[0161] The processor(s) of the receiver **704** can calculate distances and angles of arrival corresponding to reflected waveforms (e.g., the distance and angle of arrival corresponding to the Rx waveform **718**) by using signal processing, machine learning algorithms, any other suitable technique, or any combination thereof. In one or more examples, the receiver **704** can transmit or send the RF sensing data to at least one processor of another computing device, such as a server, that can perform the calculations to obtain the distance and angle of arrival corresponding to the Rx waveform **718** or other reflected waveforms (not shown).

[0162] In one or more examples, a processor(s) of the receiver **704** can calculate the angle of arrival (AOA) of the Rx waveform **718** by measuring the TDOA of the Rx waveform **718** between individual elements of a receive antenna array of the receiver **704**. In some examples, the TDOA can be calculated by measuring the difference in received phase at each element in the receive antenna array. In one illustrative example, to determine TDOA, the processor(s) can determine the difference time of arrival of the Rx waveform **718** to the receive antenna array elements, using one of them as a reference. The time difference is proportional to distance differences.

[0163] In some cases, the processor(s) of the receiver **704** can use the distance, the AOA, the TDOA, other measured information (e.g., AoD, etc.), any combination thereof, of the Rx waveform **718** to determine the distance between the receiver **704** and the target **702**, and determine the position of target **702** relative to the receiver **704**. In one example, the processor(s) can apply a multilateration or other location-based algorithm using the distance. AOA, and/or TDOA information as input to determine a position (e.g., 3D position) of the target **702**. In other examples, the processor (s) can use the distance, the AOA, and/or the TDOA of the Rx waveform **718** to determine a presence, movement (e.g., velocity or speed, heading or direction or movement, etc.), proximity, identity, any combination thereof, or other characteristic of the target **702**. For instance, the processor(s) of the receiver **704** may use the distance, the AOA, and/or the TDOA corresponding to the Rx waveform **718** to determine that the target is moving towards the receiver **704**.

[0164] FIG. **8** is a diagram illustrating geometry for bistatic (or monostatic) sensing. FIG. **8** shows a bistatic radar North-reference coordinate system in two-dimensions. In particular, FIG. **8** shows a coordinate system and parameters defining bistatic radar operation in a plane (referred to as a bistatic plane) containing a transmitter **800**, a receiver **804**, and a target **802**. A bistatic triangle lies in the bistatic plane. The transmitter **800**, the target **802**, and the receiver **804** are shown in relation to one another. The transmitter **800** and the receiver **804** are separated by a baseline distance L. The extended baseline is defined as continuing the baseline distance L beyond either the transmitter **800** or the receiver **804**. The target **802** and the transmitter **800** are separated by a distance RT, and the target **802** and the receiver **804** are separated by a distance RR.

[0165] Angles θ_T and θ_R are, respectively, the transmitter **800** and receiver **804** look angles, which are taken as positive when measured clockwise from North (N). The angles θ_T and θ_R are also referred to as angles of arrival (AOA) or lines of sight (LOS). A bistatic angle (β) is the angle subtended between the transmitter **800**, the target **802**, and the receiver **804** in the radar. In particular, the bistatic angle is the angle between the transmitter **800** and the receiver **804** with the vertex located at the target **802**. The bistatic angle is equal to the transmitter **800** look angle minus the receiver **804** look angle θ_R (e.g., $\beta=\theta_T-\theta_R$).

[0166] When the bistatic angle is exactly zero (0), the radar is considered to be a monostatic radar; when the bistatic angle is close to zero, the radar is considered to be pseudo-monostatic; and when the bistatic angle is close to 180 degrees, the radar is considered to be a forward scatter radar. Otherwise, the radar is simply considered to be, and referred to as, a bistatic radar. The bistatic angle (β) can be used in determining the radar cross section of the target.

[0167] FIG. **9** is a diagram illustrating an example of a bistatic range **910** of bistatic sensing. In this figure, a transmitter (Tx) **900**, a target **902**, and a receiver (Rx) **904** of a radar are shown in relation to one another. The transmitter **900** and the receiver **904** are separated by a baseline distance L, the target **902** and the transmitter **900** are separated by a distance Rtx, and the target **902** and the receiver **904** are separated by a distance Rrx.

[0168] Bistatic range **910** (shown as an ellipse) refers to the measurement range made by radar with a separate transmitter **900** and receiver **904** (e.g., the transmitter **900** and the receiver **904** are located remote from one another). The receiver **904** measures the time of arrival from when the signal is transmitted by the transmitter **900** to when the signal is received by the receiver **904** from the transmitter **900** via the target **902**. The bistatic range **910** defines an ellipse of constant bistatic range, referred to an iso-range contour, on which the target **902** lies, with foci centered on the transmitter **900** and the receiver **904**. If the target **902** is at range Rrx from the receiver **904** and range Rtx from the transmitter **900**, and the receiver **904** and the transmitter **900** are located a distance L apart from one another, then the bistatic range is equal to Rrx+Rtx−L. It should be noted that motion of the target **902** causes a rate of change of bistatic range, which results in bistatic Doppler shift.

[0169] Generally, constant bistatic range points draw an ellipsoid, with the transmitter **900** and the receiver **904** positions as the focal points. The bistatic iso-range contours are where the ground slices the ellipsoid. When the ground is flat, this intercept forms an ellipse (e.g., bistatic range **910**). Note that except when the two platforms have equal altitude, these ellipses are not centered on a specular point.

[0170] FIG. **10** illustrates an example **1000** of wireless communication between devices based on sidelink communications. The communication may be based on a slot structure (e.g., the slot structure as shown in FIG. **3**). For example, transmitting UE **1002** may transmit a transmission **1014**, e.g., comprising a control channel and/or a corresponding data channel, that may be received by receiving UEs **1004**, **1006**, **1008**. At least one UE may be in the form of an autonomous vehicle or an unmanned aerial vehicle. A control channel may include information for decoding a data channel and may also be used by receiving device to avoid interference by refraining from transmitting on the occupied resources during a data transmission. The number of transmission time intervals (TTIs), as well as the RBs, that will be occupied by the data transmission, may be indicated in a control message from the transmitting device. The UEs **1002**, **1004**, **1006**, **1008** may each be capable of operating as a transmitting device in addition to operating as a receiving device. Thus, UEs **1006**, **1008** are illustrated as transmitting transmissions **1016**, **1020**. The transmissions **1014**, **1016**, **1020** (and **1018** by a network device **1007**, such as a roadside unit) may be broadcast or multicast to nearby devices. For example, UE **1014** may transmit communication intended for receipt by other UEs within a range **1001** of UE **1014**. Additionally/alternatively, network device **1007** may receive communication from and/or transmit communication **1018** to UEs **1002**, **1004**, **1006**, **1008**. UEs **1002**, **1004**, **1006**, **1008** or network device **1007** may include a detection component. UEs **1002**, **1004**, **1006**, **1008** or network device **1007** may also include a vehicle-based safety message or mitigation component.

[0171] Examples of comb structures for reference signals (e.g., a PRS, SRS, etc.) are shown in FIG. **11**. For example, the comb structure **1110** is a comb-2 structure with two symbols (denoted as a comb-2/2-symbol structure). According to the comb-2/2-symbol structure of the comb structure **1110**, every alternate symbol is assigned to the reference signal resources. The comb patterns in FIG. **11** are for one Transmission-Reception Point (TRP). A summary of the comb structures **1110**, **1112**, **1114**, **1116**, **1118**, **1120**, **1122**, and **1124** are provided in Table 2 below:

TABLE 2

	2-Symbols	4-Symbols	6-Symbols	12-Symbols
Comb-2	{0, 1}	{0, 1, 0, 1}	{0, 1, 0, 1, 0, 1}	{0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1}
Comb-4	N/A	{0, 2, 1, 3}	N/A	{0, 2, 1, 3, 0, 2, 1, 3, 0, 2, 1, 3}
Comb-6	N/A	N/A	{0, 3, 1, 4, 2, 5}	{0, 3, 1, 4, 2, 5, 0, 1, 3, 4, 2, 5}
Comb-12	N/A	N/A	N/A	{0, 6, 3, 9, 1, 7, 4, 10, 2, 8, 5, 11}

[0172] As previously noted, systems and techniques are described herein that apply solutions associated with enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. FIG. **12** is a diagram illustrating an example of a system **1200** for applying solutions (e.g., methods or rules) for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. In FIG. **12**, the system **1200** is shown to include a network device **1210** in the form of a UE. The network device **1210** (e.g., UE) can operate as a radar Rx for sensing purposes. Also shown is a network device **1220** in the form of a base station (e.g., gNB or a portion of a gNB, such as a CU, DU, RU, Near-RT RIC, Non-RT RIC, etc.). The network device **1220** (e.g., gNB) can operate as a radar Tx for sensing purposes. The system **1200** also includes a plurality of network entities **1240**, **1250**, where network entity **1240** is in the form of a radar server and network entity **1250** is in the form of a location server.

[0173] The system **1200** may include more or less network devices and/or more or less network entities, than as shown in FIG. **12**. In addition, the system **1200** may include different types of network devices (e.g., vehicles) and/or different types of network entities (e.g., network servers) than as shown in FIG. **12**. Also, a UE may be employed as the radar Tx instead of a base station (e.g., gNB) as is shown in FIG. **12**. In addition, in one or more examples, the network device **1210** (e.g., UE) may be equipped with heterogeneous capability, which may include, but is not limited to, 4G/5G cellular connectivity, GPS capability, camera capability, radar capability, and/or LIDAR capability. The network devices **1210**, **1220** and network entities **1240**, **1250** may be capable of performing wireless communications with each other via communications signals (e.g., signals **1270***a*, **1270***b*, **1270***c*, **1270***d*).

[0174] In one or more examples, the network devices **1210**, **1220** may be capable of transmitting and receiving sensing signals of some kind (e.g., camera, RF sensing signals, optical sensing signals, etc.). In some cases, the network devices **1210**, **1220** may transmit and receive sensing signals (e.g., RF sensing signals **1260***a*, **1260***b*) for using one or more sensors to detect nearby targets (e.g., target **1230**, which is in the form of a vehicle). In some cases, the network devices **1210**, **1220** can detect nearby targets based on one or more images or frames captured using one or more cameras.

[0175] The network device **1220**, which may operate as a radar, may perform RF sensing (e.g., bistatic sensing or monostatic sensing) of at least one target (e.g., target **1230**) to obtain RF sensing measurements (e.g., Doppler, RTT, TOA, and/or TDOA measurements) of the target(s) (e.g., target **1230**). The RF sensing measurements of the target(s) (e.g., target **1230**) can be used (e.g., by at least one processor(s) of at least one of the network devices **1210**, **1220** and/or at least one of the network entities **1240**, **1250**) to determine one or more characteristics (e.g., speed, location, distance, movement, heading, size, and/or other characteristics) of the target(s) (e.g., target **1230**).

[0176] As previously mentioned, generally, sensing involves monitoring moving targets (e.g., target **1230**) with different motions (e.g., a moving car or pedestrian, a body motion of a person, such as breathing, and/or other micro-motions related to a target). Doppler, which measures the phase variation in a signal and is indicative of motion, is an important characteristic for sensing of a target (e.g., target **1230**). As such, in order to obtain an accurate estimation of the motion of the target, the phase of the signal should be continuous (e.g., the signal should maintain phase continuity).

[0177] During operation of the system **1200**, for example when performing bistatic sensing of a target (e.g., target **1230**), a network device **1220** (e.g., base station), operating as a radar Tx, may transmit an RF sensing signal **1260***a* towards the target (e.g., target **1230**). The RF sensing signal **1260***a* may be included within communication signals and sensing signals multiplexed (e.g., via time division multiplexing and/or frequency division multiplexing) together for joint communications and sensing purposes. The sensing signal **1260***a* can reflect off of the target (e.g., target **1230**) to produce an RF reflection sensing signal **1260***b*, which may be reflected towards network device **1210** (e.g., UE). The network device **1210** (e.g., UE), operating as a radar Rx, can receive the reflection sensing signal **1260***b*. After the network device (e.g., UE) receives the reflection sensing signal **1260***b*, the network device (e.g., UE) can obtain measurements (e.g., Doppler, RTT, TOA, and/or TDOA measurements) of the reflection sensing signal **1260***b*. At least one processor (e.g., processor **2010** of FIG. **20**) of at least one of the network devices **1210**, **1220** and/or at least one of the network entities **1240**, **1250** may then determine or compute the characteristics (e.g., speed, location, distance, movement, heading, size, etc.) of the target (e.g., target **1230**) by using sensing measurements (e.g., Doppler. TOA, and/or TDOA measurements) from the received reflection sensing signal **1260***b*.

[0178] In some examples, the network device **1210** (e.g., UE) may transmit the measurements (e.g., Doppler, RTT, TOA, and/or TDOA measurements) and/or determined characteristics (e.g., speed, location, distance, movement, heading, size, etc.) of the target (e.g., target **1230**) to the network device **1220** (e.g., base station) and/or network entity **1240** (e.g., radar server) via communication signals **1270***a*, **1270***b*. The network device **1220** (e.g., base station) and/or network entity **1240** (e.g., radar server) may then transmit the measurements (e.g., Doppler, RTT, TOA, and/or TDOA measurements) and/or determined characteristics (e.g., speed, location, distance, movement, heading, size, etc.) of the target (e.g., target **1230**) to the network entity **1240** (e.g., radar server) and/or network entity **1250** (e.g., location server such as a location management function (LMF)) via communication signals **1270***c*, **1270***d*.

[0179] As previously mentioned, MIMO is a multi-antenna spectrum-efficient technique. MIMO has become a leading driver of next-generation antenna technology for cellular networks. A MIMO system can transmit more than one signal over the same channel, which can provide for an increase in spectral efficiency and overall throughput. By taking advantage of spatial separation, the antennas of a MIMO system are spaced at specific distances and angles for various purposes, such as to reduce the correlation between different sub-channels, to achieve precoding/beamforming purposes, etc to compensate for self-interference. A MIMO system can provide a robust wireless communication mechanism to address fading and shadowing caused by multiple transmission paths and long distances. Within a MIMO system, various streams of data may be transmitted at the same time, which can provide for multiplexing gains and an improved overall throughput. For at least these reasons, MIMO has been recently implemented in cellular wireless communications technology and is included in various wireless projects and standards (e.g., including 5G NR).

[0180] A simple form of MIMO is point-to-point MIMO, where two systems (e.g., a base station and a UE) each employ multiple antennas to communicate with each other. The use of multiple antennas can provide for an increase in the air interface capacity. However, point-to-point MIMO employs a multi-antenna configuration that requires additional hardware at the base station as well as the end-user device (e.g., in the UE). The additional hardware requirement at both the base station and the user device is a disadvantage to point-to-point MIMO because it leads to an increase the overall system complexity. As noted previously, in some cases, end-user equipment (e.g., UE) of a mobile communication system may not be able to support multiple antennas, such as due to its small physical size and/or the low-cost requirements of the UE devices.

[0181] As noted previously, a feature of point-to-point MIMO is single-user MIMO (SU-MIMO). SU-MIMO provides for an increase in the data rate by transmitting multiple data streams to a specific user device (e.g., specific UE). Similar to point-to-point MIMO, SU-MIMO has the disadvantage of requiring the user device (e.g., UE) to support multiple antennas.

[0182] Conversely to point-to-point MIMO and SU-MIMO, multiple-user MIMO (MU-MIMO) does not have the disadvantage of requiring the user device to support multiple antennas. For MU-MIMO, multiple users share the same time and frequency resources, while each base station (e.g., gNB or eNB), or portion thereof such as a CU, a DU, an RU, a Near-RT RIC, or a Non-RT RIC is equipped with multiple antennas (e.g., antenna arrays) and serves many users (e.g., UEs) simultaneously. Each end-user device (e.g., UE) can employ a single antenna or multiple antennas, where when a single antenna is used, complex hardware may only be required at the base station side. The cost and complexity of the antenna system are significantly reduced for a MU-MIMO system because low-cost single antennas (e.g., dipole antennas) can be employed for the end-user devices (e.g., UEs), and the more expensive, complex hardware can be utilized only at the base station side.

[0183] Due to the variety in the distance, angle, and quality of the signals of the multiple users in MU-MIMO systems, the performance of MU-MIMO systems is generally less affected by the transmission environment as compared to point-to-point MIMO. This advantage is achieved by MU-MIMO systems utilizing selective beamforming and power control to cancel out interference. MU-MIMO systems offer high reliability and throughput and, as such, have become an integral part of wireless communication systems, including Wi-Fi, LTE, and 5G networks.

[0184] Massive MIMO (mMIMO) is a form a MU-MIMO that employs a larger number of antennas at the base stations than MU-MIMO and, as such, the number of users (e.g., UEs) served may be increased significantly over MU-MIMO systems. For example, in mMIMO, a single base station with many antennas can serve a large number of users. With a large number of antennas in each base station, the channel vectors between users (e.g., UEs) and the base station are per pair almost rectangular, which can provide for exceptional linear transmissions. In mMIMO, a large throughput can be achieved due to multiplexing gain, diversity gain, and array gain. The large number of antennas at the base stations, in mMIMO, can serve hundreds of users with the same frequency resource by taking advantage of antenna beamforming techniques.

[0185] In mMIMO, the more antennas employed for each base station, the more robust the communications operation. mMIMO can, theoretically, employ an infinite number of antennas at each of the base stations. However, usually (e.g., in 5G networks), 64 to 128 (e.g., 64 receive antennas and 64 transmit antennas) antennas have been utilized practically in mMIMO base stations. An advantage of mMIMO is that sophisticated hardware may only be required at the base stations, not at the user devices (e.g., UEs), which each may use a single antenna and a simple antenna design. Another advantage of mMIMO is that it has an extensible architecture that may be easily scaled up to serve more users by only having to upgrade the antenna systems on the base stations.

[0186] Currently, some radar (e.g., such as automotive radar) transmit signals having frequency modulated continuous wave (FMCW) waveforms. An FMCW waveform (e.g., also referred to as a chirp or a pulse) is a complex sinusoid with a frequency that increases (e.g., ramps) linearly with time. FMCW radar transmit chirps (e.g., chirps **1310***a*, **1310***b*, **1310***c* of FIG. **13**) in a periodic fashion, with a period referred to as a pulse repetition interval (PRI).

[0187] FIG. **13** is a diagram **1300** illustrating an example of chirps (or pulses) **1320** being transmitted by a plurality of antennas (e.g., transmit antennas of a FMCW radar, which may be a MIMO radar, of a network device, such as a UE or base station, for example a gNB). In FIG. **13**, the plurality of antennas are shown to be transmitting chirps, where each antenna is transmitting chirps sequentially over a pulse repetition interval T_{PRI}. For example, a first antenna is transmitting N number of chirps **1310***a*, **1310***b*, **1310***c* over the pulse repetition interval T_{PRI}. The plurality of antennas can be transmitting at the same time and frequency resources. The antennas can be simultaneously transmitting a respective sensing waveform, which can be formulated by multiplying a common FMCW waveform with a phase code that is different for each antenna and changes between pulses. As will be discussed later in detail, the common FMCW waveform can be multiplied by a phase code denoted as am (n), where M is the index of the antenna, M_t is the number of antennas, and n is the index of the chirp (or pulse). The antennas may be concurrently transmitting at the same time and frequency resource, but each antenna may be using a different phase code. The phase code may be referred to as a "slow time phase code" because the phase code is applied across chirps (or pulses), not across the samples within the same chirp (or pulse). The phase coding may be performed chirp-by-chirp, not sample-by-sample.

[0188] A target echo received at the radar receiver can contain a delayed and attenuated copy of the transmitted chirp. The received signal may be mixed with the transmitted chirp, which can result in a complex sinusoid, which may be referred to as a beat signal.

[0189] The process of obtaining the beat signal may be implemented in the RF domain by using a mixer, followed by a BPF to remove signals with frequencies outside of the band of interest, which can also place a limit on the maximum detectable range. The estimation of the beat frequency may be implemented in the digital domain, after the sampling of the beat signal. In many scenarios, such as in automotive scenarios, the beat frequency may be much smaller than the signal bandwidth and, as such, a low-speed ADC (e.g., which is low cost) can be used to sample the beat signal. FMCW waveforms are often used in the radar industry because of their low performance-to-cost ratio, which is at least in part allowed for by the use of a low cost ADC. The time during one period or chirp is generally referred to as the "fast time," while the time across multiple periods or chirps is generally referred to as the "slow time." For example, if a beat signal is sampled and the samples of each chirp are placed within columns of a matrix, the row indices of the matrix can correspond to the fast time and the column indices of the matrix can correspond to the slow time. By applying a FFT on the sampled beat signal along the fast time, the range frequency may be determined. A second FFT may be applied along the slow time to determine the Doppler frequency (e.g., Doppler frequency **1400** of FIG. **14**A). The application of these two FFTs can be equivalent to a 2D FFT of the beat signal in the fast and slow times. The result of this 2D FFT operation can produce a 2D range-Doppler spectrum (e.g., graph **1402** of FIG. **14**B).

[0190] FIG. **14**A is a diagram illustrating an example of Doppler frequency **1400** of transmissions from two antennas (e.g., antenna Tx **1** and antenna Tx **2**). In particular, in FIG. **14**A, the x-axis denotes the Doppler frequency **1400**. The Doppler frequency **1400** as shown in FIG. **14**A is shown to have both negative and positive components. In particular, the Doppler frequency **1400** is shown to have three sub-bands **1410**, **1420***a*, **1420***b*, where sub-band **1410** corresponds to antenna Tx**1** and sub-bands **1420***a*, **1420***b* correspond to antenna Tx**2**.

[0191] FIG. **14**B is a graph **1402** illustrating an example of a range-velocity profile for a DDM MIMO radar with the two transmitting antennas of FIG. **14**A. In particular, for the graph **1402** of FIG. **14**B, the x-axis denotes range in meters (m), the y-axis denotes velocity (or Doppler) in meters per seconds (m/s), and the z-axis denotes magnitude in decibels (dB). For this example, the range and Doppler spectra are of a target with a range of 75 m and a velocity (or Doppler) of 10 m/s.

[0192] In the graph **1402**, two peaks **1430***a*, **1430***b* are shown. The number of peaks in the graph can correspond to the number of transmitting antennas. The real target is only within one of the peaks and, as such, there can be an ambiguity of the peaks. The other peak is just a repetition, which may be due to aliasing. In this example, the real target is located in the first peak, which is peak **1430***a*.

[0193] In some scenarios, MIMO radar can be employed to transmit FMCW sequences. The transmit antennas of the MIMO radar can transmit the FMCW sequences in a way that guarantees their orthogonality. At each receive antenna (e.g., of the MIMO radar), the contribution of each transmit antenna may be extracted by exploiting waveform orthogonality. Various different techniques may be used to achieve waveform orthogonality while transmitting FMCW including, but not limited to, slow time Doppler division multiplexing (SL-DDM).

[0194] For achieving waveform orthogonality while transmitting FMCW by using SL-DDM, a total of N number of chirps (i.e., pulses) should be transmitted sequentially with pulse-repetition interval T_{PRI}. All transmit antennas should simultaneously transmit the same FMCW waveform after multiplying the FMCW waveform with a phase code that is different for each antenna and changes between pulses, where the transmitted waveform is: $x_m(n)=e^{j2\pi\alpha_m(n)}$, where M=1, 2, . . . , M_t, and n=0, 1, 2, . . . , N−1. To separate the h^{th} transmit signal at the 1^{th} receiver, after performing the range FFT, a slow-time Doppler demodulation can be applied to all range bins corresponding to the same chirp. The Doppler demodulated outputs of N number of chirps can be assembled into a vector s_l^h. The Doppler FFT can then be applied on the vector s_l^h.

[0195] In one or more examples, to separate the transmit signals in the Doppler domain, phase codes can be employed to shift the Doppler FFT of the interference $e^{j2\pi(\alpha_m(n)-a_h(n))}$ to a frequency that is higher than the maximum detectable Doppler frequency f_{D_max}. A low-pass filter (LPF) can then be applied to remove the interference. An example of a phase code is $\alpha_m(n)=\alpha_m n$, where M=1, 2, . . . , M_t, and n=0, 1, 2, . . . , . . . , N−1, and where the starting phase am is linear across different transmit antennas, such that $\alpha_m = m\alpha_0$. With this approach, the radar pulse repetition frequency f_{PFR} should be larger than $M_t f_{D\_max}$. As such, if the f_{PFR} remains unchanged, the maximum detectable unambiguous Doppler frequency is reduced by a factor of M_t. As the number of antennas increases (e.g., M_t increases), f_{D_max} may need to be reduced such that f_{PRF} is larger than $M_t f_{D\_max}$, which can mitigate Doppler ambiguity.

[0196] A Doppler unfolding, or de-aliasing, algorithm with different f_{PRF} in different looks to mitigate Doppler ambiguity can be very useful. In one or more aspects, systems and techniques provide solutions for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. The systems and techniques provide solutions that mitigate Doppler ambiguity, which may be caused by aliasing.

[0197] In one or more aspects, Doppler spectrum puncturing may be employed to mitigate Doppler ambiguity. In one or more examples, a special Doppler spectrum with some empty sub-bands may be implemented within the MIMO radar waveform through slow time (SL) phase coding. In some examples, the empty sub-bands in the Doppler spectrum may be consecutive.

[0198] One example code that may be used for a special Doppler spectrum with some consecutive empty sub-bands may be $\alpha_m(n) = \alpha_m n$, $\alpha_m = (m-1)/(M_t + M_{empty})$, where m=1, 2, ... M_t, and where M_t is the totally number of Tx antennas, and M_{empty} is the number of consecutive empty sub-bands in the Doppler spectrum.

[0199] FIGS. **15**A, **15**B, and **15**C illustrate an example of implementing a special Doppler spectrum with consecutive empty sub-bands within the MIMO radar waveform through SL phase coding. In particular, FIG. **15**A is a diagram **1500** illustrating an example of chirps (or pulses) **1520** being transmitted by four Tx antennas (e.g., transmit antennas of a FMCW radar, which may be a MIMO radar of a network device, such as a UE or base station, for example a gNB). In FIG. **15**A, the four antennas are shown to be transmitting chirps, where each of the four antennas is transmitting chirps sequentially over a pulse repetition interval T_{PRI}. For example, a first antenna is transmitting N number of chirps **1510***a*, **1510***b*, **1510***c* over the pulse repetition interval T_{PRI} (e.g., corresponding to sub-band Tx**1** **1530** of FIG. **15**B). The four antennas may be transmitting at the same time and frequency resources, and may be transmitting concurrently the same FMCW waveform. The FMCW waveforms can be multiplied by the phase code am (n), where M is the index of the antenna, M_t is the number of antennas, and n is the index of the chirp (or pulse). The four antennas may be concurrently transmitting at the same time and frequency resource, but each of the four antennas can be using a different phase code. The phase code may be referred to as a "slow time phase code" because the phase code is applied across chirps (or pulses), not across the samples within the same chirp (or pulse). The phase coding may be performed chirp-by-chirp (e.g., not sample-by-sample).

[0200] FIG. **15**B is a diagram illustrating an example of Doppler frequency **1502** of transmissions from four antennas (e.g., antenna Tx**1**, antenna Tx**2**, antenna Tx**3**, and antenna Tx**4**), where the empty sub-bands **1570***a*, **1570***b* are consecutive. In particular, in FIG. **15**B, the x-axis denotes the Doppler frequency **1502**. The Doppler frequency **1502** as shown in FIG. **15**B is shown to have only positive components (e.g., note that the negative components are not shown in the figure). In particular, the Doppler frequency **1502** is shown to have six sub-bands (e.g., sub-bands **1530**, **1540**, **1550**, **1560**, **1570***a*, **1570***b*). Sub-band **1530** corresponds to antenna Tx**1**, sub-band **1540** corresponds to antenna Tx**2**, sub-band **1550** corresponds to antenna Tx**3**, and sub-band **1560** corresponds to antenna Tx**4**. Sub-bands **1570***a* and **1570***b* are empty. Sub-bands **1530**, **1540**, **1550**, **1560** are each shown to include a respective peak (e.g., peaks **1535**, **1545**, **1555**, **1565**). One of the peaks corresponds to the real target, while the remaining peaks are merely repetition, which may be due to aliasing. As such, the peaks are ambiguous.

[0201] FIG. **15**C is a table **1504** illustrating examples of Doppler spectrum patterns **1590**, where the empty sub-bands are consecutive. The Doppler spectrum patterns **1590** can be used to determine which peak of a plurality of ambiguous peaks (e.g., peaks **1535**, **1545**, **1555**, **1565** of FIG. **15**B) corresponds to the real target. The code am (n) is designed such that the peak corresponding to antenna Tx**1** is the real peak of the set of peaks.

[0202] In the table **1504**, six different Doppler spectrum patterns **1590** are shown. Each Doppler spectrum pattern **1590** has an associated Doppler spectrum hypothesis index **1580** (e.g., 1, 2, 3, 4, 5, and 6). To determine which peak of a plurality of ambiguous peaks is the real peak corresponding to the target, the resultant Doppler frequency should be matched with one of the Doppler spectrum patterns **1590**.

[0203] For example, the Doppler frequency **1502** of transmissions from the four antennas (e.g., antenna Tx**1**, antenna Tx**2**, antenna Tx**3**, and antenna Tx**4**) of FIG. **15**B matches with the Doppler spectrum pattern **1590** with a Doppler spectrum hypothesis index **1580** of 1. As mentioned, the code am (n) is designed such that the peak corresponding to antenna Tx**1** is the real peak of the set of peaks. As such, the real peak is the peak **1535** contained within the first sub-band **1530**, which corresponds to antenna Tx**1**.

[0204] As previously mentioned, Doppler spectrum puncturing can be employed to mitigate Doppler ambiguity, where a special Doppler spectrum with some empty sub-bands can be implemented within the MIMO radar waveform through SL phase coding. In one or more examples, the empty sub-bands in the Doppler spectrum may be non-consecutive.

[0205] One example code that may be used for a special Doppler spectrum with some non-consecutive empty sub-bands may be $\alpha_m(n) = \alpha_m n^* i_m$, $\alpha_m = (m-1)/(M_t + M_{empty})$, where m is the virtual antenna index, m=1, 2, ... $M_t + M_{empty}$, and M_t is the total number of physical transmit (Tx) antennas, and M_{empty} is the number of non-consecutive empty sub-bands in the Doppler spectrum. In one or more examples, $i_m = 0$, when the m_{th} sub-band is punctured, and $i_m = 1$, when the m_{th} sub-band is not punctured.

[0206] FIGS. **16**A, **16**B, and **16**C illustrate an example of implementing a special Doppler spectrum with non-consecutive empty sub-bands within the MIMO radar waveform through SL phase coding. In particular, FIG. **16**A is a diagram **1600** illustrating an example of chirps (or pulses) **1620** being transmitted by four Tx antennas (e.g., transmit antennas of a FMCW radar, which may be a MIMO radar of a network device, such as a UE or base station, for example a gNB). The four antennas in FIG. **16**A are shown to be transmitting chirps, where each of the four antennas is transmitting chirps sequentially over a pulse repetition interval T_{PRI}. For an example, a first antenna is transmitting N number of chirps **1610**_a_, **1610**_b_. **1610**_c_ over the pulse repetition interval T_{PRI} (e.g., which corresponds to sub-band Tx**1** **1630** of FIG. **16**B). The four antennas can transmit at the same time and frequency resources, and can transmit concurrently the same FMCW waveform. The FMCW waveforms may be multiplied by the phase code am (n), where M is the index of the antenna, M_t is the number of antennas, and n is the index of the chirp (or pulse). The four antennas can concurrently transmit at the same time and frequency resource, but each of the four antennas can use a different phase code. The phase code can be referred to as a "slow time phase code" because the phase code is applied across the time domain, not the frequency domain. The phase coding can be performed chirp-by-chirp (e.g., not sample-by-sample).

[0207] FIG. **16**B is a diagram illustrating an example of Doppler frequency **1602** of transmissions from four antennas (e.g., antenna Tx**1**, antenna Tx**2**, antenna Tx**3**, and antenna Tx**4**), where the empty sub-bands **1670**_a_, **1670**_b_ are non-consecutive. In particular, in FIG. **16**B, the x-axis denotes the Doppler frequency **1602**. The Doppler frequency **1602** as shown in FIG. **16**B is shown to have only positive components (e.g., note that the negative components are not shown in the figure). In particular, the Doppler frequency **1602** is shown to have six sub-bands (e.g., sub-bands **1630**, **1640**, **1650**, **1660**, **1670**_a_, **1670**_b_). Sub-band **1630** corresponds to antenna Tx**1**, sub-band **1640** corresponds to antenna Tx**2**, sub-band **1650** corresponds to antenna Tx**3**, and sub-band **1660** corresponds to antenna Tx**4**. Sub-bands **1670**_a_ and **1670**_b_ are empty. Sub-bands **1630**, **1640**, **1650**, **1660** each include a respective peak (e.g., peaks **1635**, **1645**, **1655**, **1665**). One of the peaks corresponds to the real target, while the remaining peaks are merely repetition (e.g., which may be due to aliasing). As such, the peaks are ambiguous.

[0208] FIG. **16**C is a table **1604** illustrating examples of Doppler spectrum patterns **1690**, where the empty sub-bands are non-consecutive. The Doppler spectrum patterns **1690** can be used to determine which peak of a plurality of ambiguous peaks (e.g., peaks **1635**, **1645**, **1655**, **1665** of FIG. **16**B) corresponds to the real target. The code am (n) is designed such that the peak corresponding to antenna Tx**1** is the real peak of the set of peaks.

[0209] In the table **1604**, six different Doppler spectrum patterns **1690** are shown. Each Doppler spectrum pattern **1690** has a Doppler spectrum hypothesis index **1680** (e.g., 1, 2, 3, 4, 5, and 6). To determine which peak of a plurality of ambiguous peaks is the real peak corresponding to the target, the resultant Doppler frequency should be matched with one of the Doppler spectrum patterns **1690**.

[0210] For example, the Doppler frequency **1602** of transmissions from the four antennas (e.g., antenna Tx**1**, antenna Tx**2**, antenna Tx**3**, and antenna Tx**4**) of FIG. **16**B matches with the Doppler spectrum pattern **1690** with a Doppler spectrum hypothesis index **1680** of 1. As mentioned, the code am (n) is designed such that the peak corresponding to antenna Tx**1** is the real peak of the set of peaks. As such, the real peak is the peak **1635** contained within the first sub-band **1630**, which corresponds to antenna Tx**1**.

[0211] In one or more aspects, Doppler spectrum puncturing may be employed for multi-user multiplexing. In some scenarios, multiple users may be performing sensing. Doppler spectrum puncturing may be used to multiplex these users (or nodes) using the same time and frequency resources. In one or more examples, the nodes (or users) may each be a network device, such as a UE or base station (e.g., gNB).

[0212] In one or more examples, when multiple sensing nodes (or sensor users) share the same time and frequency resource for MIMO sensing, the Doppler spectrum puncturing method (e.g., as discussed in the descriptions of FIGS. **15**A to **16**C) may be used for multi-sensing-user multiplexing to reduce interferences. In one or more examples, a group of sensing nodes (or users) may be allocated to the same SL phase codes am. As such, each user can be mapped to an antenna index, as used in the Doppler spectrum puncturing method. Previously, each antenna was mapped to an antenna index. For these examples, each node (or user) may be mapped to an antenna index for multiplexing purposes.

[0213] Each sensing node (or user) can also be allocated with a specific Doppler spectrum puncturing vector I_m, where each element of the vector is either 0 or 1.0 to indicate whether or not the corresponding sub-band spectrum is punctured (e.g., 0 may indicate that the sub-band is punctured, and 1.0 may indicate that the sub-band is not punctured). The indication of 0 or 1.0 can be used to determine whether or not to apply a phase code. For example, if the corresponding sub-band spectrum is indicated to not be punctured, then the phase code can be applied to that specific chirp or OFDM symbol. However, if the corresponding sub-band spectrum is indicated to be punctured, then the phase code does not need to be applied.

[0214] In one or more examples, the same sensing waveform can be configured for the sensing nodes within a group, but each sensing node should apply its node-specific SL phase code. In some examples, the Doppler spectrum puncturing based multiplexing can be combined with other multiplexing to increase the system capacity. For example, different group of nodes may use different sensing waveform parameters. Different sensing waveform parameters can include, but are not limited to, different starting points for the chirp signal, different frequency bands, and different slopes of the chirp signal. But, within the same group of nodes, SL-DDM can be used for further multiplexing.

[0215] In one or more examples, a sensing node can report is capability regarding SL-DDM MIMO sensing to the network (e.g., a network entity, such as a network server, for example a radar server or a location server). In some examples, the sensing node's capability regarding SL-DDM MIMO may be the maximum number of antennas for SL-DDM MIMO sensing.

[0216] FIG. **17** is a diagram illustrating examples of Doppler frequency **1700**, **1702**, **1704**, **1706** of transmissions for MIMO sensing with four different users. In particular, in FIG. **17**, the x-axis denotes the Doppler frequency. The Doppler frequency **1700**, **1702**, **1704**, **1706** of transmissions as shown in FIG. **17** is shown to have only positive components (e.g., note that the negative components are not shown in the figure). Each Doppler frequency **1700**, **1702**, **1704**, **1706** corresponds to one node (or one user). For example, Doppler frequency **1700** corresponds to node **1** (or user **1**), Doppler frequency **1702** corresponds to node **2** (or user **2**), Doppler frequency **1704** corresponds to node **3** (or user **3**), and Doppler frequency **1706** corresponds to node **4** (or user **4**). The multiplexing is such that, in the Doppler domain, the sub-bands that are not empty are not interfering (e.g., colliding) with each other.

[0217] Each Doppler frequency **1700**, **1702**, **1704**, **1706** is shown to have eight sub-bands. Doppler frequency **1700** includes sub-band **1710** (e.g., which corresponds to antenna Tx**1**), sub-band **1720** (e.g., which corresponds to antenna Tx**2**), and sub-bands **1730***a*, **1730***b*, **1730***c*. **1730***d*, **1730***e*, **1730***f* (e.g., which are empty). Doppler frequency **1702** includes sub-band **1712** (e.g., which corresponds to antenna Tx**1**), sub-band **1722** (e.g., which corresponds to antenna Tx**2**), and sub-bands **1732***a*, **1732***b*, **1732***c*, **1732***d*, **1732***e*, **1732***f* (e.g., which are empty). Doppler frequency **1704** includes sub-band **1714** (e.g., which corresponds to antenna Tx**1**), sub-band **1724** (e.g., which corresponds to antenna Tx**2**), and sub-bands **1734***a*, **1734***b*, **1734***c*, **1734***d*, **1734***e*, **1734***f* (e.g., which are empty). Doppler frequency **1706** includes sub-band **1716** (e.g., which corresponds to antenna Tx**1**), sub-band **1726** (e.g., which corresponds to antenna Tx**2**), and sub-bands **1736***a*, **1736***b*, **1736***c*, **1736***d*, **1736***e*, **1736***f* (e.g., which are empty).

[0218] In one or more aspects, a joint design of SL-DDM and multiple pulse repetition frequency (PRF) may be employed. In one or more examples, multiple PRF (or equivalently multiple sensing reference signal (RS) periodicities) can be configured jointly with the SL-DDM to mitigate the Doppler ambiguity. Multiple PRF can be used for Doppler ambiguity mitigation. For example, when a signal with multiple PRF is received and the repetition pattern is broken, the ambiguity can be mitigated (e.g., removed).

[0219] FIG. **18** shows an example of multiple PRF being used to mitigate Doppler ambiguity. In particular, FIG. **18** is a diagram illustrating an example of Doppler frequency **1800** of transmissions from four antennas, where the periodicity of one sub-band **1820** corresponding to an antenna (e.g., antenna Tx**2**) is doubled. The Doppler frequency **1800** is shown to include five sub-bands, which include sub-band **1810** (e.g., which corresponds to antenna Tx**1**), sub-band **1820** (e.g., which corresponds to antenna Tx**2**), sub-band **1830** (e.g., which corresponds to antenna Tx**3**), sub-band **1850** (e.g., which is empty), and sub-band **1840** (e.g., which corresponds to antenna Tx**4**).

[0220] For example, as shown in FIG. **18**, the sensing reference signal periodicity of antenna Tx**2** is double the sensing reference signal periodicity of antennas Tx**1**, Tx**3**, and Tx**4**. The Doppler frequency **1800** sub-band **1820** corresponding to antenna Tx**2** is doubled because periodicity of the sensing reference signal of Tx**2** is doubled. This doubling of the sub-band **1820** can be achieved by puncturing a sensing reference signal (RS) of Tx**2** (e.g., time domain puncturing or time domain down sampling). In one or more examples, puncturing of a signal, muting a signal, or performing down sampling on a signal, can increase the periodicity of a signal. Time domain puncturing based on multiple PRF may be combined with the Doppler spectrum puncturing, as shown in the example below.

[0221] In the example of FIG. **18**, the peak of sub-band **1820** is not consistent with the peaks for sub-bands **1810**, **1830**, and **1840**. Sub-bands **1810**, **1830**, and **1840** have the same periodicity, meaning that their peaks are repeated with some spatial pattern and, as such, their transmission signals will have the same gap between their repetitions (e.g., between chirps). Since the repetition (e.g., between chirps) is broken in the transmission for antenna Tx**2**, the ambiguity can be mitigated (e.g., removed).

[0222] In one or more aspects, in cellular based RF sensing, for DDM-MIMO sensing, each sensing node may be configured with a base waveform (e.g., a radar waveform, such as an FMCW or an OFDM based waveform), and a SL phase code (e.g., which can be applied over multiple radar pulses or OFDM symbols).

[0223] In one or more aspects, DDM could also be applied in multiplexing for communications. In one or more examples, the multiplexing of SRS ports can enable a longer duration of an SRS transmission with an enhanced coverage. In some examples, enhancements on DDM as previously described can also be applied for multiplexing for communications.

[0224] FIG. **19** is a flow chart illustrating an example of a process **1900** for wireless communications utilizing methods for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. The process **1900** can be performed by a network device, such as a UE, a base station (e.g., gNB), a portion of a base station (e.g., one or more of a CU, DU, RU, and/or other portion of a base station having a disaggregated architecture), or a component or system (e.g., a chipset) of the UE or base station. The UE may be a mobile device (e.g., a mobile phone), a vehicle, a wearable device (e.g., a network-connected watch or other wearable device), an extended reality (XR) device (e.g., a virtual reality (VR) or augmented reality (AR) headset or glasses), or other type of UE. The operations of the process **1900** may be implemented as software components that are executed and run on one or more processors (e.g., processor **2010** of FIG. **20** or other processor(s)). Further, the transmission and reception of signals by the wireless communications device in the process **1900** may be enabled, for example, by one or more antennas and/or one or more transceivers (e.g., wireless transceiver(s)).

[0225] At block **1910**, the network device (or component thereof) can transmit a sensing signal for sensing one or more targets. The transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of a plurality of network devices include one or more phase codes and a same frequency modulated carrier wave (FMCW). Each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns (e.g., the Doppler spectrum patterns **1690** of FIG. **16**). In some aspects, the transmitted sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources. In some cases, a phase code of the transmitted sensing signal is different from at least one phase code of the at least one other network device. In some cases, a phase code of the transmitted sensing signal is the same as at least one phase code of the at least one other network device. In some examples, the one or more Doppler spectrum patterns can include consecutive empty sub-bands, such as shown in FIGS. **15**A, **15**B, and **15**C. In some examples, the one or more Doppler spectrum patterns can include non-consecutive empty sub-bands, such as shown in FIGS. **16**A, **16**B, and **16**C.

[0226] One illustrative example of a phase code is $\alpha_m(n)=\alpha_m$, where M is the index of the antenna (e.g., M=1, 2, . . . , M_t), M_t is the number of antennas, and n is the index of the chirp (or pulse) (e.g., n=0, 1, 2, . . . , N−1), and where the starting phase am is linear across different transmit antennas, such that $\alpha_m=m\alpha_0$. For instance, as described herein, the common FMCW waveform can be multiplied by the phase code $\alpha_m(n)$, such that the antennas may be concurrently transmitting at the same time and frequency resource, but each antenna may be using a different phase code. In some cases, he phase code may be referred to as a "slow time phase code" because the phase code is applied across chirps (or pulses), not across the samples within the same chirp (or pulse). In some aspects, the phase coding may be performed chirp-by-chirp, not sample-by-sample.

[0227] At block **1920**, the network device (or component thereof) can receive at least one echo signal from the one or more targets. For instance, the at least one echo signal can include a target echo that can include a delayed and attenuated copy of a transmitted chirp. The received signal may be mixed with the transmitted chirp, which can result in a complex sinusoid, which may be referred to as a beat signal.

[0228] At block **1930**, the network device (or component thereof) can mitigate (e.g., remove) Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns. For instance, the Doppler spectrum patterns can be used to determine which peak of a plurality of ambiguous peaks (e.g., peaks **1635**, **1645**, **1655**, **1665** of FIG. **16**B) corresponds to a real target. The phase code (e.g., am (n)) is designed such that the peak corresponding to antenna Tx**1** is the real peak of the set of peaks.

[0229] In some aspects, each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector. In some cases, each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured. In some examples, a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals is increased or decreased to mitigate the Doppler ambiguity.

[0230] FIG. **20** is a block diagram illustrating an example of a computing system **2000**, which may be employed by the disclosed systems and techniques for enhancements on DDM MIMO sensing based on Doppler spectrum puncturing. In particular, FIG. **20** illustrates an example of computing system **2000**, which can be, for example, any computing device making up internal computing system, a remote computing system, a camera, or any component thereof in which the components of the system are in communication with each other using connection **2005**. Connection **2005** can be a physical connection using a bus, or a direct connection into processor **2010**, such as in a chipset architecture. Connection **2005** can also be a virtual connection, networked connection, or logical connection.

[0231] In some aspects, computing system **2000** is a distributed system in which the functions described in this disclosure can be distributed within a datacenter, multiple data centers, a peer network, etc. In some aspects, one or more of the described system components represents many such components each performing some or all of the function for which the component is described. In some aspects, the components can be physical or virtual devices.

[0232] Example system **2000** includes at least one processing unit (CPU or processor) **2010** and connection **2005** that communicatively couples various system components including system memory **2015**, such as read-only memory (ROM) **2020** and random access memory (RAM) **2025** to processor **2010**. Computing system **2000** can include a cache **2012** of high-speed memory connected directly with, in close proximity to, or integrated as part of processor **2010**.

[0233] Processor **2010** can include any general purpose processor and a hardware service or software service, such as services **2032**, **2034**, and **2036** stored in storage device **2030**, configured to control processor **2010** as well as a special-purpose processor where software instructions are incorporated into the actual processor design. Processor **2010** may essentially be a completely self-contained computing system, containing multiple cores or processors, a bus, memory controller, cache, etc. A multi-core processor may be symmetric or asymmetric.

[0234] To enable user interaction, computing system **2000** includes an input device **2045**, which can represent any number of input mechanisms, such as a microphone for speech, a touch-sensitive screen for gesture or graphical input, keyboard, mouse, motion input, speech, etc. Computing system **2000** can also include output device **2035**, which can be one or more of a number of output mechanisms. In some instances, multimodal systems can enable a user to provide multiple types of input/output to communicate with computing system **2000**.

[0235] Computing system **2000** can include communications interface **2040**, which can generally govern and manage the user input and system output. The communication interface may perform or facilitate receipt and/or transmission wired or wireless communications using wired and/or wireless transceivers, including those making use of an audio jack/plug, a microphone jack/plug, a universal serial bus (USB) port/plug, an Apple™ Lightning™ port/plug, an Ethernet port/plug, a fiber optic port/plug, a proprietary wired port/plug, 3G, 4G, 5G and/or other cellular data network wireless signal transfer, a Bluetooth™ wireless signal transfer, a Bluetooth™ low energy (BLE) wireless signal transfer, an IBEACON™ wireless signal transfer, a radio-frequency identification (RFID) wireless signal transfer, near-field communications (NFC) wireless signal transfer, dedicated short range communication (DSRC) wireless signal transfer, 802.11 Wi-Fi wireless signal transfer, wireless local area network (WLAN) signal transfer, Visible Light Communication (VLC), Worldwide Interoperability for Microwave Access (WiMAX), Infrared (IR) communication wireless signal transfer, Public Switched Telephone Network (PSTN) signal transfer, Integrated Services Digital Network (ISDN) signal transfer, ad-hoc network signal transfer, radio wave signal transfer, microwave signal transfer, infrared signal transfer, visible light signal transfer, ultraviolet light signal transfer, wireless signal transfer along the electromagnetic spectrum, or some combination thereof.

[0236] The communications interface **2040** may also include one or more range sensors (e.g., LIDAR sensors, laser range finders, RF radars, ultrasonic sensors, and infrared (IR) sensors) configured to collect data and provide measurements to processor **2010**, whereby processor **2010** can be configured to perform determinations and calculations needed to obtain various measurements for the one or more range sensors. In some examples, the measurements can include time of flight, wavelengths, azimuth angle, elevation angle, range, linear velocity and/or angular velocity, or any combination thereof. The communications interface **2040** may also include one or more Global Navigation Satellite System (GNSS) receivers or transceivers that are used to determine a location of the computing system **2000** based on receipt of one or more signals from one or more satellites associated with one or more GNSS systems. GNSS systems include, but are not limited to, the US-based GPS, the Russia-based Global Navigation Satellite System (GLONASS), the China-based BeiDou Navigation Satellite System (BDS), and the Europe-based Galileo GNSS. There is no restriction on operating on any particular hardware arrangement, and therefore the basic features here may easily be substituted for improved hardware or firmware arrangements as they are developed.

[0237] Storage device **2030** can be a non-volatile and/or non-transitory and/or computer-readable memory device and can be a hard disk or other types of computer readable media which can store data that are accessible by a computer, such as magnetic cassettes, flash memory cards, solid state memory devices, digital versatile disks, cartridges, a floppy disk, a flexible disk, a hard disk, magnetic tape, a magnetic strip/stripe, any other magnetic storage medium, flash memory, memristor memory, any other solid-state memory, a compact disc read only memory (CD-ROM) optical disc, a rewritable compact disc (CD) optical disc, digital video disk (DVD) optical disc, a blu-ray disc (BDD) optical disc, a holographic optical disk, another optical medium, a secure digital (SD) card, a micro secure digital (microSD) card, a Memory Stick® card, a smartcard chip, a EMV chip, a subscriber identity module (SIM) card, a mini/micro/nano/pico SIM card, another integrated circuit (IC) chip/card, random access memory (RAM), static RAM (SRAM), dynamic RAM (DRAM), read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash EPROM (FLASHEPROM), cache memory (e.g., Level 1 (L1) cache, Level 2 (L2) cache, Level 3 (L3) cache, Level 4 (L4) cache, Level 5 (L5) cache, or other (L #) cache), resistive random-access memory (RRAM/ReRAM), phase change memory (PCM), spin transfer torque RAM (STT-RAM), another memory chip or cartridge, and/or a combination thereof.

[0238] The storage device **2030** can include software services, servers, services, etc., that when the code that defines such software is executed by the processor **2010**, it causes the system to perform a function. In some aspects, a hardware service that performs a particular function can include the software component stored in a computer-readable medium in connection with the necessary hardware components, such as processor **2010**, connection **2005**, output device **2035**, etc., to carry out the function. The term "computer-readable medium" includes, but is not limited to, portable or non-portable storage devices, optical storage devices, and various other mediums capable of storing, containing, or carrying instruction(s) and/or data. A computer-readable medium may include a non-transitory medium in which data can be stored and that does not include carrier waves and/or transitory electronic signals propagating wirelessly or over wired connections. Examples of a non-transitory medium may include, but are not limited to, a magnetic disk or tape, optical storage media such as compact disk (CD) or digital versatile disk (DVD), flash memory, memory or memory devices. A computer-readable medium may have stored thereon code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements. A code segment may be coupled to another code segment or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, etc. may be passed, forwarded, or transmitted via any suitable means including memory sharing, message passing, token passing, network transmission, or the like.

[0239] Specific details are provided in the description above to provide a thorough understanding of the aspects and examples provided herein, but those skilled in the art will recognize that the application is not limited thereto. Thus, while illustrative aspects of the application have been described in detail herein, it is to be understood that the inventive concepts may be otherwise variously embodied and employed, and that the appended claims are intended to be construed to include such variations, except as limited by the prior art. Various features and aspects of the above-described application may be used individually or jointly. Further, aspects can be utilized in any number of environments and applications beyond those described herein without departing from the broader scope of the specification. The specification and drawings are, accordingly, to be regarded as illustrative rather than restrictive. For the purposes of illustration, methods were described in a particular order. It should be appreciated that in alternate aspects, the methods may be performed in a different order than that described.

[0240] For clarity of explanation, in some instances the present technology may be presented as including individual functional blocks comprising devices, device components, steps or routines in a method embodied in software, or combinations of hardware and software. Additional components may be used other than those shown in the figures and/or described herein. For example, circuits, systems, networks, processes, and other components may be shown as components in block diagram form in order not to obscure the aspects in unnecessary detail. In other instances, well-known circuits, processes, algorithms, structures, and techniques may be shown without unnecessary detail in order to avoid obscuring the aspects.

[0241] Further, those of skill in the art will appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the aspects disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

[0242] Individual aspects may be described above as a process or method which is depicted as a flowchart, a flow diagram, a data flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe the operations as a sequential process, many of the operations can be performed in parallel or concurrently. In addition, the order of the operations may be re-arranged. A process is terminated when its operations are completed, but could have additional steps not included in a figure. A process may correspond to a method, a function, a procedure, a subroutine, a subprogram, etc. When a process corresponds to a function, its termination can correspond to a return of the function to the calling function or the main function.

[0243] Processes and methods according to the above-described examples can be implemented using computer-executable instructions that are stored or otherwise available from computer-readable media. Such instructions can include, for example, instructions and data which cause or otherwise configure a general purpose computer, special purpose computer, or a processing device to perform a certain function or group of functions. Portions of computer resources used can be accessible over a network. The computer executable instructions may be, for example, binaries, intermediate format instructions such as assembly language, firmware, source code. Examples of computer-readable media that may be used to store instructions, information used, and/or information created during methods according to described examples include magnetic or optical disks, flash memory, USB devices provided with non-volatile memory, networked storage devices, and so on.

[0244] In some aspects the computer-readable storage devices, mediums, and memories can include a cable or wireless signal containing a bitstream and the like. However, when mentioned, non-transitory computer-readable storage media expressly exclude media such as energy, carrier signals, electromagnetic waves, and signals per se.

[0245] Those of skill in the art will appreciate that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof, in some cases depending in part on the particular application, in part on the desired design, in part on the corresponding technology, etc.

[0246] The various illustrative logical blocks, modules, and circuits described in connection with the aspects disclosed herein may be implemented or performed using hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof, and can take any of a variety of form factors. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the necessary tasks (e.g., a computer-program product) may be stored in a computer-readable or machine-readable medium. A processor(s) may perform the necessary tasks. Examples of form factors include laptops, smart phones, mobile phones, tablet devices or other small form factor personal computers, personal digital assistants, rackmount devices, standalone devices, and so on. Functionality described herein also can be embodied in peripherals or add-in cards. Such functionality can also be implemented on a circuit board among different chips or different processes executing in a single device, by way of further example.

[0247] The instructions, media for conveying such instructions, computing resources for executing them, and other structures for supporting such computing resources are example means for providing the functions described in the disclosure.

[0248] The techniques described herein may also be implemented in electronic hardware, computer software, firmware, or any combination thereof. Such techniques may be implemented in any of a variety of devices such as general purposes computers, wireless communication device handsets, or integrated circuit devices having multiple uses including application in wireless communication device handsets and other devices. Any features described as modules or components may be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a computer-readable data storage medium comprising program code including instructions that, when executed, performs one or more of the methods, algorithms, and/or operations described above. The computer-readable data storage medium may form part of a computer program product, which may include packaging materials. The computer-readable medium may comprise memory or data storage media, such as random access memory (RAM) such as synchronous dynamic random access memory (SDRAM), read-only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), FLASH memory, magnetic or optical data storage media, and the like. The techniques additionally, or alternatively, may be realized at least in part by a computer-readable communication medium that carries or communicates program code in the form of instructions or data structures and that can be accessed, read, and/or executed by a computer, such as propagated signals or waves.

[0249] The program code may be executed by a processor, which may include one or more processors, such as one or more digital signal processors (DSPs), general purpose microprocessors, an application specific integrated circuits (ASICs), field programmable logic arrays (FPGAs), or other equivalent integrated or discrete logic circuitry. Such a processor may be configured to perform any of the techniques described in this disclosure. A general-purpose processor may be a microprocessor; but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Accordingly, the term "processor," as used herein may refer to any of the foregoing structure, any combination of the foregoing structure, or any other structure or apparatus suitable for implementation of the techniques described herein.

[0250] One of ordinary skill will appreciate that the less than ("<") and greater than (">") symbols or terminology used herein can be replaced with less than or equal to ("≤") and greater than or equal to ("≥") symbols, respectively, without departing from the scope of this description.

[0251] Where components are described as being "configured to" perform certain operations, such configuration can be accomplished, for example, by designing electronic circuits or other hardware to perform the operation, by programming programmable electronic circuits (e.g., microprocessors, or other suitable electronic circuits) to perform the operation, or any combination thereof.

[0252] The phrase "coupled to" or "communicatively coupled to" refers to any component that is physically connected to another component either directly or indirectly, and/or any component that is in communication with another component (e.g., connected to the other component over a wired or wireless connection, and/or other suitable communication interface) either directly or indirectly.

[0253] Claim language or other language reciting "at least one of" a set and/or "one or more" of a set indicates that one member of the set or multiple members of the set (in any combination) satisfy the claim. For example, claim language reciting "at least one of A and B" or "at least one of A or B" means A, B, or A and B. In another example, claim language reciting "at least one of A, B, and C" or "at least one of A, B, or C" means A, B, C, or A and B, or A and C, or B and C, or A and B and C. The language "at least one of" a set and/or "one or more" of a set does not limit the set to the items listed in the set. For example, claim language reciting "at least one of A and B" or "at least one of A or B" can mean A, B, or A and B, and can additionally include items not listed in the set of A and B.

[0254] Illustrative aspects of the disclosure include:

[0255] Aspect 1. A network device of a plurality of network devices for wireless communications, the network device comprising: at least one memory; and at least one processor coupled to the at least one memory and configured to: output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receive at least one echo signal from the one or more targets; and mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0256] Aspect 2. The network device of Aspect 1, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

[0257] Aspect 3. The network device of any one of Aspects 1 or 2, wherein the sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

[0258] Aspect 4. The network device of any one of Aspects 1 to 3, wherein a phase code of the sensing signal is different from at least one phase code of the at least one other network device.

[0259] Aspect 5. The network device of Aspect 4, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

[0260] Aspect 6. The network device of Aspect 4, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

[0261] Aspect 7. The network device of any one of Aspects 1 to 6, wherein a phase code of the sensing signal is the same as at least one phase code of the at least one other network device.

[0262] Aspect 8. The network device of Aspect 7, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

[0263] Aspect 9. The network device of Aspect 8, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

[0264] Aspect 10. The network device of any one of Aspects 1 to 9, wherein the at least one processor is configured to increase or decrease a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals to mitigate the Doppler ambiguity.

[0265] Aspect 11. A method for wireless communications at a network device of a plurality of network devices, the method comprising: transmitting, by the network device, a sensing signal for sensing one or more targets, wherein the transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receiving, by the network device, at least one echo signal from the one or more targets; and mitigating, by the network device, Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0266] Aspect 12. The method of Aspect 11, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

[0267] Aspect 13. The method of any one of Aspects 11 or 12, wherein the transmitted sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

[0268] Aspect 14. The method of any one of Aspects 11 to 13, wherein a phase code of the transmitted sensing signal is different from at least one phase code of the at least one other network device.

[0269] Aspect 15. The method of Aspect 14, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

[0270] Aspect 16. The method of Aspect 14, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

[0271] Aspect 17. The method of any one of Aspects 11 to 16, wherein a phase code of the transmitted sensing signal is the same as at least one phase code of the at least one other network device.

[0272] Aspect 18. The method of Aspect 17, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

[0273] Aspect 19. The method of Aspect 18, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

[0274] Aspect 20. The method of any one of Aspects 11 to 19, wherein a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals is increased or decreased to mitigate the Doppler ambiguity.

[0275] Aspect 21. A non-transitory computer-readable medium of a network device of a plurality of network devices, the non-transitory computer-readable medium having stored thereon instructions that, when executed by at least one processor, cause the at least one processor to: output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns; receive at least one echo signal from the one or more targets; and mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

[0276] Aspect 22. The non-transitory computer-readable medium of Aspect 21, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

[0277] Aspect 23. The non-transitory computer-readable medium of any one of Aspects 21 or 22, wherein the sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

[0278] Aspect 24. The non-transitory computer-readable medium of any one of Aspects 21 to 23, wherein a phase code of the sensing signal is different from at least one phase code of the at least one other network device.

[0279] Aspect 25. The non-transitory computer-readable medium of Aspect 24, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

[0280] Aspect 26. The non-transitory computer-readable medium of Aspect 24, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

[0281] Aspect 27. The non-transitory computer-readable medium of any one of Aspects 21 to 26, wherein a phase code of the sensing signal is the same as at least one phase code of the at least one other network device.

[0282] Aspect 28. The non-transitory computer-readable medium of Aspect 27, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

[0283] Aspect 29. The non-transitory computer-readable medium of Aspect 28, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

[0284] Aspect 30. The non-transitory computer-readable medium of any one of Aspects 21 to 29, wherein a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals is increased or decreased to mitigate the Doppler ambiguity.

[0285] Aspect 31. A network device of a plurality of network devices for wireless communications, comprising one or more means for performing operations according to any of Aspects 11 to 20.

[0286] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language claims, wherein reference to an element in the singular is not intended to mean "one and only one" unless specifically so stated, but rather "one or more."

What is claimed is:

1. A network device of a plurality of network devices for wireless communications, the network device comprising:

at least one memory; and

at least one processor coupled to the at least one memory and configured to:

output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns;

receive at least one echo signal from the one or more targets; and

mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

2. The network device of claim **1**, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

3. The network device of claim **1**, wherein the sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

4. The network device of claim **1**, wherein a phase code of the sensing signal is different from at least one phase code of the at least one other network device.

5. The network device of claim **4**, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

6. The network device of claim **4**, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

7. The network device of claim **1**, wherein a phase code of the sensing signal is the same as at least one phase code of the at least one other network device.

8. The network device of claim **7**, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

9. The network device of claim **8**, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

10. The network device of claim **1**, wherein the at least one processor is configured to increase or decrease a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals to mitigate the Doppler ambiguity.

11. A method for wireless communications at a network device of a plurality of network devices, the method comprising:

transmitting, by the network device, a sensing signal for sensing one or more targets, wherein the transmitted sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns;

receiving, by the network device, at least one echo signal from the one or more targets; and

mitigating, by the network device, Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

12. The method of claim **11**, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

13. The method of claim **11**, wherein the transmitted sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

14. The method of claim **11**, wherein a phase code of the transmitted sensing signal is different from at least one phase code of the at least one other network device.

15. The method of claim **14**, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

16. The method of claim **14**, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

17. The method of claim **11**, wherein a phase code of the transmitted sensing signal is the same as at least one phase code of the at least one other network device.

18. The method of claim **17**, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

19. The method of claim **18**, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

20. The method of claim **11**, wherein a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals is increased or decreased to mitigate the Doppler ambiguity.

21. A non-transitory computer-readable medium of a network device of a plurality of network devices, the non-transitory computer-readable medium having stored thereon instructions that, when executed by at least one processor, cause the at least one processor to:

output a sensing signal for transmission for sensing one or more targets, wherein the sensing signal and at least one sensing signal transmitted by at least one other network device of the plurality of network devices comprise one or more phase codes and a same frequency modulated carrier wave (FMCW), and wherein each phase code of each sensing signal corresponds to one or more Doppler spectrum patterns;

receive at least one echo signal from the one or more targets; and

mitigate Doppler ambiguity in a Doppler spectrum from the at least one echo signal based on the one or more Doppler spectrum patterns.

22. The non-transitory computer-readable medium of claim **21**, wherein each network device of the plurality of network devices is one of user equipment (UE) or a base station.

23. The non-transitory computer-readable medium of claim **21**, wherein the sensing signal and the at least one sensing signal are transmitted at a same time and using a same one or more frequency resources.

24. The non-transitory computer-readable medium of claim **21**, wherein a phase code of the sensing signal is different from at least one phase code of the at least one other network device.

25. The non-transitory computer-readable medium of claim **24**, wherein the one or more Doppler spectrum patterns comprise consecutive empty sub-bands.

26. The non-transitory computer-readable medium of claim **24**, wherein the one or more Doppler spectrum patterns comprise non-consecutive empty sub-bands.

27. The non-transitory computer-readable medium of claim **21**, wherein a phase code of the sensing signal is the same as at least one phase code of the at least one other network device.

28. The non-transitory computer-readable medium of claim **27**, wherein each network device of the plurality of network devices is associated with a respective Doppler spectrum puncturing vector.

29. The non-transitory computer-readable medium of claim **28**, wherein each element of the Doppler spectrum puncturing vector indicates whether a corresponding sub-band is punctured.

30. The non-transitory computer-readable medium of claim **21**, wherein a pulse repetition frequency (PRF) of one or more sensing signals of the plurality of sensing signals is increased or decreased to mitigate the Doppler ambiguity.

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