US012395854B2

(12) **United States Patent**
Montalvo et al.

(10) **Patent No.: US 12,395,854 B2**
(45) **Date of Patent: *Aug. 19, 2025**

(54) **SYSTEM, METHOD, AND APPARATUS FOR PROVIDING OPTIMIZED NETWORK RESOURCES**

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(73) Assignee: **Digital Global Systems, Inc.**, Tysons Corner, VA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **19/056,105**

(22) Filed: **Feb. 18, 2025**

(65) **Prior Publication Data**

US 2025/0193685 A1 Jun. 12, 2025

Related U.S. Application Data

(63) Continuation of application No. 18/802,740, filed on Aug. 13, 2024, now Pat. No. 12,284,526, which is a (Continued)

(51) **Int. Cl.**
H04W 16/10 (2009.01)
H04W 24/02 (2009.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04W 16/10*** (2013.01); ***H04W 24/02*** (2013.01); ***H04W 24/08*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H04L 2025/03414; H04L 27/01; H04L 25/03159; H04L 27/2647; H04L 5/0007;
(Continued)

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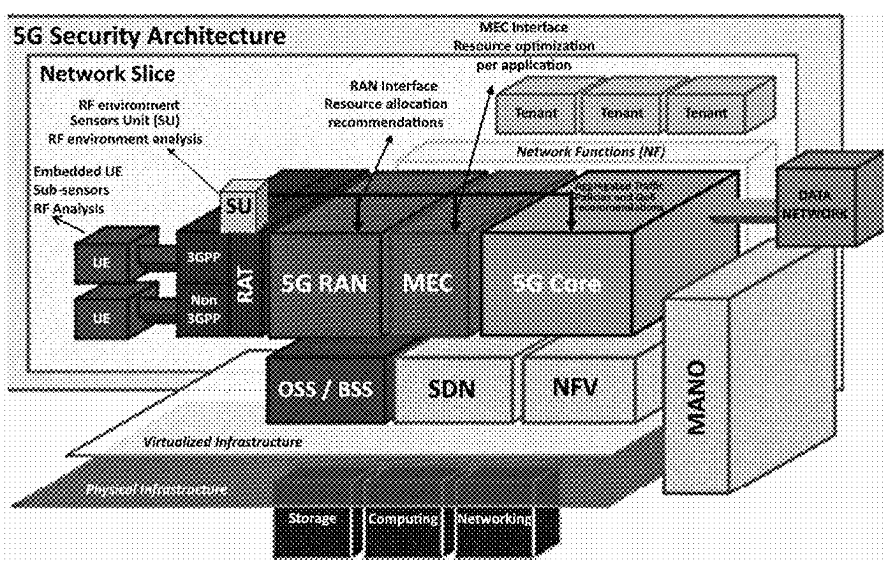
(74) *Attorney, Agent, or Firm* — NEO IP

(57) **ABSTRACT**

Systems, methods, and apparatuses for providing optimization of network resources. The system is operable to monitor the electromagnetic environment, analyze the electromagnetic environment, and extract environmental awareness of the electromagnetic environment. The system extracts the environmental awareness of the electromagnetic environment by including customer goals. The system is operable to use the environmental awareness with the customer goals and/or user defined policies and rules to extract actionable information to help the customer optimize the network resources.

18 Claims, 136 Drawing Sheets



Related U.S. Application Data

continuation of application No. 18/799,623, filed on Aug. 9, 2024, which is a continuation-in-part of application No. 18/789,220, filed on Jul. 30, 2024, now Pat. No. 12,250,558, which is a continuation-in-part of application No. 18/738,760, filed on Jun. 10, 2024, now Pat. No. 12,294,865, which is a continuation-in-part of application No. 18/646,330, filed on Apr. 25, 2024, now Pat. No. 12,156,037, which is a continuation-in-part of application No. 18/417,659, filed on Jan. 19, 2024, now Pat. No. 12,041,460, which is a continuation of application No. 18/411,817, filed on Jan. 12, 2024, now Pat. No. 12,185,114, which is a continuation of application No. 18/405,531, filed on Jan. 5, 2024, now Pat. No. 12,075,259, which is a continuation of application No. 18/526,329, filed on Dec. 1, 2023, now Pat. No. 11,968,539, which is a continuation of application No. 18/237,970, filed on Aug. 25, 2023, now Pat. No. 11,843,953, which is a continuation-in-part of application No. 18/086,115, filed on Dec. 21, 2022, now Pat. No. 11,751,064, which is a continuation-in-part of application No. 18/085,904, filed on Dec. 21, 2022, now Pat. No. 11,659,401, which is a continuation of application No. 18/085,791, filed on Dec. 21, 2022, now Pat. No. 11,659,400, which is a continuation of application No. 18/085,733, filed on Dec. 21, 2022, now Pat. No. 11,711,726, which is a continuation-in-part of application No. 17/901,035, filed on Sep. 1, 2022, now Pat. No. 11,570,627.

(60) Provisional application No. 63/370,184, filed on Aug. 2, 2022.

(51) **Int. Cl.**

H04W 24/08	(2009.01)
H04W 28/08	(2023.01)
H04W 72/0453	(2023.01)
H04W 16/14	(2009.01)

(52) **U.S. Cl.**
CPC ... ***H04W 28/0925*** (2020.05); ***H04W 28/0967*** (2020.05); ***H04W 72/0453*** (2013.01); *H04W 16/14* (2013.01)

(58) **Field of Classification Search**
CPC H04L 2025/03522; H04L 25/03006; H04L 25/022
See application file for complete search history.

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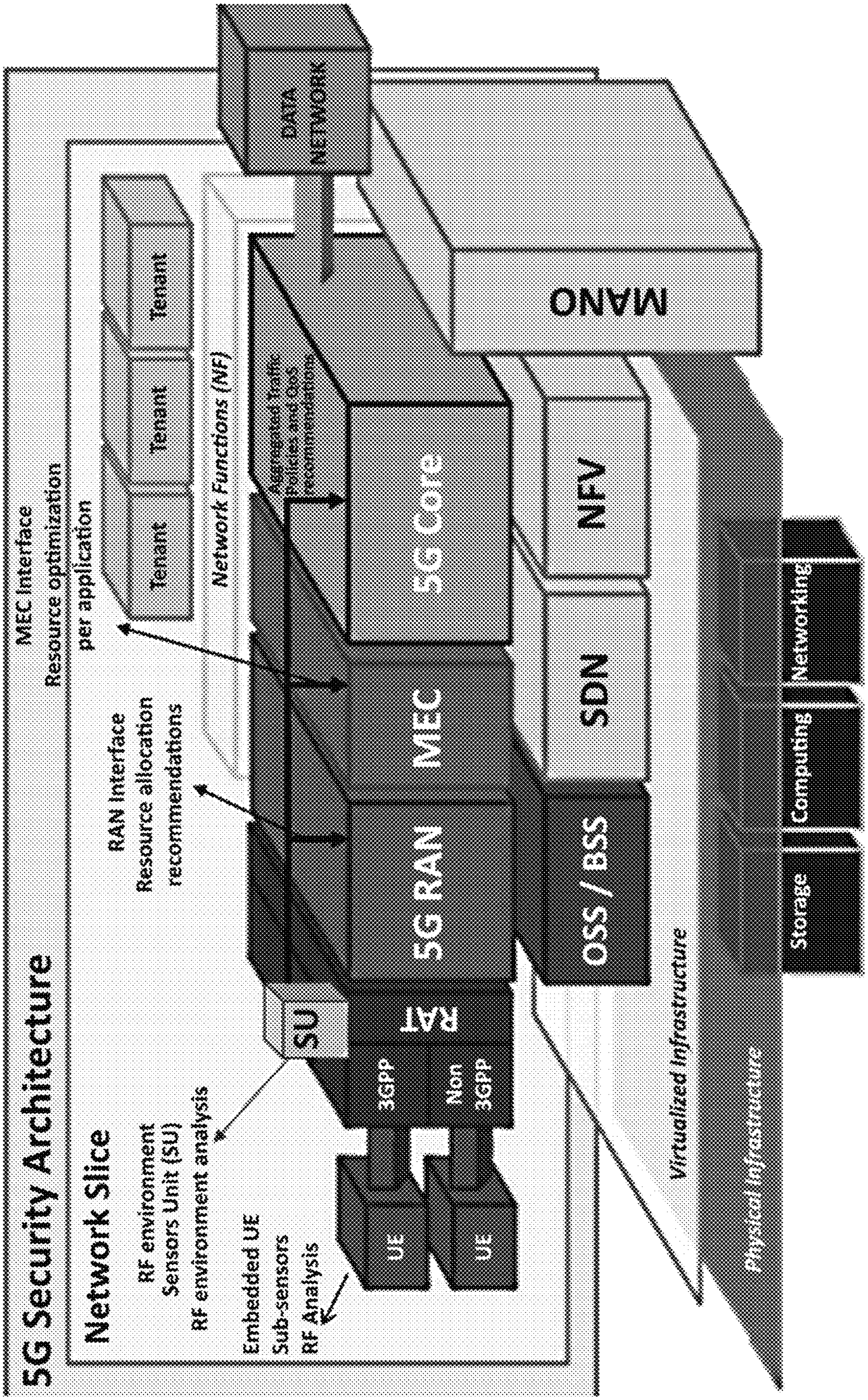

5G Security Architecture
Network Slice
RF environment Sensors Unit (SU) RF environment analysis
Embedded UE Sub-sensors RF Analysis
UE
UE
3GPP
Non 3GPP
RAT
SU
5G RAN
MEC
5G Core
RAN Interface Resource allocation recommendations
MEC Interface Resource optimization per application
Tenant
Tenant
Tenant
Network Functions (NF)
Aggregated Traffic Policies and Qos recommendations
DATA NETWORK
MANO
NFV
SDN
OSS / BSS
Virtualized Infrastructure
Physical Infrastructure
Storage
Computing
Networking

FIG. 1

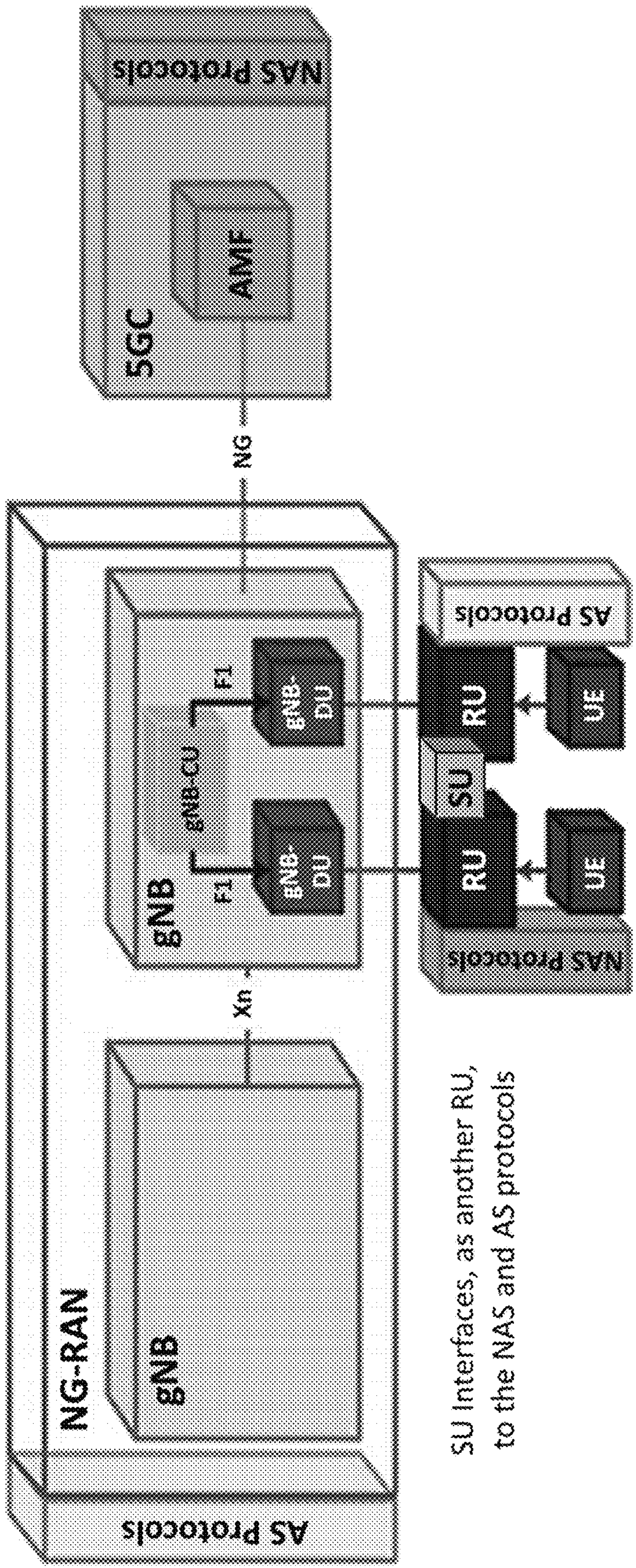

5GC
AMF
NAS Protocols
NG
NG-RAN
gNB
Xn
gNB
gNB-CU
F1
F1
gNB-DU
gNB-DU
RU
RU
SU
UE
UE
AS Protocols
NAS Protocols
AS Protocols
SU Interfaces, as another RU, to the NAS and AS protocols

FIG. 2

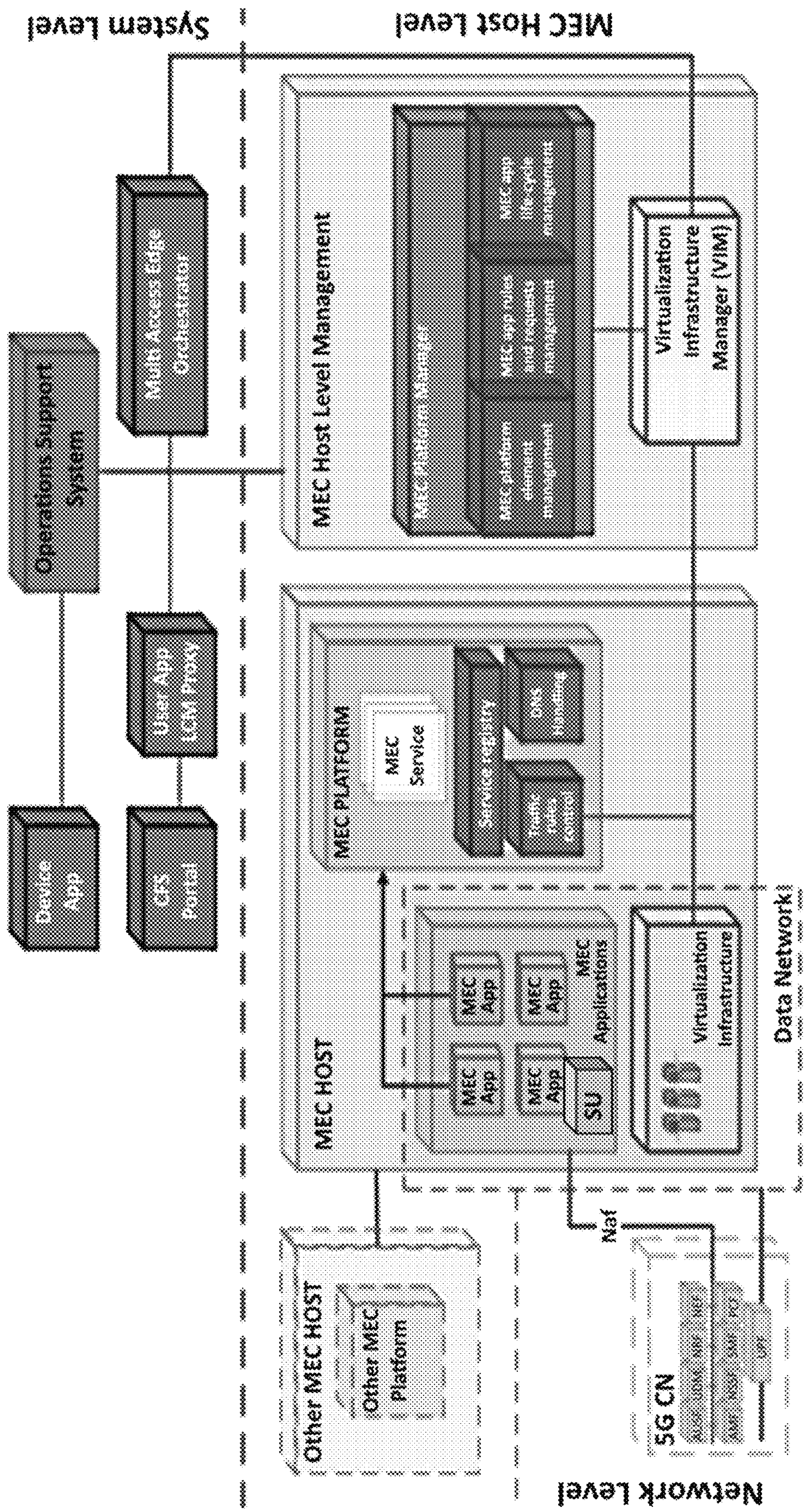

System Level
MEC Host Level
Network Level
Operations Support System
Multi Access Edge Orchestrator
User App LCM Proxy
CFS Portal
Device App
MEC Host Level Management
MEC Platform Manager
Virtualization Infrastructure Manager (VIM)
MEC HOST
MEC PLATFORM
MEC Service
Service Registry
Traffic Rules Control
DNS Handling
MEC App
MEC Applications
SU
Virtualization Infrastructure
Data Network
Naf
5G CN
Other MEC HOST
Other MEC Platform

FIG. 3

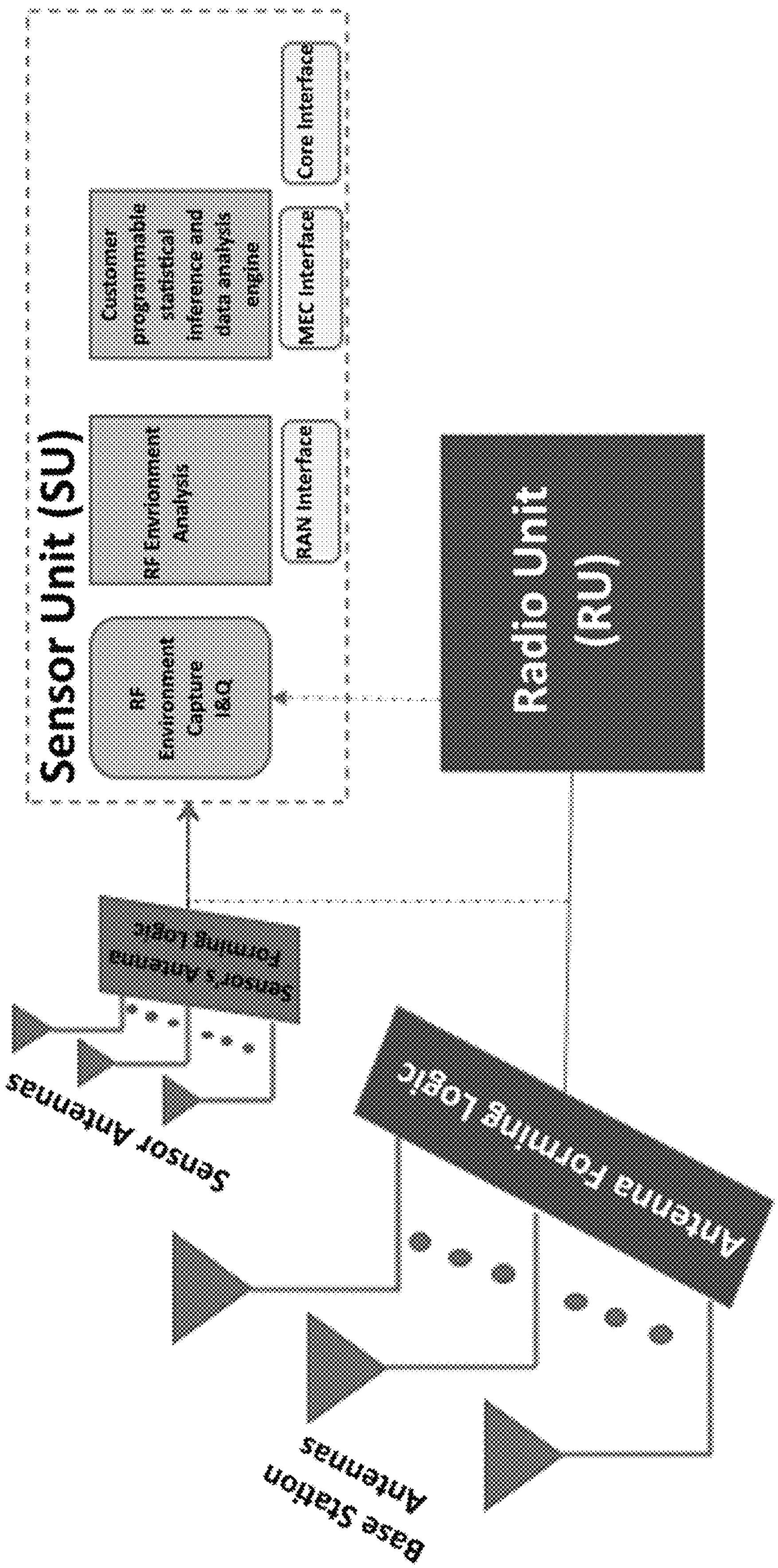

Sensor Unit (SU)
RF Environment Capture I&Q
RF Envrionment Analysis
Customer programmable statistical inference and data analysis engine
RAN Interface
MEC Interface
Core Interface
Radio Unit (RU)
Sensor's Antenna Forming Logic
Sensor Antennas
Antenna Forming Logic
Base Station Antennas

FIG. 4

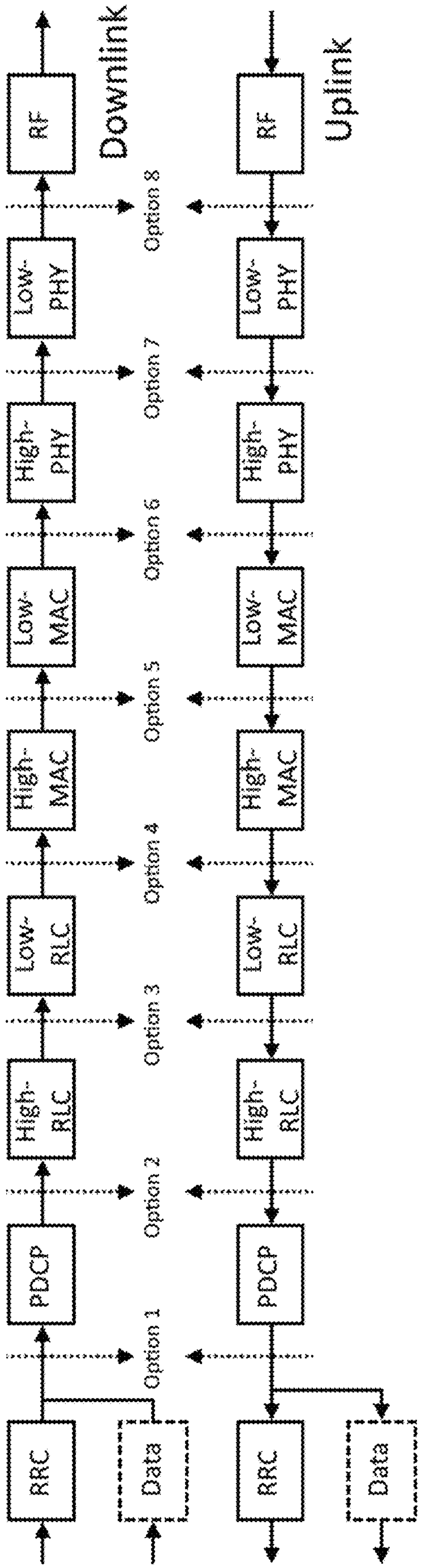

Downlink
Uplink
RRC
Data
PDCP
High-RLC
Low-RLC
High-MAC
Low-MAC
High-PHY
Low-PHY
RF
Option 1
Option 2
Option 3
Option 4
Option 5
Option 6
Option 7
Option 8

FIG. 5

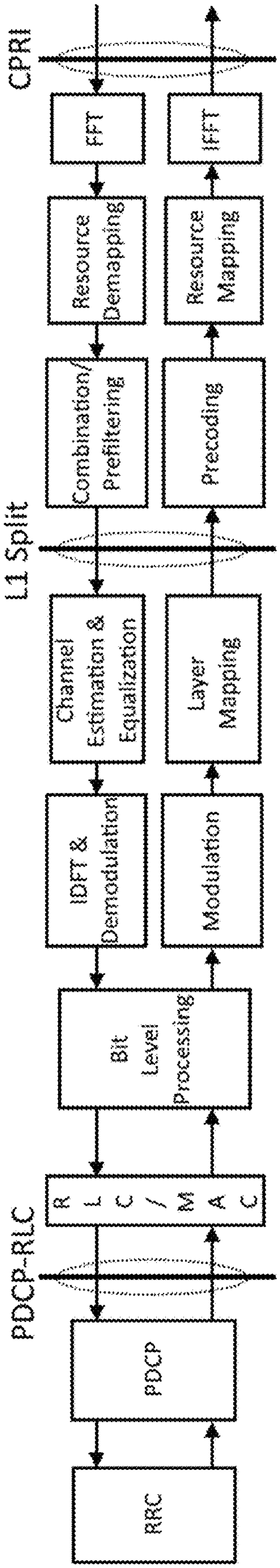

CPRI
FFT
IFFT
Resource Demapping
Resource Mapping
Combination/ Prefiltering
Precoding
L1 Split
Channel Estimation & Equalization
Layer Mapping
IDFT & Demodulation
Modulation
Bit Level Processing
RLC/MAC
PDCP-RLC
PDCP
RRC

FIG. 6

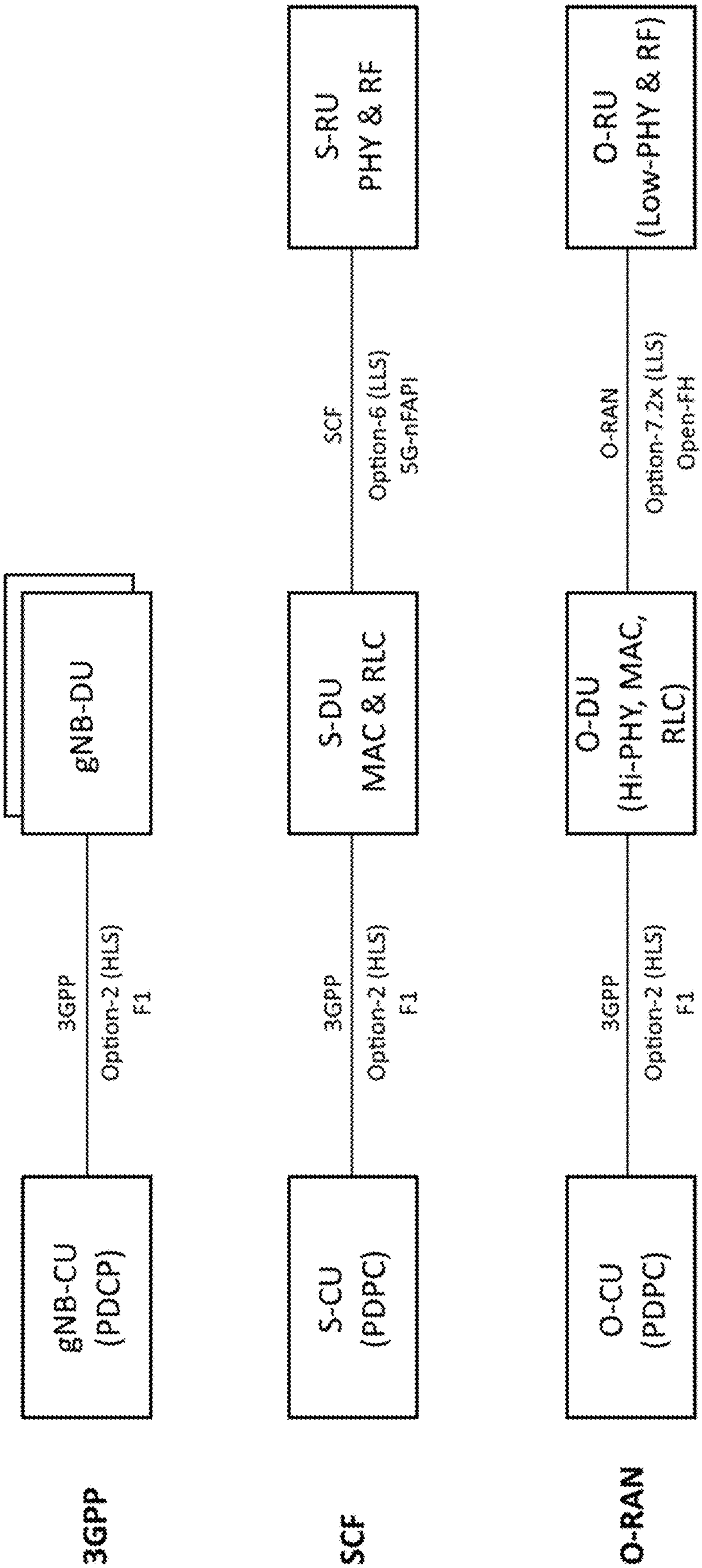
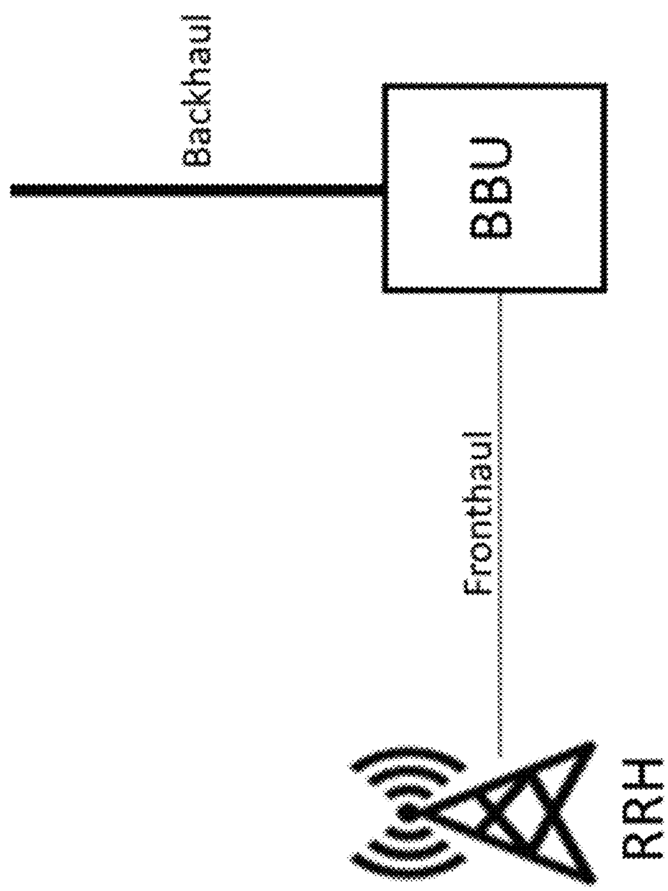
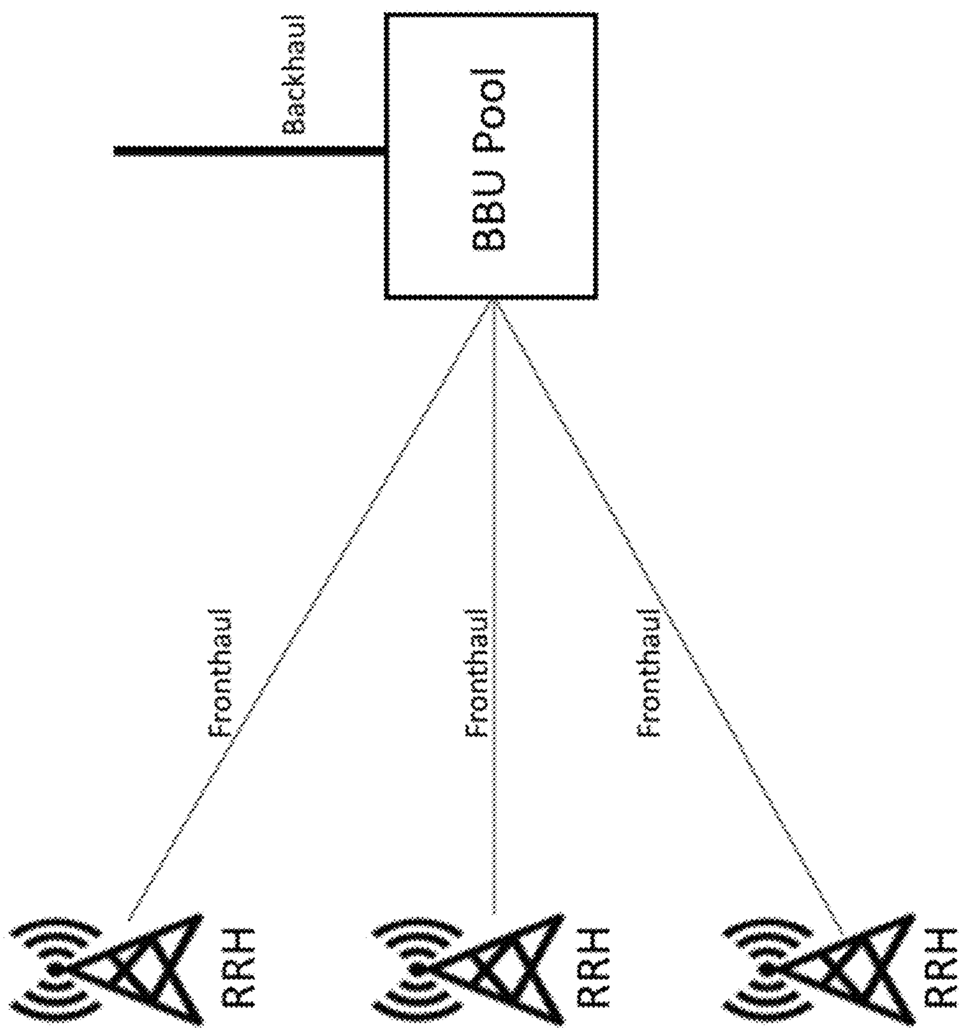

3GPP
gNB-CU (PDCP)
3GPP
Option-2 (HLS)
F1
gNB-DU
SCF
S-CU (PDPC)
3GPP
Option-2 (HLS)
F1
S-DU
MAC & RLC
SCF
Option-6 (LLS)
5G-nFAPI
S-RU
PHY & RF
O-RAN
O-CU (PDPC)
3GPP
Option-2 (HLS)
F1
O-DU
(Hi-PHY, MAC, RLC)
O-RAN
Option-7.2x (LLS)
Open-FH
O-RU
(Low-PHY & RF)

FIG. 7



Traditional Base Station with RRH

FIG. 8



Centralized RAN with multiple RRHs

FIG. 9

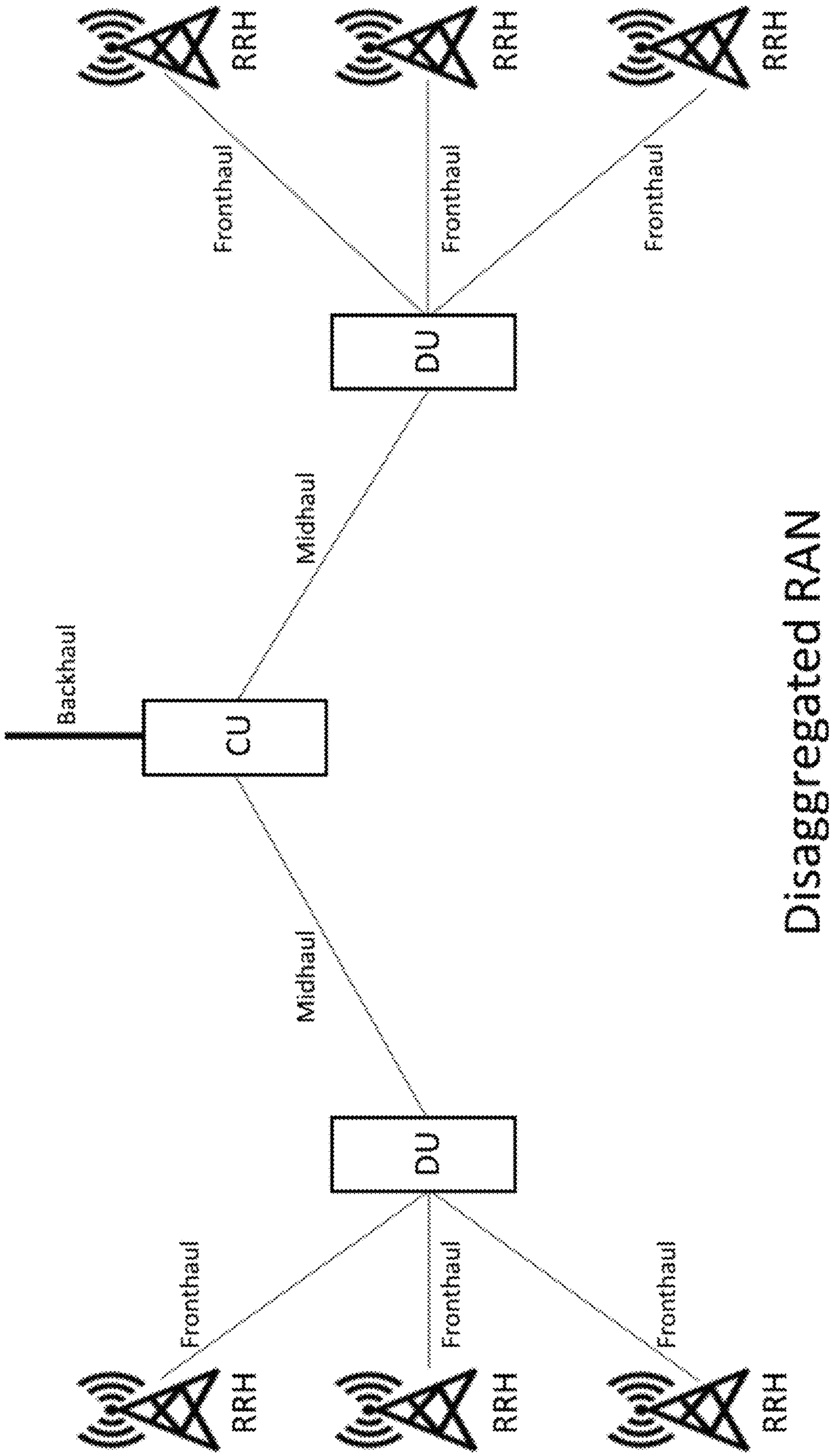

RRH
RRH
RRH
Fronthaul
Fronthaul
Fronthaul
DU
Midhaul
Backhaul
CU
Midhaul
DU
Fronthaul
Fronthaul
Fronthaul
RRH
RRH
RRH
Disaggregated RAN

FIG. 10

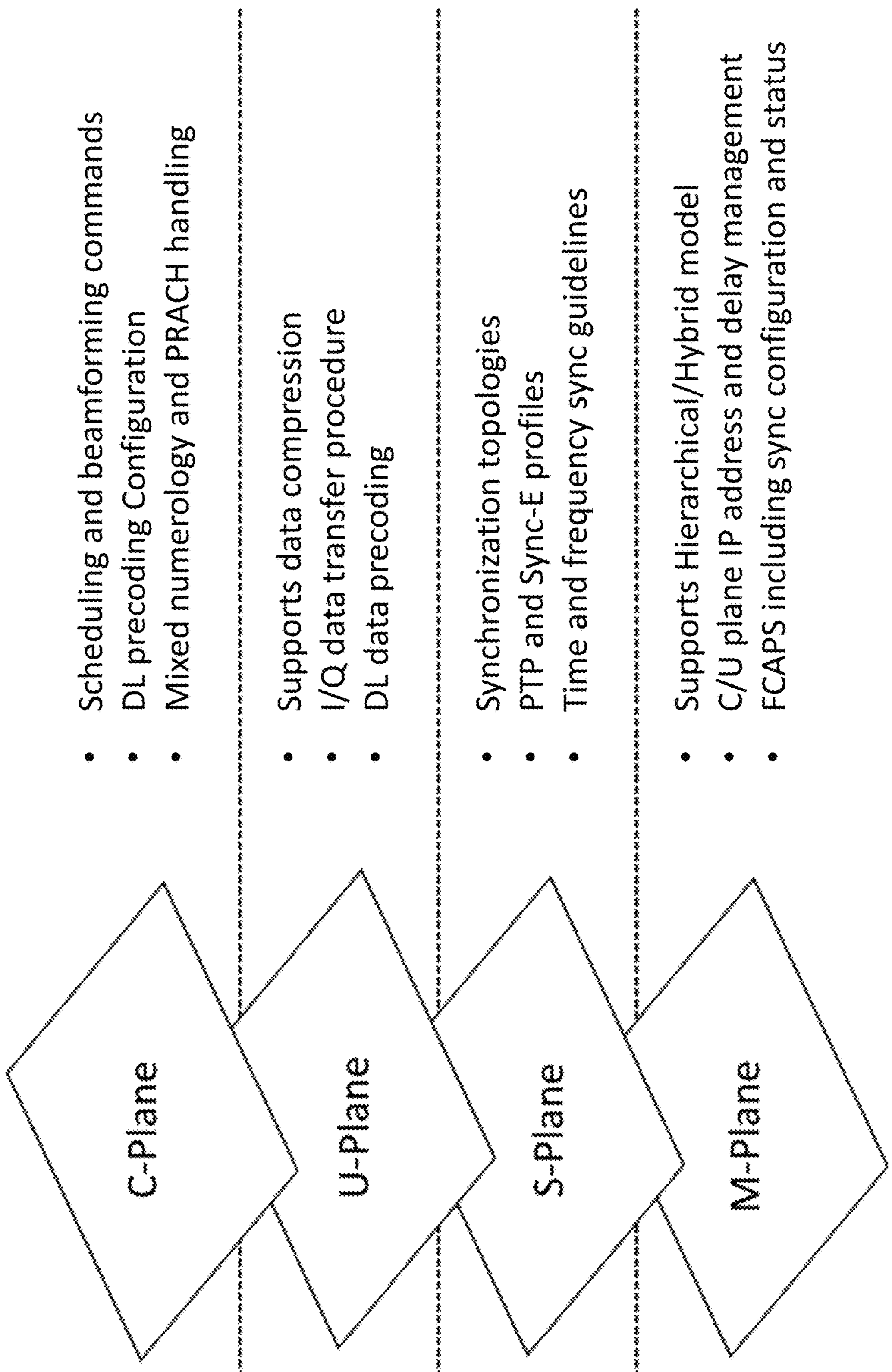

C-Plane
Scheduling and beamforming commands
DL precoding Configuration
Mixed numerology and PRACH handling
U-Plane
Supports data compression
I/Q data transfer procedure
DL data precoding
S-Plane
Synchronization topologies
PTP and Sync-E profiles
Time and frequency sync guidelines
M-Plane
Supports Hierarchical/Hybrid model
C/U plane IP address and delay management
FCAPS including sync configuration and status

FIG. 11

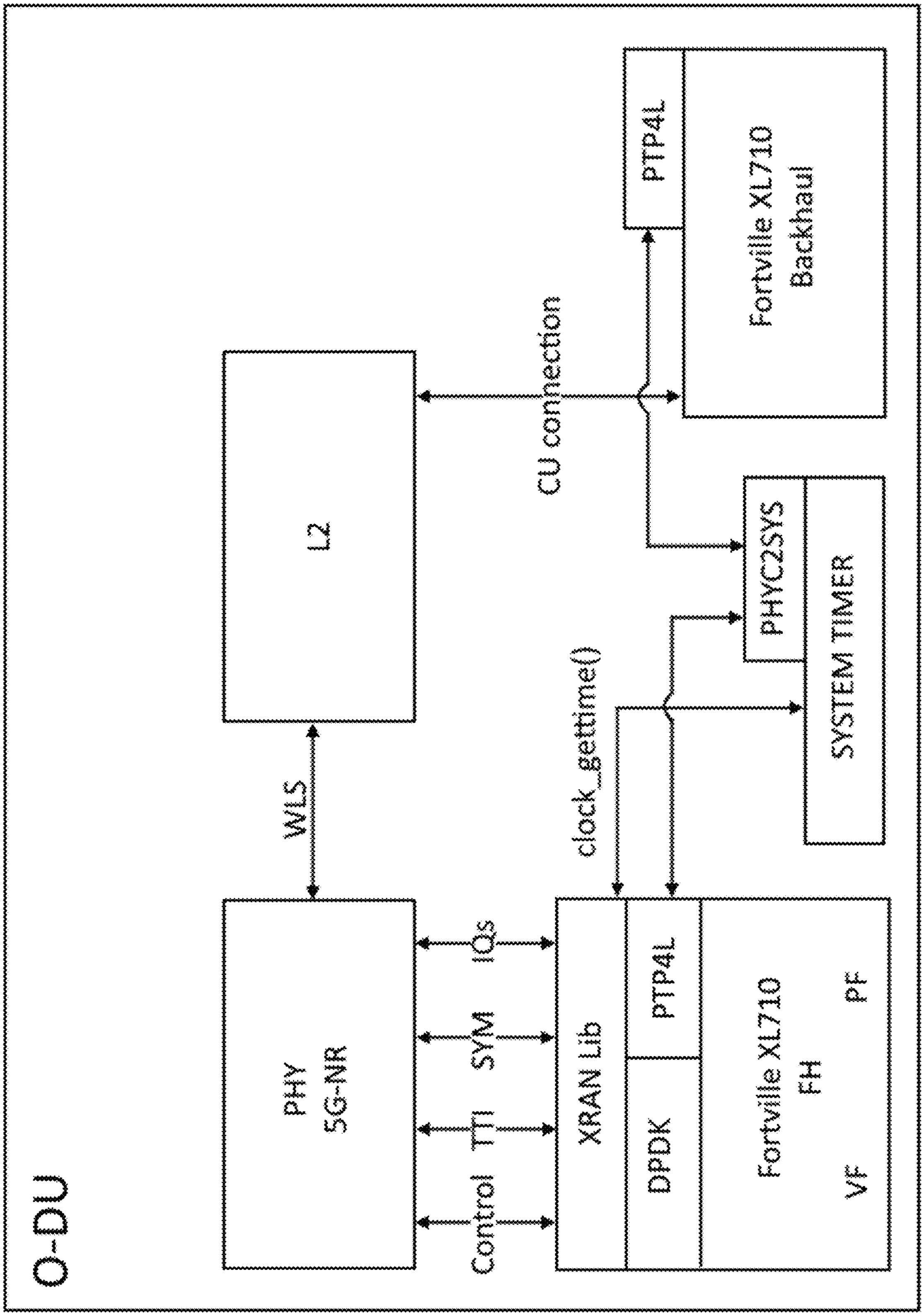

O-DU
PHY
5G-NR
L2
WLS
Control
TTI
SYM
IQs
XRAN Lib
DPDK
PTP4L
Fortville XL710
FH
VF
PF
clock_gettime()
CU connection
PHYC2SYS
SYSTEM TIMER
PTP4L
Fortville XL710
Backhaul

FIG. 12

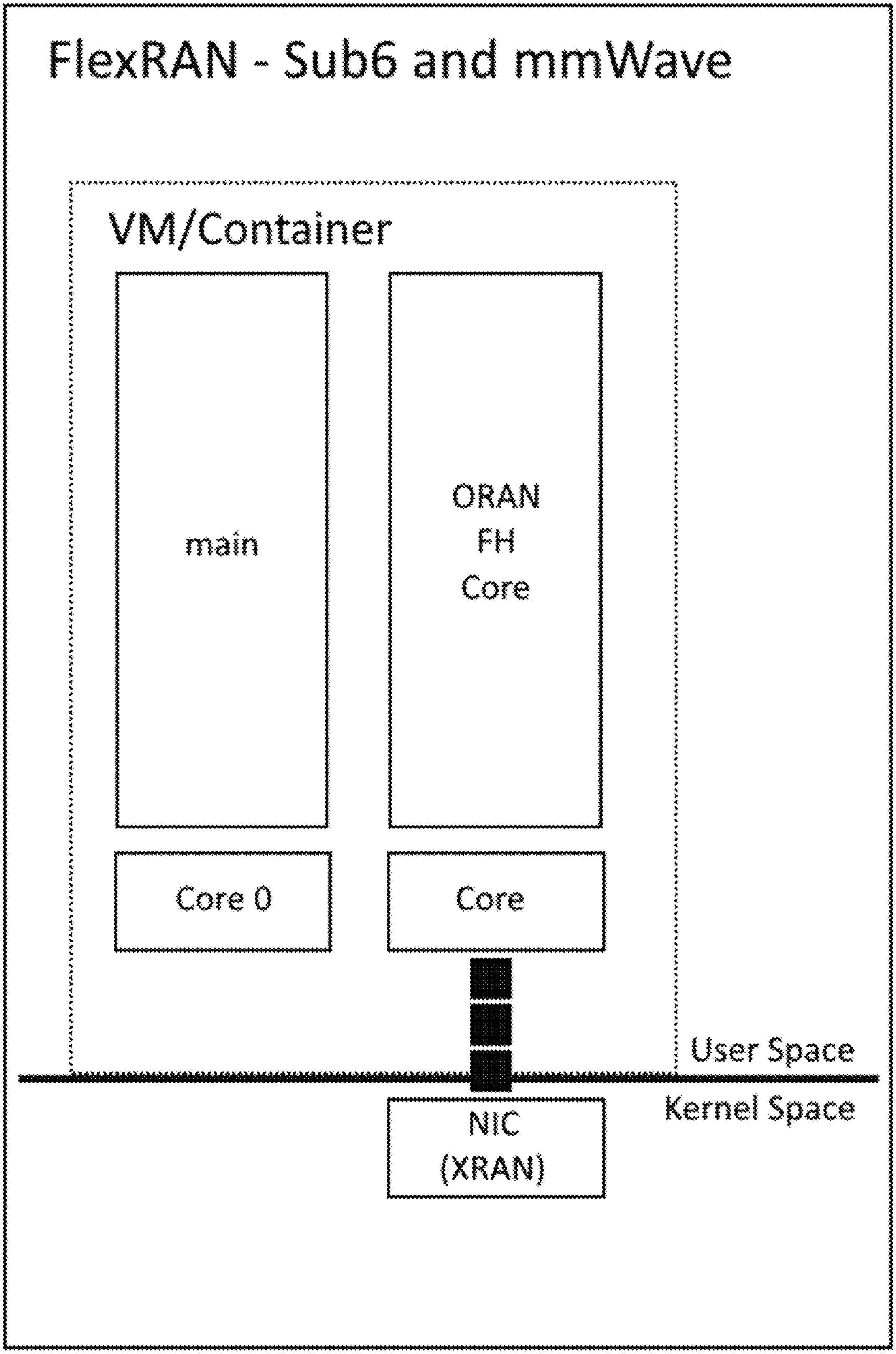

FlexRAN - Sub6 and mmWave
VM/Container
main
ORAN
FH
Core
Core 0
Core
User Space
Kernel Space
NIC
(XRAN)

FIG. 13

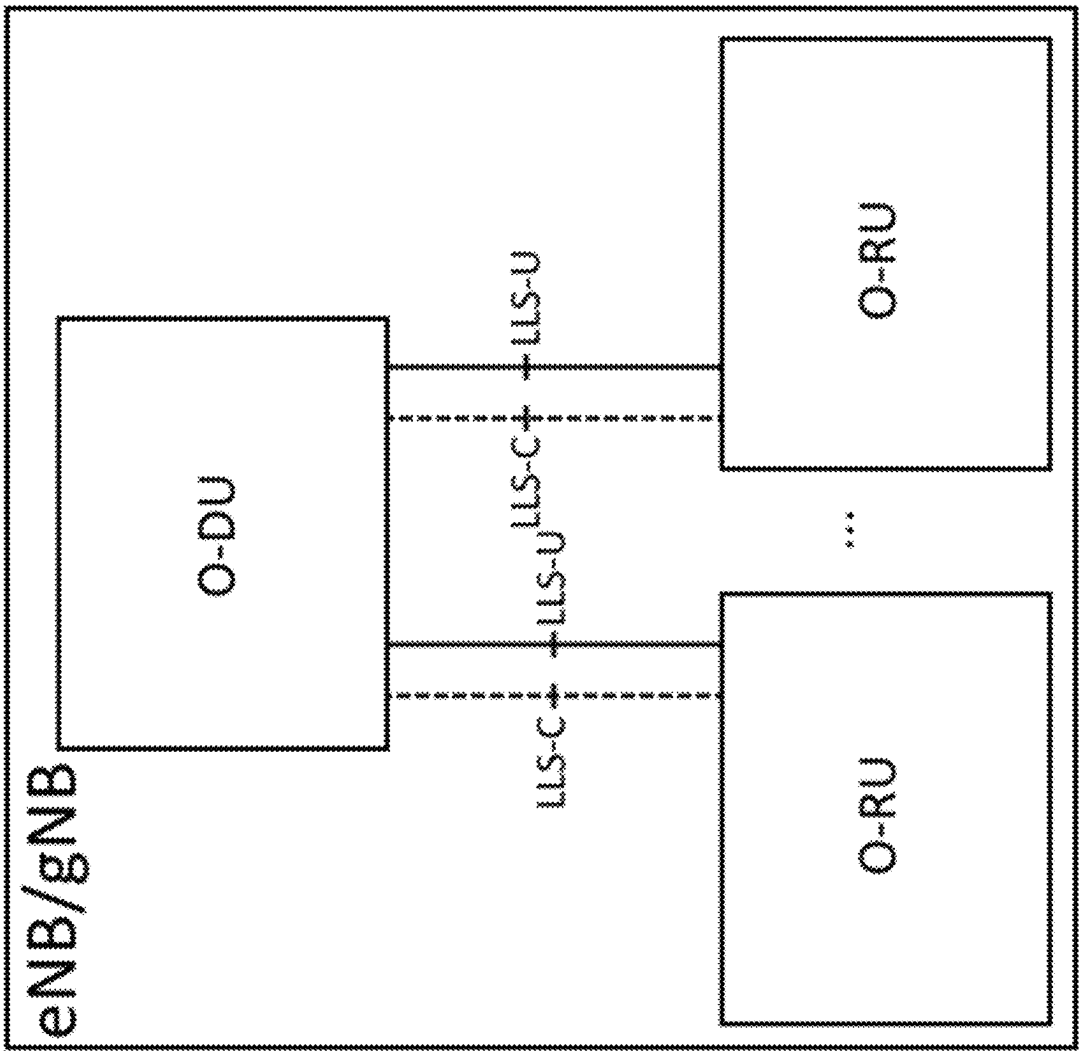


FIG. 14

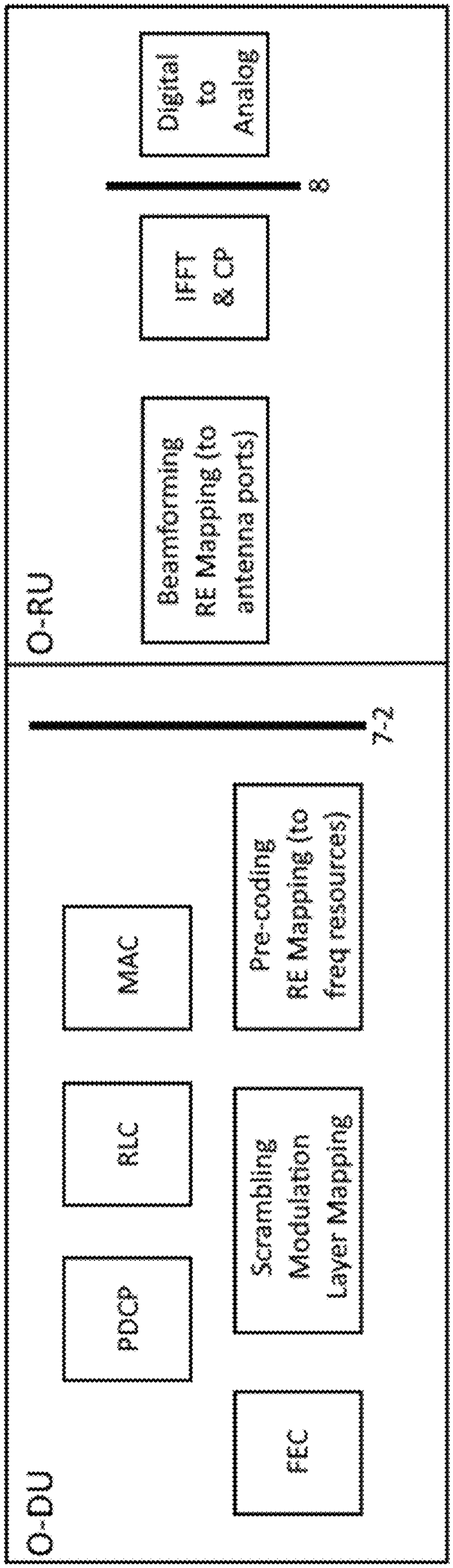

O-DU
FEC
PDCP
RLC
MAC
Scrambling
Modulation
Layer Mapping
Pre-coding
RE Mapping (to
freq resources)
7-2
O-RU
Beamforming
RE Mapping (to
antenna ports)
IFFT
& CP
8
Digital
to
Analog

FIG. 15

Plane	ID	Name	Contents	Periodicity
U-Plane	1a	DL Frequency Domain IQ Data	DL user data (PDSCH), control channel data (PDCCH, etc.)	symbol
	1b	UL Frequency Domain IQ Data	UL user data (PUSCH), control channel data (PUCCH, etc.)	symbol
	1c	PRACH Frequency Domain IQ Data	UL PRACH data	slot or symbol
C-Plane	2a	Scheduling Commands (Beamforming is not supported)	Scheduling information, FFT size, CP length, Subcarrier spacing, UL PRACH scheduling	~ slot
S-Plane	S	Timing and Synchronization	IEEE 1588 PTP packets	

FIG. 16

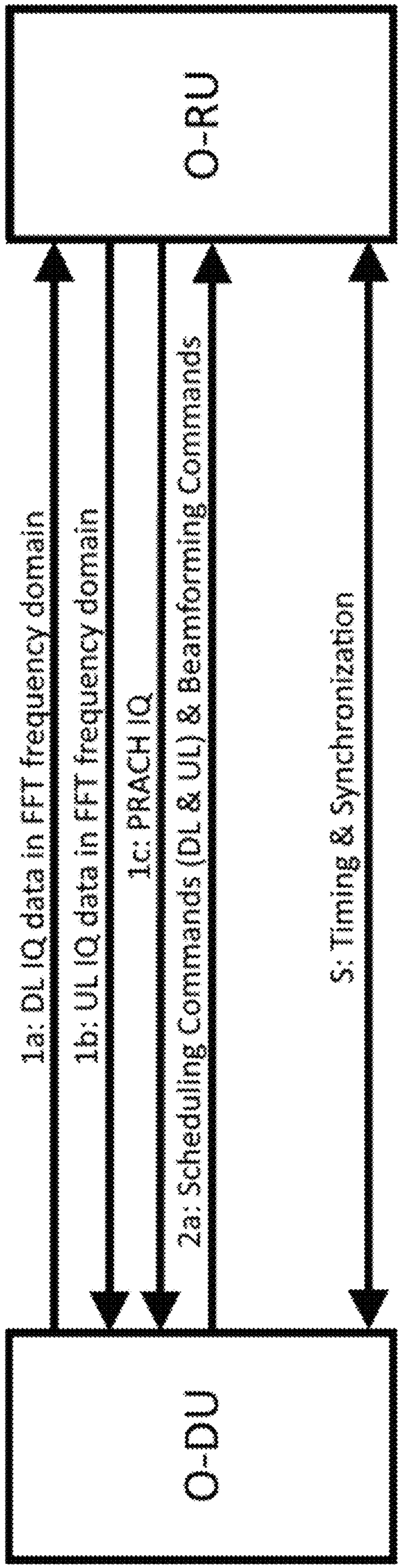

O-RU
O-DU
1a: DL IQ data in FFT frequency domain
1b: UL IQ data in FFT frequency domain
1c: PRACH IQ
2a: Scheduling Commands (DL & UL) & Beamforming Commands
S: Timing & Synchronization

FIG. 17

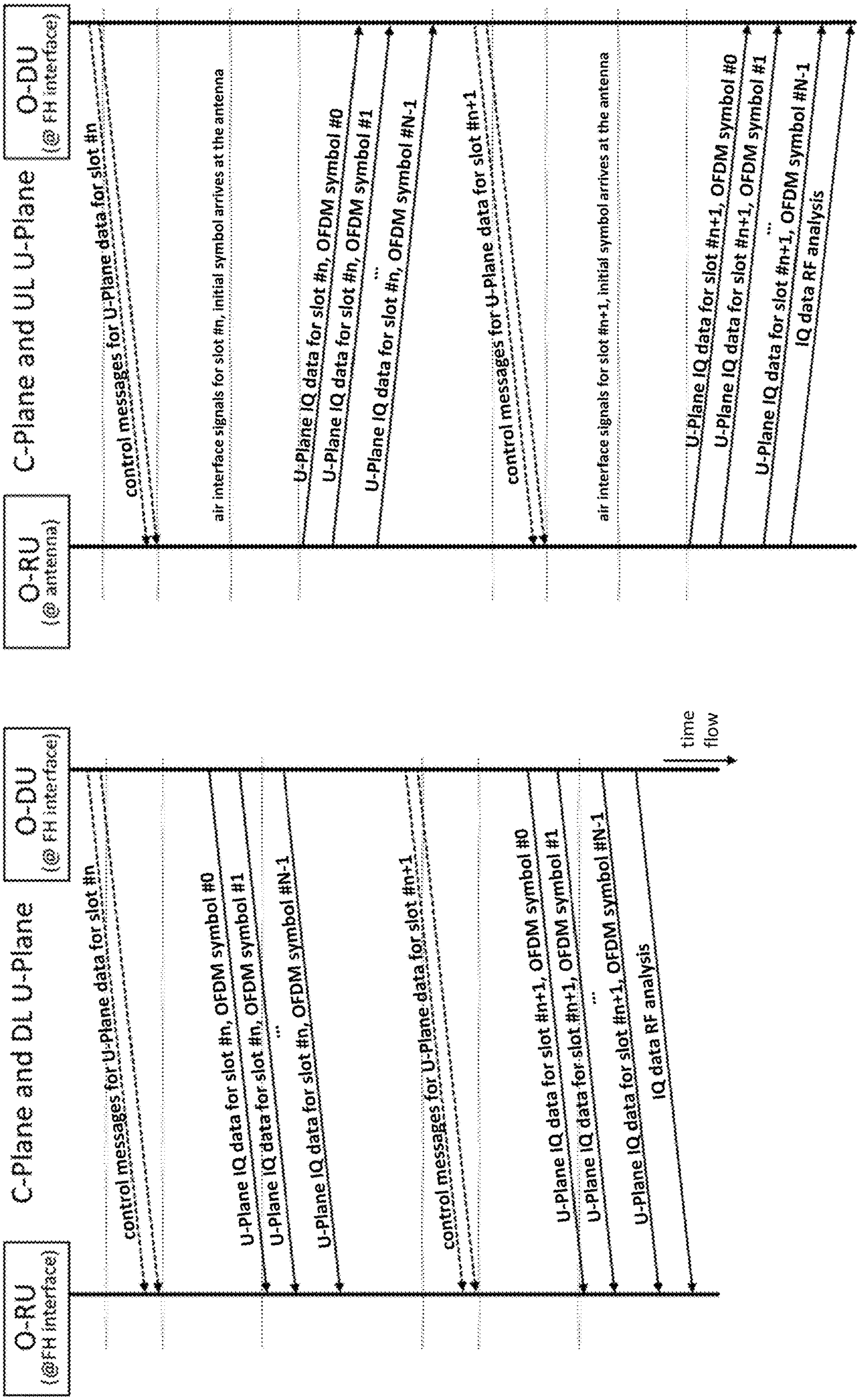

C-Plane and DL U-Plane
O-RU
(@FH interface)
O-DU
(@ FH interface)
control messages for U-Plane data for slot #n
U-Plane IQ data for slot #n, OFDM symbol #0
U-Plane IQ data for slot #n, OFDM symbol #1
...
U-Plane IQ data for slot #n, OFDM symbol #N-1
control messages for U-Plane data for slot #n+1
U-Plane IQ data for slot #n+1, OFDM symbol #0
U-Plane IQ data for slot #n+1, OFDM symbol #1
...
U-Plane IQ data for slot #n+1, OFDM symbol #N-1
IQ data RF analysis
time flow
C-Plane and UL U-Plane
O-RU
(@ antenna)
O-DU
(@ FH interface)
control messages for U-Plane data for slot #n
air interface signals for slot #n, initial symbol arrives at the antenna
U-Plane IQ data for slot #n, OFDM symbol #0
U-Plane IQ data for slot #n, OFDM symbol #1
...
U-Plane IQ data for slot #n, OFDM symbol #N-1
control messages for U-Plane data for slot #n+1
air interface signals for slot #n+1, initial symbol arrives at the antenna
U-Plane IQ data for slot #n+1, OFDM symbol #0
U-Plane IQ data for slot #n+1, OFDM symbol #1
...
U-Plane IQ data for slot #n+1, OFDM symbol #N-1
IQ data RF analysis

FIG. 18

Front Haul Interface Latency (numerology 3 – mmWave)

	Model Parameters	C-Plane	U-Plane		
		DL	UL	DL	UL
O-RU	T2amin	T2a_min_cp_dl=50	T2a_min_cp_ul=50	T2a_min_up=25	NA
	T2amax	T2a_max_cp_dl=140	T2a_max_cp_ul=140	T2a_max_up=140	NA
		Tadv_cp_dl	NA	NA	NA
	Ta3min	NA	NA	NA	Ta3_min=20
	Ta3max	NA	NA	NA	Ta3_max=32
O-DU	T1amin	T1a_min_cp_dl=70	T1a_min_cp_ul=60	T1a_min_up=35	NA
	T1amax	T1a_max_cp_dl=100	T1a_max_cp_ul=70	T1a_max_up=50	NA
	Ta4min	NA	NA	NA	Ta4_min=0
	Ta4max	NA	NA	NA	Ta4_max=45

FIG. 19

Front Haul Interface Latency (numerology 0 – Sub6)

	Model Parameters	**C-Plane**	**U-Plane**		
		DL	UL	DL	UL
O-RU	T2amin	T 2a_min_c p_dl=400	T 2a_min_c p_ul=400	T2a_min_up=200	NA
	T2amax	T2 a_max_cp _dl=1120	T2 a_max_cp _ul=1120	T2a_max _up=1120	NA
		Ta dv_cp_dl	NA	NA	NA
	Ta3min	NA	NA	NA	Ta3 _min=160
	Ta3max	NA	NA	NA	Ta3 _max=256
O-DU	T1amin	T 1a_min_cp_dl=560	T 1a_min_cp_ul=480	T1a_min_up=280	NA
	T1amax	T 1a_max_cp_dl=800	T 1a_max_cp_ul=560	T1a_max_up=400	NA
	Ta4min	NA	NA	NA	T a4_min=0
	Ta4max	NA	NA	NA	Ta4 _max=360

FIG. 20

Front Haul Interface Latency (numerology 1 – Sub6)

	Model Parameters	C-Plane	U-Plane		
		DL	UL	DL	UL
O-RU	T2amin	T2a_min_cp_dl=285	T2a_min_cp_ul=285	T2a_min_up=71	NA
	T2amax	T2a_max_cp_dl=429	T2a_max_cp_ul=429	T2a_max_up=428	NA
		Tadv_cp_dl	NA	NA	NA
	Ta3min	NA	NA	NA	Ta3_min=20
	Ta3max	NA	NA	NA	Ta3_max=32
O-DU	T1amin	T1a_min_cp_dl=285	T1a_min_cp_ul=285	T1a_min_up=96	NA
	T1amax	T1a_max_cp_dl=429	T1a_max_cp_ul=300	T1a_max_up=196	NA
	Ta4min	NA	NA	NA	Ta4_min=0
	Ta4max	NA	NA	NA	Ta4_max=75

FIG. 21

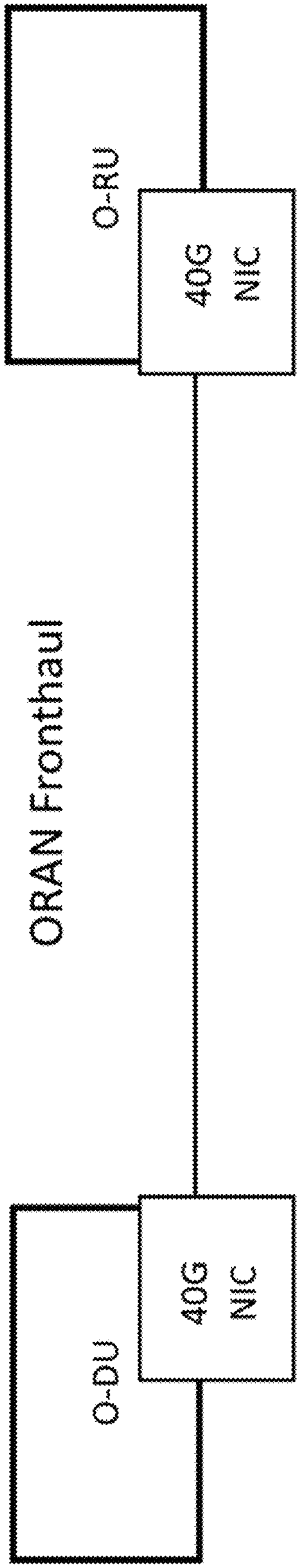


FIG. 22

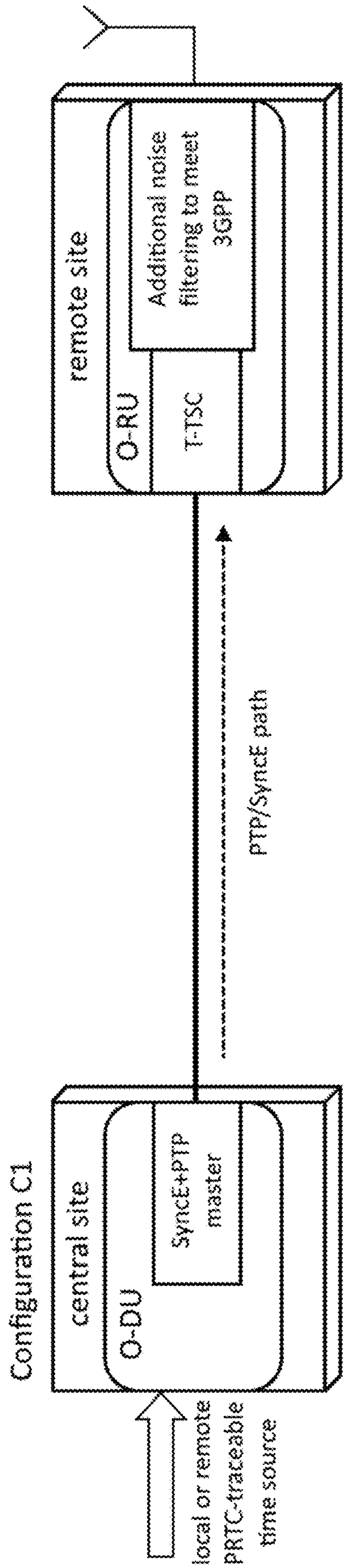

Configuration C1
central site
O-DU
SyncE+PTP master
local or remote PRTC-traceable time source
PTP/SyncE path
remote site
O-RU
T-TSC
Additional noise filtering to meet 3GPP

FIG. 23

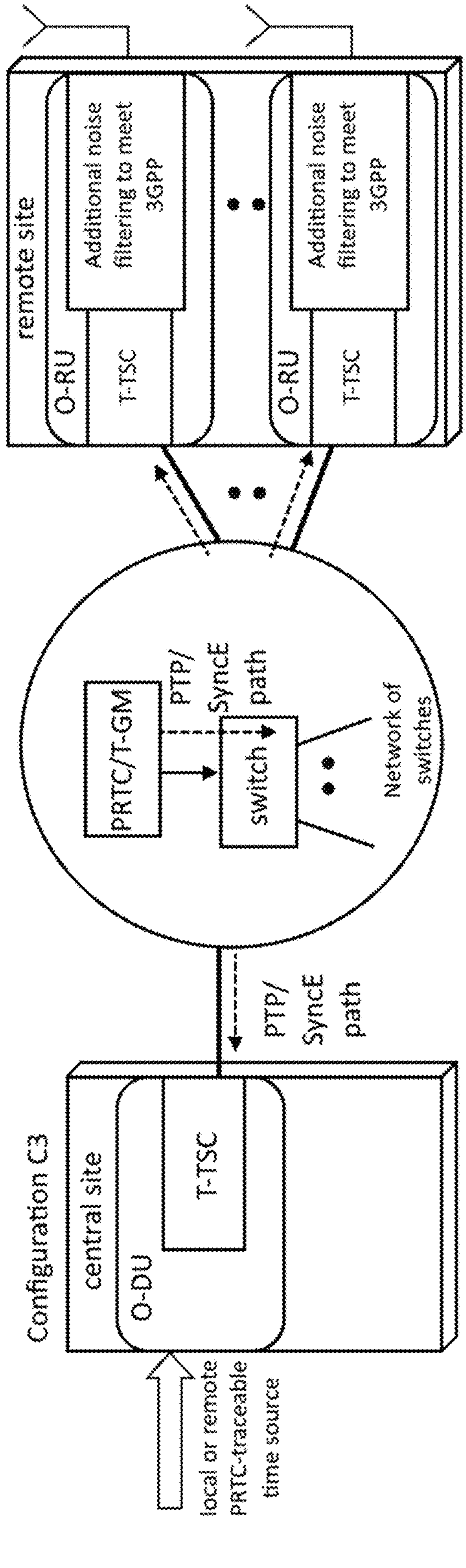

remote site
O-RU
T-TSC
Additional noise filtering to meet 3GPP
O-RU
T-TSC
Additional noise filtering to meet 3GPP
PRTC/T-GM
switch
PTP/ SyncE path
Network of switches
PTP/ SyncE path
Configuration C3
central site
O-DU
T-TSC
local or remote PRTC-traceable time source

FIG. 24

Preamble (8 Bytes)	Destination MAC Address (6 Bytes)	Source MAC Address (6 Bytes)	VLAN Tag (4 Bytes)	Type/Length (Ethertype) (2 Bytes)	Payload (42 ... 1500 Bytes)	FCS (4 Bytes)	IFG (12 Bytes)

FIG. 25

Section Type: any									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
ecpriVersion				ecpriReserved			ecpriConcatenation	1	Octet 1
ecpriMessage								1	Octet 2
ecpriPayload								2	Octet 3
ecpriRtcid/ecpriPcid								2	Octet 5
ecpriSeqid								2	Octet 7

FIG. 26

0 (msb)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15 (lsb)	Number of Octets
CU_Port_ID				BandSector_ID				CC_ID				RU_Port_ID				2

FIG. 27

Section Type 1,3: DL/UL IQ Data Messages

0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
sectionID								1	Octet 13
sectionID				rb	symInc	startPrbu		1	Octet 14
startPrbu								1	Octet 15
numPrbu								1	Octet 16
udCompHdr (not always present)								1	Octet 17
reserved (not always present)								1	Octet 18
UdCompHdr (not always present)								1	Octet 17/19
iSample (1st RE in the PRB)								1*	Octet 18/20
qSample (1st RE in the PRB)								1*	Octet 19/21*
...									
iSample (12th RE in the PRB)								1*	Octet 40/42*
qSample (12th RE in the PRB) + padding when needed								1*	Octet 41/43*
udComp Param (not always present)								1*	Octet 42/44*
iSample (1st RE in the PRB)								1*	Octet 43/45*
qSample (1st in the PRB)								1*	Octet 44/46*
...									
iSample (12th RE in the PRB)								1*	Octet 65/67*
qSample (12th RE in the PRB) + padding when needed								1*	Octet 66/68*
...									
sectionID								1	Octet M
sectionID				rb	symInc	startPrbu		1	M+1
startPrbu								1	M+2
numPrb								1	M+3
udCompHdr (not always present)								1	M+4
reserved (not always present)								1	M+5
UdCompHdr (not always present)								1	M+4/6
iSample (1st RE in the PRB)								1*	M+5/7
qSample (1st RE in the PRB)								1*	M+4/6*
...									
iSample (12th RE in the PRB)								1*	M+27/29*
qSample (12th RE in the PRB) + padding when needed								1*	M+28/30*
udComp Param (not always present)								1*	M+29/31*
iSample (1st RE in the PRB)								1*	M+30/32*
qSample (1st in the PRB)								1*	M+31/33*
...									
iSample (12th RE in the PRB)								1*	M+52/54*
qSample (12th RE in the PRB) + padding when needed								1*	M+53/55*

FIG. 28

Section Type 1,3: DL/UL IQ Data Messages									
0 (msb)	**1**	**2**	**3**	**4**	**5**	**6**	**7 (lsb)**	**# of bytes**	**Octet**
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12

FIG. 29

Section Type 1,3: DL/UL IQ Data Messages									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
sectionID								1	Octet 13
sectionID				rb	symInc	startPrbu		1	Octet 14
startPrbu								1	Octet 15
numPrbu								1	Octet 16
udCompHdr (not always present)								1	Octet 17
reserved (not always present)								1	Octet 18

FIG. 30

Section Type 1,3: DL/UL IQ Data Messages									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
sectionID								1	Octet 13
sectionID				rb	syminc	startPrbu		1	Octet 14
startPrbu								1	Octet 15
numPrbu								1	Octet 16
udCompHdr (not always present)								1	Octet 17
reserved (not always present)								1	Octet 18
UdCompHdr (not always present)								1	Octet 17/19
iSample (1st RE in the PRB)								1*	Octet 18/20
qSample (1st RE in the PRB)								1*	Octet 19/21*
...									
iSample (12th RE in the PRB)								1*	Octet 40/42*
qSample (12th RE in the PRB) + padding when needed								1*	Octet 41/43*
udComp Param (not always present)								1*	Octet 42/44*
iSample (1st RE in the PRB)								1*	Octet 43/45*
qSample (1st in the PRB)								1*	Octet 44/46*
...									
iSample (12th RE in the PRB)								1*	Octet 65/67*
qSample (12th RE in the PRB) + padding when needed								1*	Octet 66/68*
...									
sectionID								1	Octet M
sectionID				rb	syminc	startPrbu		1	M+1
startPrbu								1	M+2
numPrb								1	M+3
udCompHdr (not always present)								1	M+4
reserved (not always present)								1	M+5
UdCompHdr (not always present)								1	M+4/6
iSample (1st RE in the PRB)								1*	M+5/7
qSample (1st RE in the PRB)								1*	M+4/6*
...									
iSample (12th RE in the PRB)								1*	M+27/29*
qSample (12th RE in the PRB) + padding when needed								1*	M+28/30*
udComp Param (not always present)								1*	M+29/31*
iSample (1st RE in the PRB)								1*	M+30/32*
qSample (1st in the PRB)								1*	M+31/33*
...									
iSample (12th RE in the PRB)								1*	M+52/54*
qSample (12th RE in the PRB) + padding when needed								1*	M+53/55*

FIG. 31

Section Type	Target Scenario	Remarks
0	Unused Resource Blocks or symbols in Downlink or Uplink	Not supported
1	Most DL/UL radio channels	Supported
2	reserved for future use	N/A
3	PRACH and mixed-numerology channels	Only PRACH is supported. Mixed numerology is not supported.
4	Reserved for future use	Not supported
5	UE scheduling information (UE-ID assignment to section)	Not supported
6	Channel information	Not supported
7	LAA	Not supported
8-255	Reserved for future use	N/A

FIG. 32

Section Type 1: DL/UL Control Messages									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
numberOfSections								1	Octet 13
sectionType = 1								1	Octet 14

FIG. 33

Section Type 0: Idle/Guard Periods									
0 (msb)	**1**	**2**	**3**	**4**	**5**	**6**	**7 (lsb)**	**# of bytes**	**Octet**
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
numberOfSections								1	Octet 13
sectionType = 0								1	Octet 14
timeOffset								2	Octet 15
frameStructure								1	Octet 17
cpLength								2	Octet 18
reserved								1	Octet 20
sectionID								1	Octet 21
sectionID				rb	symInc	startPrbc		1	Octet 22
startPrbc								1	Octet 23
numPrbc								1	Octet 24
reMask[11:4]								1	Octet 25
reMask[3:0]				numSymbol				1	Octet 26
reserved (16 bits)								2	Octet 27
...									
sectionID								1	Octet N
sectionID				rb	symInc	startPrbc		1	N+1
startPrbc								1	N+2
numPrbc								1	N+3
reMask[11:4]								1	N+4
reMask[3:0]				numSymbol				1	N+5
reserved (16 bits)								2	N+6
									Octet M

FIG. 34

Section Type 1: DL/UL Control Messages									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
numberOfSections								1	Octet 13
sectionType = 1								1	Octet 14
udCompHdr								1	Octet 15
reserved								1	Octet 16
sectionID								1	Octet 17
sectionID				rb	symInc	startPrbc		1	Octet 18
startPrbc								1	Octet 19
numPrbc								1	Octet 20
reMask[11:4]								1	Octet 21
reMask[3:0]				numSymbol				1	Octet 22
ef = 1	beamId[14:8]							1	Octet 23
beamId[7:0]								1	Octet 24
section extensions as indicated by "ef"								var	Octet 25
...									
sectionID								1	Octet N
sectionID				rb	symInc	startPrbc		1	N+1
startPrbc								1	N+2
numPrbc								1	N+3
reMask[11:4]								1	N+4
reMask[3:0]				numSymbol				1	N+5
ef = 0	beamId[14:8]							1	N+6
beamId[7:0]								1	N+7
section extensions as indicated by "ef"								var	N+8
									Octet M

FIG. 35

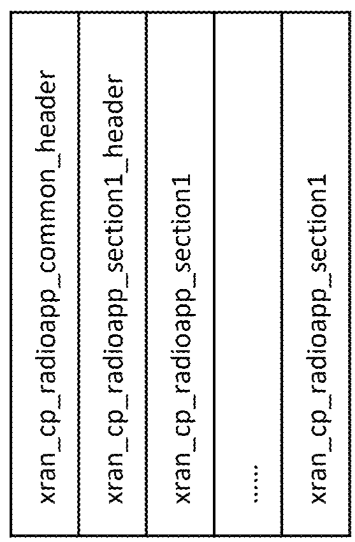

xran_cp_radioapp_common_header
xran_cp_radioapp_section1_header
xran_cp_radioapp_section1
......
xran_cp_radioapp_section1

FIG. 36

Section Type 3: PRACH & mixed numerology								
0 (msb)	**1**	**2**	**3**	**4**	**5**	**6**	**7 (lsb)**	**# of bytes**
transport header, see xRAN specification section 3.13								8
dataDirection	payloadVersion			filterIndex				1
frameID								1
subframeID				slotID				1
slotID		symbolId						1
numberOfSections								1
sectionType = 3								1
timeOffset								2
framStructure								1
cpLength								2
udCompHdr								1
sectionID								1
sectionID				rb	symInc	startPrbc		1
startPrbc								1
numPrbc								1
reMask[11:4]								1
reMask[3:0]				numSymbol				1
ef	beamId[14:8]							1
beamId[7:0]								1
frequencyOffset								3
reserved (8 bits)								1
section extensions as indicated by “ef”								var
...								
sectionID								
sectionID				rb	symInc	startPrbc		1
startPrbc								1
numPrbc								1
reMask[11:4]								1
reMask[3:0]				numSymbol				1
reserved (16 bits)								1
ef	beamId[14:8]							1
beamId[7:0]								1
frequencyOffset								3
reserved (8 bits)								1
section extensions as indicated by “ef”								var

FIG. 37

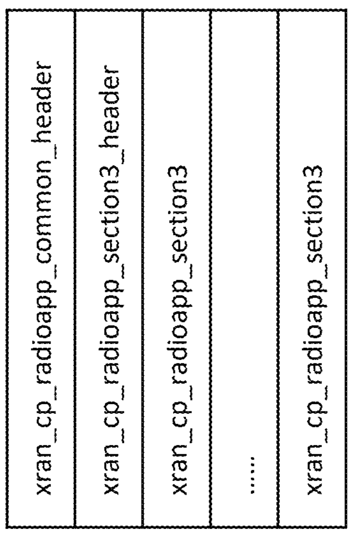

xran_cp_radioapp_common_header
xran_cp_radioapp_section3_header
xran_cp_radioapp_section3
......
xran_cp_radioapp_section3

FIG. 38

Section Type 5: UE Scheduling Information conveyance

0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
numberOfSections								1	Octet 13
sectionType = 5								1	Octet 14
udCompHdr								1	Octet 15
reserved								1	Octet 16
sectionID								1	Octet 17
sectionID				rb	symInc	startPrbc		1	Octet 18
startPrbc								1	Octet 19
numPrbc								1	Octet 20
reMask[11:4]								1	Octet 21
reMask[3:0]				numSymbol				1	Octet 22
ef	ueId[14:8]							1	Octet 23
ueId[7:0]								1	Octet 24
section extensions as indicated by "ef"								var	Octet 25
...									
sectionID								1	Octet N
sectionID				rb	symInc	startPrbc		1	N+1
startPrbc								1	N+2
numPrbc								1	N+3
reMask[11:4]								1	N+4
reMask[3:0]				numSymbol				1	N+5
ef	ueId[14:8]							1	N+6
ueId[7:0]								1	N+7
section extensions as indicated by "ef"								var	N+8
									Octet M

FIG. 39

Section Type 6: Channel Information Conveyance									
0 (msb)	1	2	3	4	5	6	7 (lsb)	# of bytes	Octet
transport header, see xRAN specification section 3.13								8	Octet 1
dataDirection	payloadVersion			filterIndex				1	Octet 9
frameID								1	Octet 10
subframeID				slotID				1	Octet 11
slotID		symbolId						1	Octet 12
numberOfSections								1	Octet 13
sectionType = 6								1	Octet 14
numberOfUEs								1	Octet 15
reserved								1	Octet 16
ef	ueId[14:8]							1	Octet 17
ueId[7:0]								1	Octet 18
regularizationFactor								2	Octet 19
reserved				rb	symInc	startPrbc		1	Octet 21
startPrbc								1	Octet 22
numPrbc								1	Octet 23
ciIsample (first PRB, first antenna)								var	Octet 24
ciQsample (first PRB, first antenna)								var	
ciIsample (first PRB, second antenna)								var	
ciQsample (first PRB, second antenna)								var	
...									
ciIsample (first PRB, last antenna)								var	
ciQsample (first PRB, last antenna)								var	
...									
ciIsample (last PRB, last antenna)								var	
ciQsample (last PRB, last antenna)								var	
section extensions as indicated by "ef"								var	
...									
ef	ueId[14:8]							1	Octet N
ueId[7:0]								1	N+1
regularizationFactor								2	N+2
reserved				rb	symInc	startPrbc		1	N+4
startPrbc								1	N+5
numPrbc								1	N+6
ciIsample (first PRB, first antenna)								var	N+7
ciQsample (first PRB, first antenna)								var	
ciIsample (first PRB, second antenna)								var	
ciQsample (first PRB, second antenna)								var	
...									
ciIsample (first PRB, last antenna)								var	
ciQsample (first PRB, last antenna)								var	
...									
ciIsample (last PRB, last antenna)								var	
ciQsample (last PRB, last antenna)								var	

FIG. 40

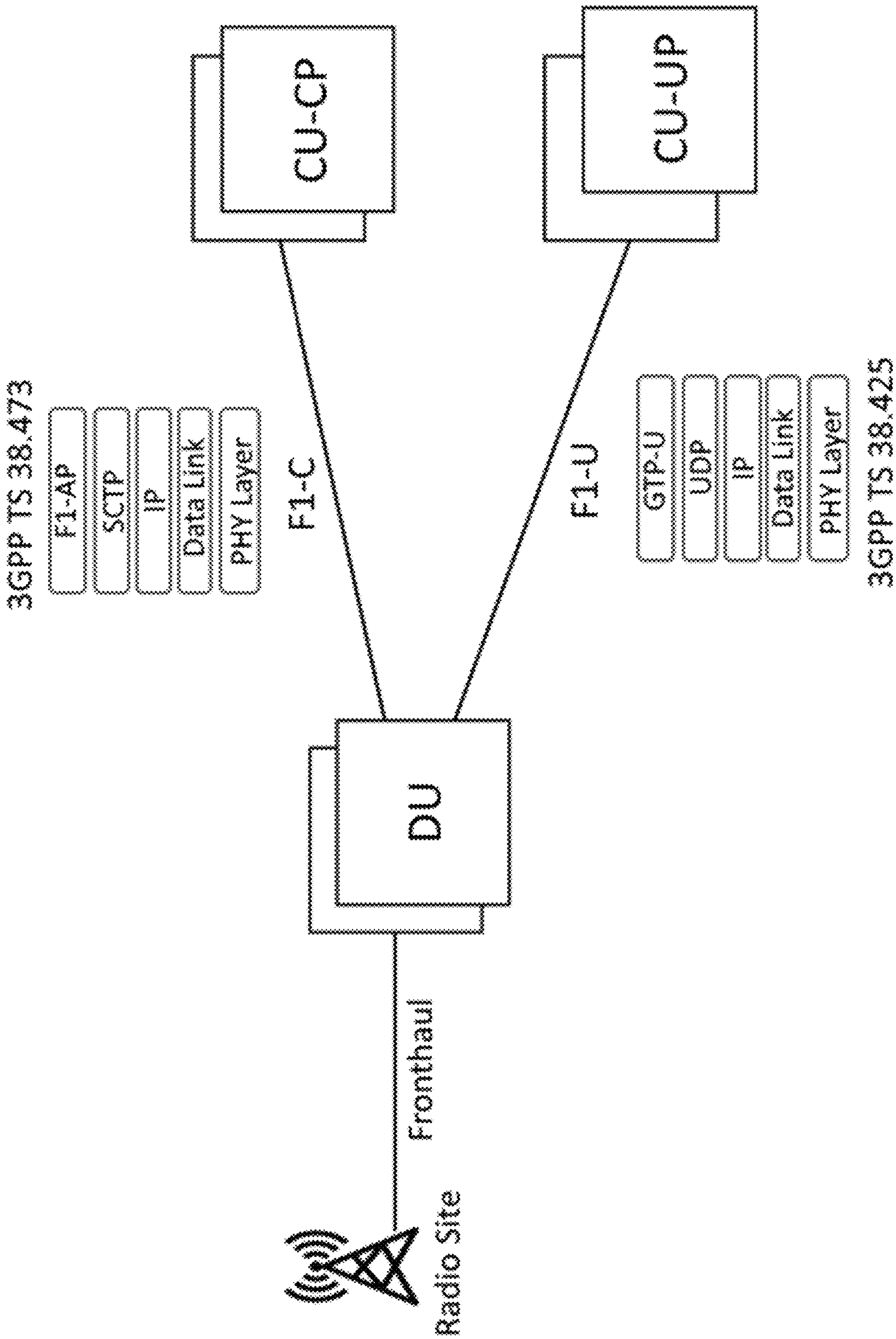

CU-CP
CU-UP
3GPP TS 38.473
F1-AP
SCTP
IP
Data Link
PHY Layer
F1-C
F1-U
GTP-U
UDP
IP
Data Link
PHY Layer
3GPP TS 38.425
DU
Fronthaul
Radio Site

FIG. 41

Interface Management Procedures	UE Context Management Procedures	RRC Message Transfer Procedures
• F1 Setup • Reset • Error Indication • gNB-DU Configuration Updates • gNB-CU Configuration Updates • gNB-DU Resource Indication	• UE Context Setup • UE Context Modification (gNB-CU initiated) • UE Context Modification Required (gNB-DU Initiated) • UE Context Release • UE Context Release Request • UE Inactivity Notification • Notify	• Initial UL RRC Message Transfer • DL RRC Message Transfer • UL RRC Message Transfer
SI & Paging Procedures		**Warning Message Transfer Procedures**
• System Information Delivery • Paging		• Write-Replace Warning • PWS Cancel • PWS Restart Indication • PWS Failure Indication

FIG. 42

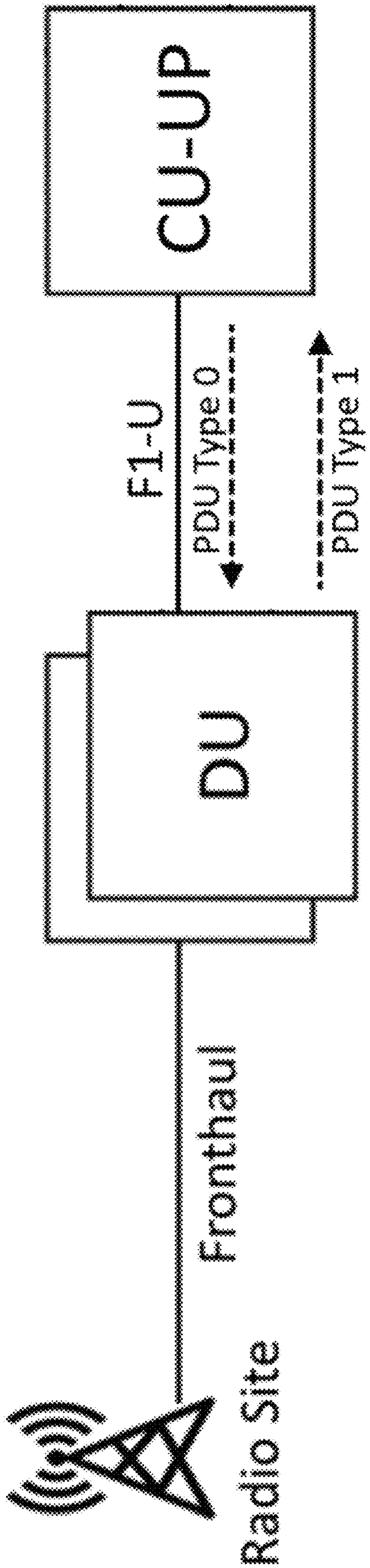


FIG. 43

Downlink User Data (PDU Type 0)				
PDU Type 0	Spare	DL Discard Blocks	DL Flush	Report Polling
Spare	Report Delivery	User Data Exits	Assisted Info Report Poll	ReTx Flag
NR-U Sequence Number				
DL Discard NR PDCP PDU SN				
DL Discard Number of Blocks				
DL Discord NR PDCP PDU SN Start (first block)				
Discarded Block size (first block)				
...				
DL Discard NR PDCP PDU SN Start (last block)				
Discarded Block size (last block)				
DL Report NR PDCP POU SN				

FIG. 44

Downlink Data Delivery Status (PDU Type 1)				
PDU Type 1	Highest Tx NR PDCP SN Indication	Highest Delivered NR PDCP SN Indication	Final Frame Indication	Last Packet Report
Spare	Data Rate Indication	Highest ReTx NR PDCP SN Indication	Highest Delivered ReTx NR PDCP SN Indication	Cause Report
Desired Buffered Size for the Data Radio Bearer				
Desired Data Rate				
Number of Lost NR-U Sequence Number Ranges Reported				
Start of Lost NR-U Sequence Number Range				
End of Lost NR-U Sequence Number Range				
Highest Successful Delivered NR PDCP Sequence Number				
Highest Transmitted NR PDCP Sequence Number				
Cause Value				
Highest Successful Delivered RxTx NR PDCP Sequence Number				
Highest Retransmitted NR PDCP Sequence Number				

FIG. 45

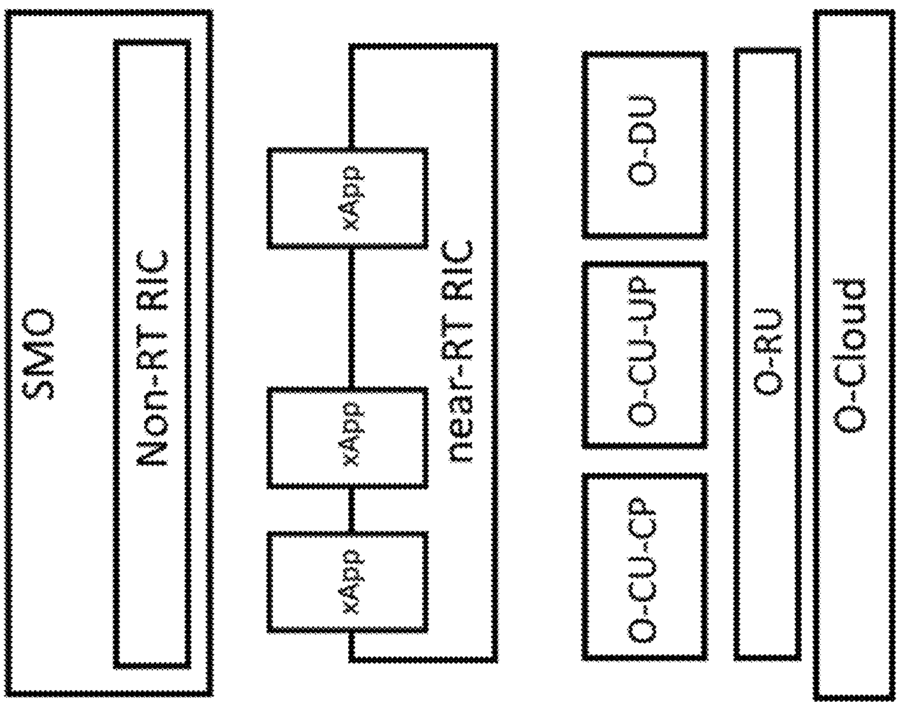

SMO
Non-RT RIC
xApp
xApp
xApp
near-RT RIC
O-CU-CP
O-CU-UP
O-DU
O-RU
O-Cloud

FIG. 46

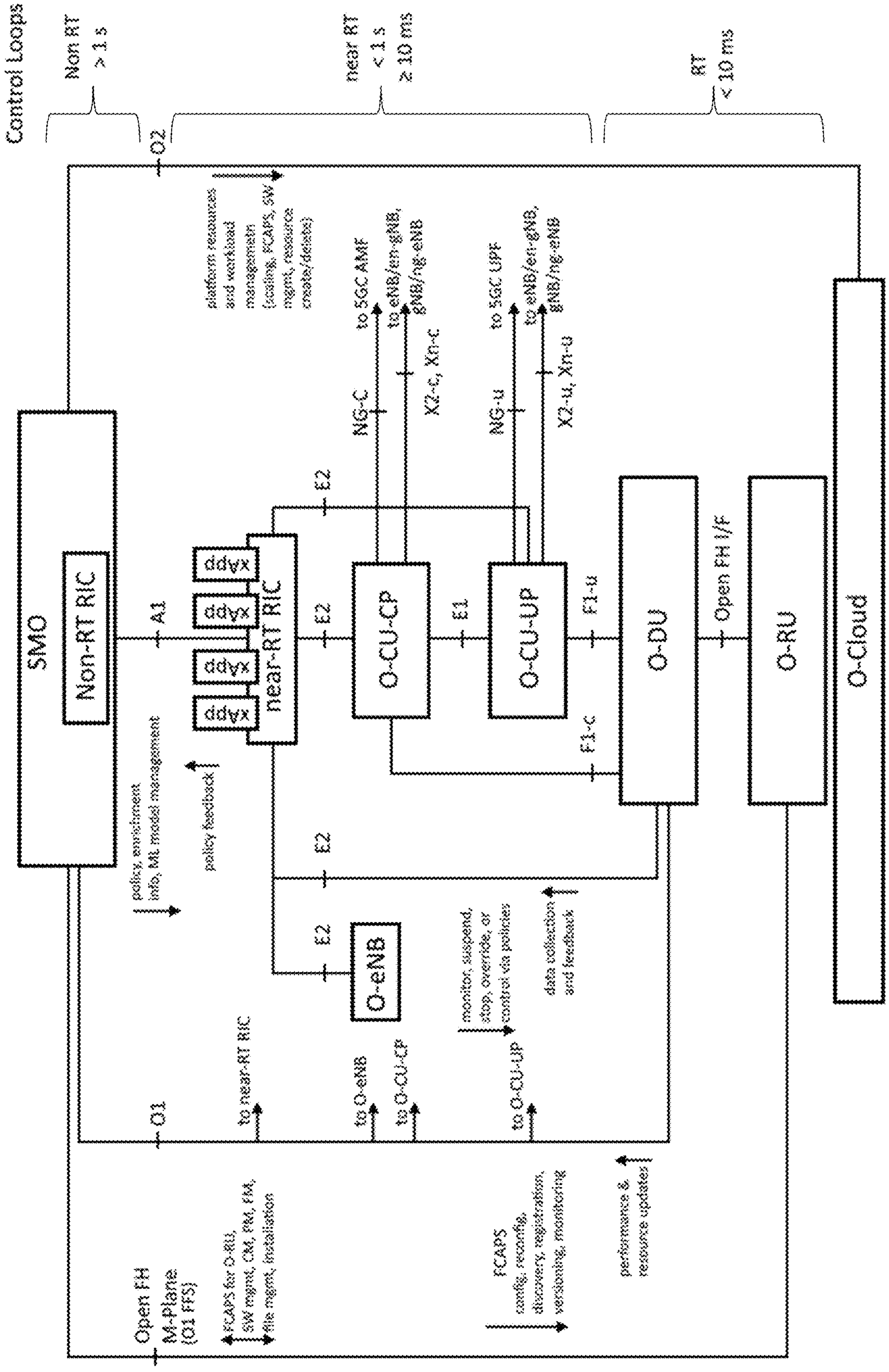

Control Loops
Non RT
> 1 s
near RT
< 1 s
≥ 10 ms
RT
< 10 ms
SMO
Non-RT RIC
A1
O2
O1
xApp
xApp
xApp
xApp
near-RT RIC
E2
E2
E2
E2
O-eNB
O-CU-CP
O-CU-UP
E1
F1-c
F1-u
O-DU
Open FH I/F
O-RU
O-Cloud
NG-C
X2-c, Xn-c
NG-u
X2-u, Xn-u
to 5GC AMF
to eNB/en-gNB, gNB/ng-eNB
to 5GC UPF
to eNB/en-gNB, gNB/ng-eNB
platform resources and workload management (scaling, FCAPS, SW mgmt, resource create/delete)
policy, enrichment info, ML model management
policy feedback
monitor, suspend, stop, override, or control via policies
data collection and feedback
to near-RT RIC
to O-eNB
to O-CU-CP
to O-CU-UP
Open FH M-Plane (O1 FFS)
FCAPS for O-RU, SW mgmt, CM, PM, FM, file mgmt, installation
FCAPS config, reconfig, discovery, registration, versioning, monitoring
performance & resource updates

FIG. 47

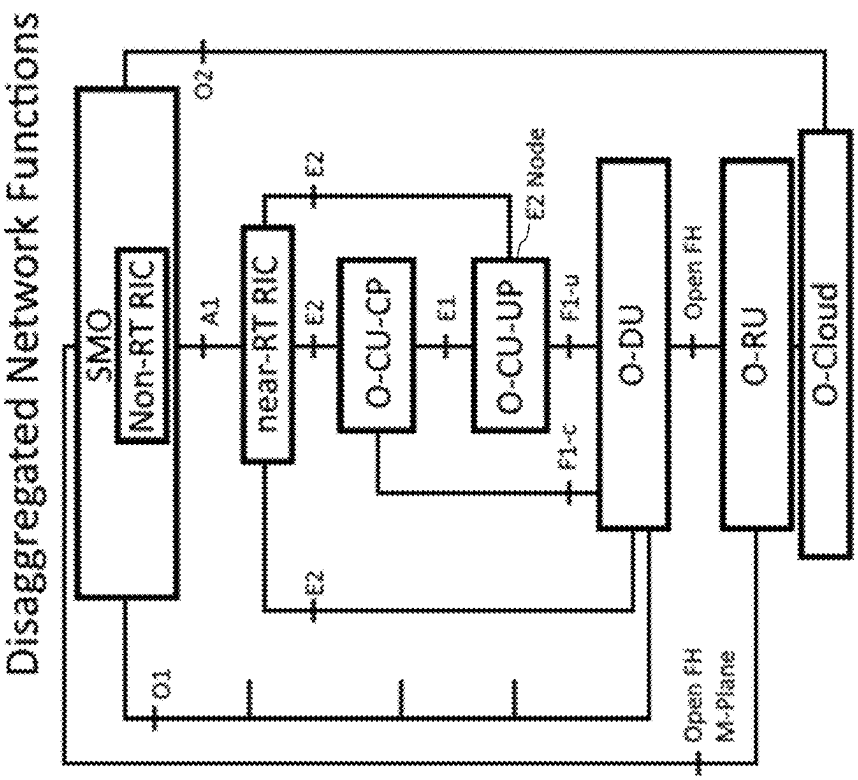

Disaggregated Network Functions
SMO
Non-RT RIC
O1
O2
A1
near-RT RIC
E2
E2
E2
O-CU-CP
E1
O-CU-UP
E2 Node
F1-u
F1-c
O-DU
Open FH
Open FH
M-Plane
O-RU
O-Cloud

FIG. 48

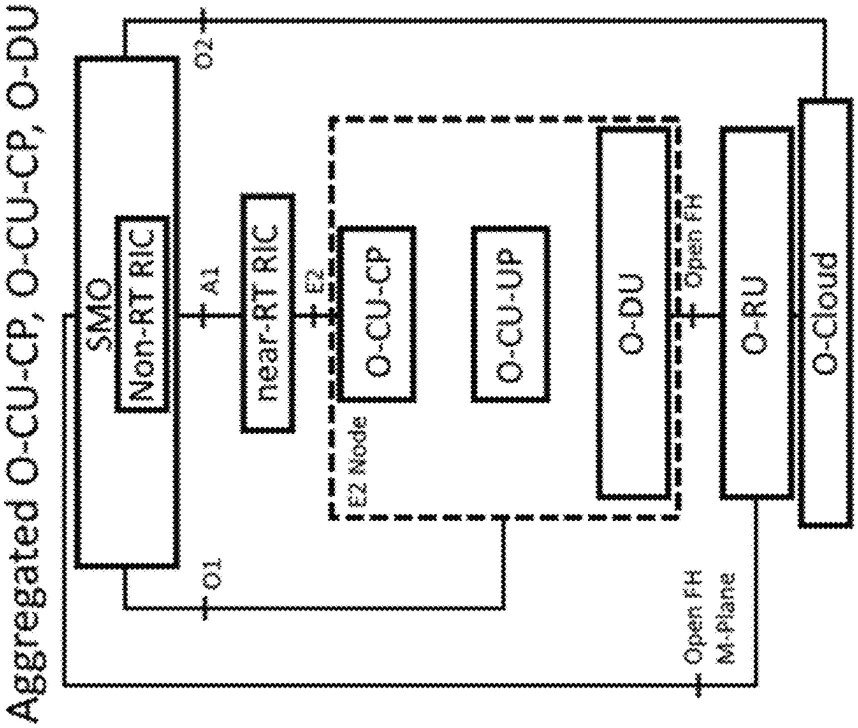

Aggregated O-CU-CP, O-CU-CP, O-DU
SMO
Non-RT RIC
O1
O2
A1
near-RT RIC
E2
E2 Node
O-CU-CP
O-CU-UP
O-DU
Open FH
Open FH
M-Plane
O-RU
O-Cloud

FIG. 49

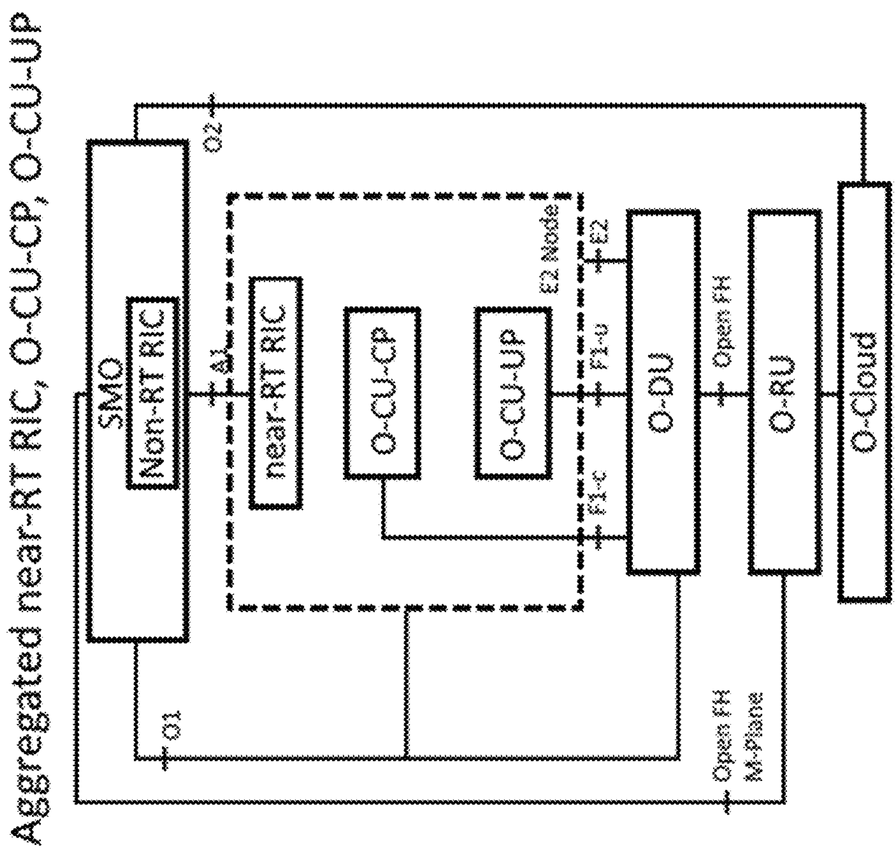

Aggregated near-RT RIC, O-CU-CP, O-CU-UP
SMO
Non-RT RIC
O1
O2
A1
near-RT RIC
O-CU-CP
O-CU-UP
E2 Node
E2
F1-u
F1-c
O-DU
Open FH
O-RU
O-Cloud
Open FH
M-Plane

FIG. 50

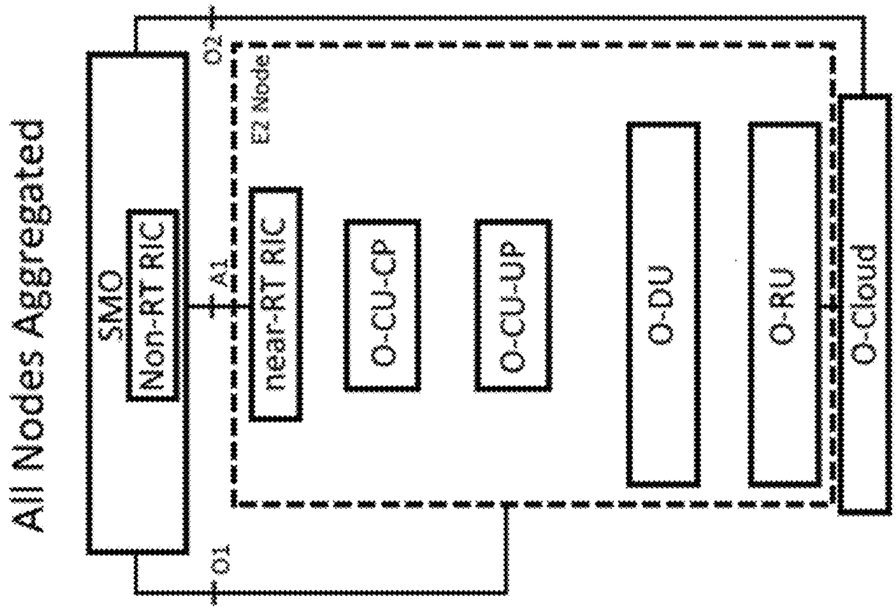

All Nodes Aggregated
SMO
Non-RT RIC
O1
O2
A1
near-RT RIC
O-CU-CP
O-CU-UP
E2 Node
O-DU
O-RU
O-Cloud

FIG. 51

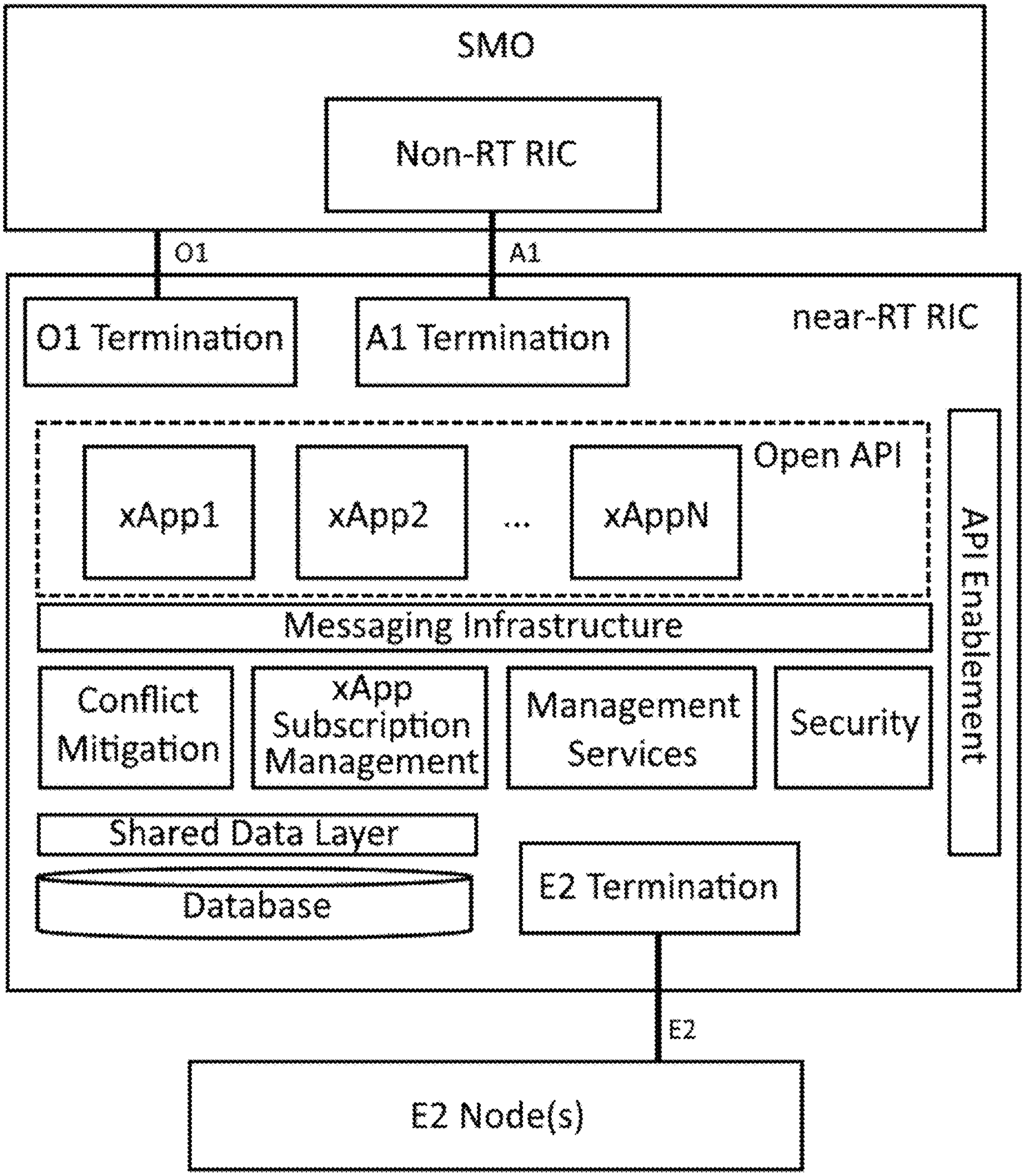

SMO
Non-RT RIC
O1
A1
O1 Termination
A1 Termination
near-RT RIC
Open API
xApp1
xApp2
...
xAppN
API Enablement
Messaging Infrastructure
Conflict Mitigation
xApp Subscription Management
Management Services
Security
Shared Data Layer
Database
E2 Termination
E2
E2 Node(s)

FIG. 52

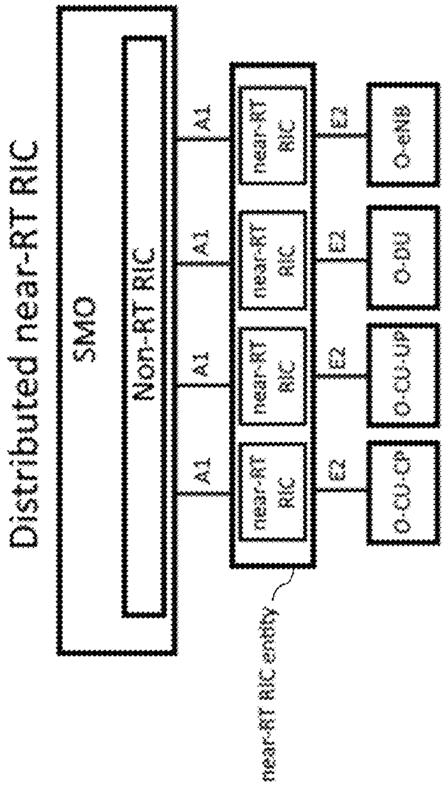

Distributed near-RT RIC
SMO
Non-RT RIC
A1
A1
A1
A1
near-RT RIC
near-RT RIC
near-RT RIC
near-RT RIC
E2
E2
E2
E2
O-CU-CP
O-CU-UP
O-DU
O-eNB
near-RT RIC entity

FIG. 54

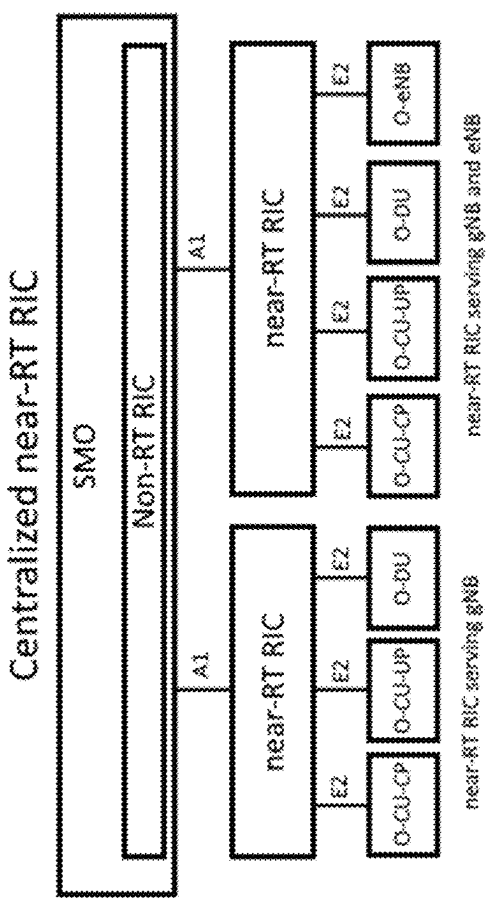

Centralized near-RT RIC
SMO
Non-RT RIC
A1
A1
near-RT RIC
near-RT RIC
E2
E2
E2
E2
E2
E2
E2
O-CU-CP
O-CU-UP
O-DU
O-CU-CP
O-CU-UP
O-DU
O-eNB
near-RT RIC serving gNB
near-RT RIC serving gNB and eNB

FIG. 53

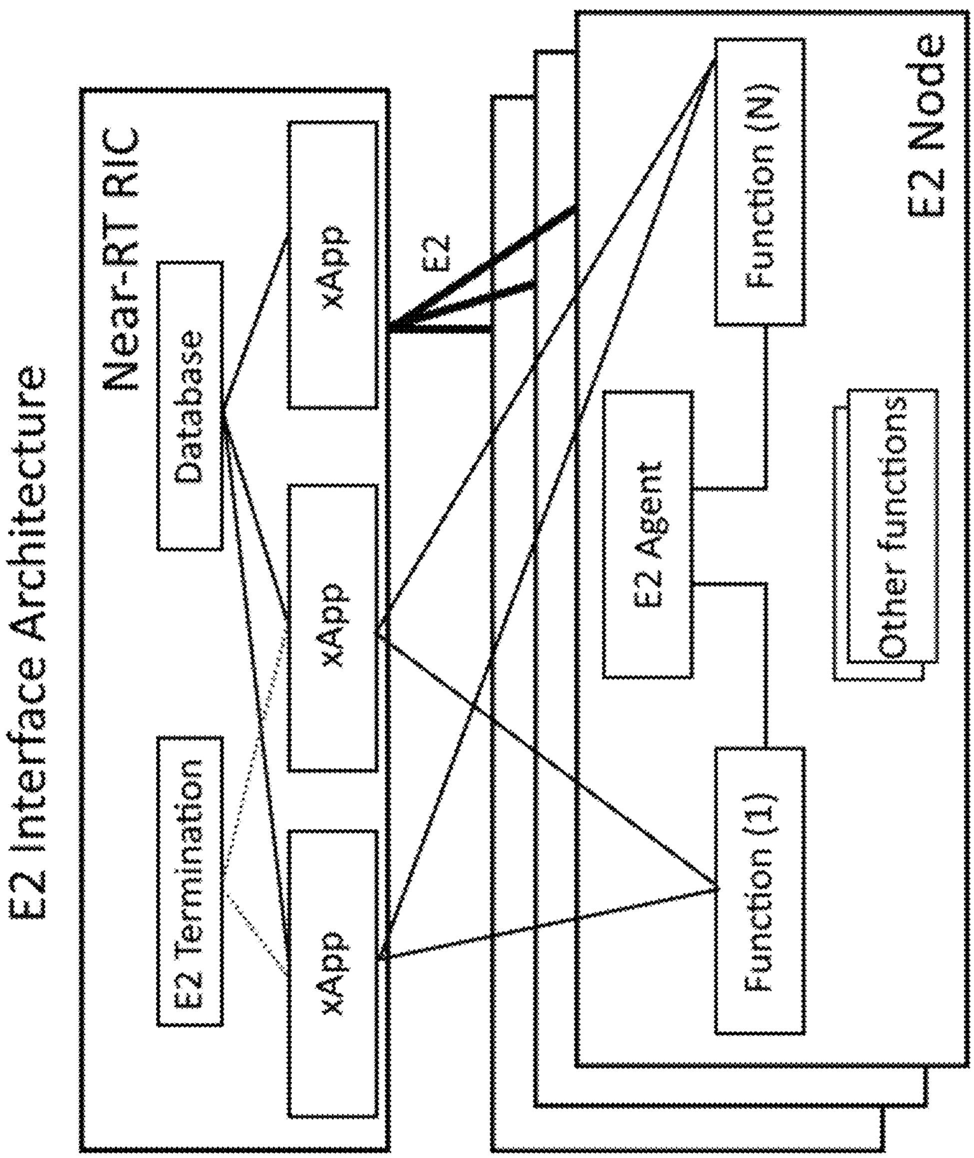

E2 Interface Architecture
Near-RT RIC
Database
E2 Termination
xApp
xApp
xApp
E2
E2 Node
Function (N)
E2 Agent
Other functions
Function (1)

FIG. 55

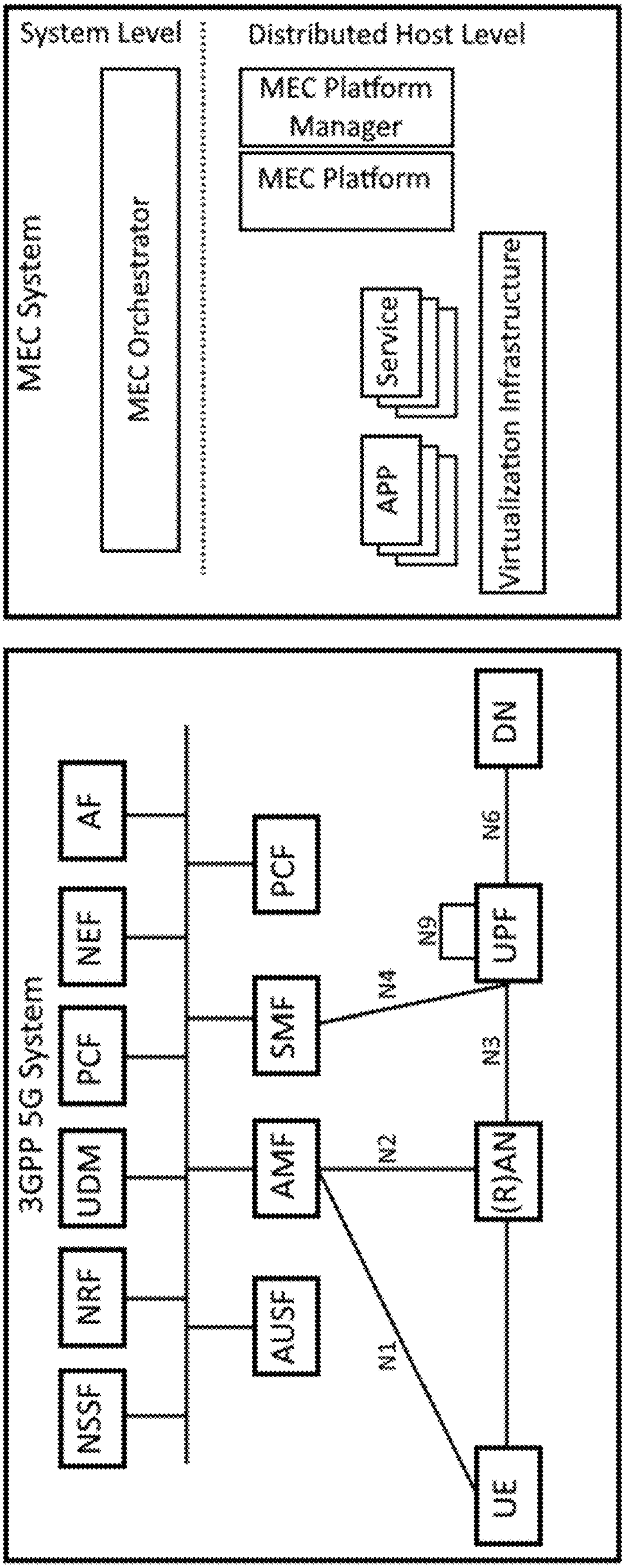

MEC System
System Level
Distributed Host Level
MEC Orchestrator
MEC Platform Manager
MEC Platform
APP
Service
Virtualization Infrastructure
3GPP 5G System
NSSF
NRF
UDM
PCF
NEF
AF
AUSF
AMF
SMF
PCF
UE
(R)AN
UPF
DN
N1
N2
N3
N4
N6
N9

FIG. 56

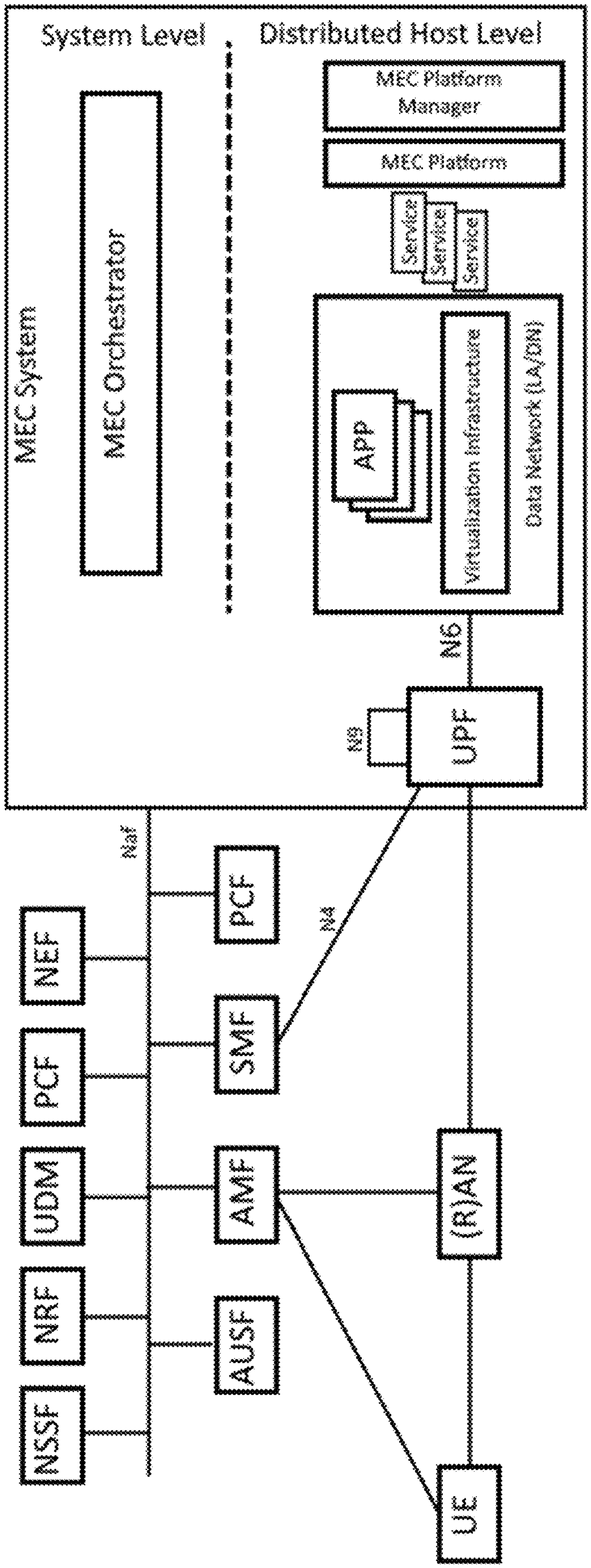

MEC System
System Level
Distributed Host Level
MEC Orchestrator
MEC Platform Manager
MEC Platform
Service
Service
Service
APP
Virtualization Infrastructure
Data Network (LA/DN)
N6
N9
UPF
Naf
NSSF
NRF
UDM
PCF
NEF
AUSF
AMF
SMF
PCF
N4
(R)AN
UE

FIG. 57

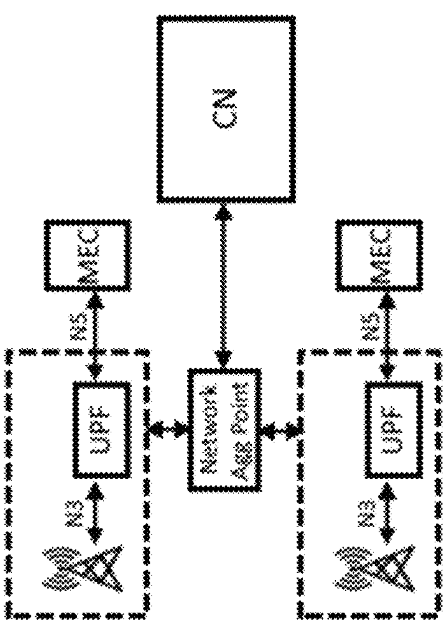


FIG. 58A

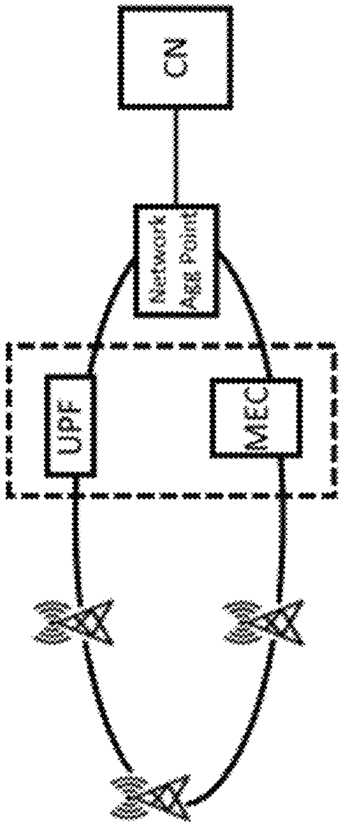


FIG. 58B

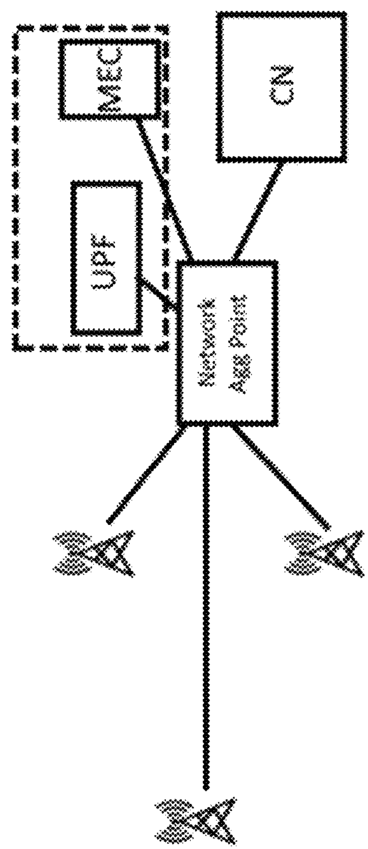


FIG. 58C

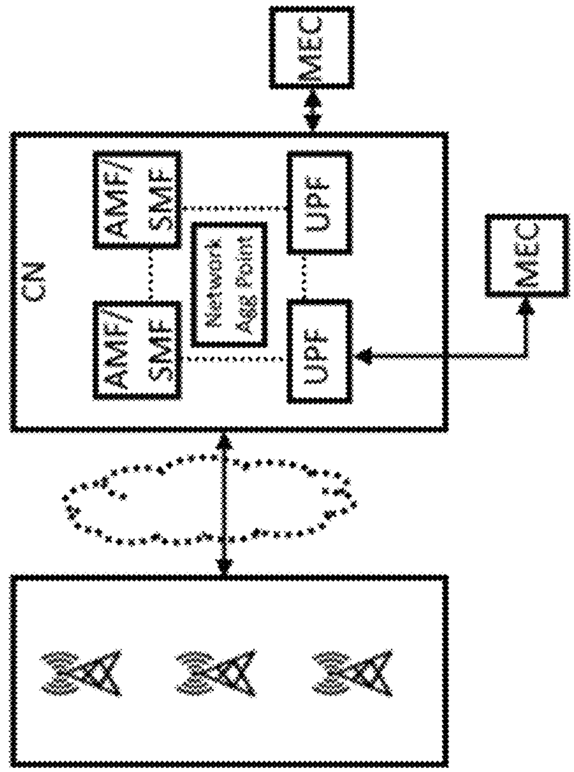
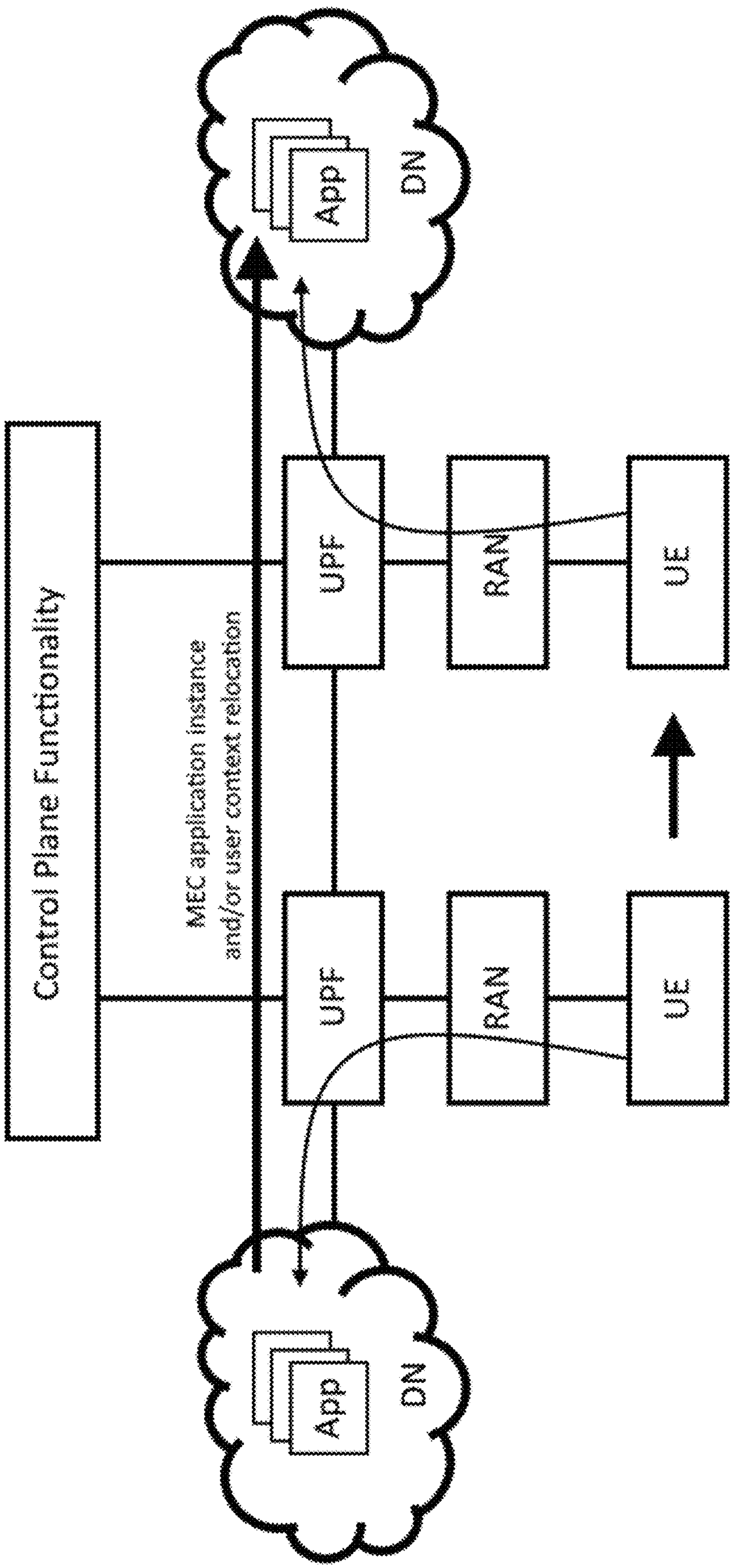


FIG. 58D



Control Plane Functionality
MEC application instance
and/or user context relocation
UPF
RAN
UE
UPF
RAN
UE
App
DN
App
DN

FIG. 59

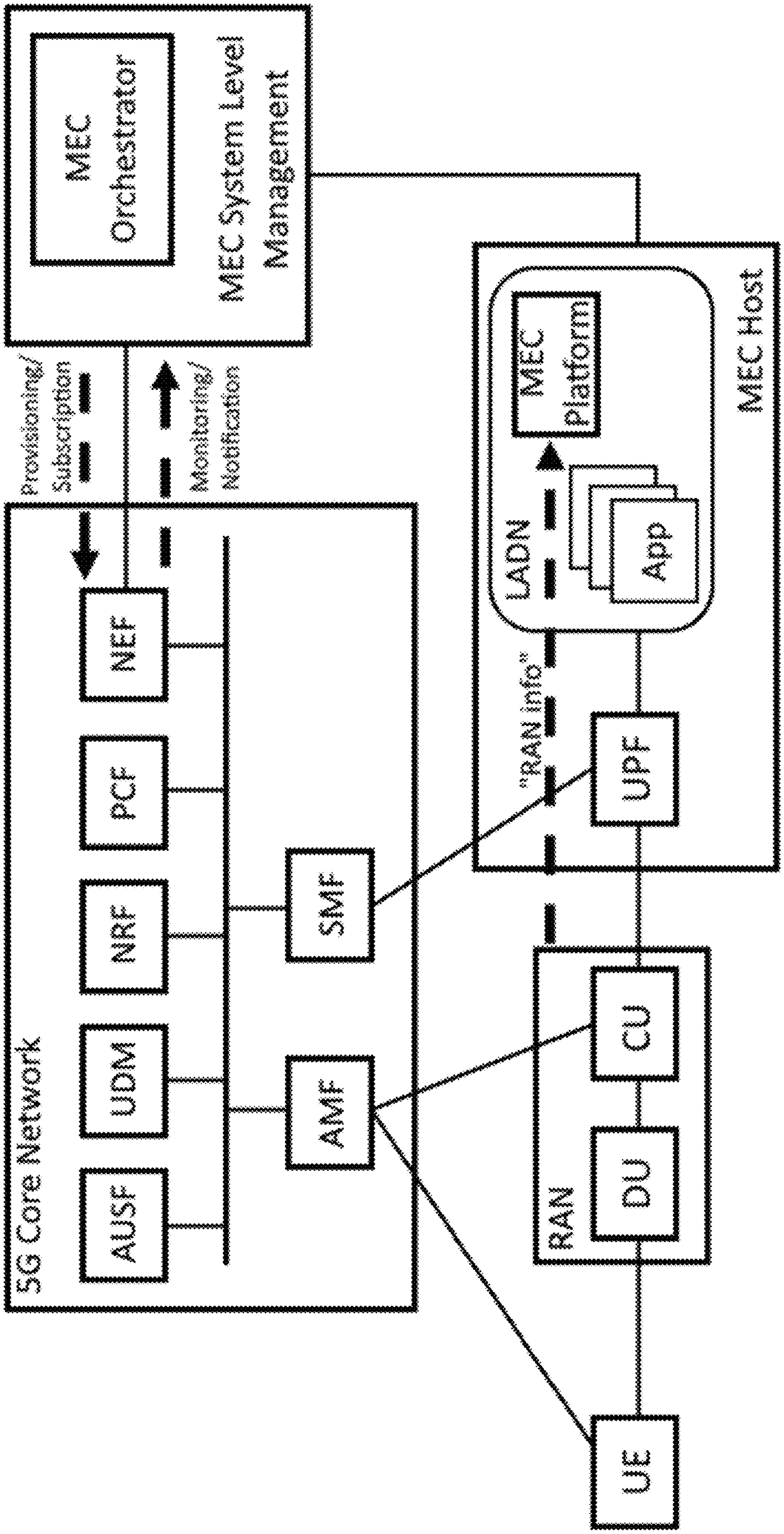
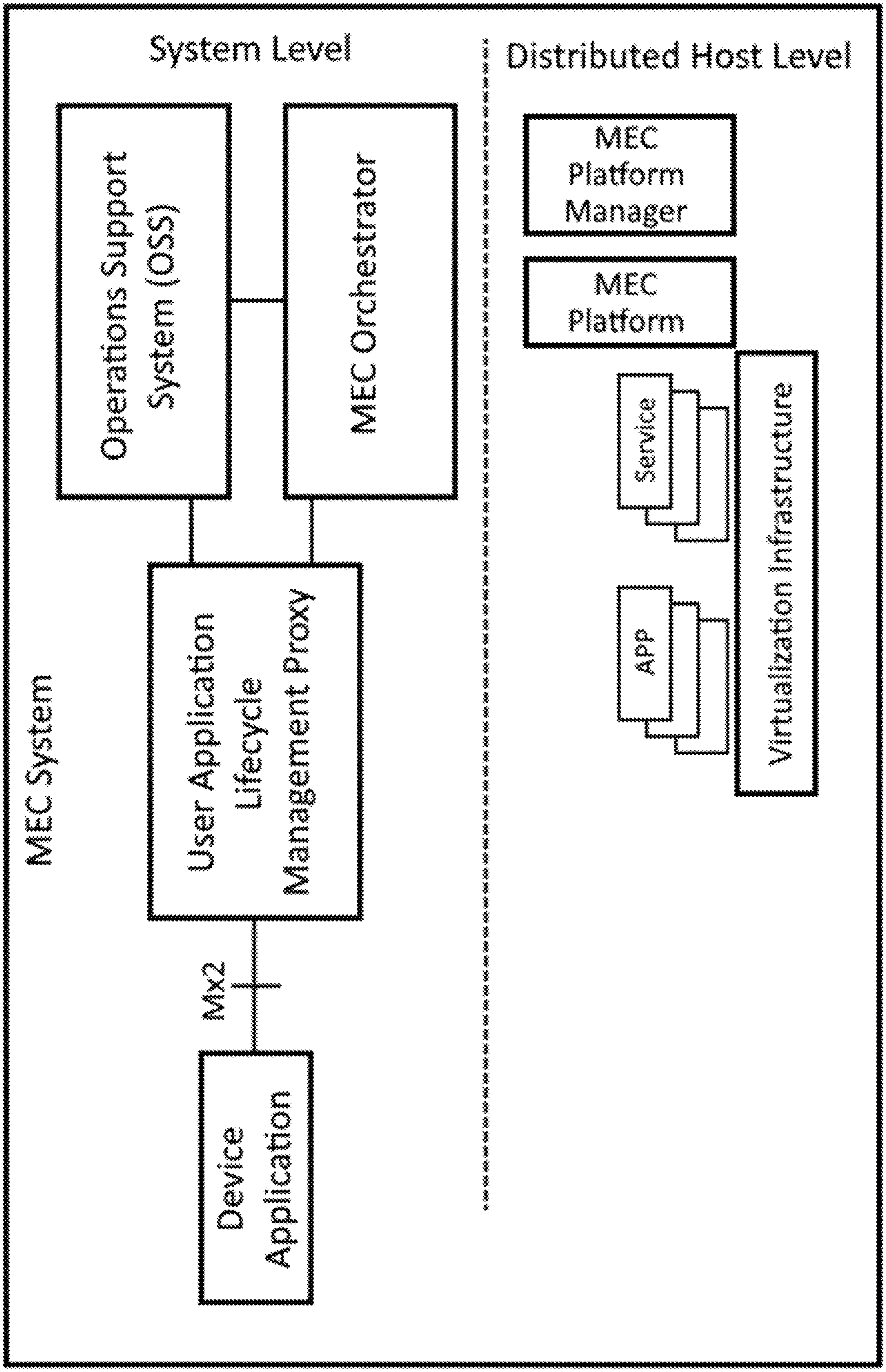

MEC Orchestrator
MEC System Level Management
Provisioning/ Subscription
Monitoring/ Notification
5G Core Network
AUSF
UDM
NRF
PCF
NEF
AMF
SMF
MEC Host
LADN
App
MEC Platform
"RAN info"
UPF
RAN
DU
CU
UE

FIG. 60



MEC System
System Level
Operations Support System (OSS)
MEC Orchestrator
User Application Lifecycle Management Proxy
Mx2
Device Application
Distributed Host Level
MEC Platform Manager
MEC Platform
Service
APP
Virtualization Infrastructure

FIG. 61

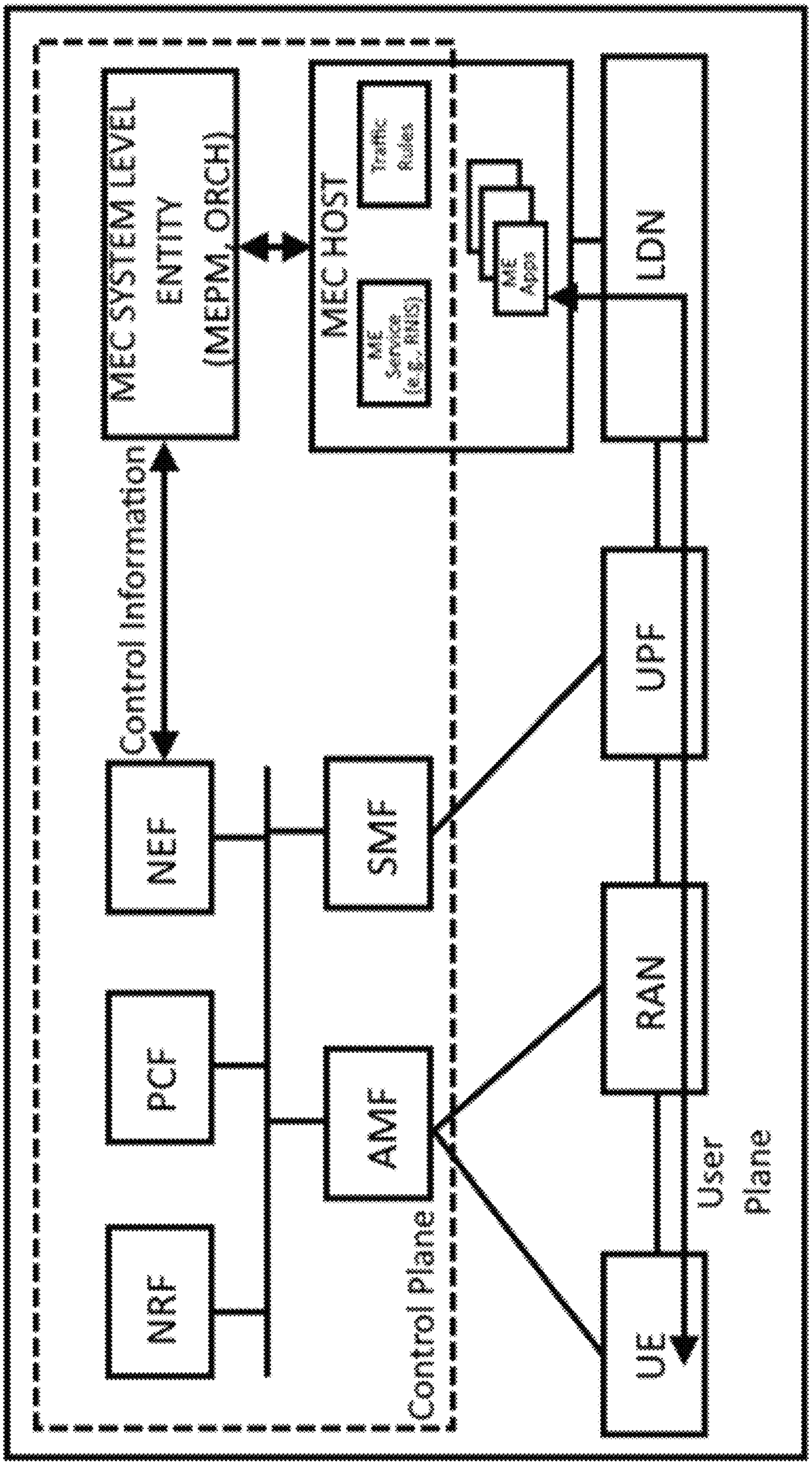

MEC SYSTEM LEVEL ENTITY (MEPM, ORCH)
MEC HOST
ME Service (e.g., RNIS)
Traffic Rules
ME Apps
LDN
Control Information
NRF
PCF
NEF
AMF
SMF
UE
RAN
UPF
Control Plane
User Plane

FIG. 62

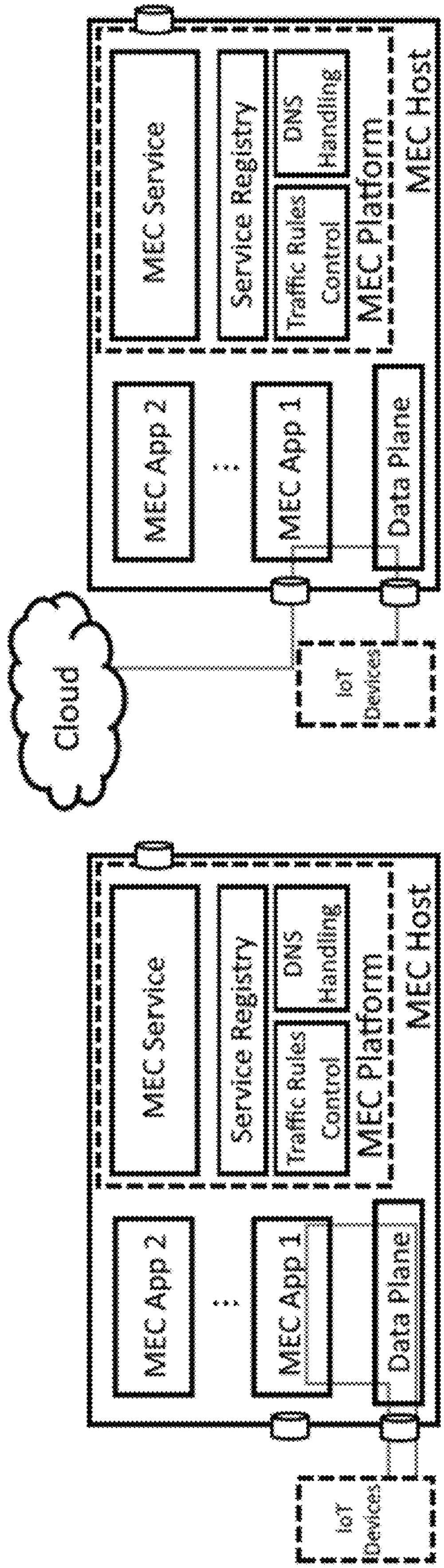

MEC Host
MEC Platform
MEC Service
Service Registry
Traffic Rules Control
DNS Handling
MEC App 2
MEC App 1
Data Plane
Cloud
IoT Devices
MEC Host
MEC Platform
MEC Service
Service Registry
Traffic Rules Control
DNS Handling
MEC App 2
MEC App 1
Data Plane
IoT Devices

FIG. 63

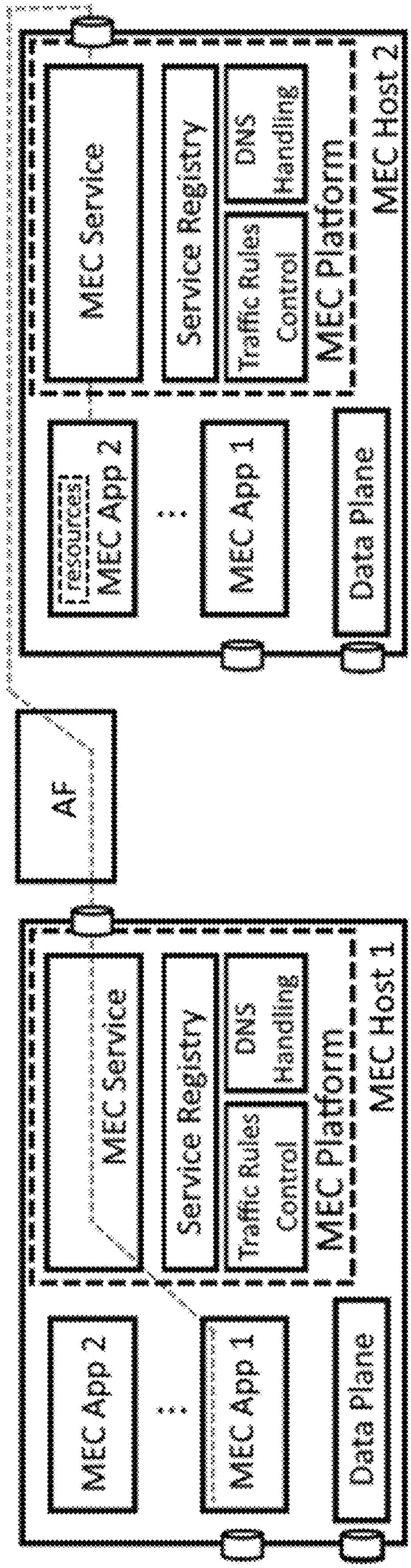

MEC Service
Service Registry
DNS Handling
Traffic Rules Control
MEC Platform
MEC Host 2
resources
MEC App 2
...
MEC App 1
Data Plane
AF
MEC Service
Service Registry
DNS Handling
Traffic Rules Control
MEC Platform
MEC Host 1
MEC App 2
...
MEC App 1
Data Plane

FIG. 64

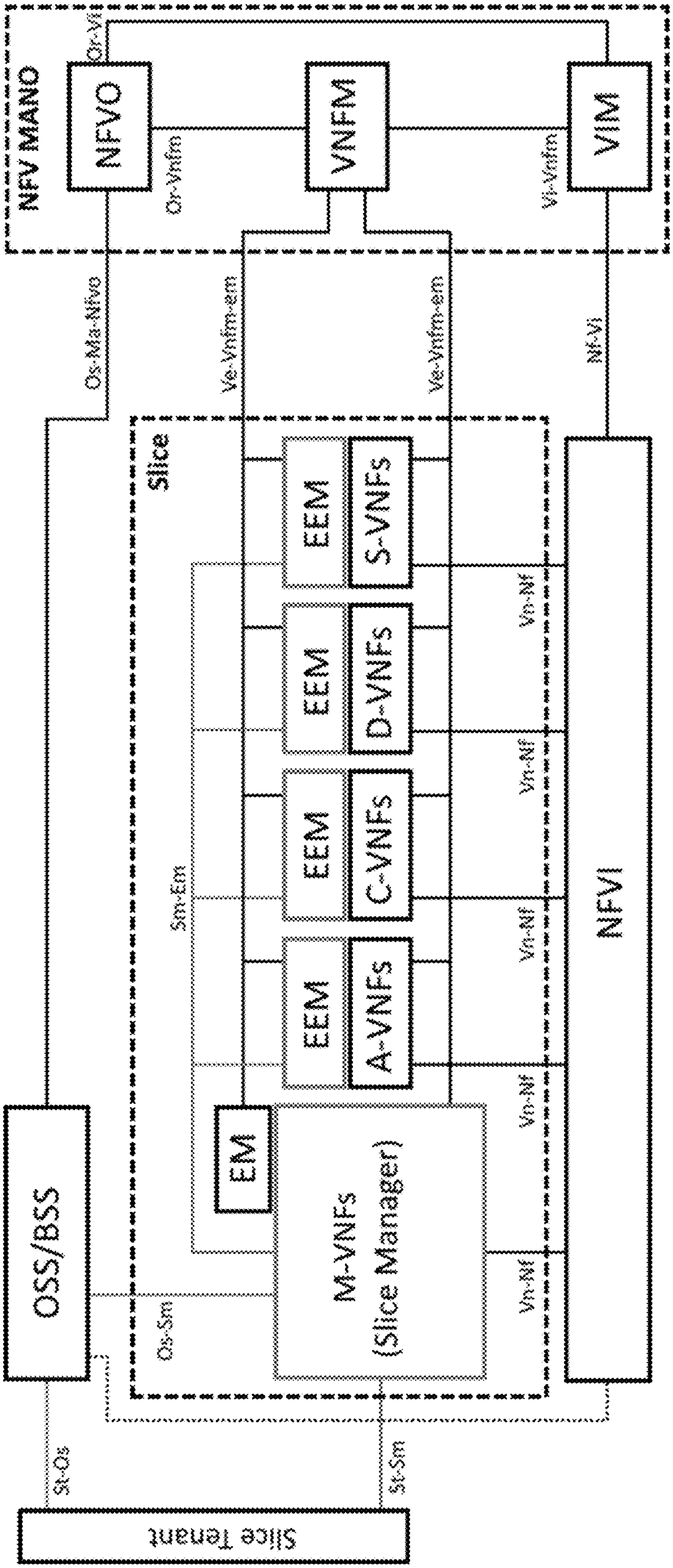

NFV MANO
NFVO
VNFM
VIM
Or-Vi
Or-Vnfm
Vi-Vnfm
Os-Ma-Nfvo
Ve-Vnfm-em
Ve-Vnfm-em
Nf-Vi
Slice
EEM
S-VNFs
EEM
D-VNFs
EEM
C-VNFs
EEM
A-VNFs
Sm-Em
Vn-Nf
Vn-Nf
Vn-Nf
Vn-Nf
Vn-Nf
NFVI
OSS/BSS
EM
M-VNFs
(Slice Manager)
Os-Sm
St-Os
St-Sm
Slice Tenant

FIG. 65

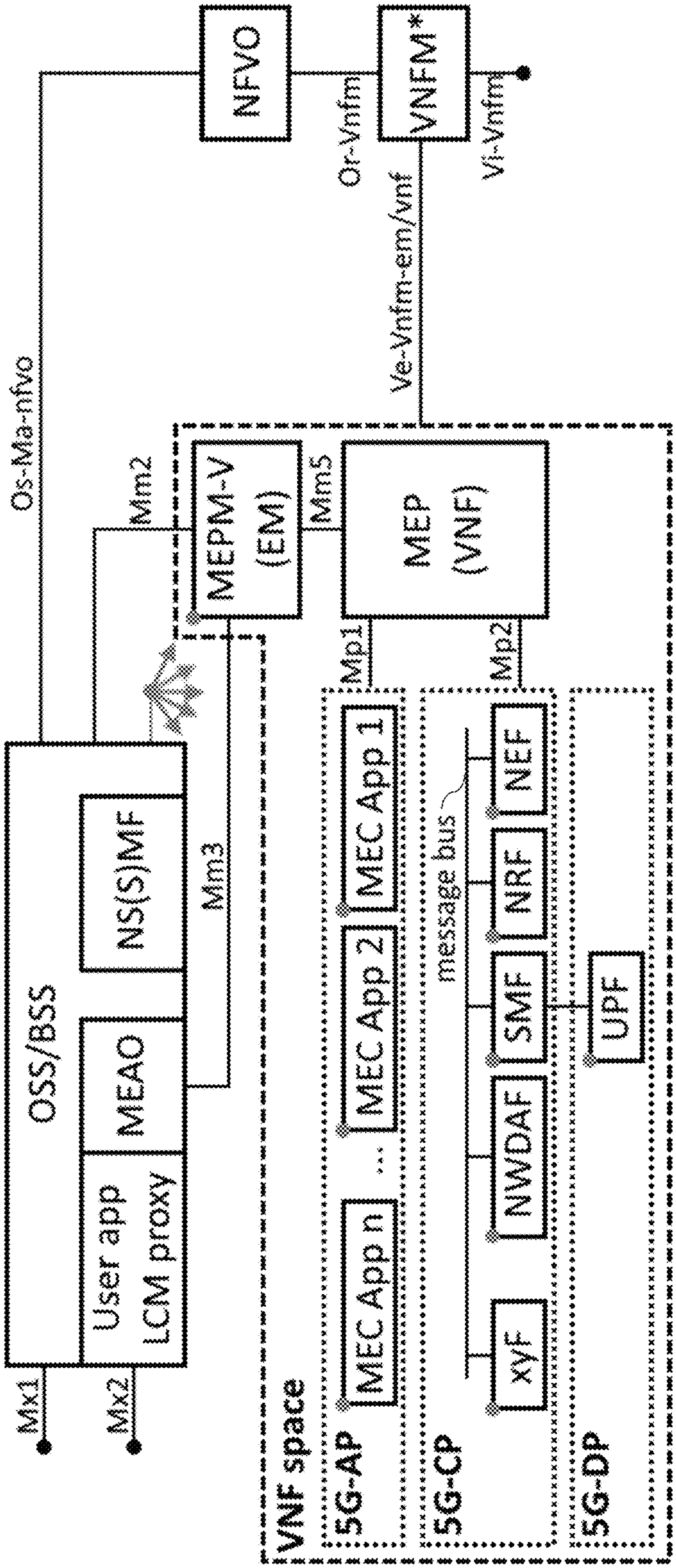

NFVO
VNFM*
Os-Ma-nfvo
Or-Vnfm
Vi-Vnfm
Ve-Vnfm-em/vnf
Mm2
MEPM-V
(EM)
Mm5
MEP
(VNF)
Mp1
Mp2
OSS/BSS
User app
LCM proxy
MEAO
NS(S)MF
Mm3
Mx1
Mx2
VNF space
5G-AP
MEC App n
...
MEC App 2
MEC App 1
5G-CP
xyF
NWDAF
SMF
NRF
NEF
message bus
5G-DP
UPF

FIG. 66

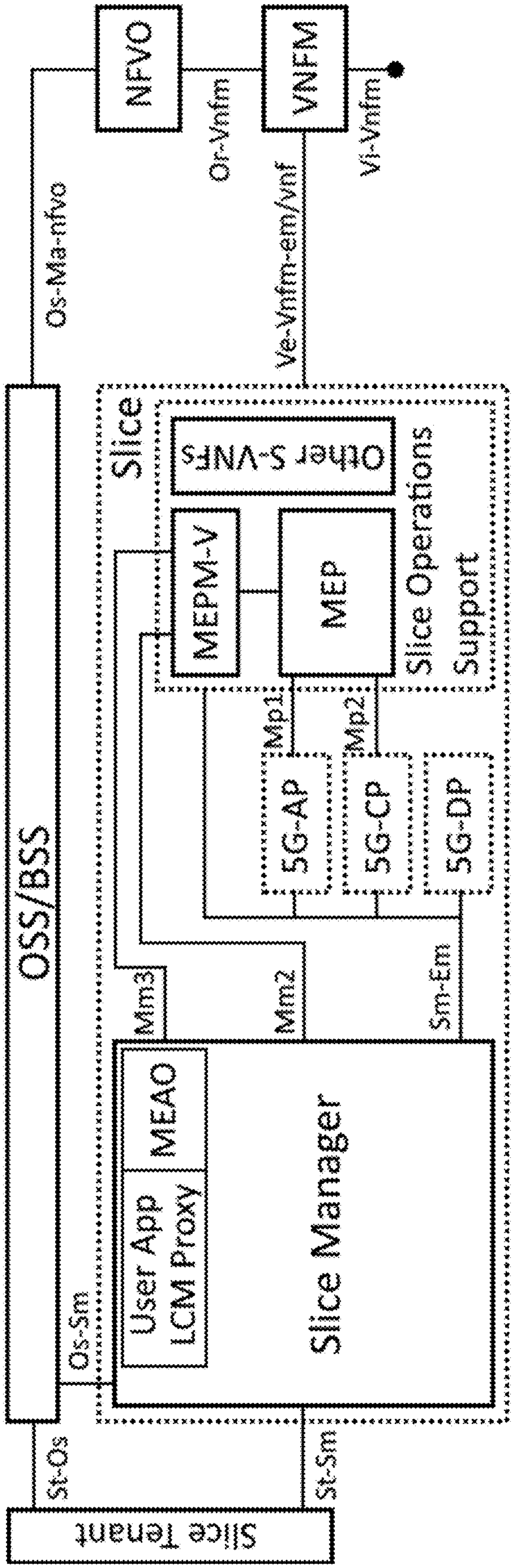

NFVO
VNFM
Os-Ma-nfvo
Or-Vnfm
Ve-Vnfm-em/vnf
Vi-Vnfm
OSS/BSS
Slice
Other S-VNFs
MEPM-V
MEP
Slice Operations Support
Mp1
Mp2
5G-AP
5G-CP
5G-DP
Mm3
Mm2
Sm-Em
MEAO
User App LCM Proxy
Slice Manager
Os-Sm
St-Os
St-Sm
Slice Tenant

FIG. 67

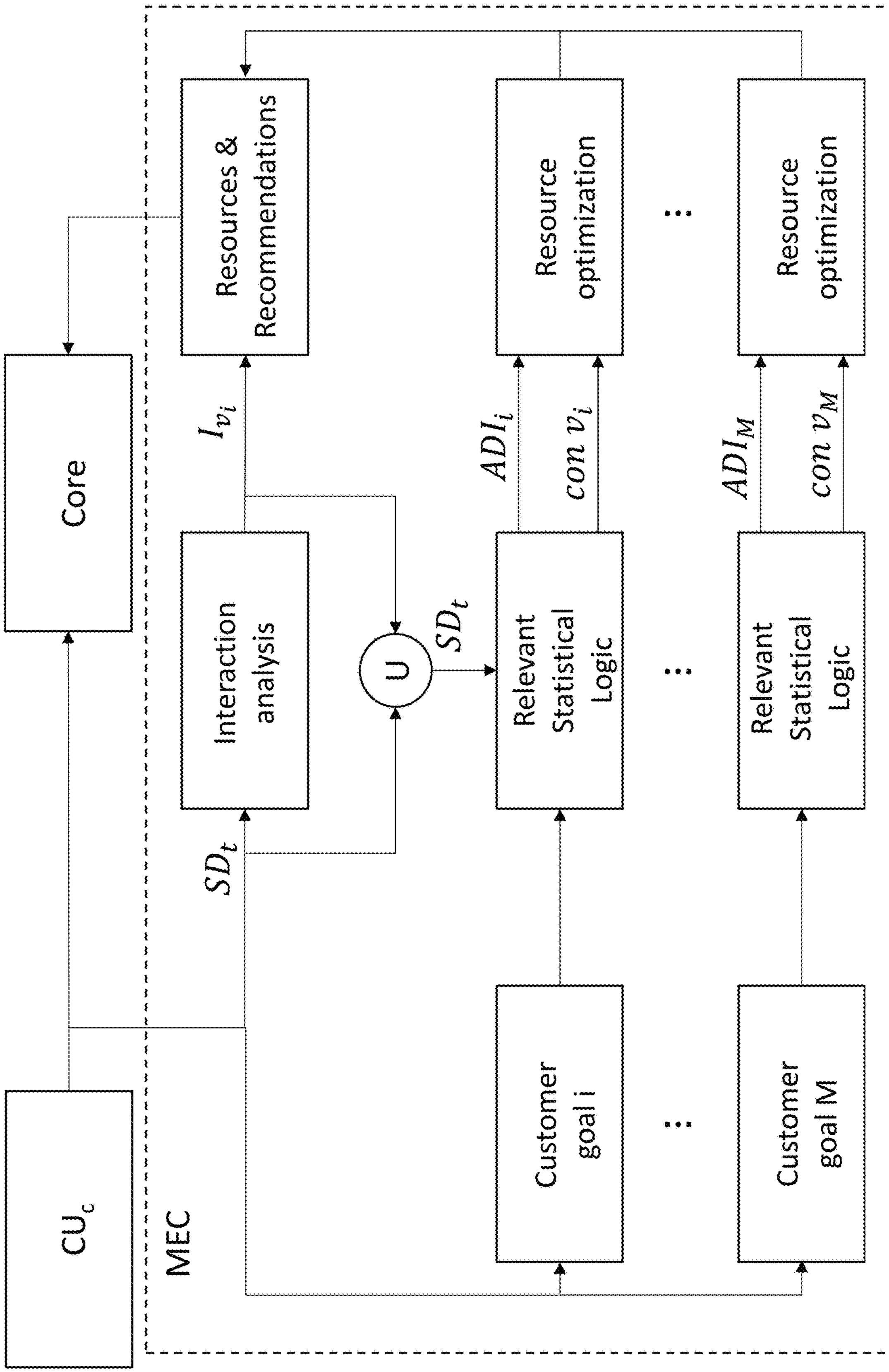

Core
CUc
MEC
Resources & Recommendations
Resource optimization
...
Resource optimization
I_{v_i}
ADI_i
$con\ v_i$
ADI_M
$con\ v_M$
Interaction analysis
U
SD_t
Relevant Statistical Logic
...
Relevant Statistical Logic
SD_t
Customer goal i
...
Customer goal M

FIG. 68

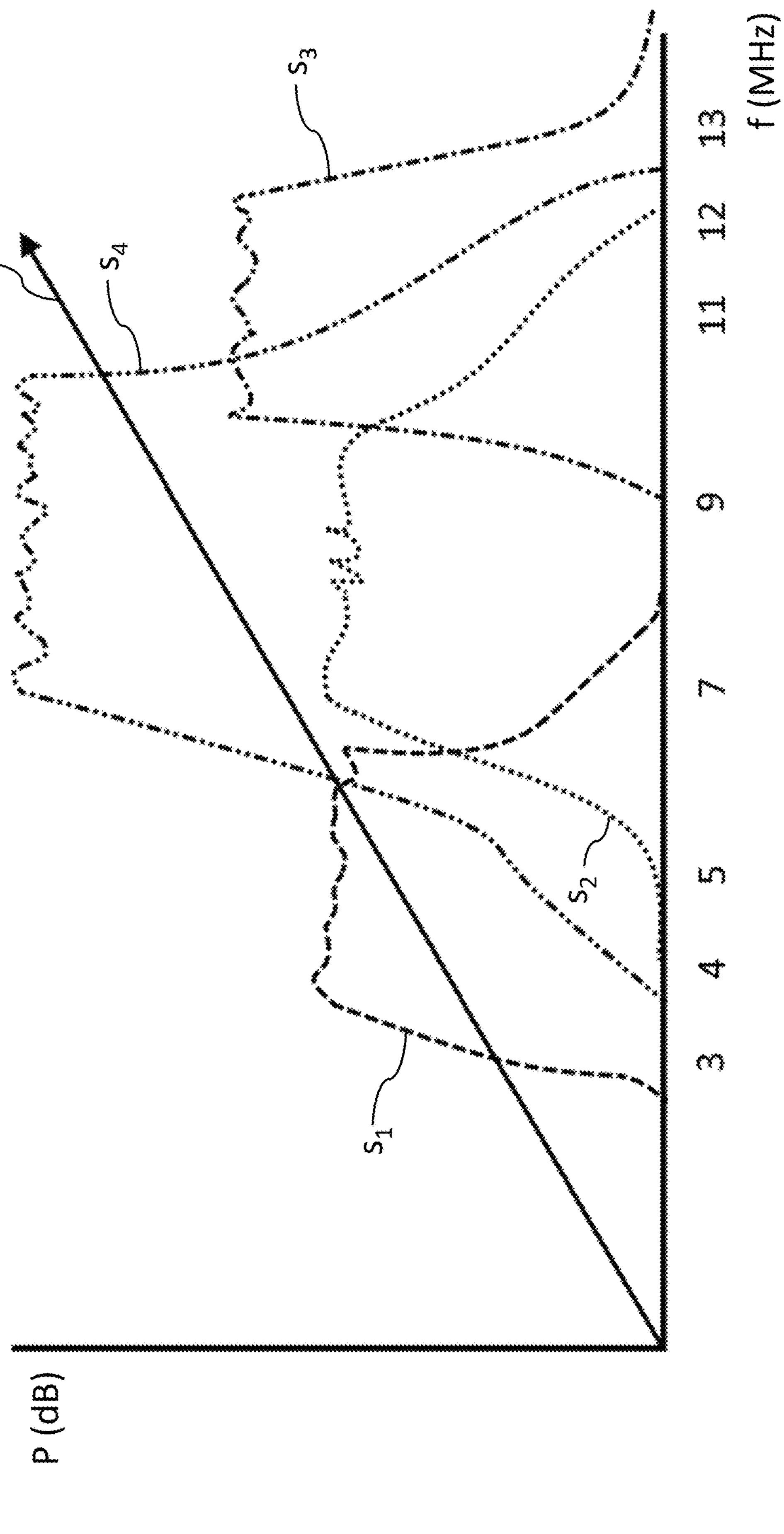


FIG. 69

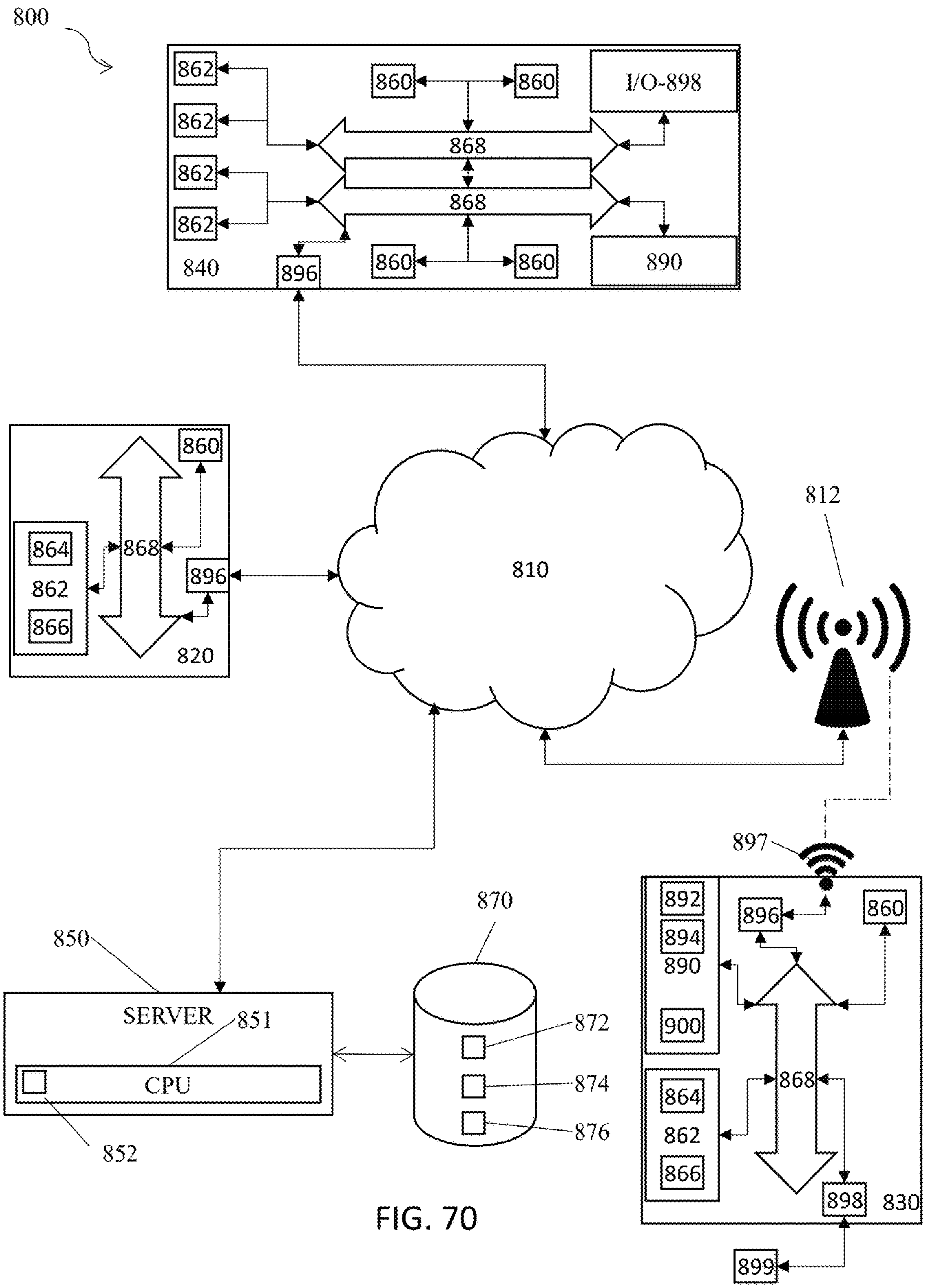

800
862
862
862
862
860
860
860
860
I/O-898
868
868
840
896
890
860
864
868
862
896
866
820
810
812
897
892
896
860
894
890
900
868
864
862
866
898
830
899
870
850
SERVER
851
CPU
852
872
874
876

FIG. 70

Interference Template

Network [PWN] *Date | time* [Date | time] | *Location* [Location]

Specified Channel	2	**Total Analysis Time**	1 Hour
Start/Stop Frequency	3560/3570 (MHz)	**Start/Stop Time**	1300/1400 (UTC)
Channel Bandwidth	10 (MHz)	**Sample Rate**	50 MSPS (Optional)
Total Channels Surveyed	15	**Resolution Bandwidth**	5 KHz (Optional)
Total Bandwidth	150 (MHz)	**Reference Point**	Positioned in Network

Interference Metrics

Duration of Interference (Duty Cycle)	**Observation Time**	**Analysis Time**	**Duty Cycle**
	180 seconds	1 Hour	.05

Observable	**Average Value**	**Peak Value**	**Minimum**
Signal to Noise Ratio (dB)	- 2.1	6.22	- 7.3
Signal to Interference Ratio (dB)	- 4.2	5.13	- 8.4
Data Throughput Rate (Bits/Sec)	202.6	231.4	134.8
RSRP (dBm)	- 101.8	- 93.4	- 111.2
RSRQ (dB)	- 18.1	-12.6	- 19.5
EC/IO (dB)	- 15.3	2.2	-7.3
Bit Error Rate	.032	.014	.047

Adjacent Channel Measurements (Channelized)

Adjacent Channel Information	**Avg. Power (dBm)**	**Peak Power (dBm)**	**Occupancy %**
Channel 1 / 3550 – 3560 MHz	-62	-74	32
Channel 3 / 3570 – 3580 MHz	-51	-61	48

Geolocation

Geolocation Available	**Reference Point**
No	No (Optional)

FIG. 71A

Additional Evidence of External Interference

Evidence Available	**Topic**	**Notes**
Yes	Observation Description	Wideband Signal (Type)
Type of Interference	Method of Observation	Spectrum Monitoring
Intermittent		
Signal Characteristics	Protocol	LTE
	Modulation	QPSK
	Envelope	PAR
	Cyclostationary	Cycle Frequency = 20
	Center Frequency	3565.250 MHz
	Bandwidth	1.5 MHz
	Average Power	20 dBFS

FIG. 71B

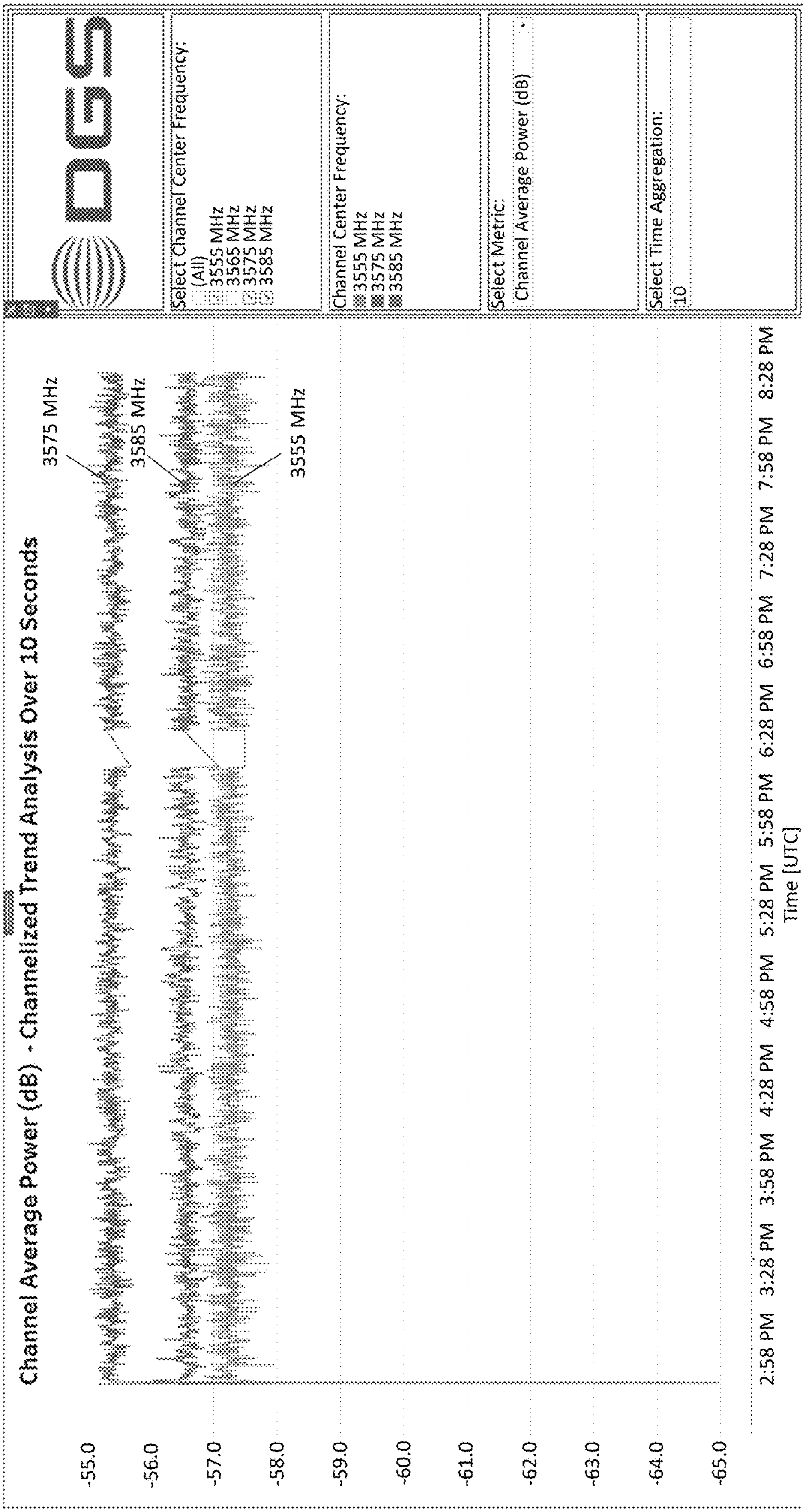

Channel Average Power (dB) - Channelized Trend Analysis Over 10 Seconds
-55.0
-56.0
-57.0
-58.0
-59.0
-60.0
-61.0
-62.0
-63.0
-64.0
-65.0
3575 MHz
3585 MHz
3555 MHz
2:58 PM
3:28 PM
3:58 PM
4:28 PM
4:58 PM
5:28 PM
5:58 PM
6:28 PM
6:58 PM
7:28 PM
7:58 PM
8:28 PM
Time [UTC]
DGS
Select Channel Center Frequency:
(All)
3555 MHz
3565 MHz
3575 MHz
3585 MHz
Channel Center Frequency:
3555 MHz
3575 MHz
3585 MHz
Select Metric:
Channel Average Power (dB)
Select Time Aggregation:
10

FIG. 72

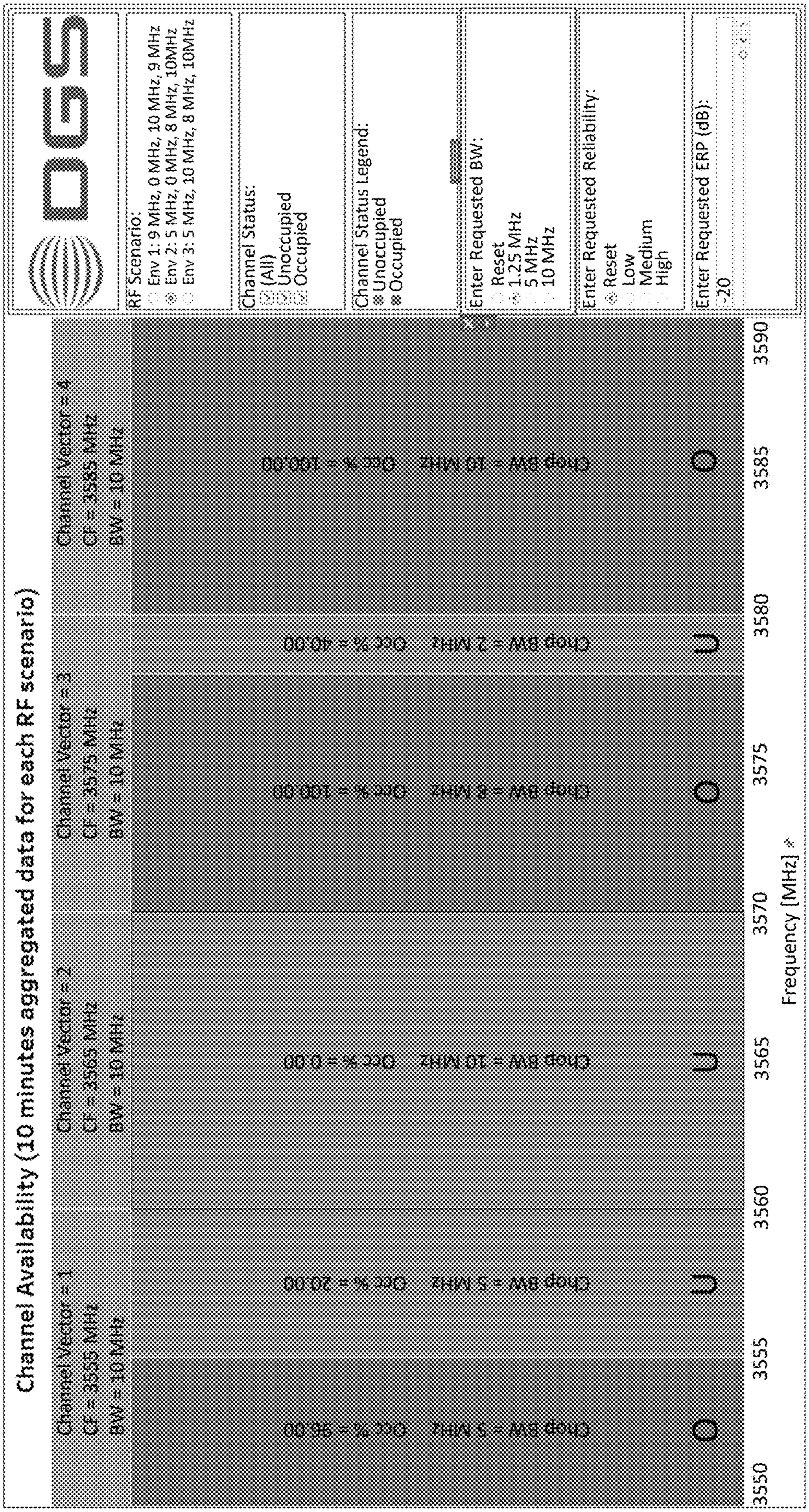

Channel Availability (10 minutes aggregated data for each RF scenario)
Channel Vector = 1
CF = 3555 MHz
BW = 10 MHz
Channel Vector = 2
CF = 3565 MHz
BW = 10 MHz
Channel Vector = 3
CF = 3575 MHz
BW = 10 MHz
Channel Vector = 4
CF = 3585 MHz
BW = 10 MHz
Chop BW = 5 MHz
Occ % = 96.00
O
Chop BW = 5 MHz
Occ % = 20.00
U
Chop BW = 10 MHz
Occ % = 0.00
U
Chop BW = 8 MHz
Occ % = 100.00
O
Chop BW = 2 MHz
Occ % = 40.00
U
Chop BW = 10 MHz
Occ % = 100.00
O
3550
3555
3560
3565
3570
3575
3580
3585
3590
Frequency [MHz]
DGS
RF Scenario:
Env 1: 9 MHz, 0 MHz, 10 MHz, 9 MHz
Env 2: 5 MHz, 0 MHz, 8 MHz, 10MHz
Env 3: 5 MHz, 10 MHz, 8 MHz, 10MHz
Channel Status:
(All)
Unoccupied
Occupied
Channel Status Legend:
Unoccupied
Occupied
Enter Requested BW:
Reset
1.25 MHz
5 MHz
10 MHz
Enter Requested Reliability:
Reset
Low
Medium
High
Enter Requested ERP (dB):
-20

FIG. 73

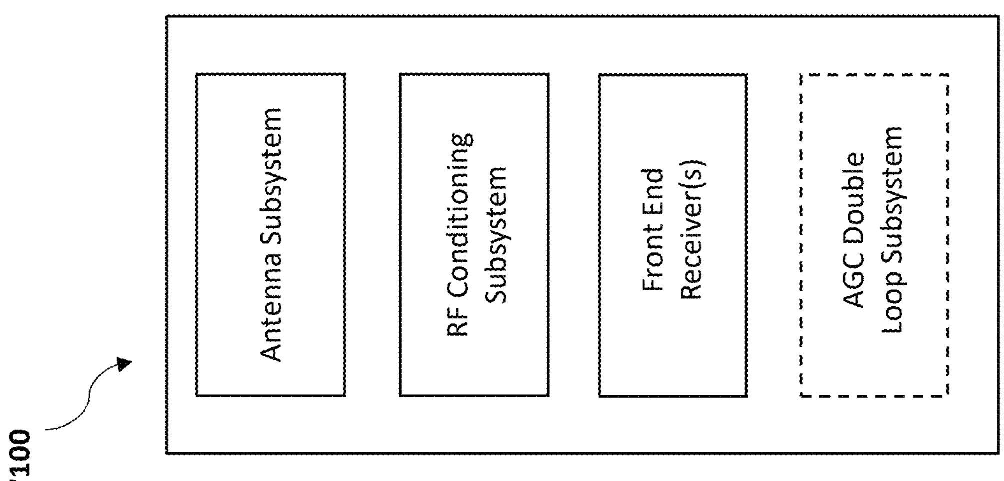

7100
Antenna Subsystem
RF Conditioning Subsystem
Front End Receiver(s)
AGC Double Loop Subsystem

FIG. 74

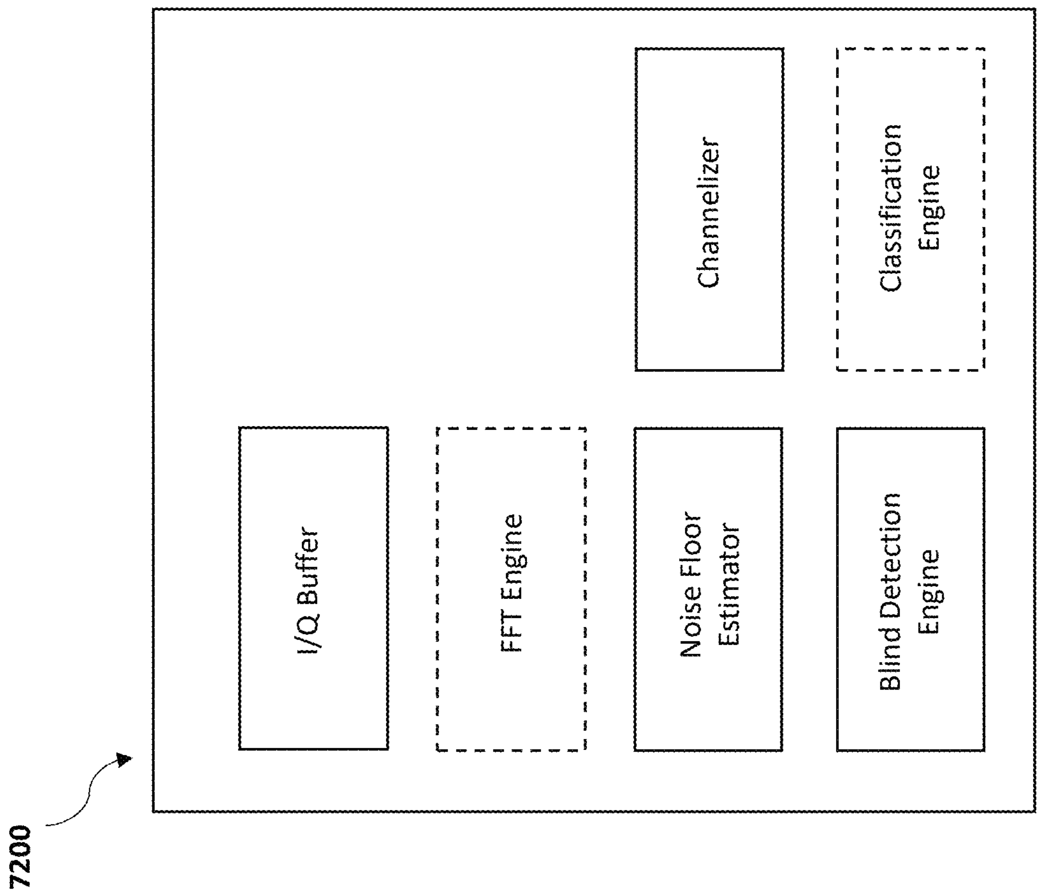

7200
I/Q Buffer
FFT Engine
Noise Floor Estimator
Blind Detection Engine
Channelizer
Classification Engine

FIG. 75

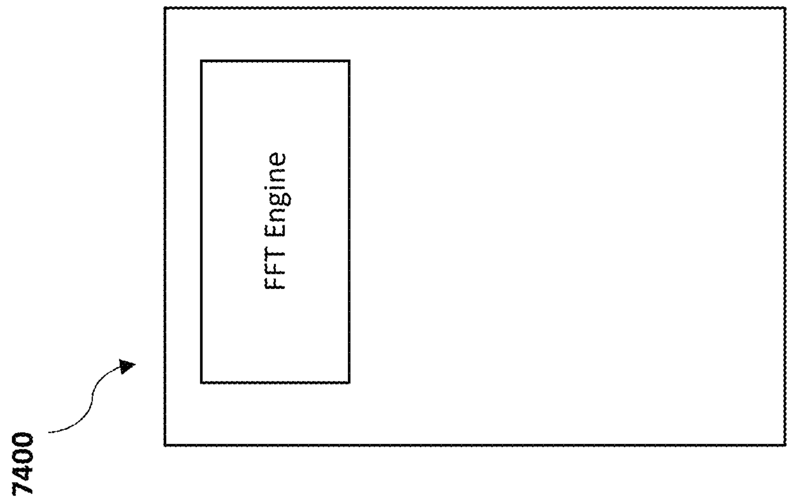

7400
FFT Engine

FIG. 77

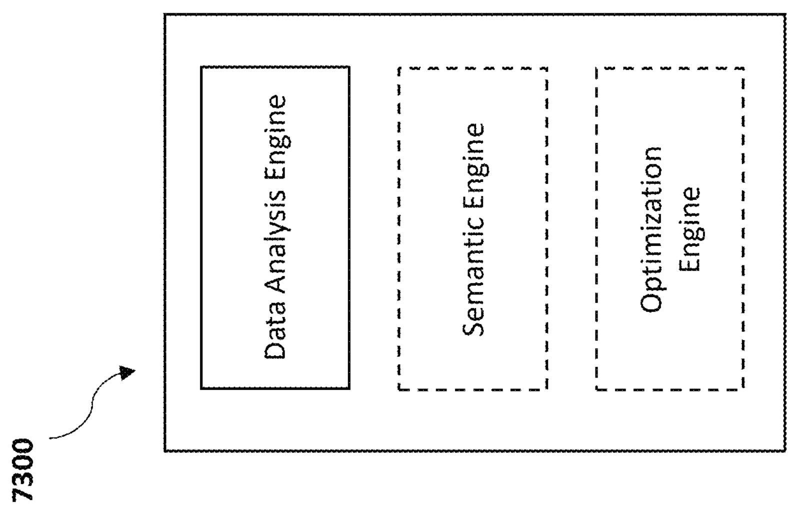

7300
Data Analysis Engine
Semantic Engine
Optimization Engine

FIG. 76

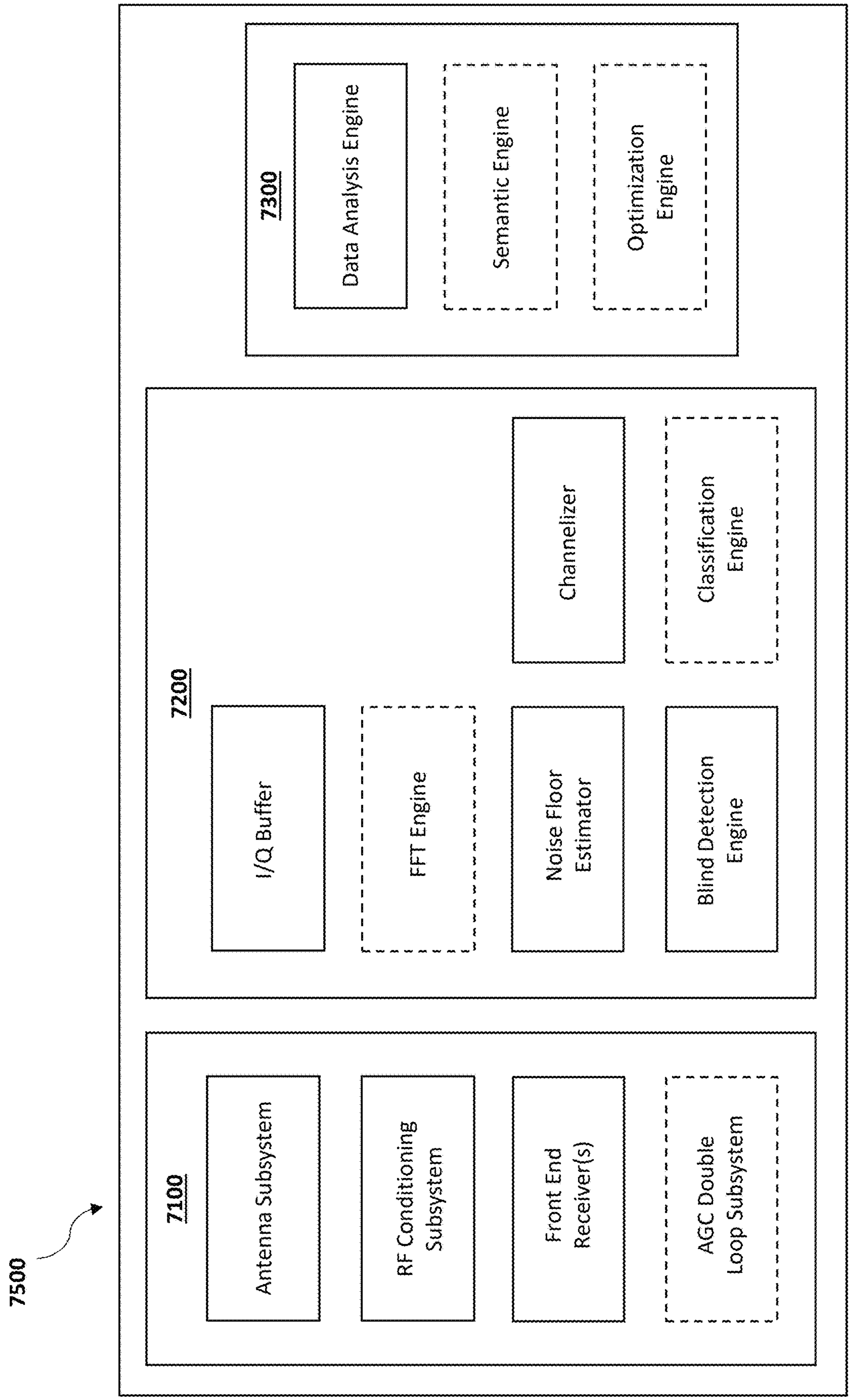

7500
7100
Antenna Subsystem
RF Conditioning Subsystem
Front End Receiver(s)
AGC Double Loop Subsystem
7200
I/Q Buffer
FFT Engine
Noise Floor Estimator
Blind Detection Engine
Channelizer
Classification Engine
7300
Data Analysis Engine
Semantic Engine
Optimization Engine

FIG. 78

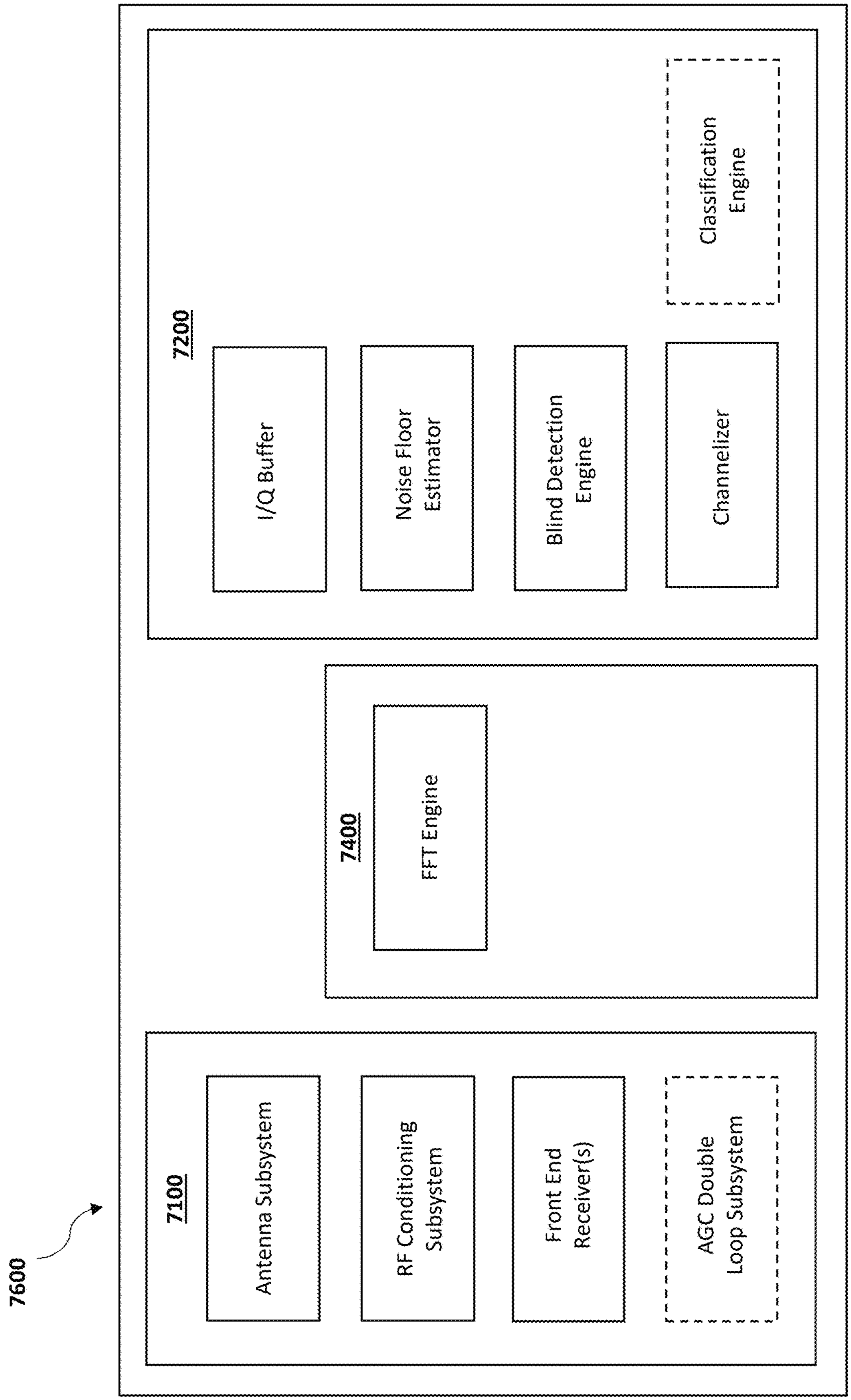

7600
7100
Antenna Subsystem
RF Conditioning Subsystem
Front End Receiver(s)
AGC Double Loop Subsystem
7400
FFT Engine
7200
I/Q Buffer
Noise Floor Estimator
Blind Detection Engine
Channelizer
Classification Engine

FIG. 79

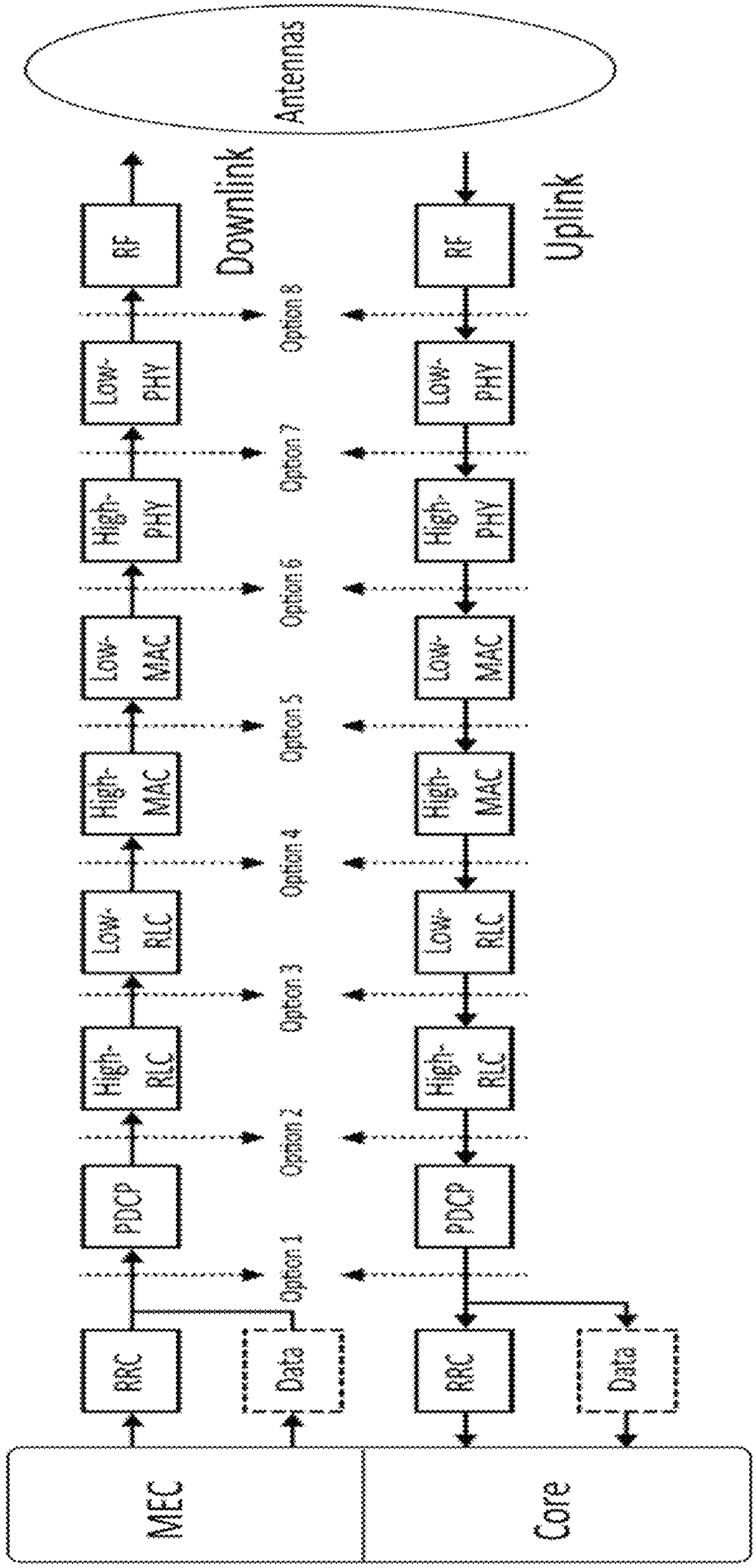

Antennas
Downlink
Uplink
RF
Low-PHY
High-PHY
Low-MAC
High-MAC
Low-RLC
High-RLC
PDCP
RRC
Data
Option 1
Option 2
Option 3
Option 4
Option 5
Option 6
Option 7
Option 8
MEC
Core

FIG. 80

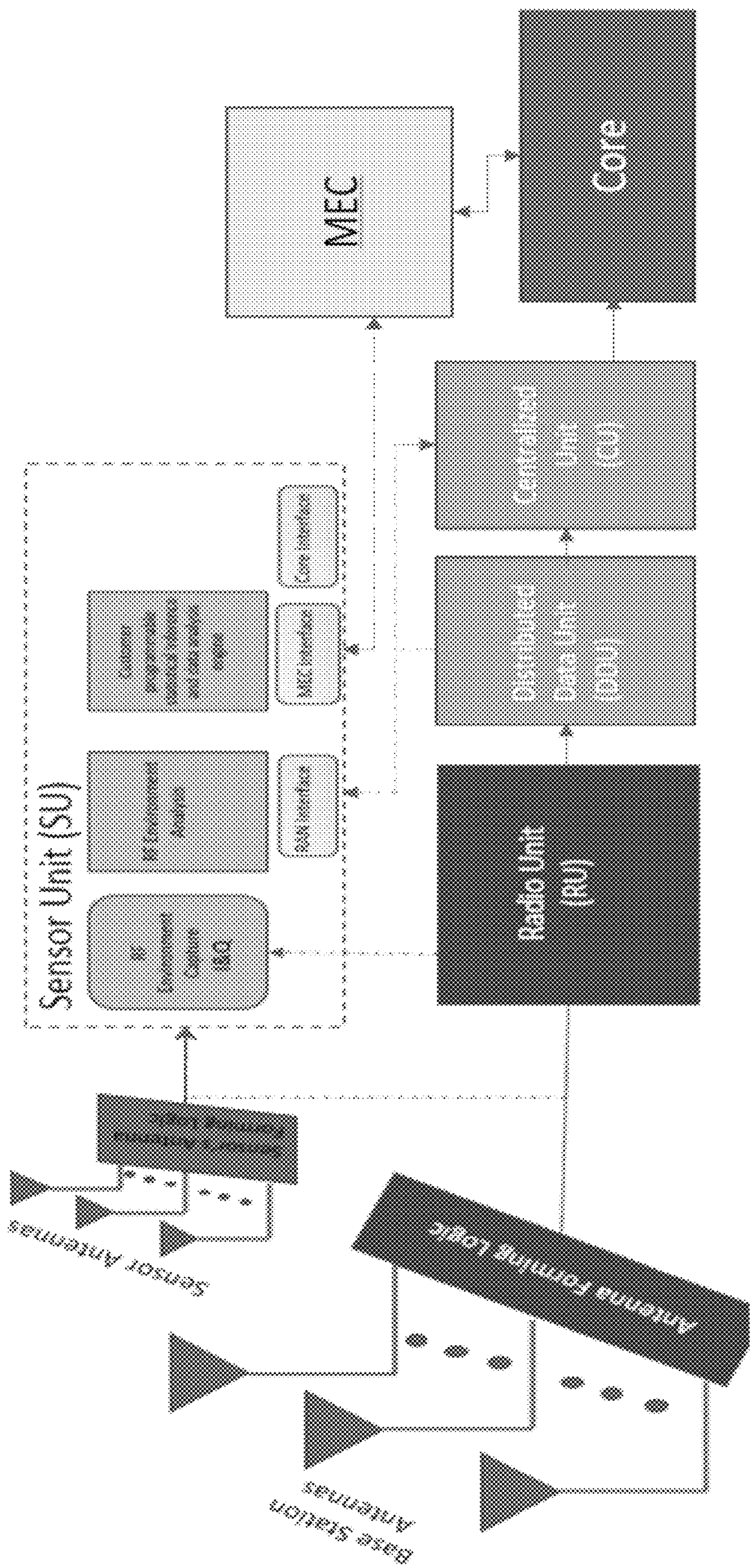
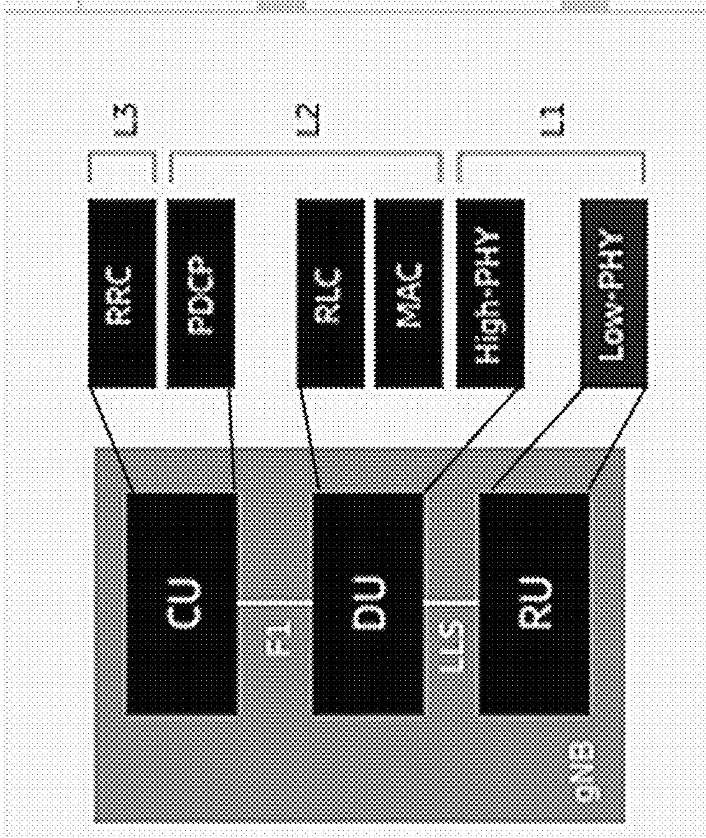

MEC
Core
Centralized Unit (CU)
Distributed Data Unit (DDU)
Radio Unit (RU)
Sensor Unit (SU)
Antenna Forming Logic
Sensor Antennas
Base Station Antennas

FIG. 81



Function	Subfunction	Main processing function
CU	Control plane (CU-C)	Radio Resource Control
	User plane (CU-U)	Packet Data Convergence Protocol
Higher Layer Split (HLS / F1)		
DU	Digital Unit	Radio Link Control
		Medium Access Protocol
		Physical layers
Lower Layer Split (LLS)		
RU	Radio Unit	Beamforming (if applicable)

FIG. 82A

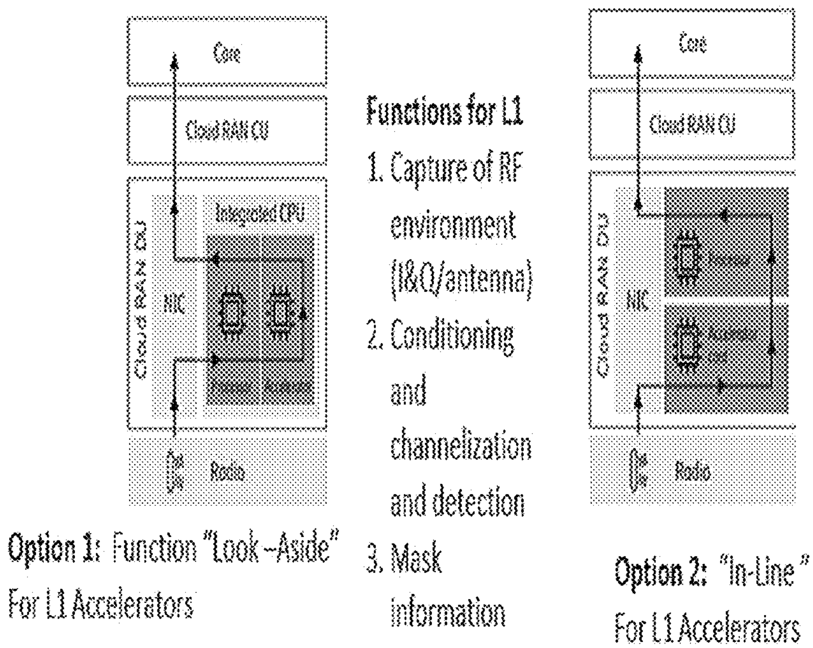

Core
Cloud RAN CU
Integrated CPU
NIC
Cloud RAN DU
Radio
Option 1: Function "Look -Aside"
For L1 Accelerators
Functions for L1
1. Capture of RF environment (I&Q/antenna)
2. Conditioning and channelization and detection
3. Mask information
Core
Cloud RAN CU
NIC
Cloud RAN DU
Radio
Option 2: "In-Line"
For L1 Accelerators

FIG. 82B

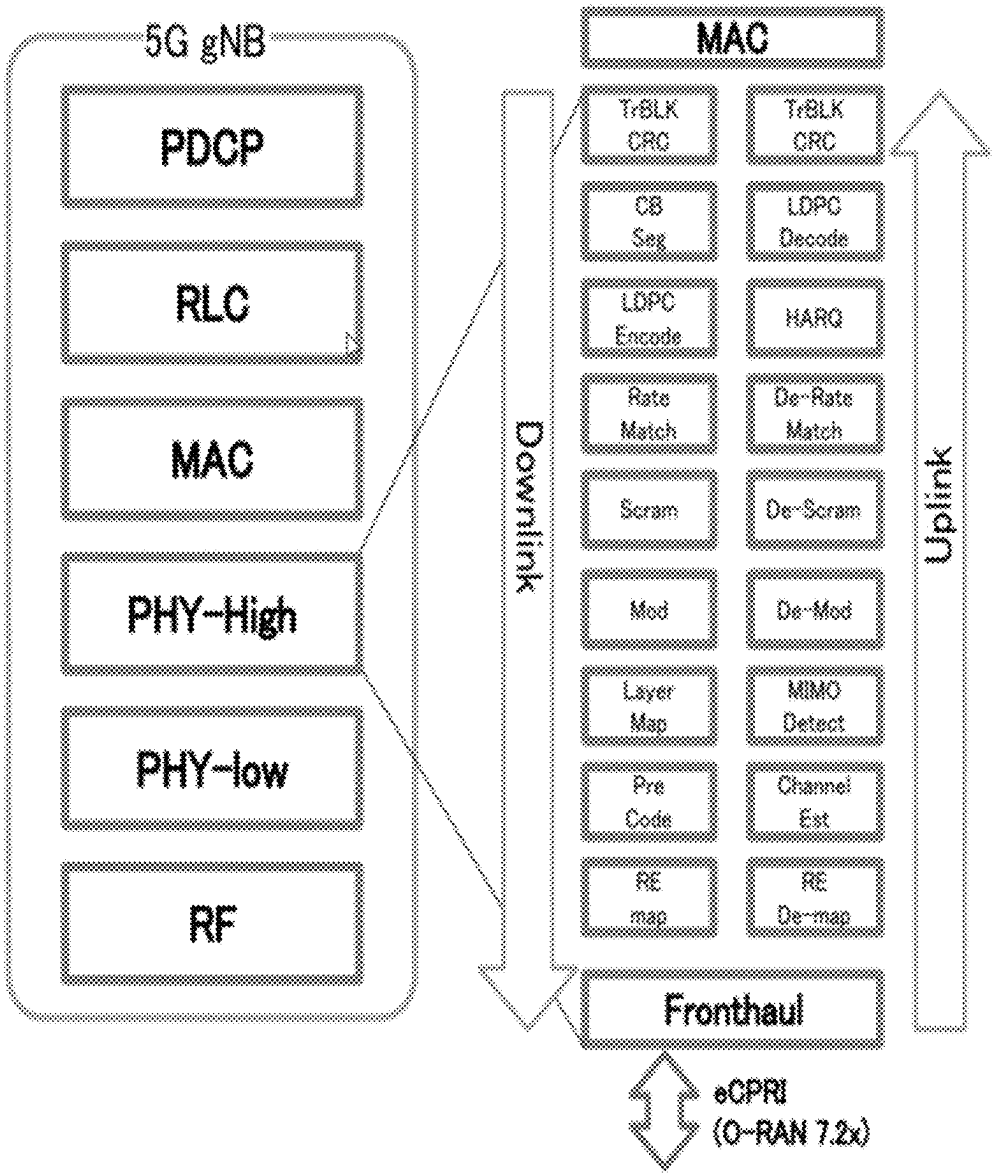

5G gNB
PDCP
RLC
MAC
PHY-High
PHY-low
RF
MAC
TrBLK CRC
TrBLK CRC
CB Seg
LDPC Decode
LDPC Encode
HARQ
Rate Match
De-Rate Match
Scram
De-Scram
Mod
De-Mod
Layer Map
MIMO Detect
Pre Code
Channel Est
RE map
RE De-map
Downlink
Uplink
Fronthaul
eCPRI
(O-RAN 7.2x)

FIG. 83A

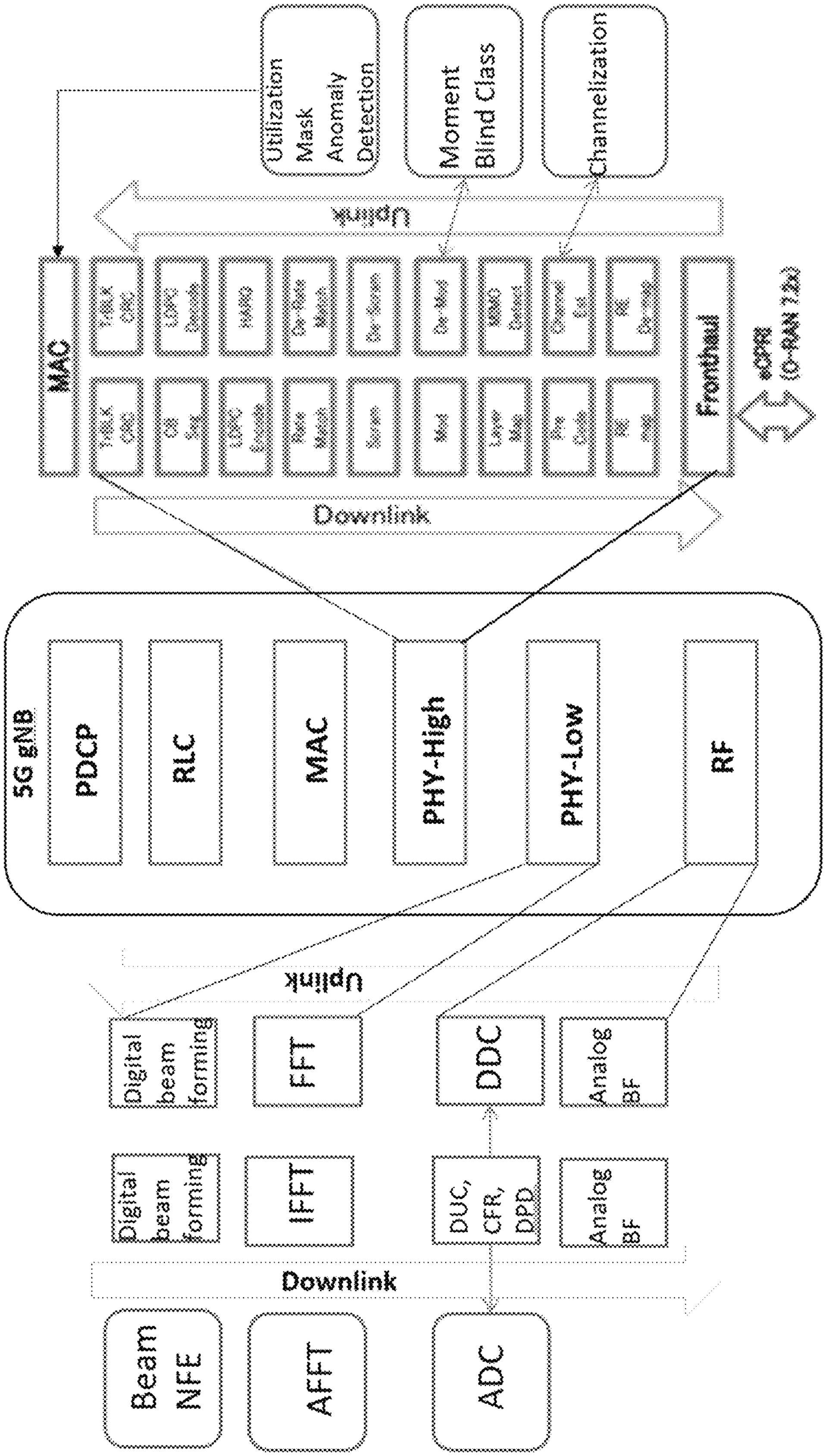

Utilization Mask Anomaly Detection
Moment Blind Class
Channelization
Uplink
MAC
Fronthaul
Downlink
5G gNB
PDCP
RLC
MAC
PHY-High
PHY-Low
RF
Uplink
Digital beam forming
FFT
DDC
Analog BF
Digital beam forming
IFFT
DUC, CFR, DPD
Analog BF
Downlink
Beam NFE
AFFT
ADC

FIG. 83B

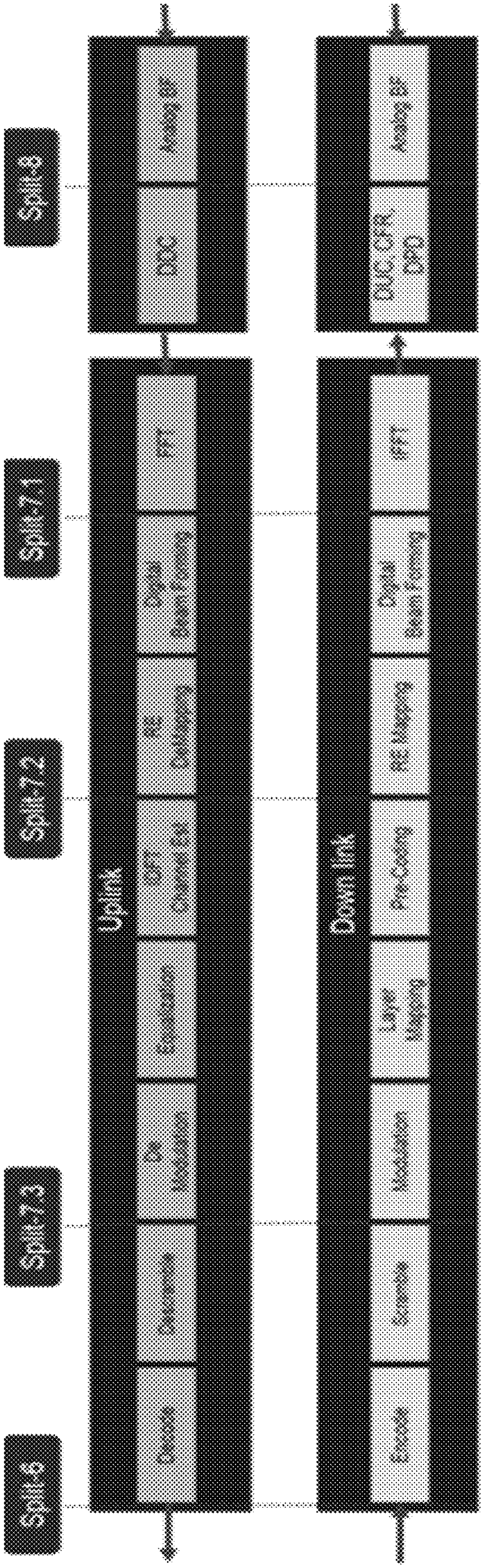

Split-6
Split-7.3
Split-7.2
Split-7.1
Split-8
Uplink
Decode
Descramble
De Modulation
Equalization
IDFT Channel Est
RE DeMapping
Digital Beam Forming
FFT
DDC
Analog BF
Down link
Encode
Scramble
Modulation
Layer Mapping
Pre-Coding
RE Mapping
Digital Beam Forming
iFFT
DUC, CFR DPD
Analog BF

FIG. 84A

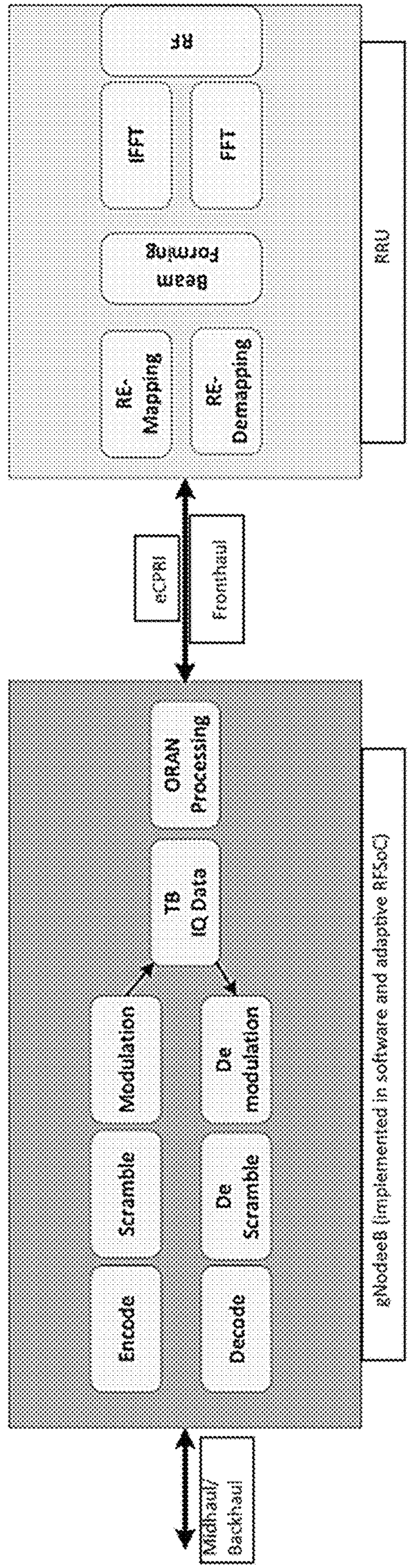

RF
IFFT
FFT
Beam
Forming
RE-
Mapping
RE-
Demapping
RRU
eCPRI
Fronthaul
ORAN
Processing
TB
IQ Data
Modulation
De
modulation
Scramble
De
Scramble
Encode
Decode
gNodeeB (implemented in software and adaptive RFSoC)
Midhaul/
Backhaul

FIG. 84B

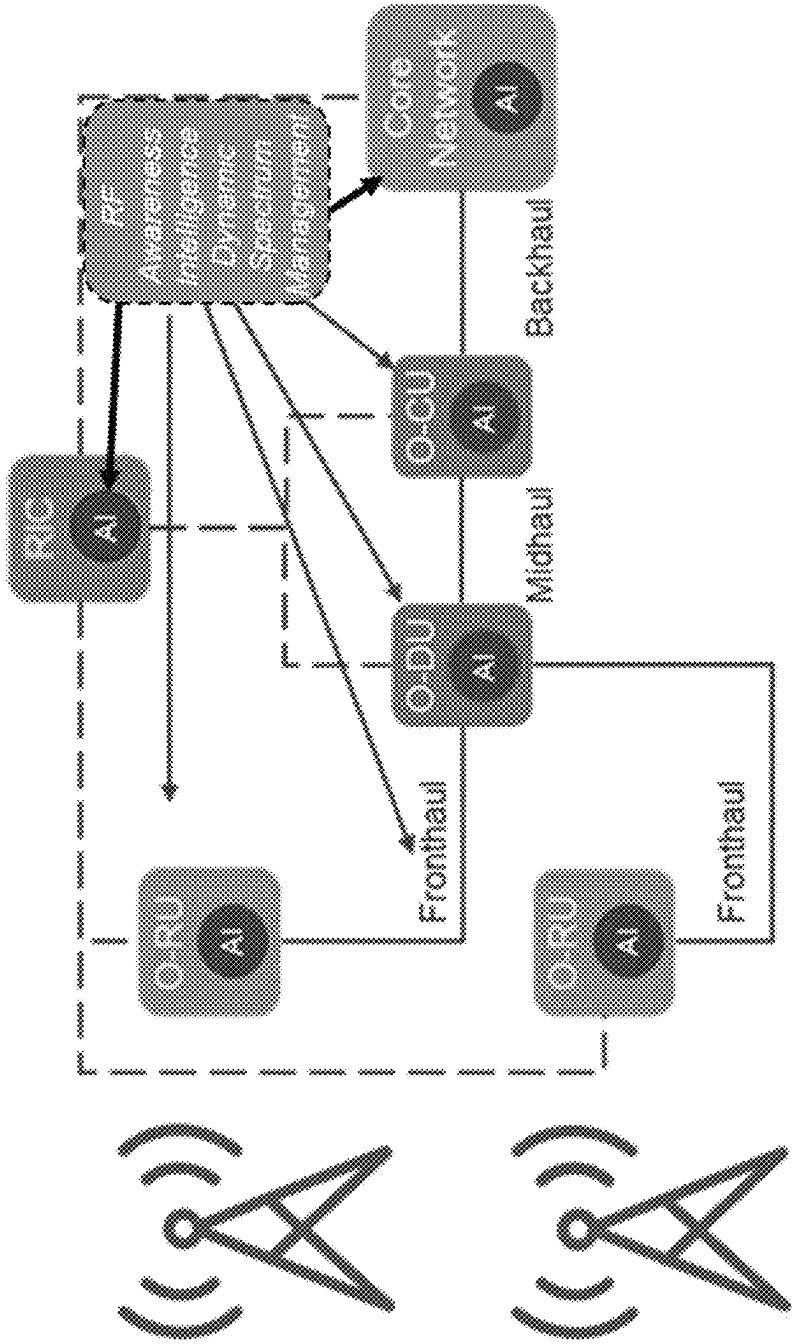

RF Awareness Intelligence Dynamic Spectrum Management
Core Network
AI
RIC
AI
O-CU
AI
O-DU
AI
O-RU
AI
O-RU
AI
Backhaul
Midhaul
Fronthaul
Fronthaul

FIG. 85

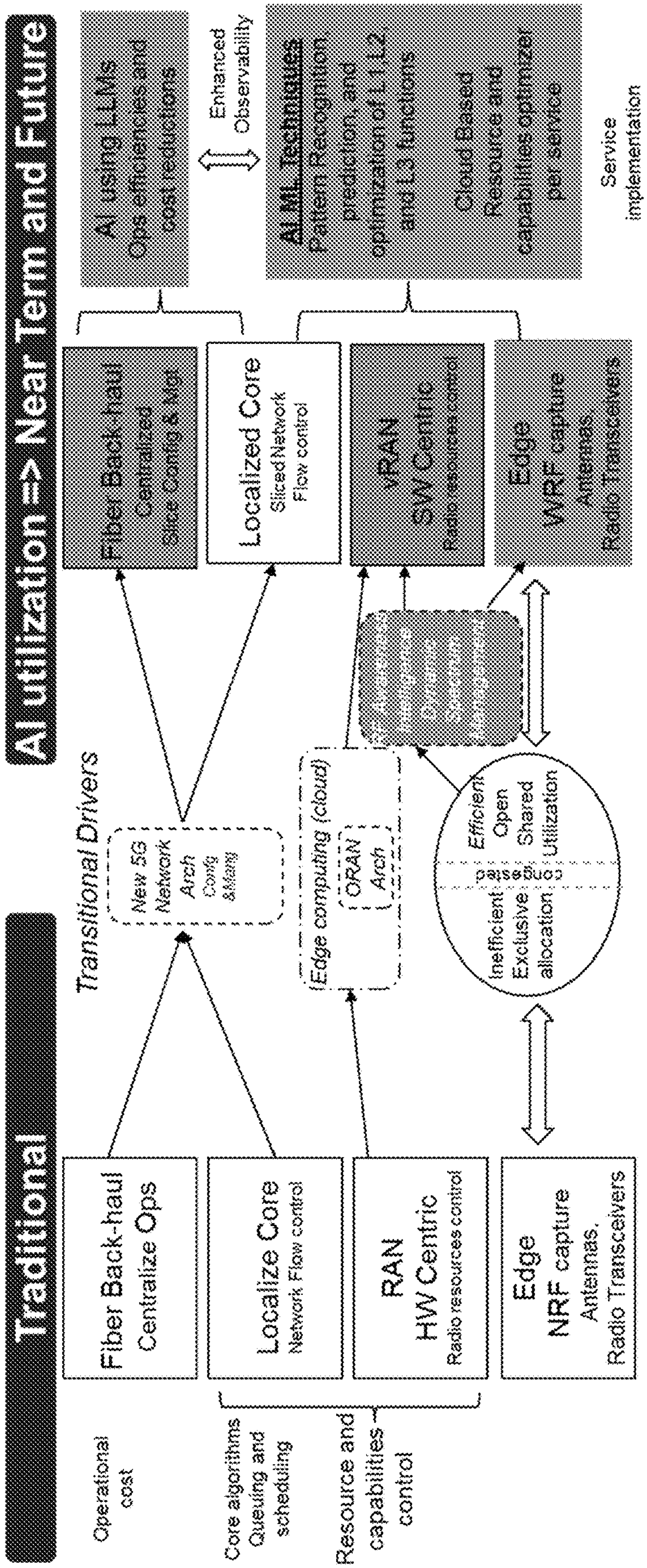

Traditional
AI utilization => Near Term and Future
Operational cost
Core algorithms Queuing and scheduling
Resource and capabilities control
Fiber Back-haul
Centralize Ops
Localize Core
Network Flow control
RAN
HW Centric
Radio resources control
Edge
NRF capture
Antennas,
Radio Transceivers
Transitional Drivers
New 5G Network Arch Config &Mang
Edge computing (cloud)
ORAN Arch
Inefficient Exclusive allocation
congested
Efficient Open Shared Utilization
Fiber Back-haul
Centralized
Slice Config & Mgt
Localized Core
Sliced Network
Flow control
vRAN
SW Centric
Radio resources control
Edge
WRF capture
Antennas,
Radio Transceivers
AI using LLMs
Ops efficiencies and cost reductions
Enhanced Observability
AI ML Techniques
Pattern Recognition, prediction, and optimization of L1 L2 and L3 functions
Cloud Based Resource and capabilities optimizer per service
Service implementation

FIG. 86

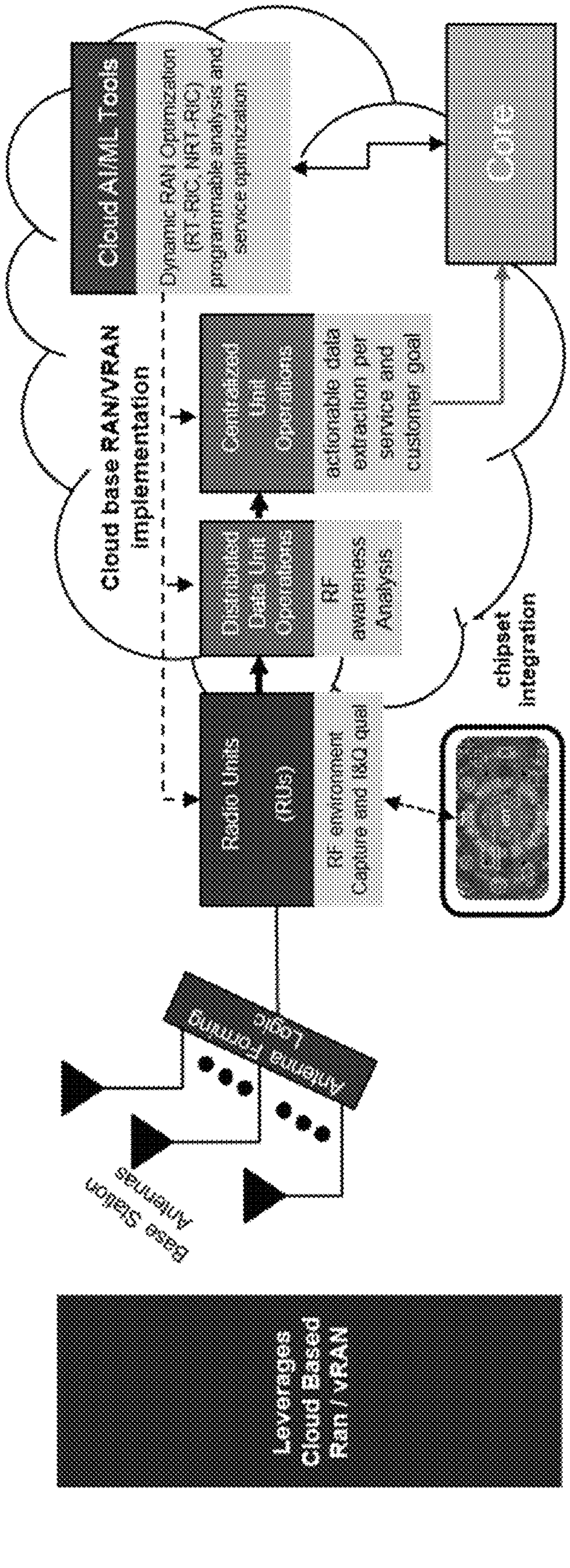

Cloud AI/ML Tools
Dynamic RAN Optimization (RT-RIC, NRT-RIC) programmable analysis and service optimization
Core
Cloud base RAN/VRAN implementation
Centralized Unit Operations
actionable data extraction per service and customer goal
Distributed Data Unit Operations
RF awareness Analysis
Radio Units (RUs)
RF environment Capture and I&Q qual
chipset integration
Antenna Forming Logic
Base Station Antennas
Leverages Cloud Based Ran / vRAN

FIG. 87A

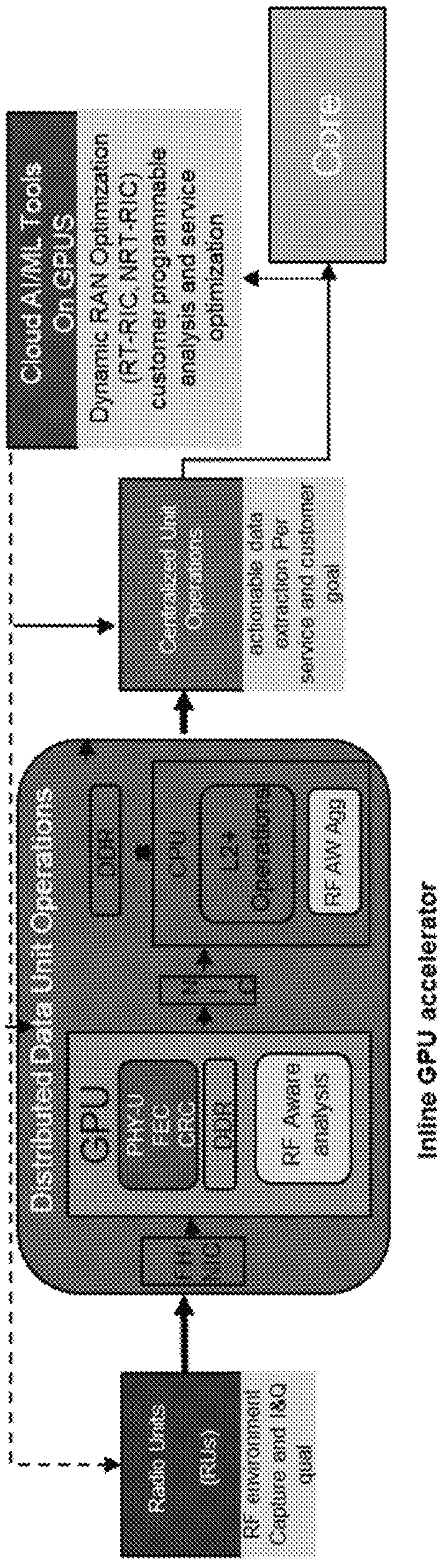

Cloud AI/ML Tools On GPUS
Dynamic RAN Optimization (RT-RIC, NRT-RIC) customer programmable analysis and service optimization
Core
Centralized Unit Operations
actionable data extraction Per service and customer goal
Distributed Data Unit Operations
DDR
CPU
L2+ Operations
RF AW Agg
NIC
GPU
PHY-U FEC CRC
DDR
RF Aware analysis
FH NIC
Inline GPU accelerator
Radio Units (RUs)
RF environment Capture and I&Q qual

FIG. 87B

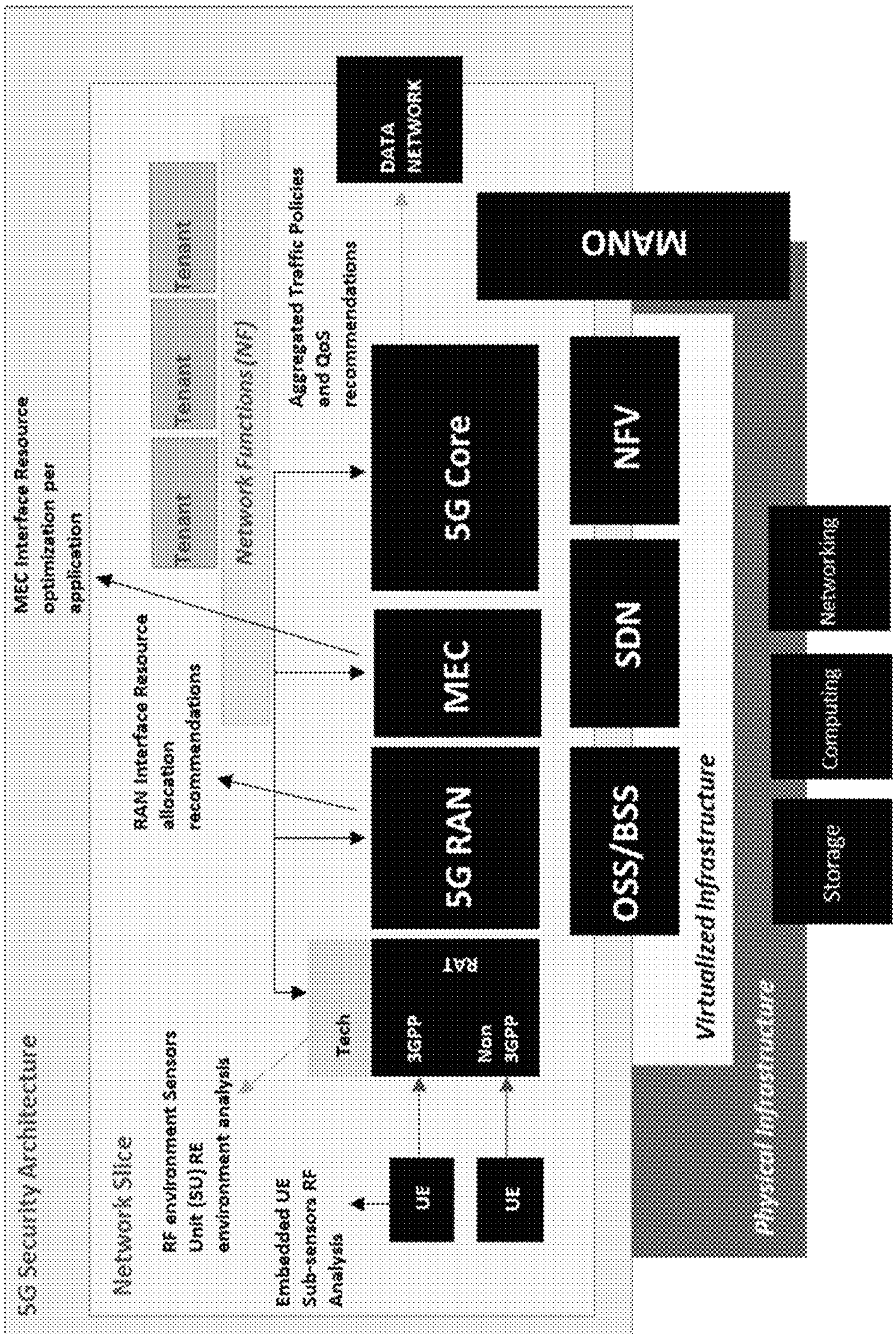

5G Security Architecture
Network Slice
RF environment Sensors Unit (SU) RE environment analysis
Embedded UE Sub-sensors RF Analysis
UE
UE
3GPP
Non 3GPP
RAT
Tech
RAN Interface Resource allocation recommendations
MEC Interface Resource optimization per application
Tenant
Tenant
Tenant
Network Functions (NF)
Aggregated Traffic Policies and QoS recommendations
DATA NETWORK
5G RAN
MEC
5G Core
OSS/BSS
SDN
NFV
MANO
Virtualized Infrastructure
Physical Infrastructure
Storage
Computing
Networking

FIG. 88

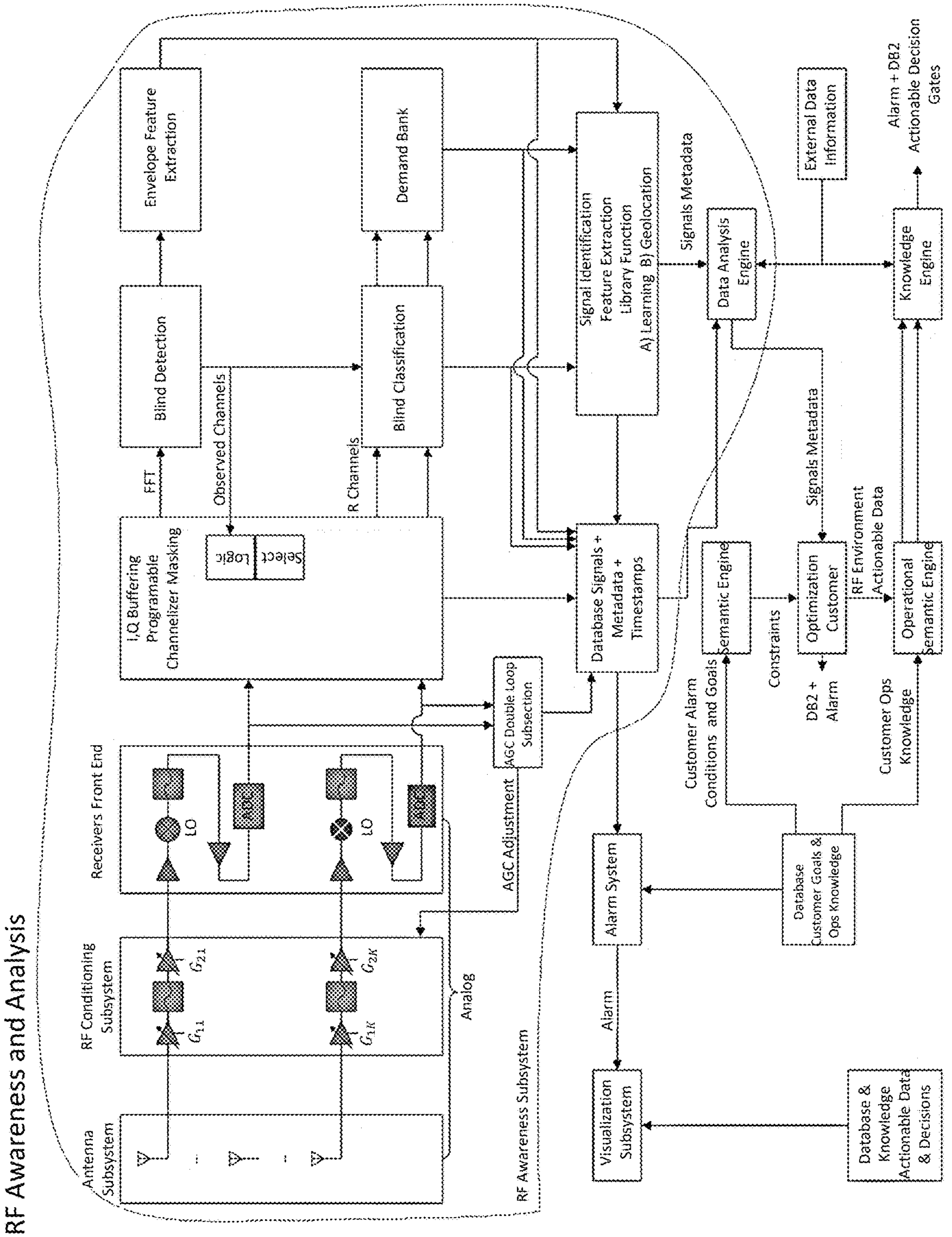

RF Awareness and Analysis
Antenna Subsystem
RF Conditioning Subsystem
Analog
Receivers Front End
LO
ADC
AGC Adjustment
AGC Double Loop Subsection
RF Awareness Subsystem
I,Q Buffering Programable Channelizer Masking
Logic
Select
FFT
Observed Channels
R Channels
Blind Detection
Blind Classification
Envelope Feature Extraction
Demand Bank
Signal Identification Feature Extraction Library Function A) Learning B) Geolocation
Database Signals + Metadata + Timestamps
Signals Metadata
Data Analysis Engine
Semantic Engine
Optimization Customer
Operational Semantic Engine
Knowledge Engine
External Data Information
Alarm + DB2 Actionable Decision Gates
Constraints
DB2 + Alarm
RF Environment Actionable Data
Customer Alarm Conditions and Goals
Customer Ops Knowledge
Database Customer Goals & Ops Knowledge
Alarm System
Alarm
Visualization Subsystem
Database & Knowledge Actionable Data & Decisions

FIG.89

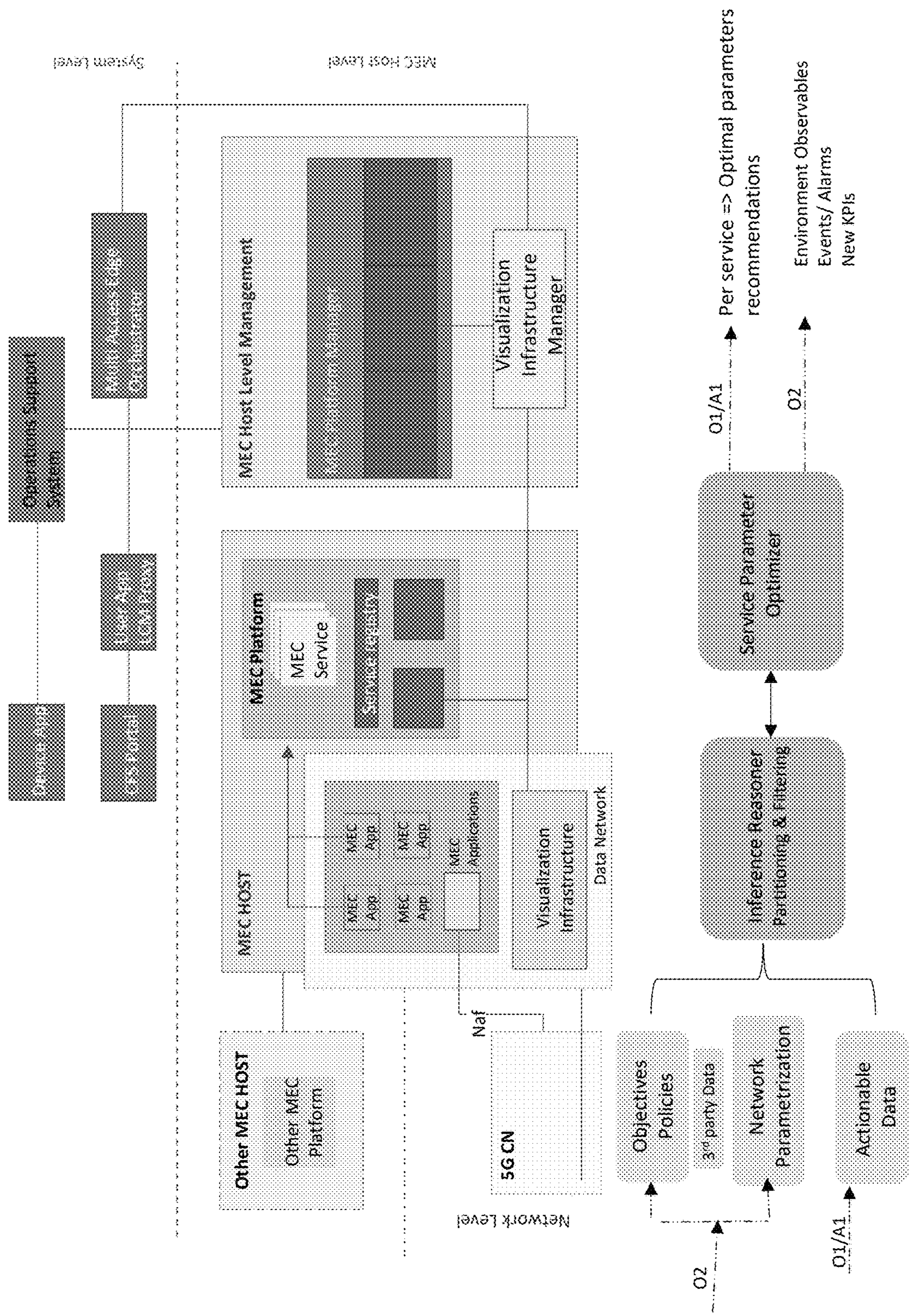

System Level
MEC Host Level
Network Level
Operations Support System
MEC HOST
MEC Platform
MEC Service
MEC App
MEC App
MEC App
MEC App
MEC Applications
Visualization Infrastructure
Data Network
MEC Host Level Management
Visualization Infrastructure Manager
Other MEC HOST
Other MEC Platform
5G CN
Naf
Objectives Policies
3rd party Data
Network Parametrization
Actionable Data
O2
O1/A1
Inference Reasoner
Partitioning & Filtering
Service Parameter Optimizer
O1/A1
O2
Per service => Optimal parameters recommendations
Environment Observables
Events/ Alarms
New KPIs

FIG.90

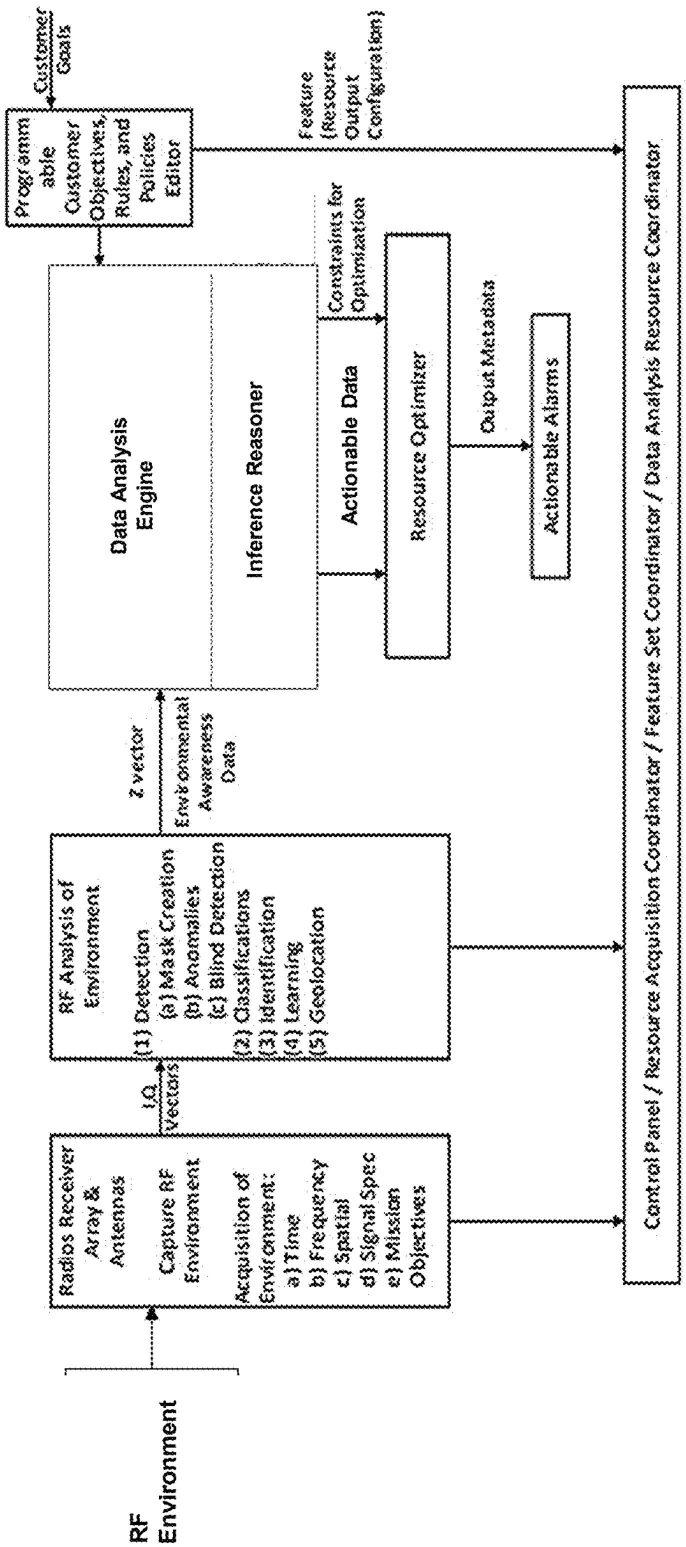

RF Environment
Radios Receiver Array & Antennas
Capture RF Environment
Acquisition of Environment:
a) Time
b) Frequency
c) Spatial
d) Signal Spec
e) Mission Objectives
I,Q Vectors
RF Analysis of Environment
(1) Detection
(a) Mask Creation
(b) Anomalies
(c) Blind Detection
(2) Classification
(3) Identification
(4) Learning
(5) Geolocation
Z vector
Environmental Awareness Data
Data Analysis Engine
Inference Reasoner
Actionable Data
Constraints for Optimization
Resource Optimizer
Output Metadata
Actionable Alarms
Programmable Customer Objectives, Rules, and Policies Editor
Customer Goals
Feature (Resource Output Configuration)
Control Panel / Resource Acquisition Coordinator / Feature Set Coordinator / Data Analysis Resource Coordinator

FIG.91

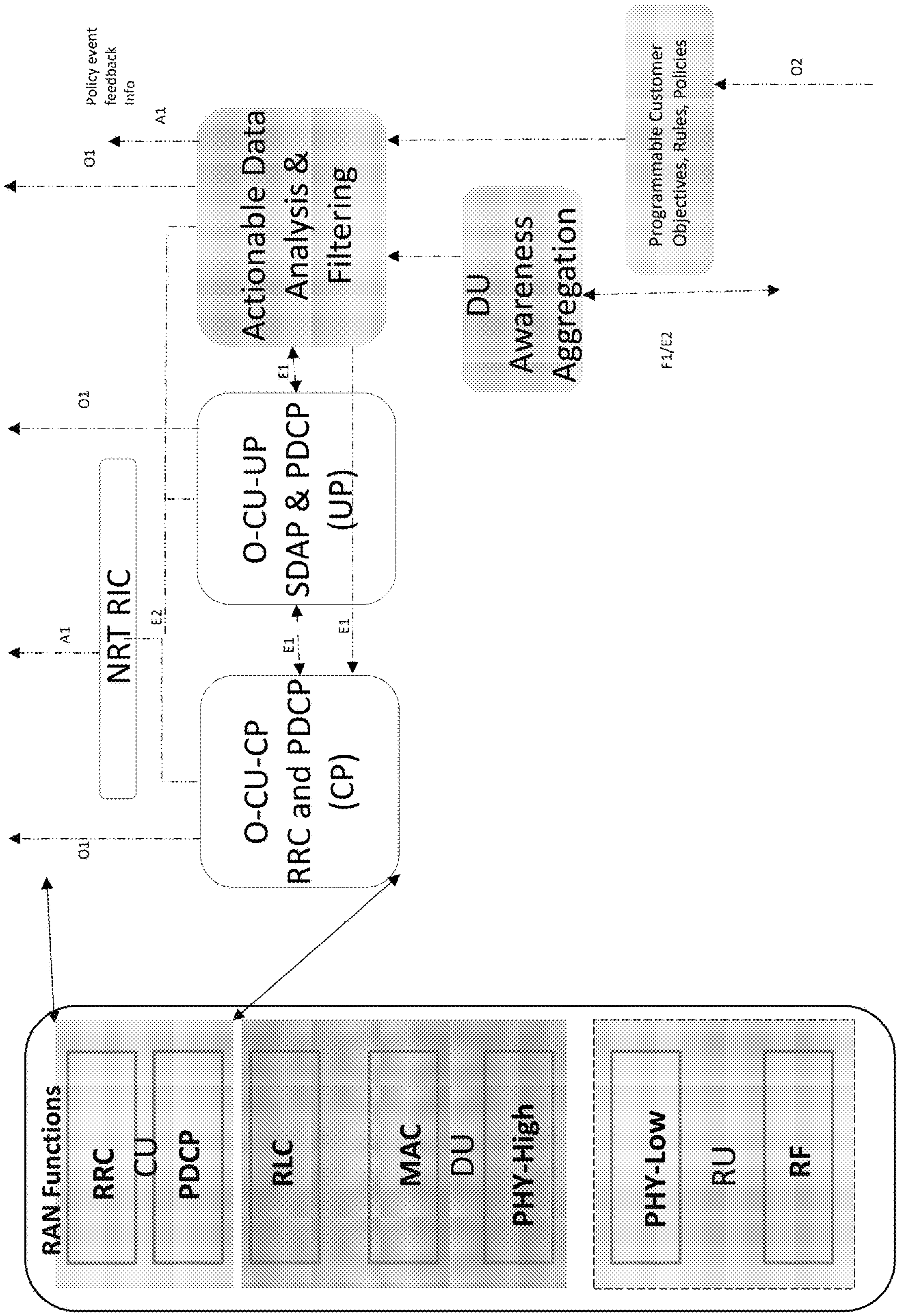

Policy event feedback Info
A1
O1
Actionable Data Analysis & Filtering
Programmable Customer Objectives, Rules, Policies
O2
DU Awareness Aggregation
F1/E2
E1
O1
O-CU-UP SDAP & PDCP (UP)
NRT RIC
A1
E2
E1
E1
O-CU-CP RRC and PDCP (CP)
O1
RAN Functions
RRC
CU
PDCP
RLC
MAC
DU
PHY-High
PHY-Low
RU
RF

FIG.92

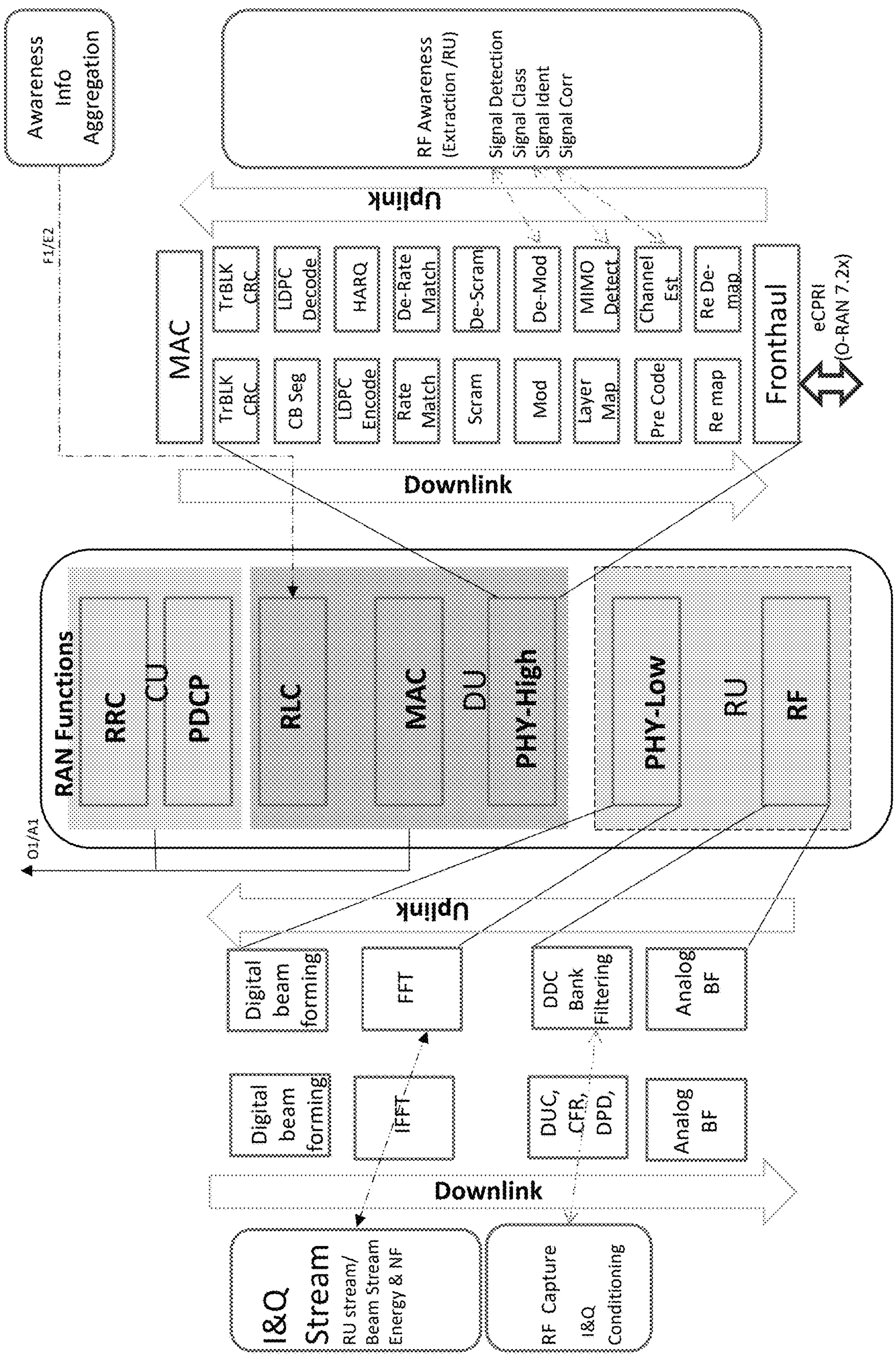

Awareness Info Aggregation
RF Awareness (Extraction /RU)
Signal Detection
Signal Class
Signal Ident
Signal Corr
Uplink
F1/E2
MAC
TrBLK CRC
LDPC Decode
HARQ
De-Rate Match
De-Scram
De-Mod
MIMO Detect
Channel Est
Re De-map
TrBLK CRC
CB Seg
LDPC Encode
Rate Match
Scram
Mod
Layer Map
Pre Code
Re map
Fronthaul
eCPRI (O-RAN 7.2x)
Downlink
RAN Functions
RRC
CU
PDCP
RLC
MAC
DU
PHY-High
PHY-Low
RU
RF
O1/A1
Uplink
Digital beam forming
FFT
DDC Bank Filtering
Analog BF
Digital beam forming
IFFT
DUC, CFR, DPD,
Analog BF
Downlink
I&Q Stream
RU stream/ Beam Stream Energy & NF
RF Capture
I&Q Conditioning

FIG.93A

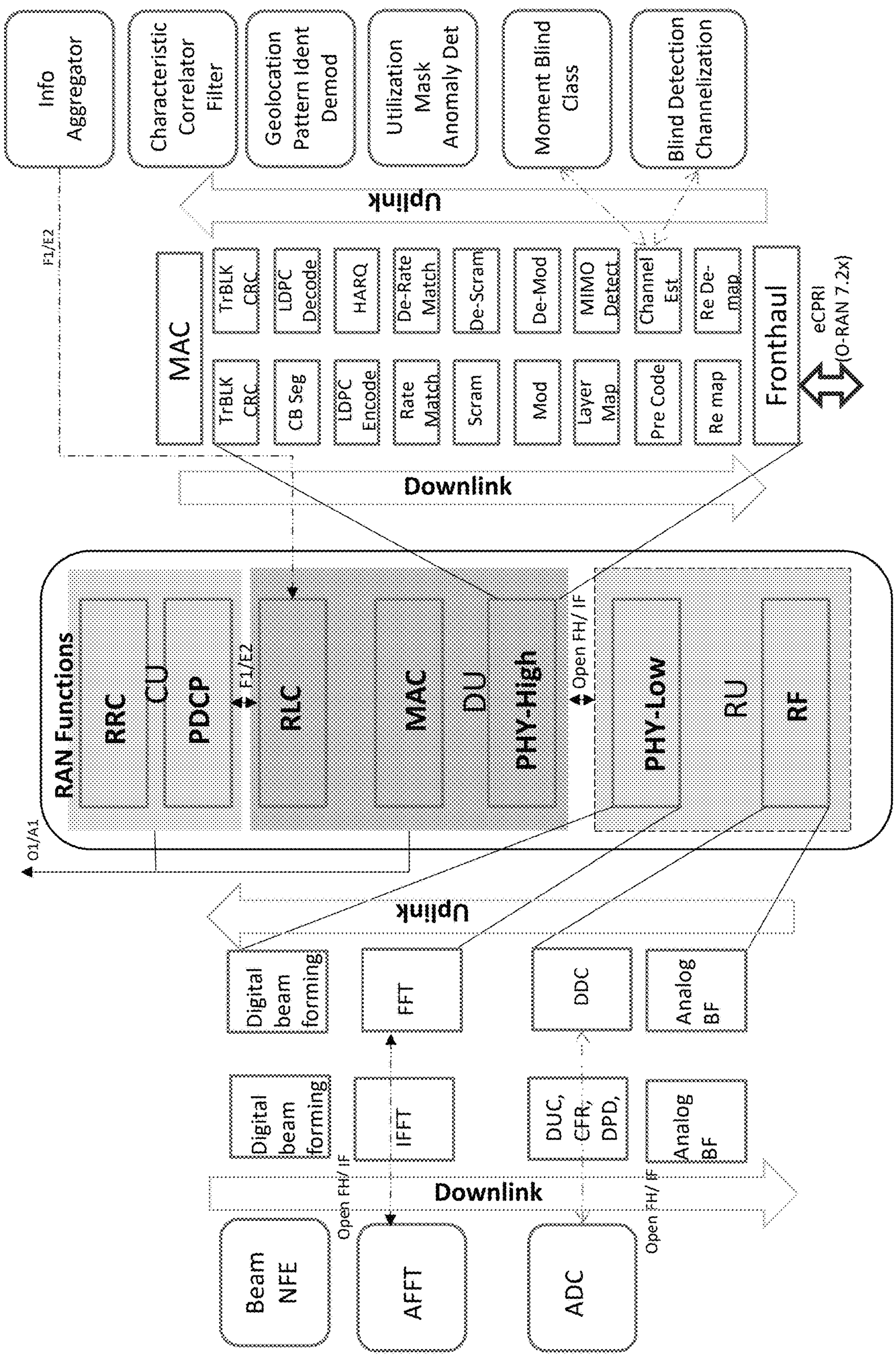

Info Aggregator
Characteristic Correlator Filter
Geolocation Pattern Ident Demod
Utilization Mask Anomaly Det
Moment Blind Class
Blind Detection Channelization
Uplink
F1/E2
MAC
TrBLK CRC
LDPC Decode
HARQ
De-Rate Match
De-Scram
De-Mod
MIMO Detect
Channel Est
Re De-map
Fronthaul
eCPRI (O-RAN 7.2x)
TrBLK CRC
CB Seg
LDPC Encode
Rate Match
Scram
Mod
Layer Map
Pre Code
Re map
Downlink
RAN Functions
RRC
CU
PDCP
F1/E2
RLC
MAC
DU
PHY-High
Open FH/ IF
PHY-Low
RU
RF
O1/A1
Uplink
Digital beam forming
FFT
DDC
Analog BF
Digital beam forming
IFFT
DUC, CFR, DPD,
Analog BF
Downlink
Open FH/ IF
Open FH/ IF
Beam NFE
AFFT
ADC

FIG.93B

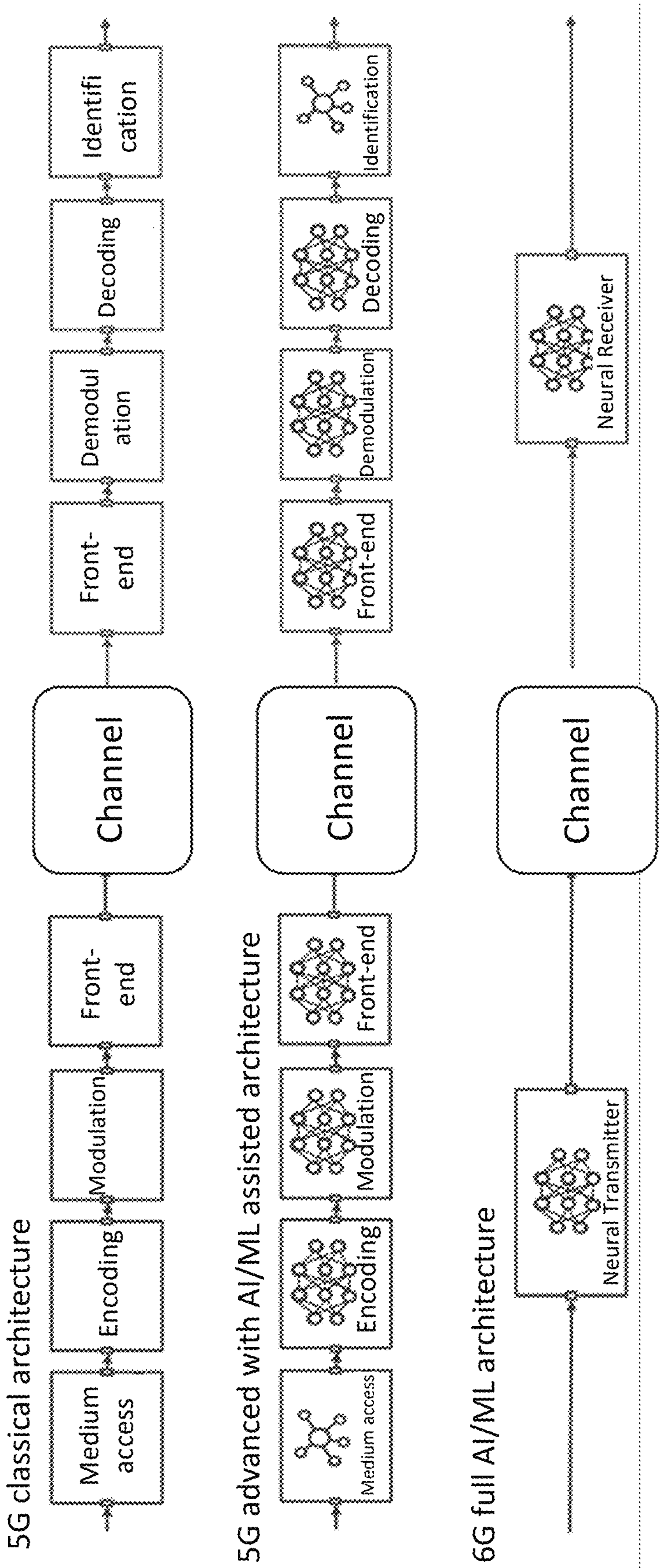

5G classical architecture
Medium access
Encoding
Modulation
Front-end
Channel
Front-end
Demodulation
Decoding
Identification
5G advanced with AI/ML assisted architecture
Medium access
Encoding
Modulation
Front-end
Channel
Front-end
Demodulation
Decoding
Identification
6G full AI/ML architecture
Neural Transmitter
Channel
Neural Receiver

FIG.94

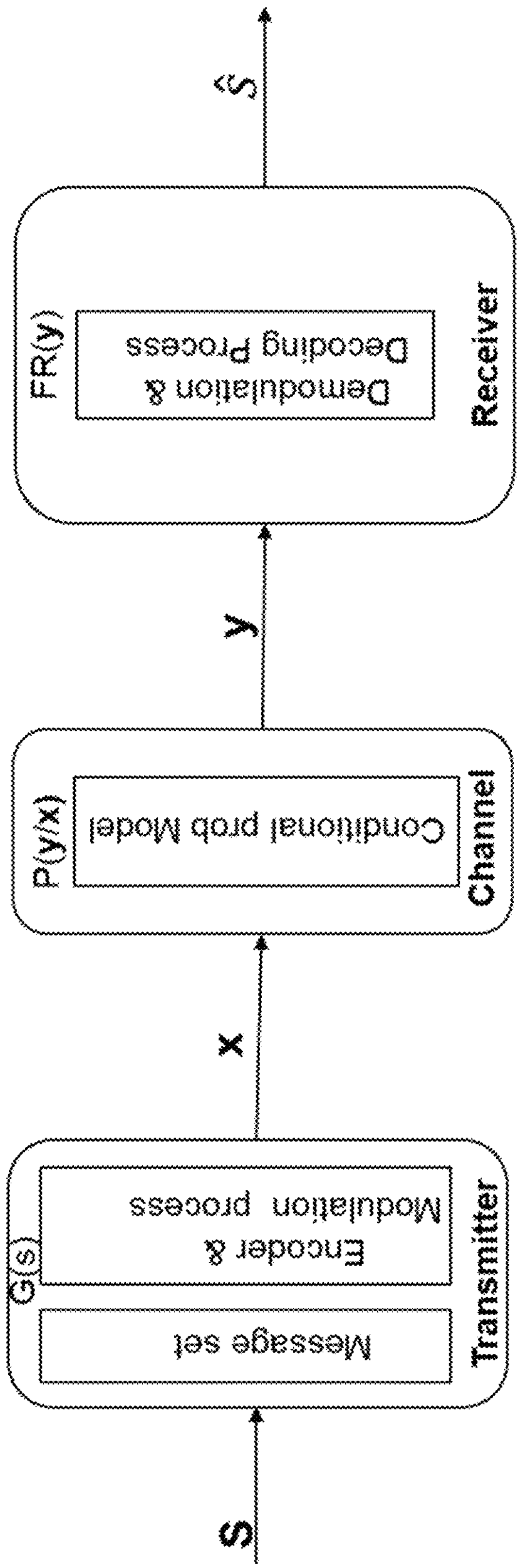

s
Message set
G(s)
Encoder &
Modulation process
Transmitter
x
P(y/x)
Conditional prob Model
Channel
y
FR(y)
Demodulation &
Decoding Process
Receiver
ŝ

FIG.95

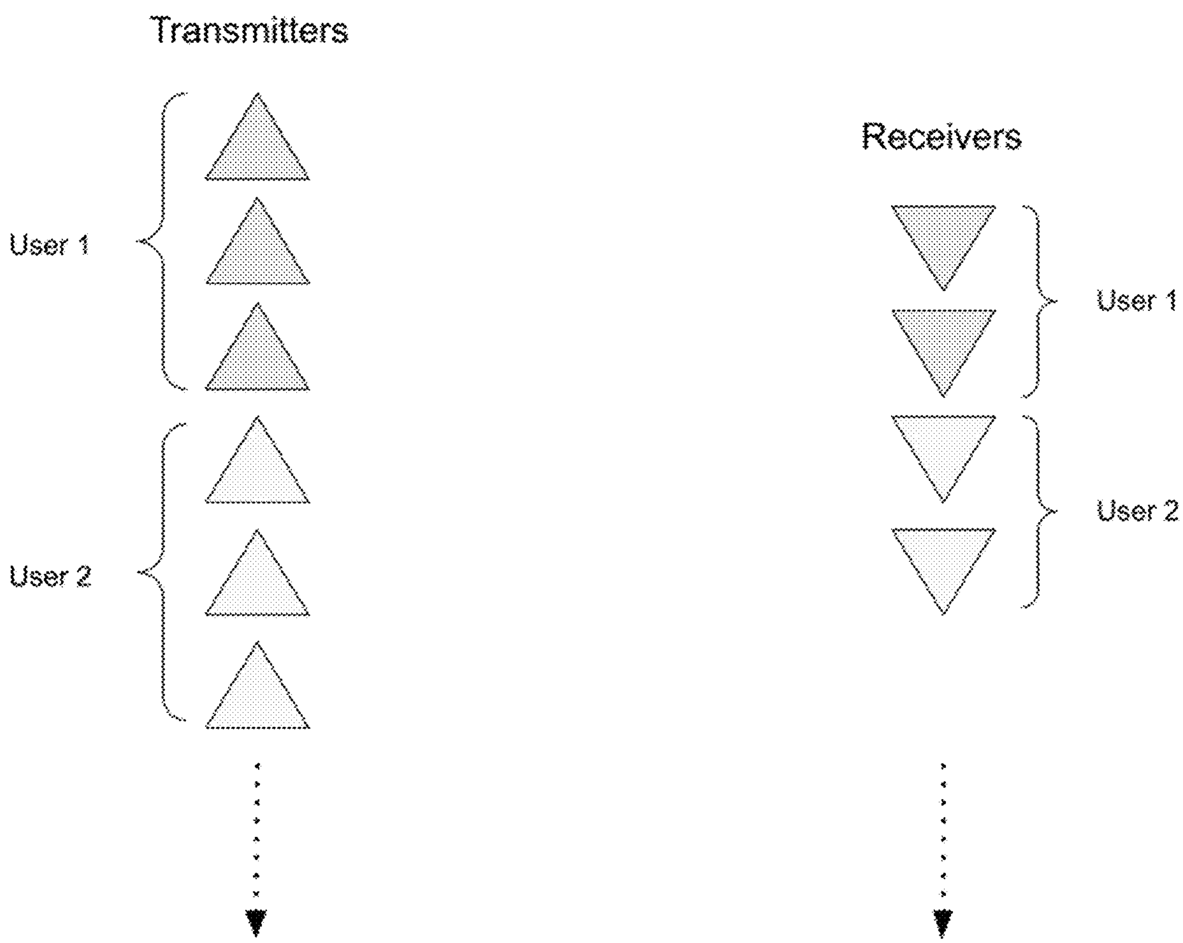


FIG. 96

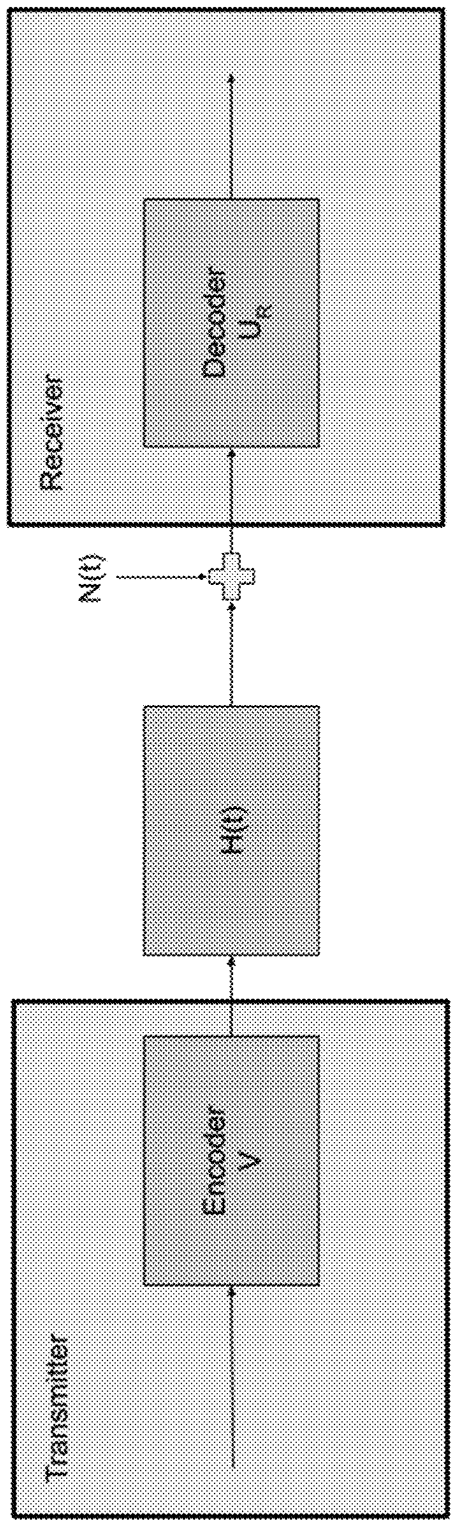


FIG. 97

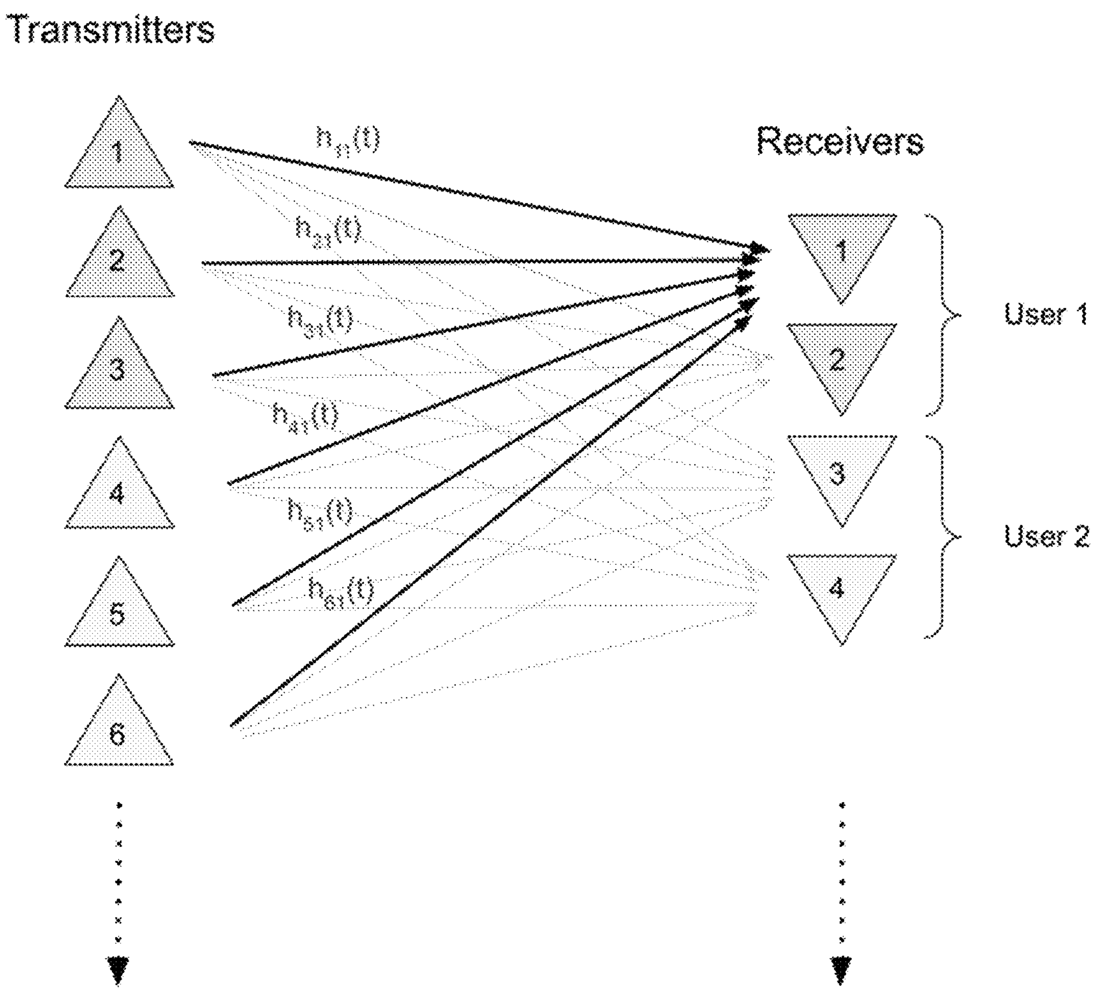

Transmitters
Receivers
1
2
3
4
5
6
$h_{11}(t)$
$h_{21}(t)$
$h_{31}(t)$
$h_{41}(t)$
$h_{51}(t)$
$h_{61}(t)$
1
2
3
4
User 1
User 2

FIG. 98

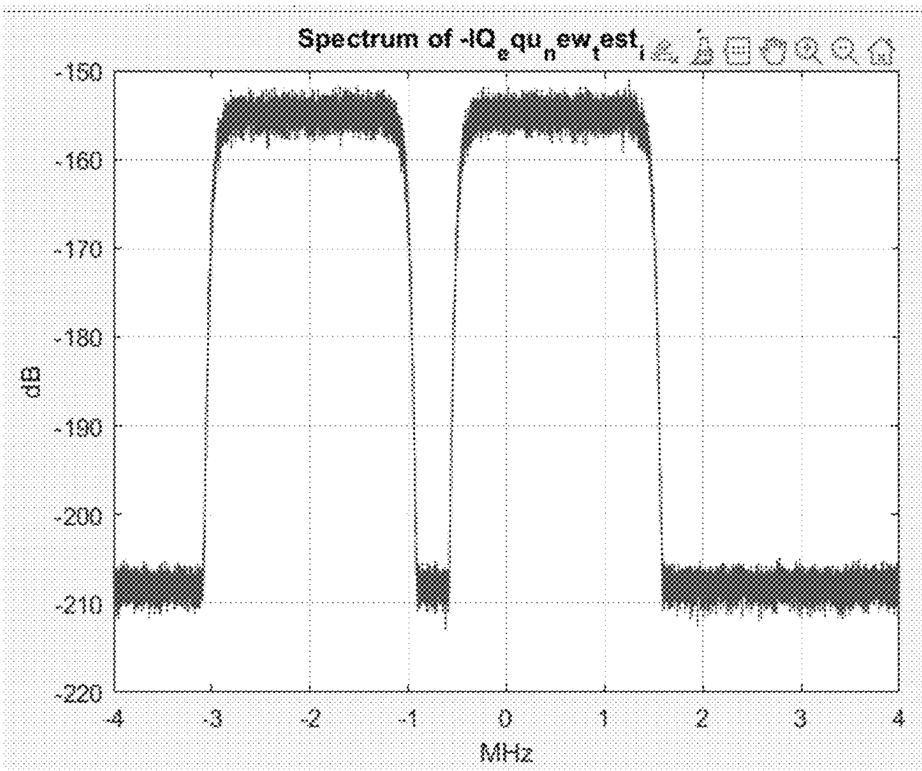


FIG. 99A

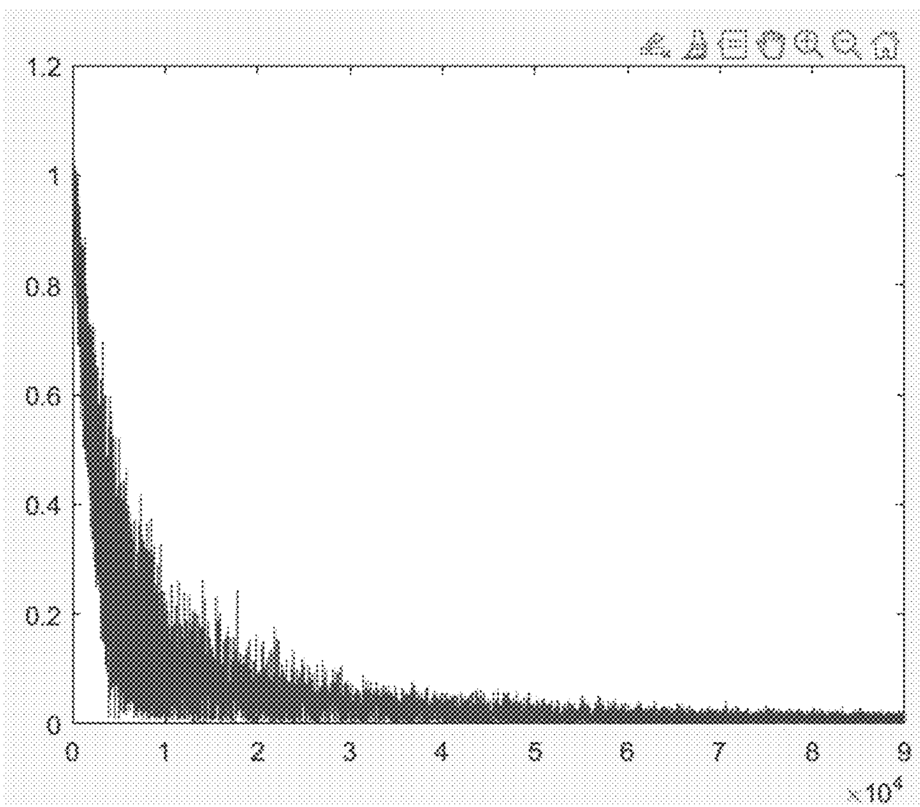


FIG. 99B

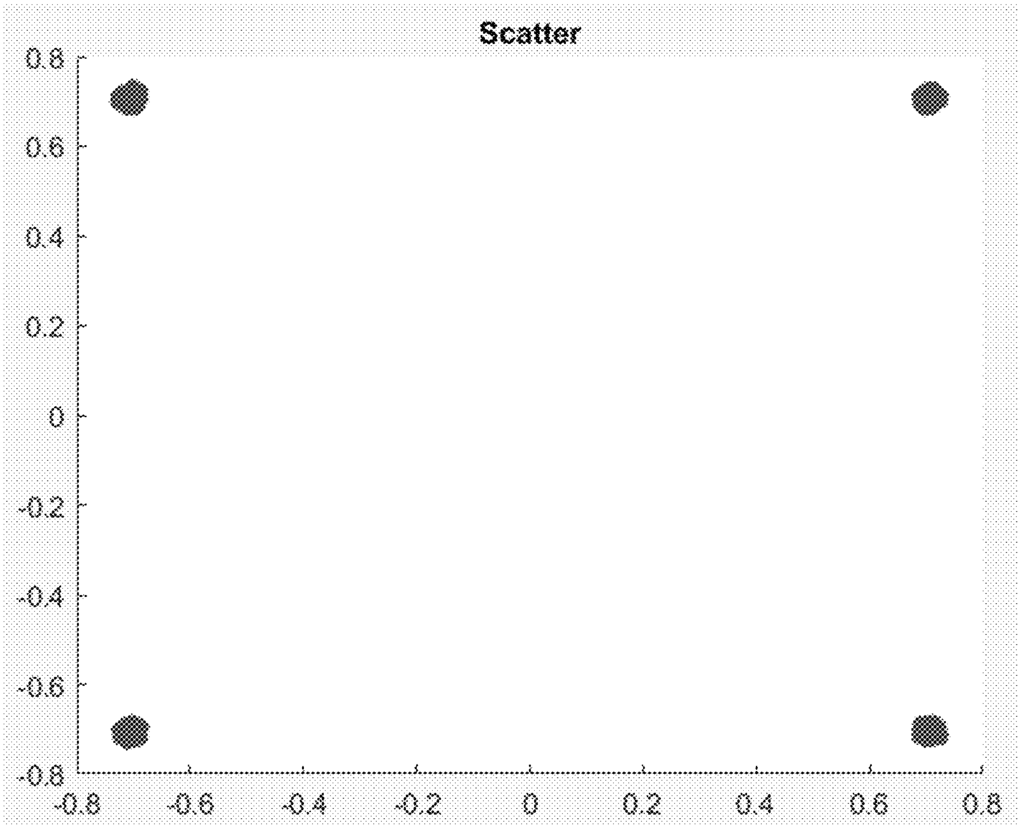


FIG. 99C

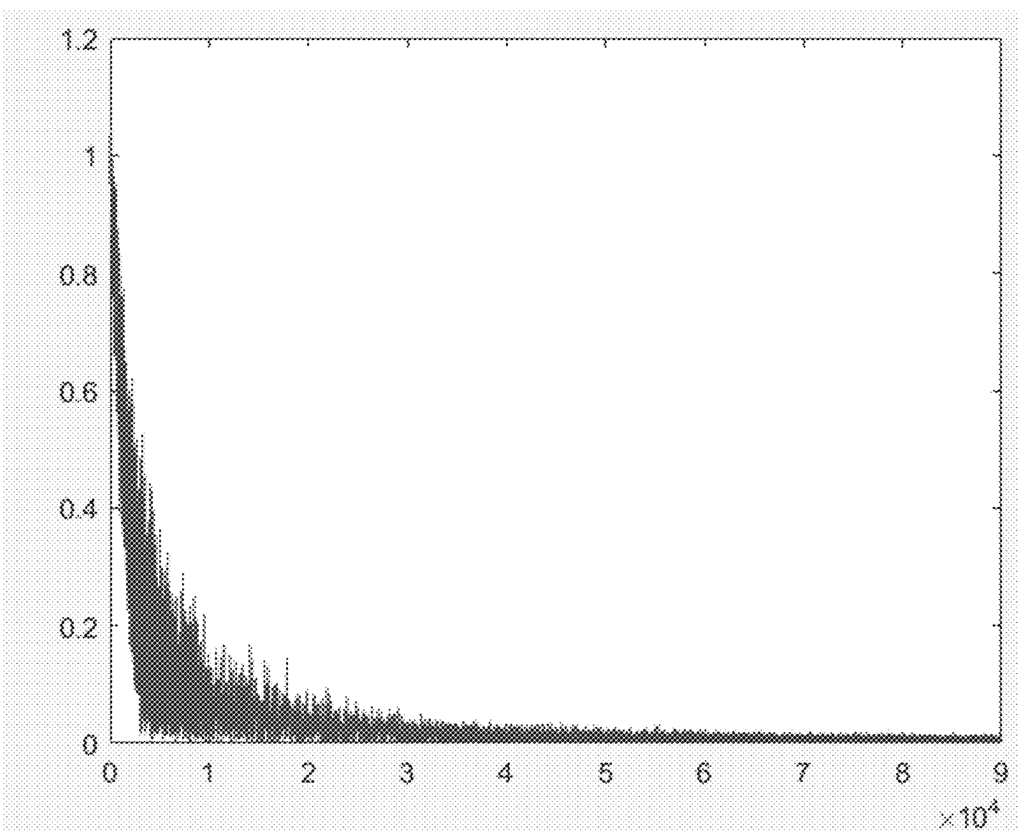


FIG. 99D

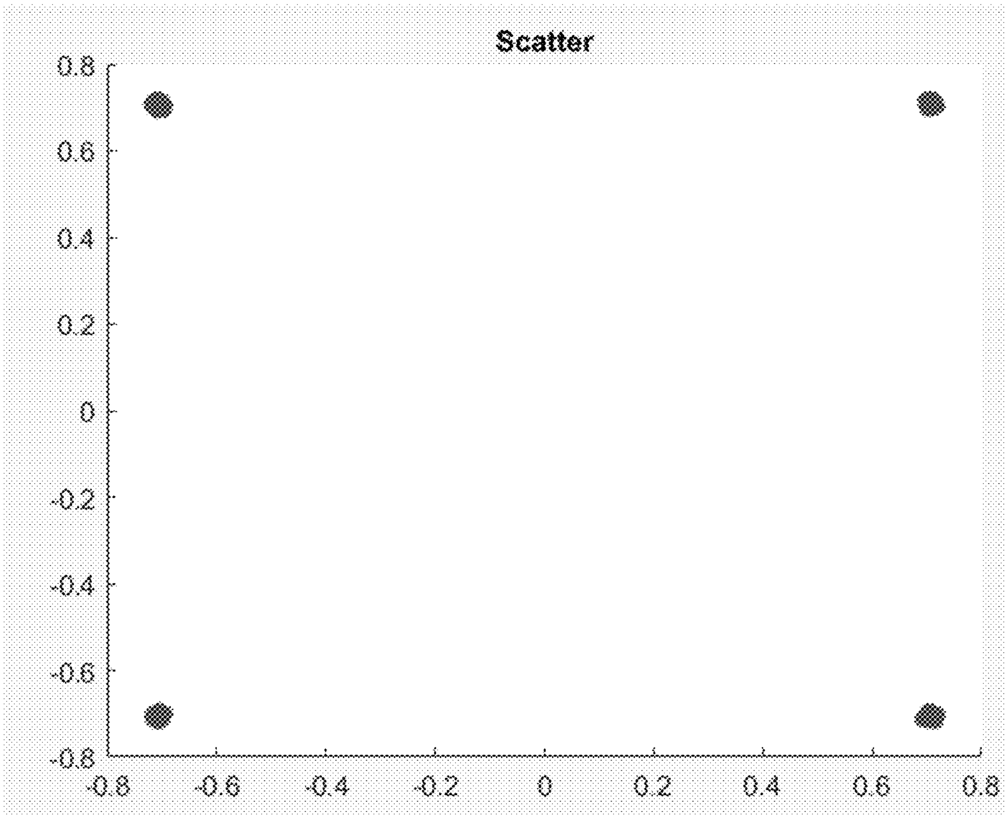


FIG. 99E

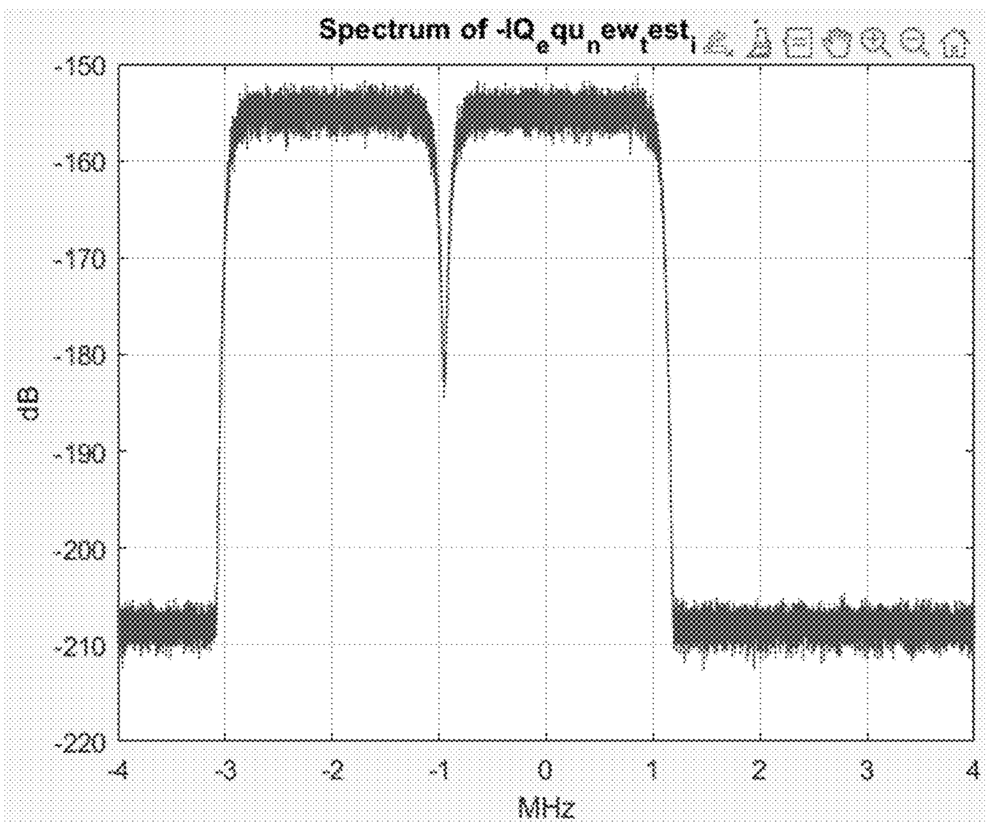


FIG. 100A

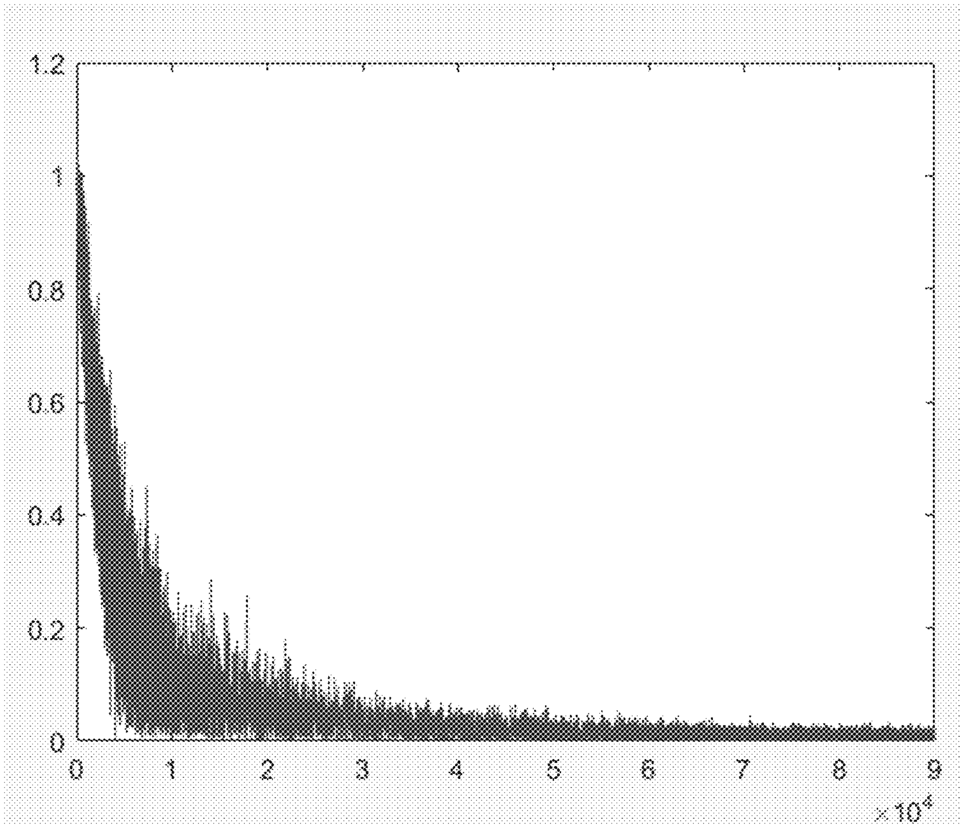


FIG. 100B

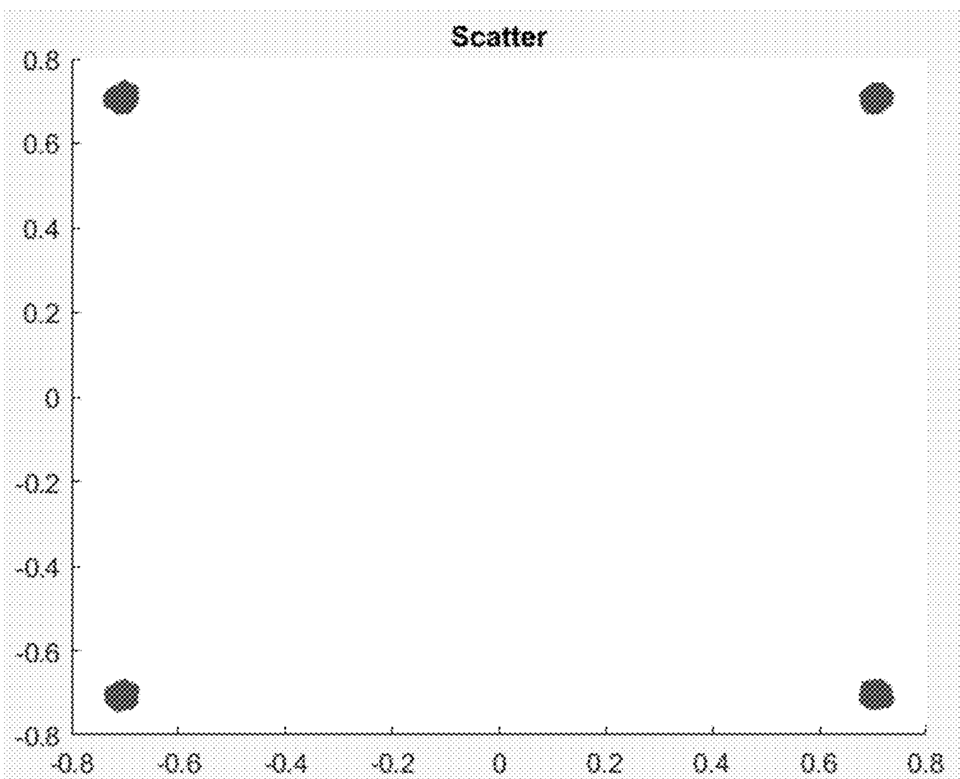


FIG. 100C

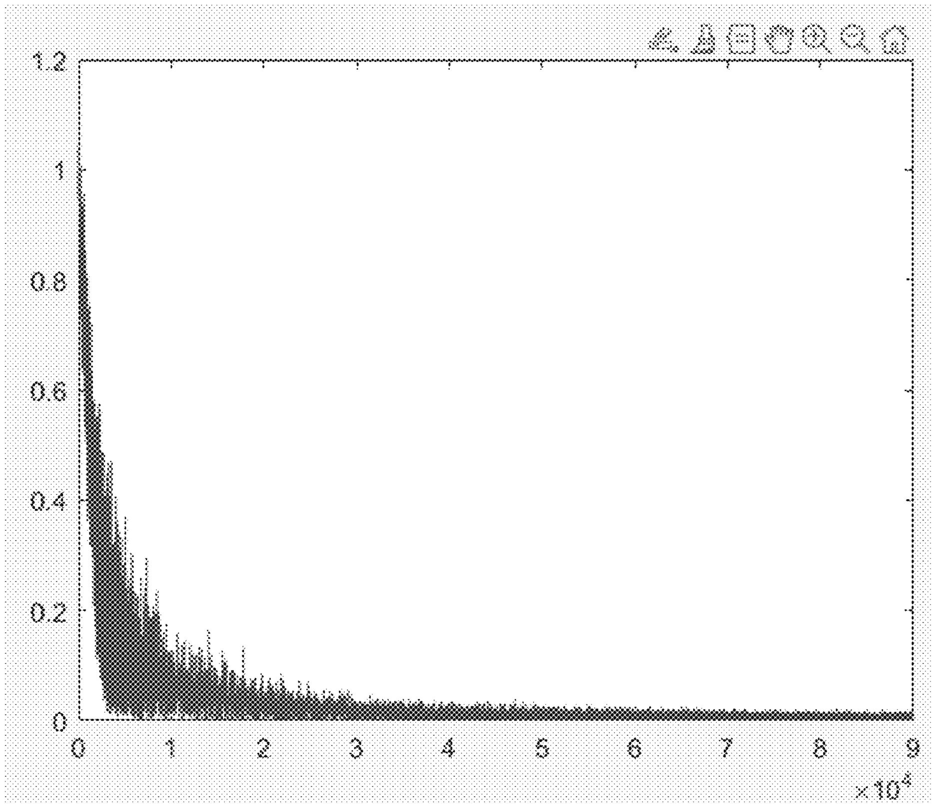


FIG. 100D

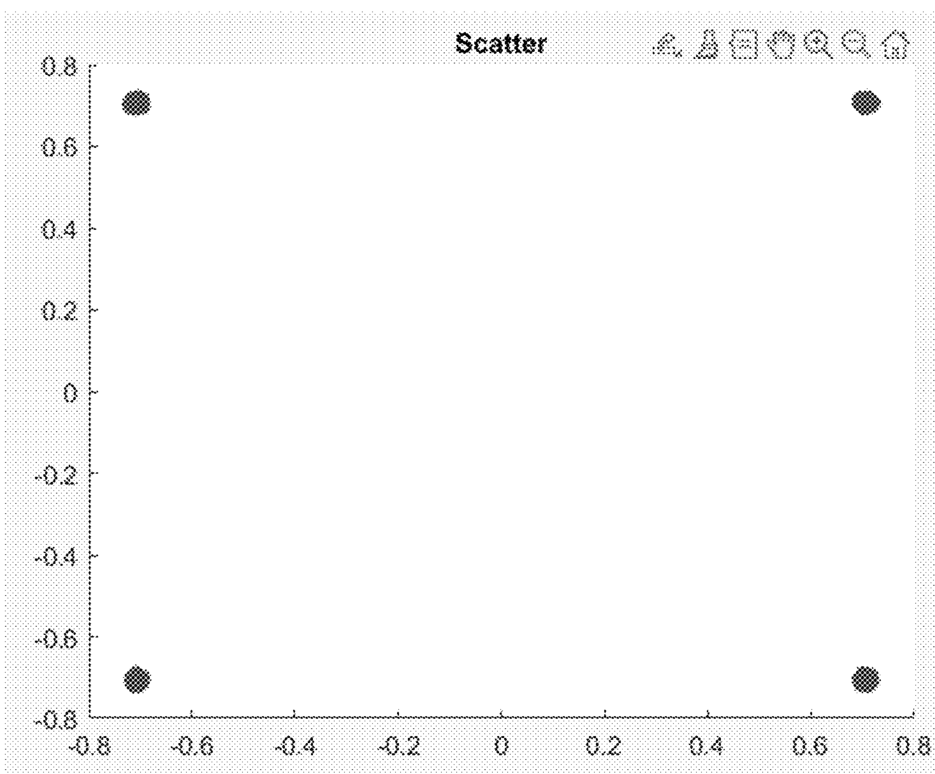


FIG. 100E

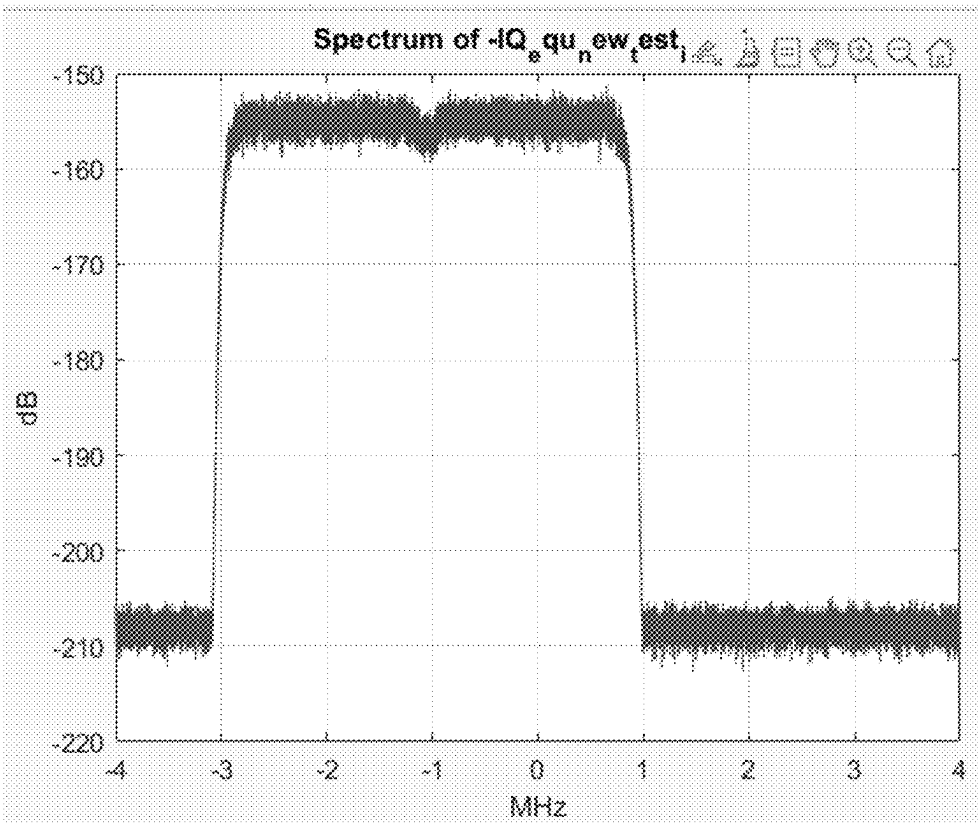


FIG. 101A

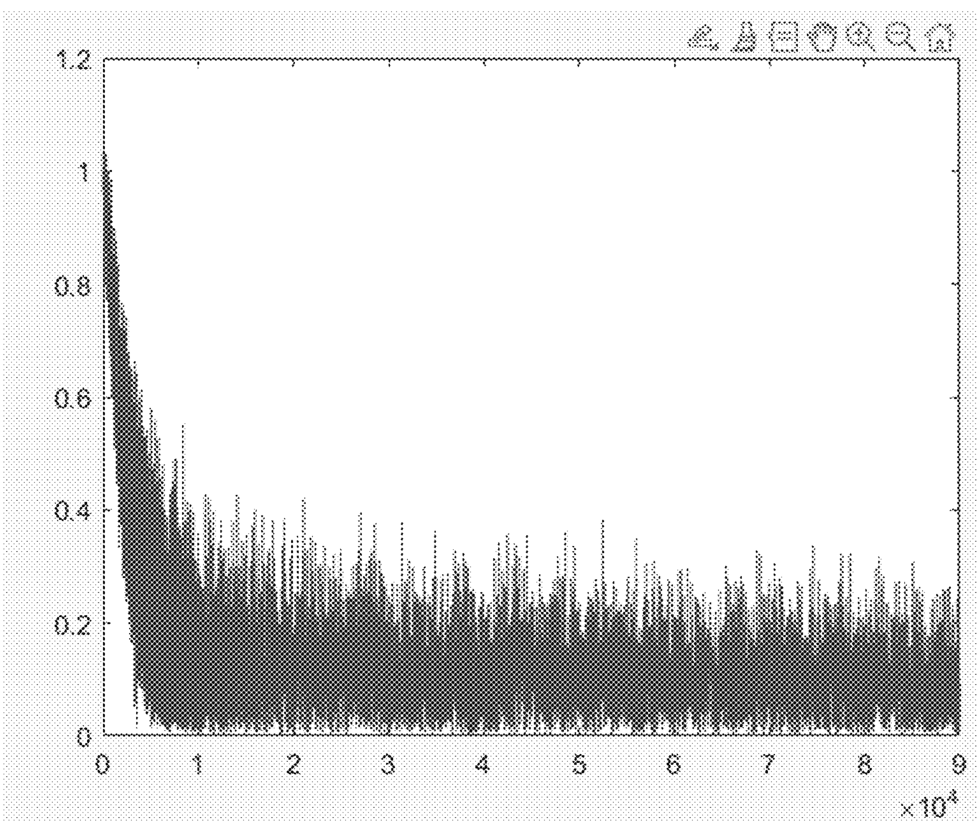


FIG. 101B

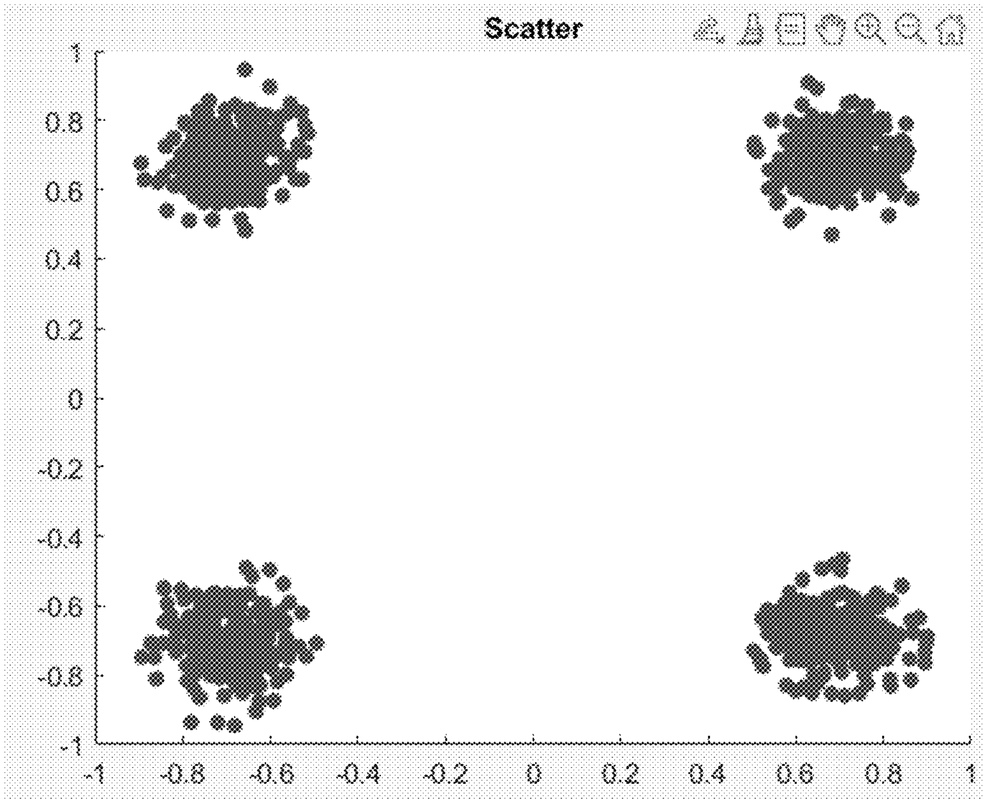


FIG. 101C

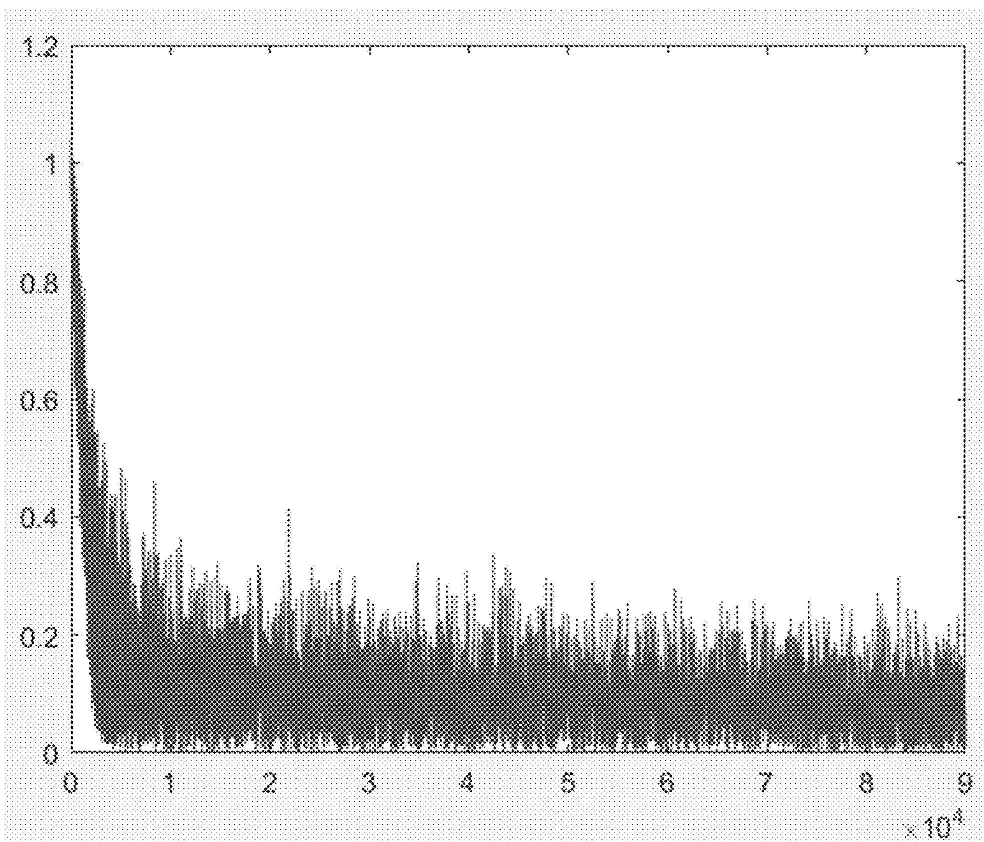


FIG. 101D

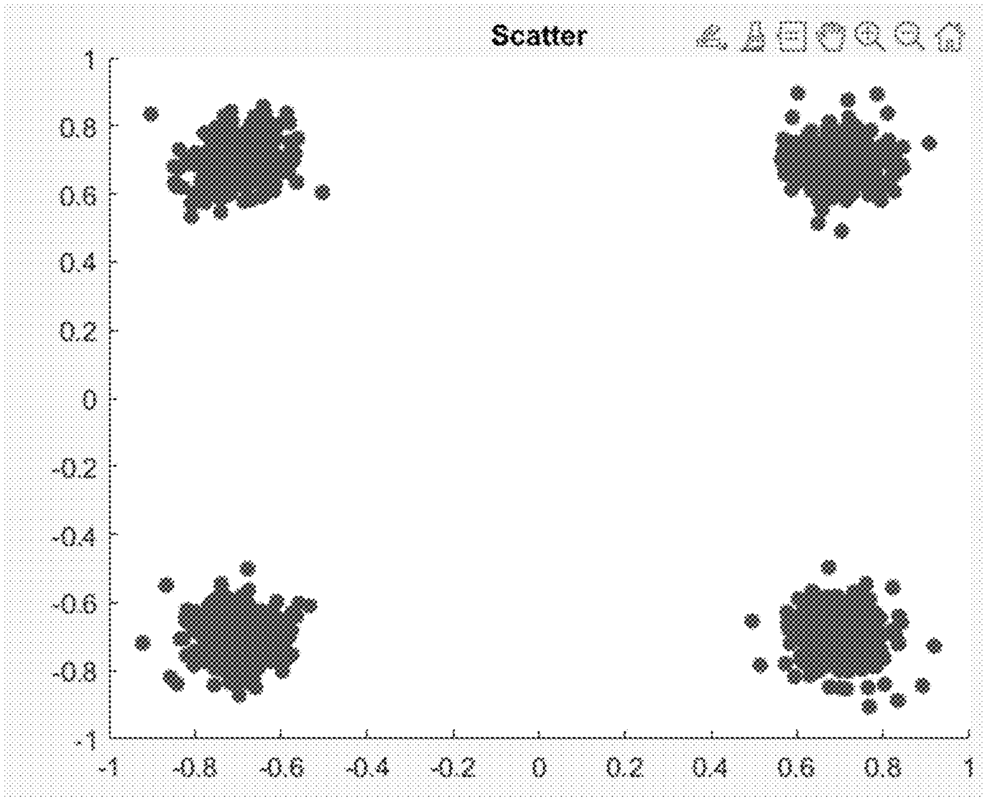


FIG. 101E

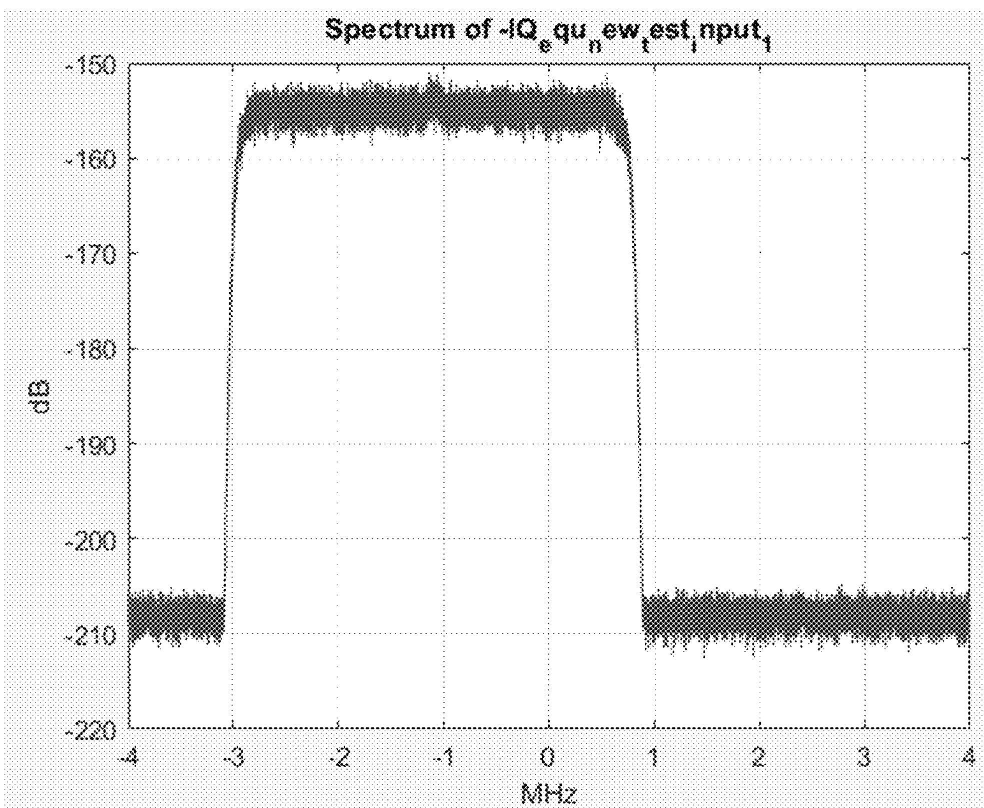


FIG. 102A

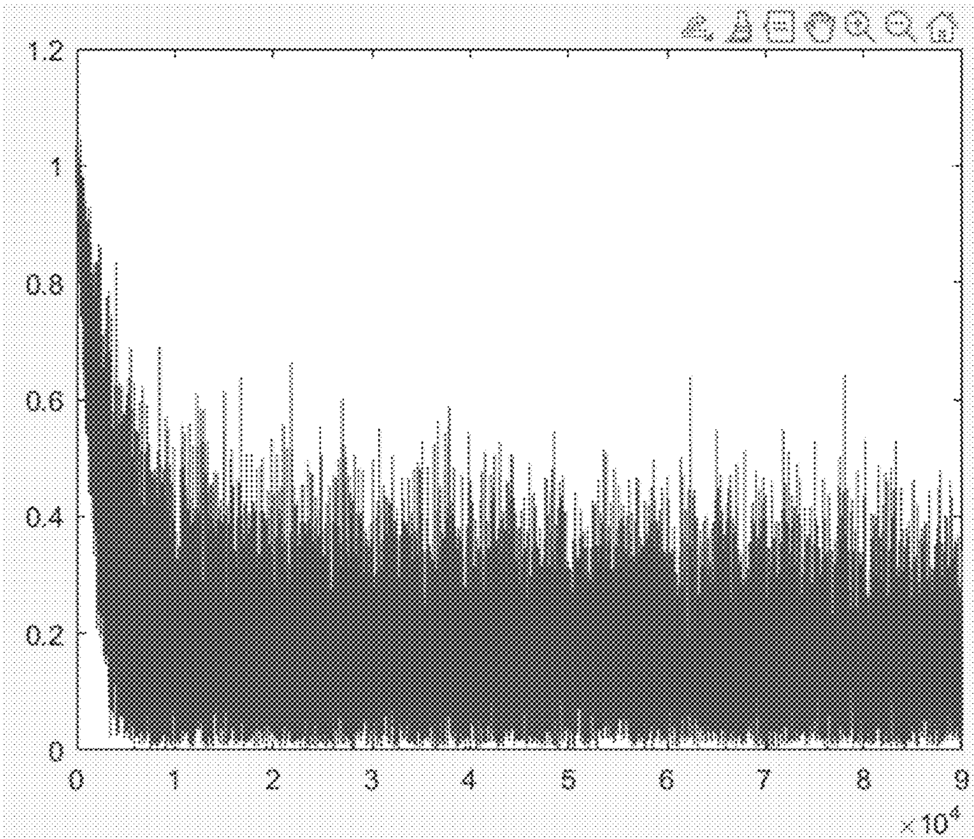


FIG. 102B

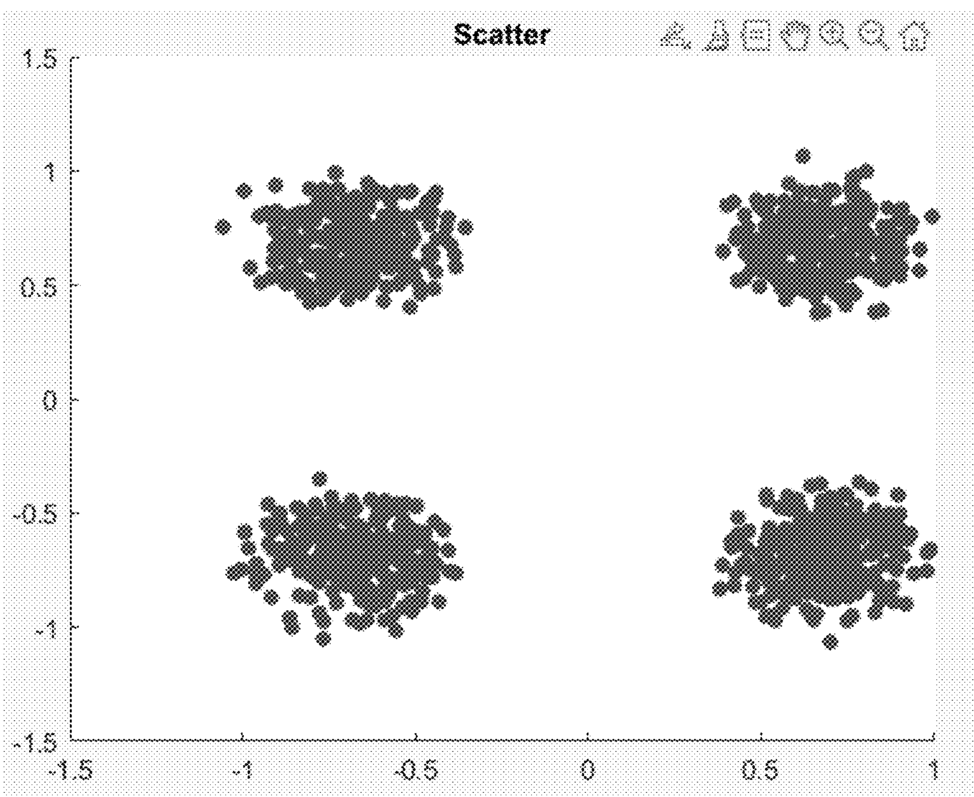


FIG. 102C

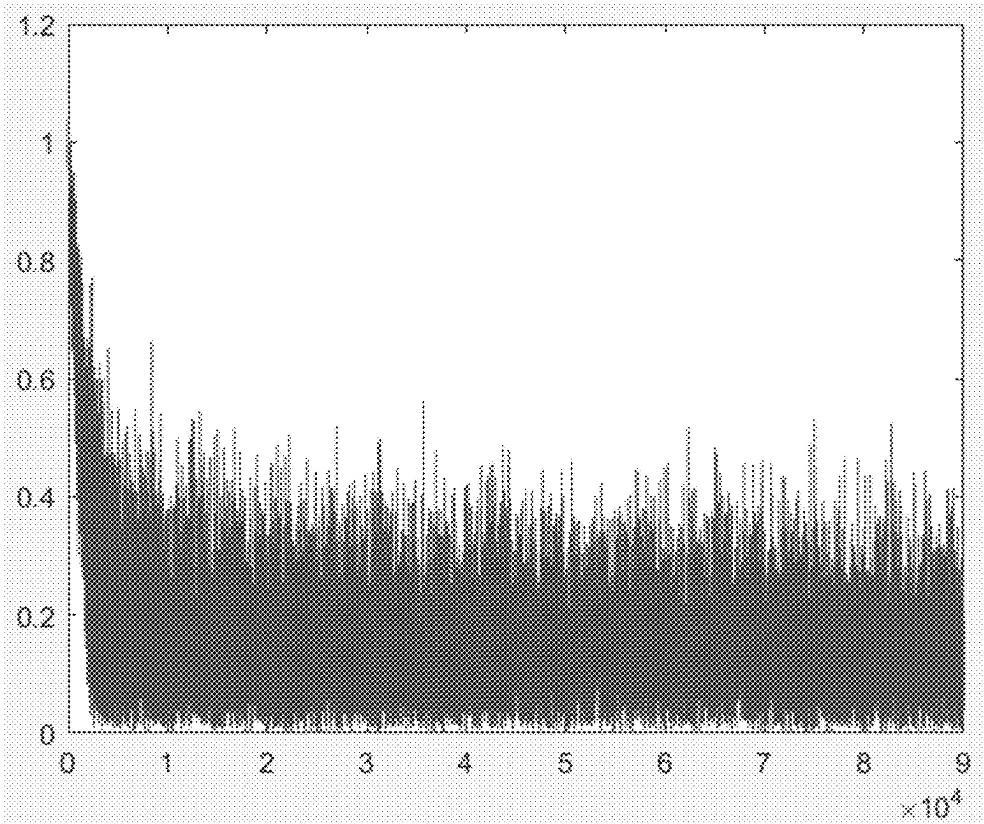


FIG. 102D

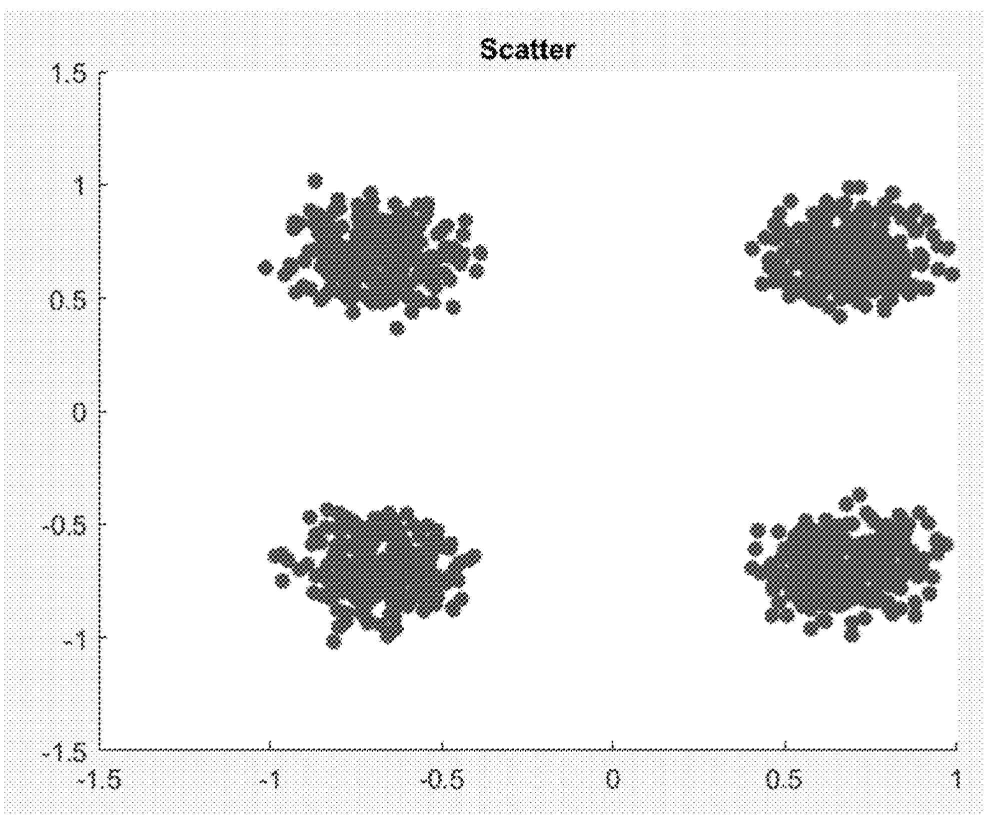


FIG. 102E

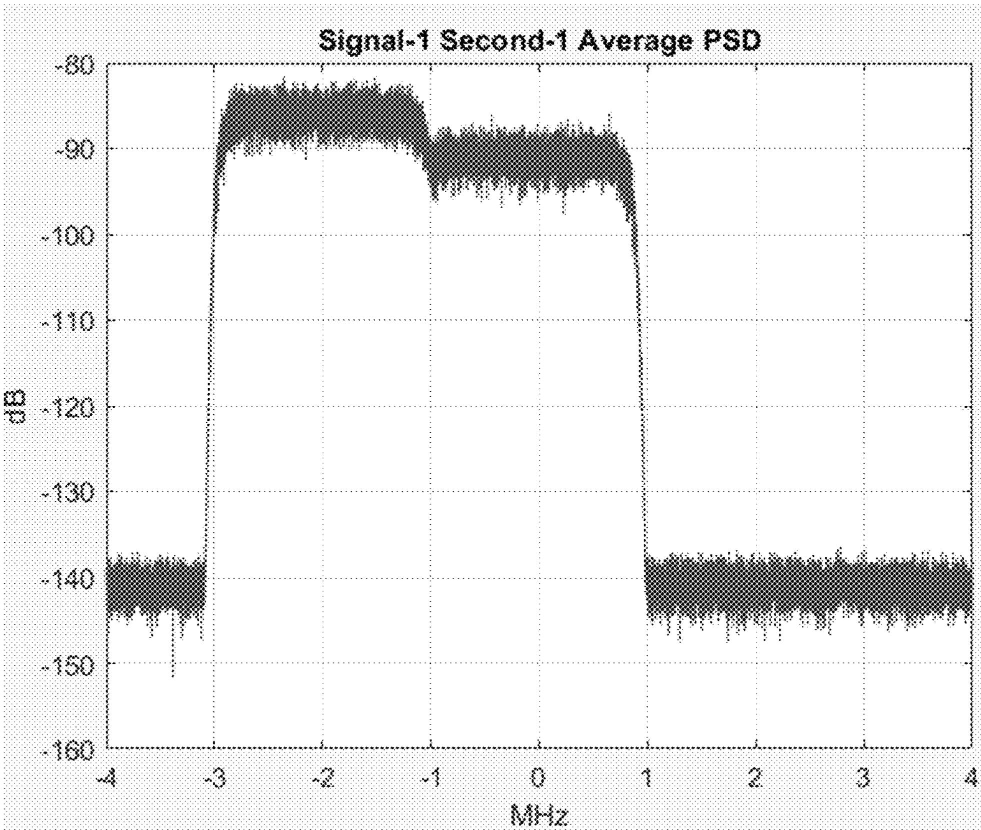


FIG. 103A

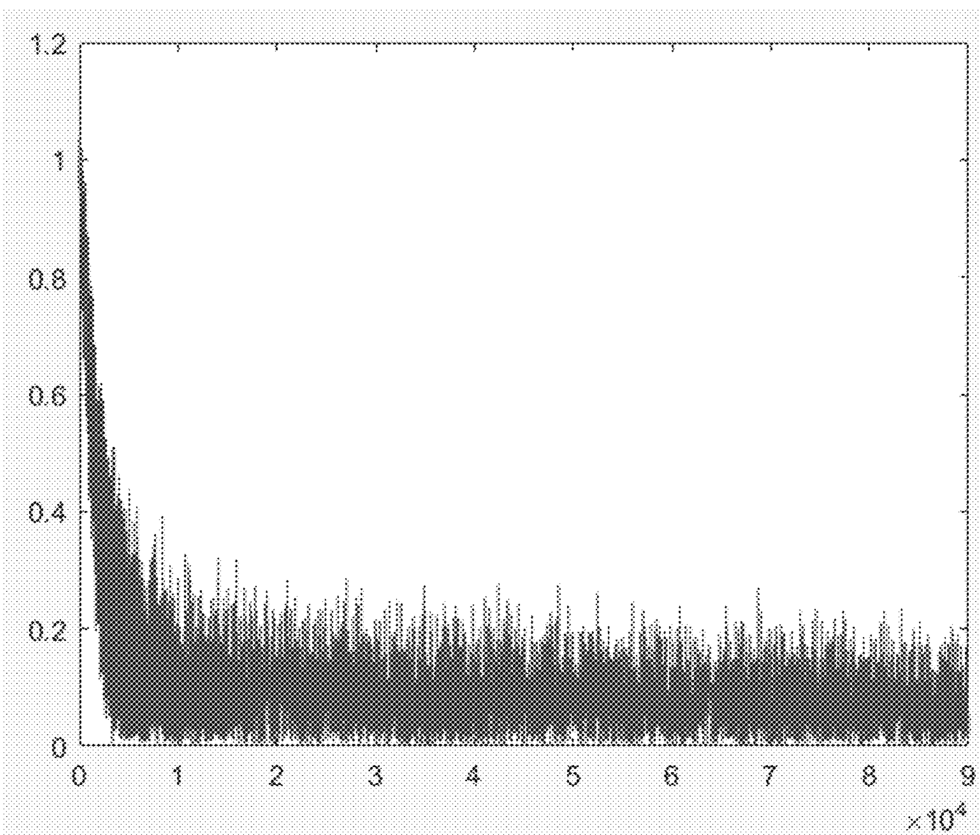


FIG. 103B

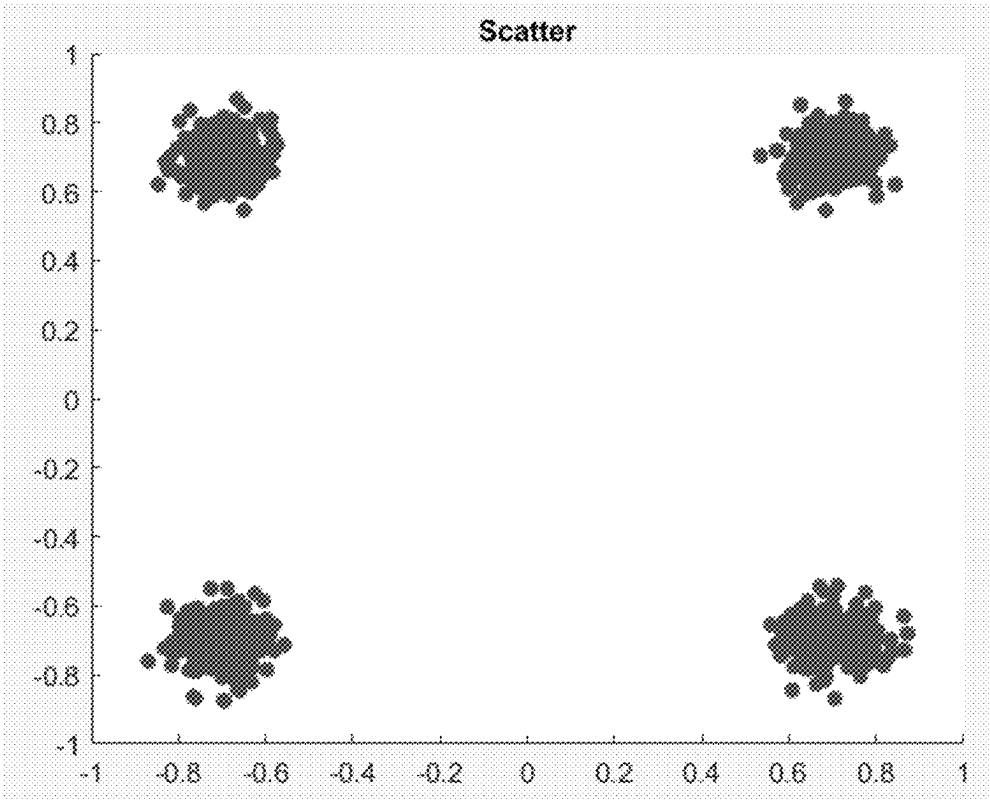


FIG. 103C

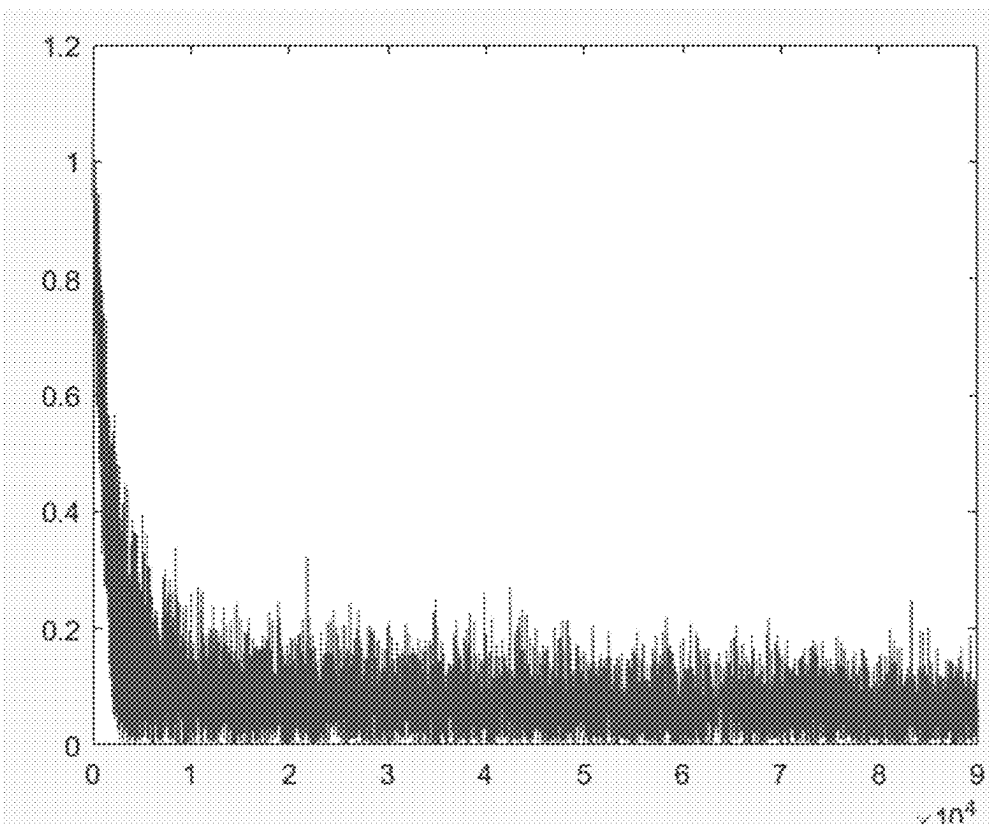


FIG. 103D

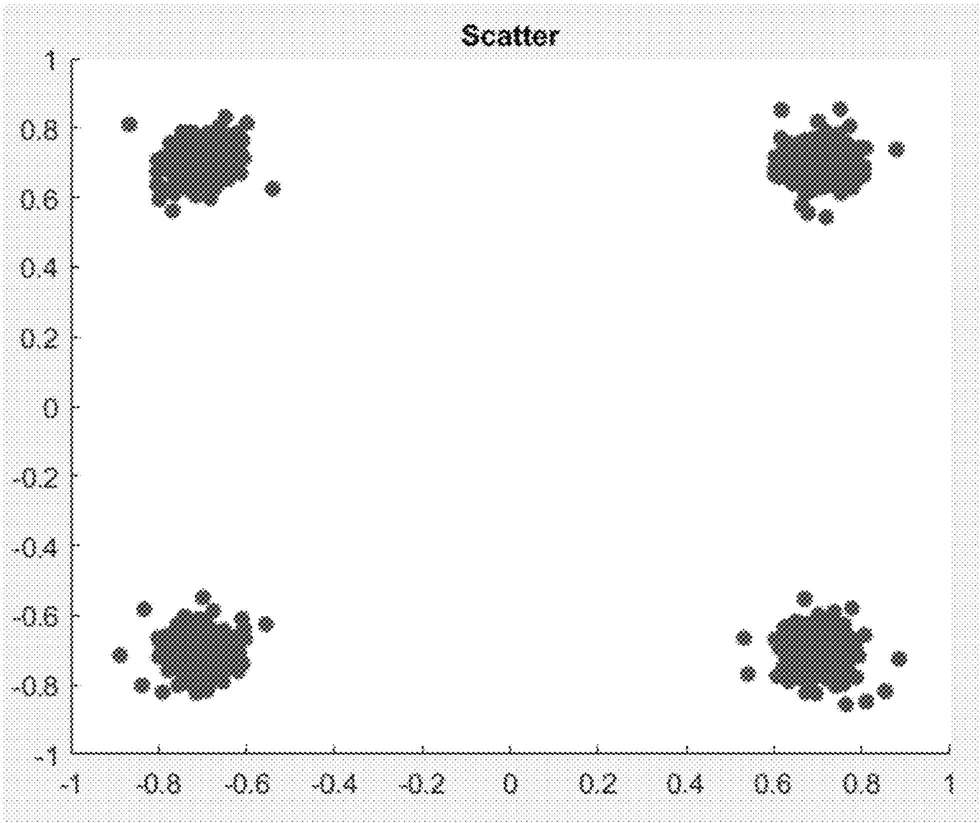


FIG. 103E

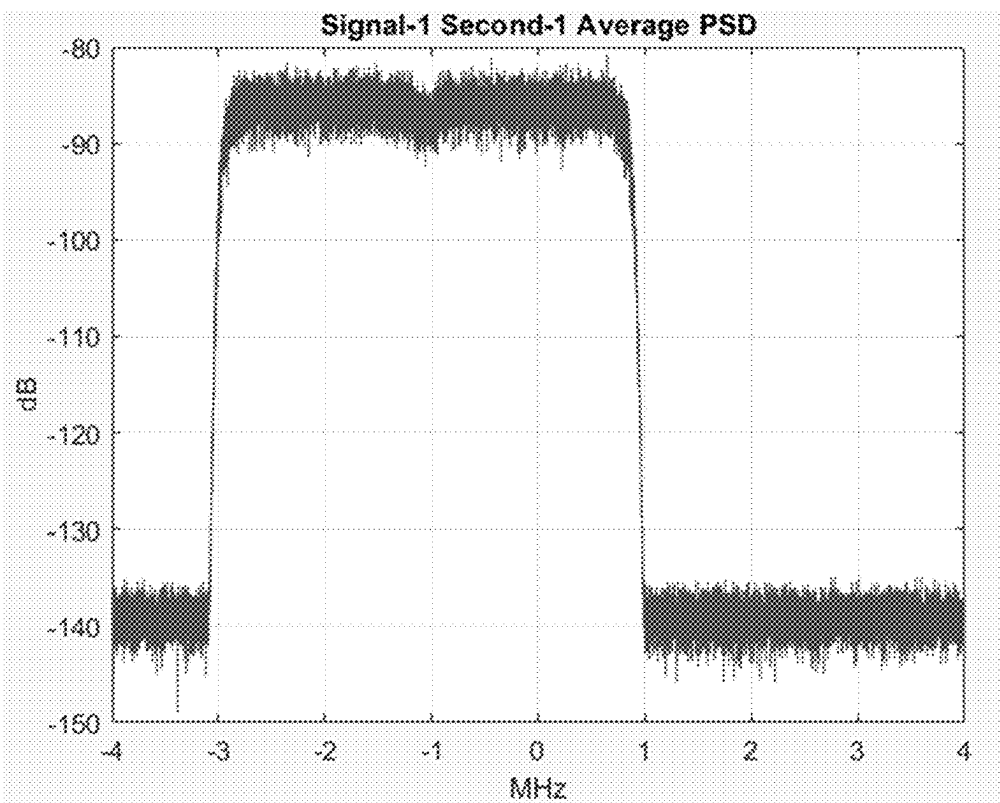


FIG. 104A

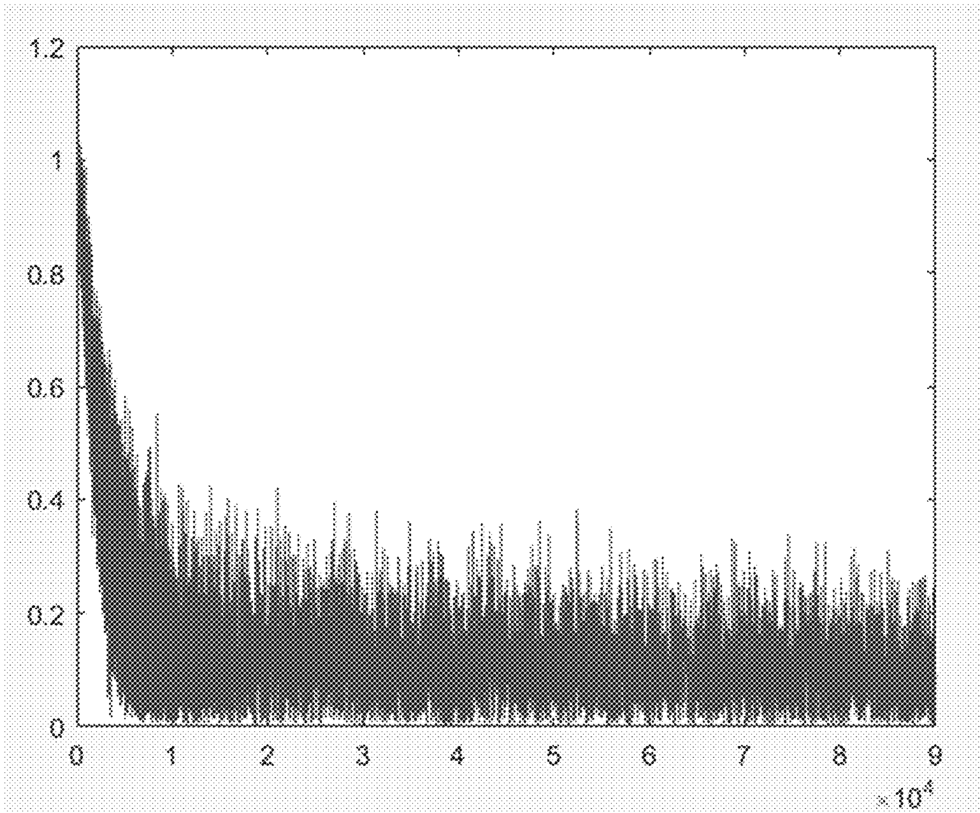


FIG. 104B

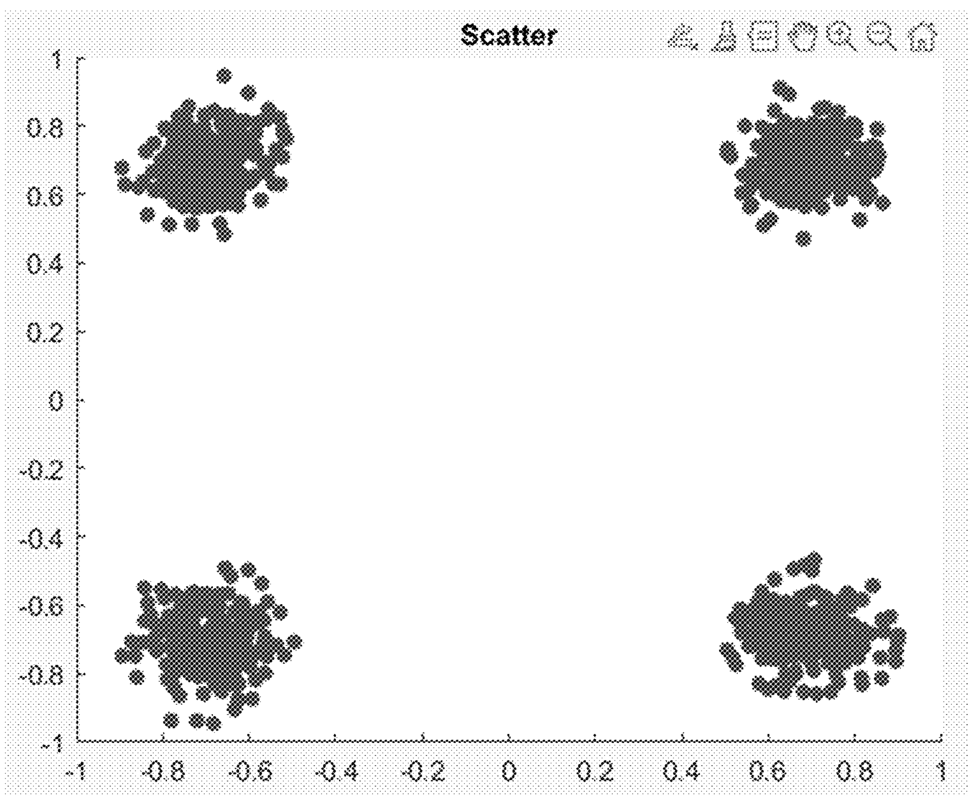


FIG. 104C

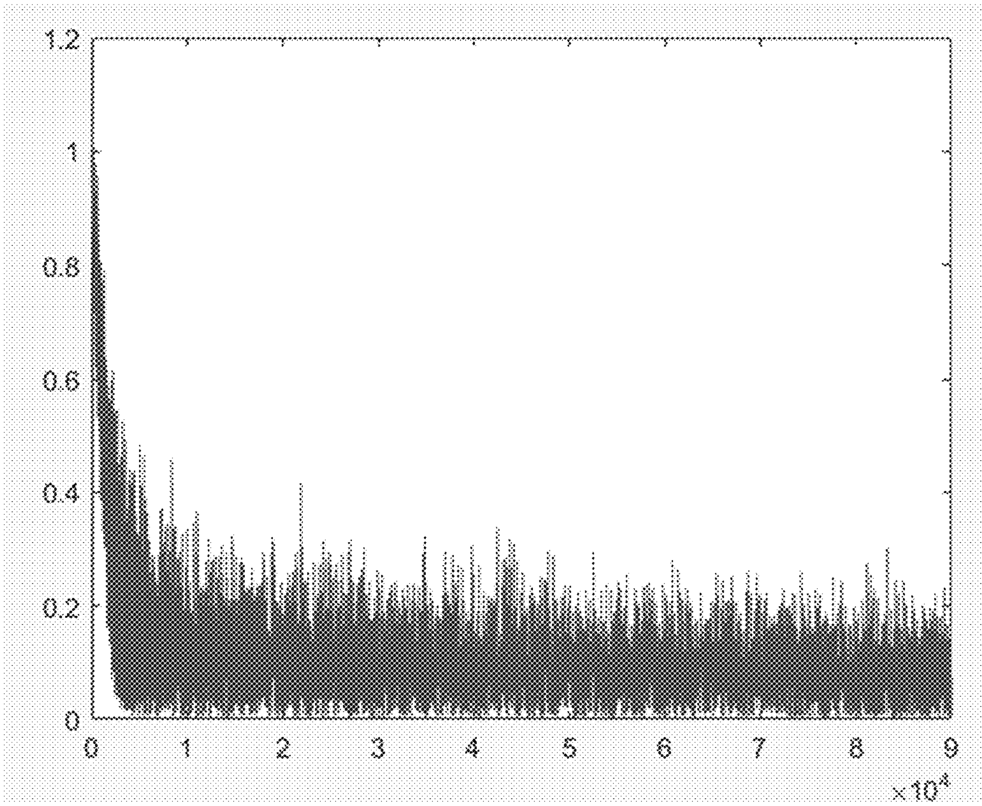


FIG. 104D

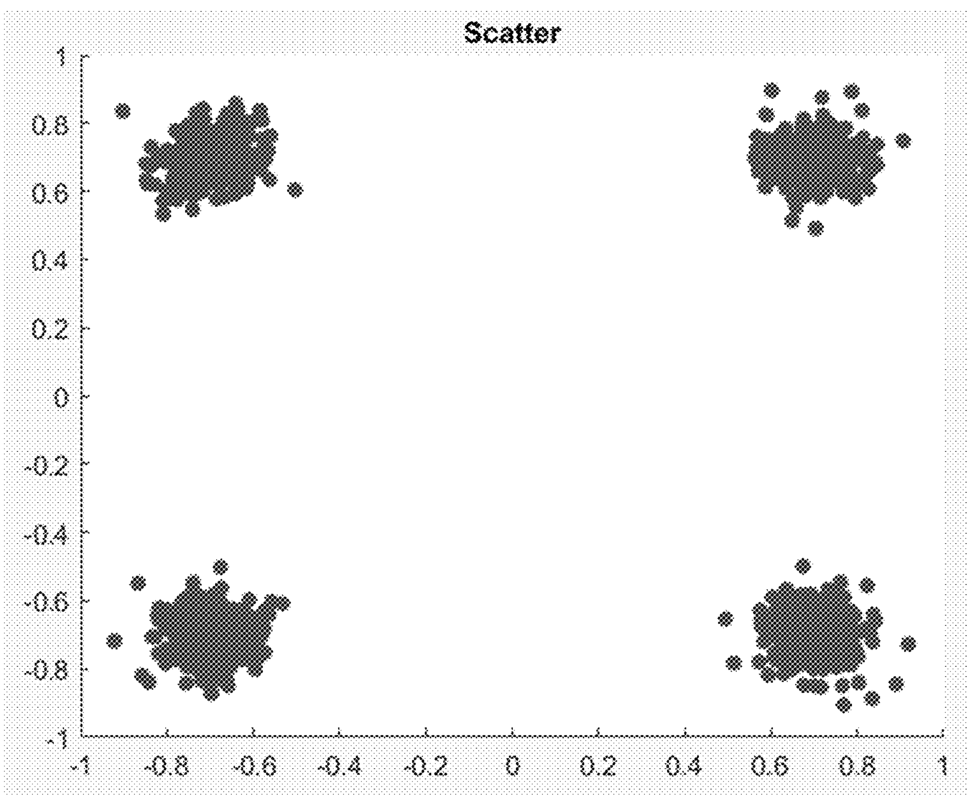


FIG. 104E

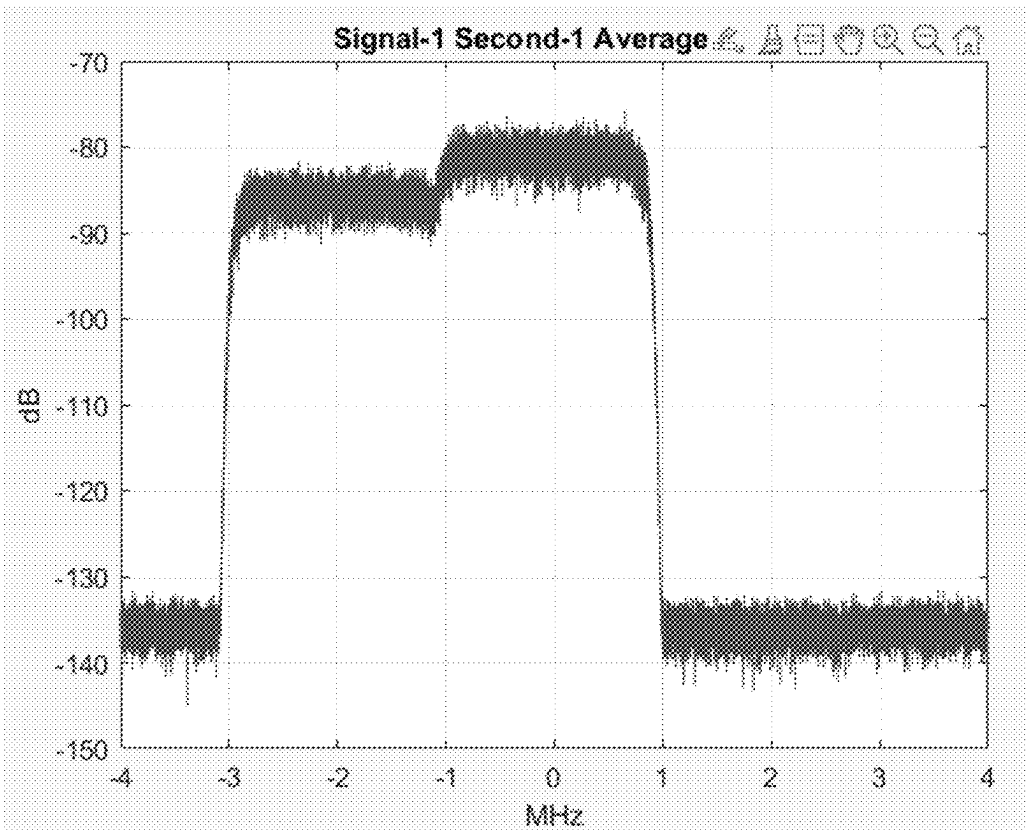

Signal-1 Second-1 Average
-70
-80
-90
-100
-110
-120
-130
-140
-150
dB
-4
-3
-2
-1
0
1
2
3
4
MHz

FIG. 105A

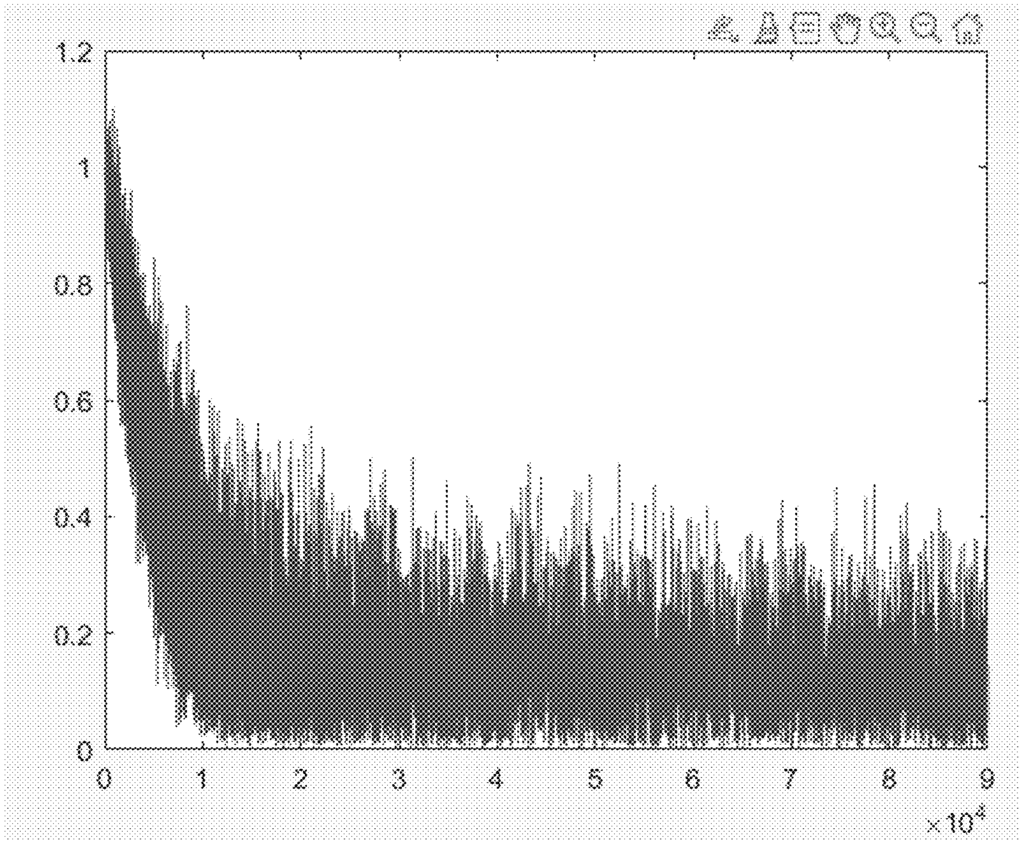


FIG. 105B

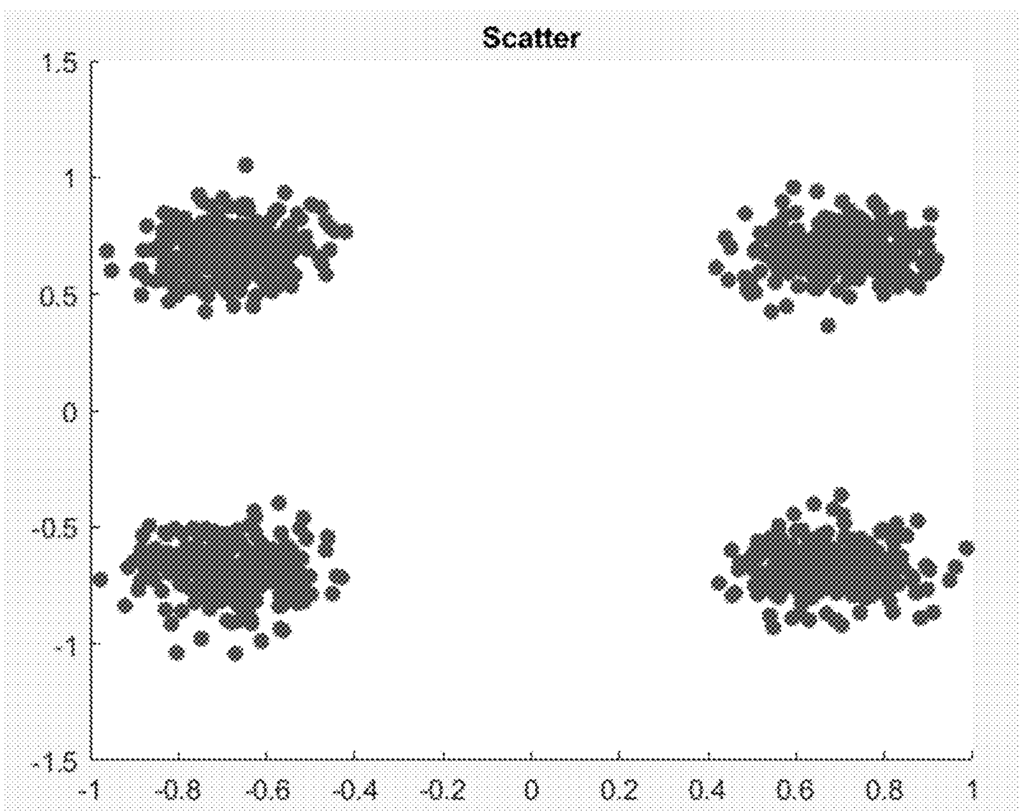


FIG. 105C

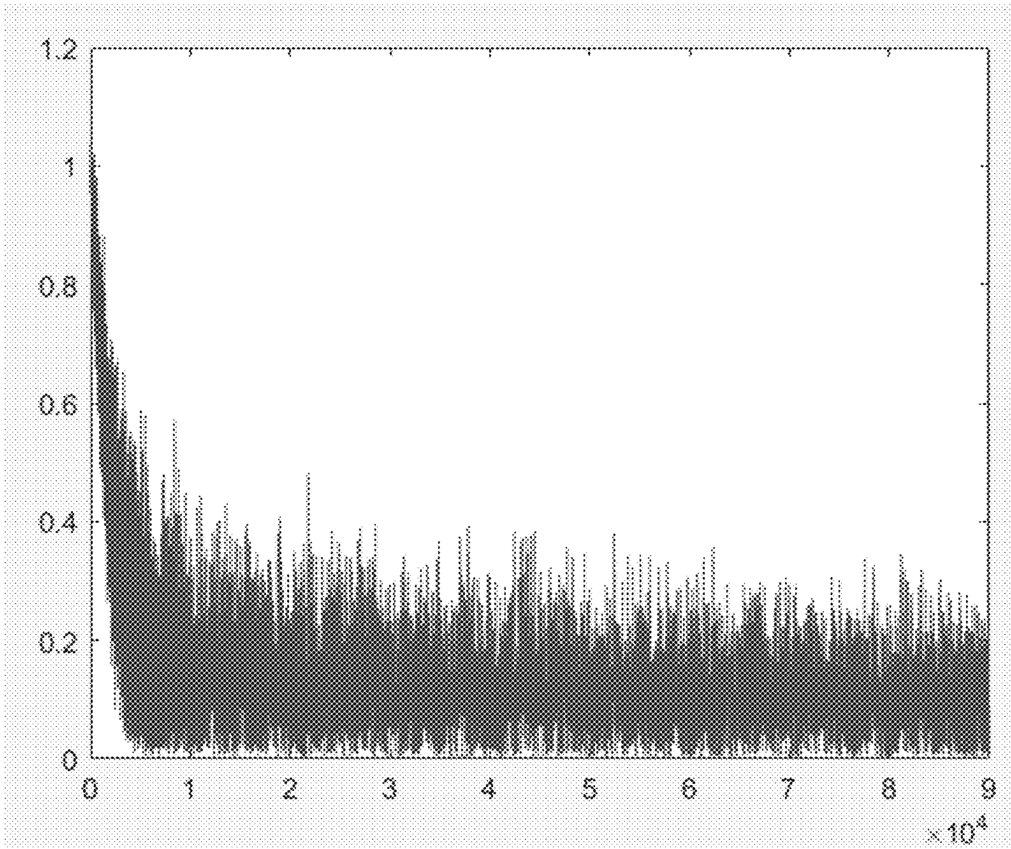


FIG. 105D

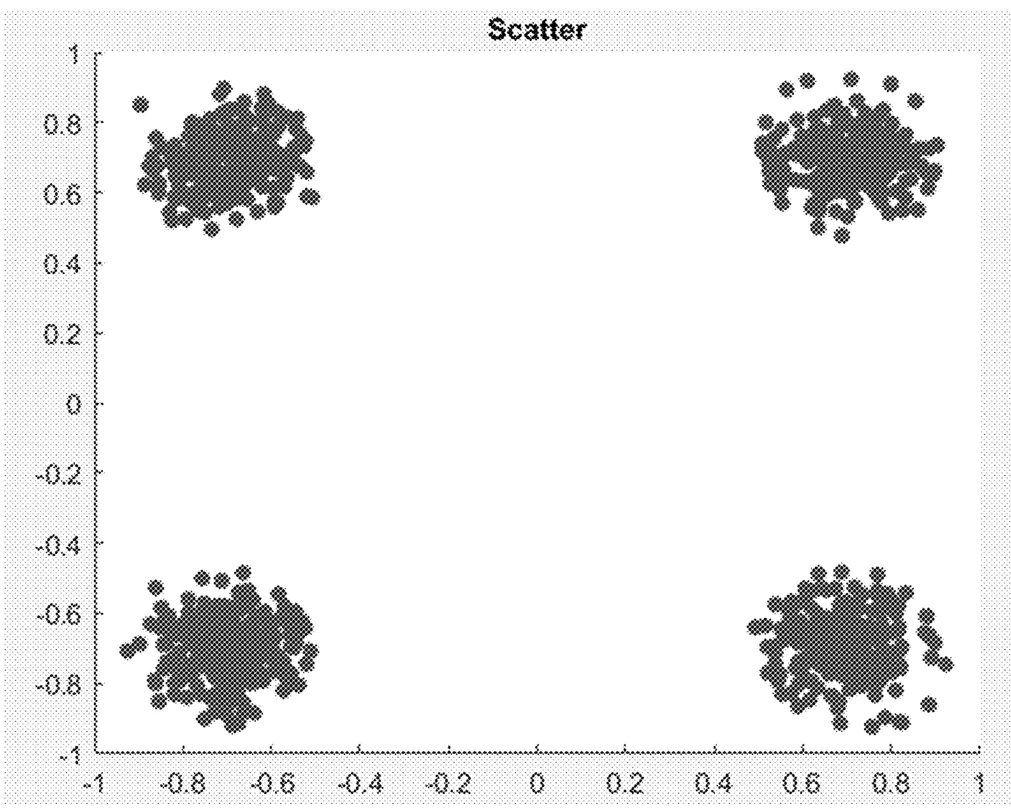


FIG. 105E

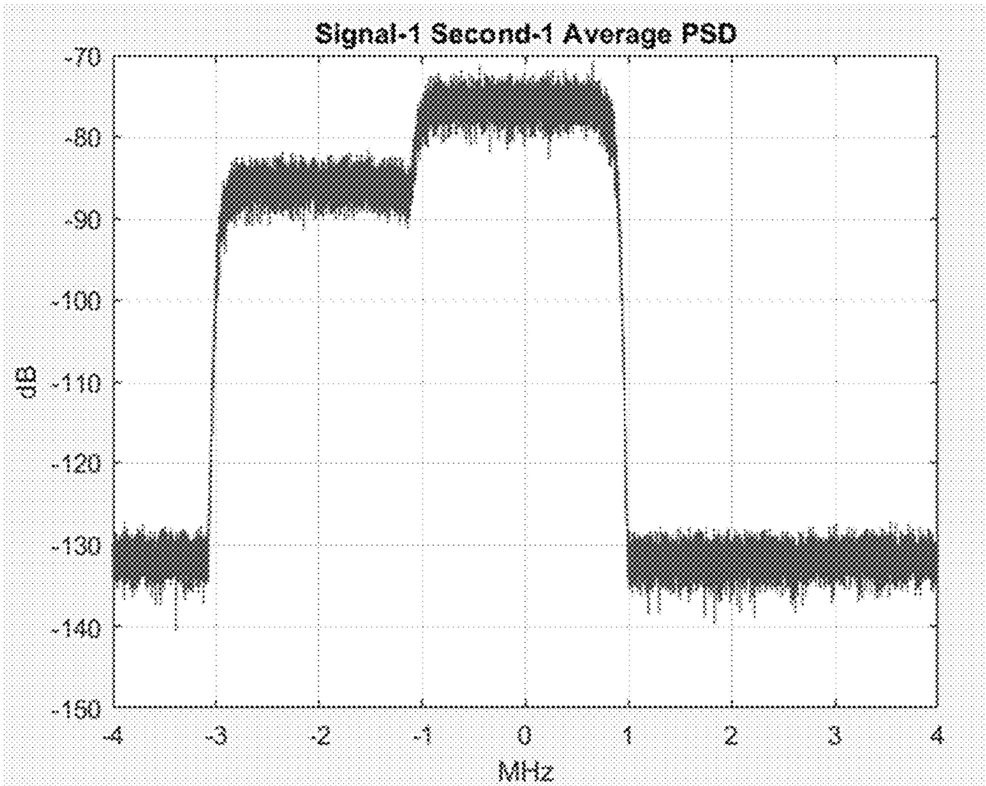


FIG. 106A

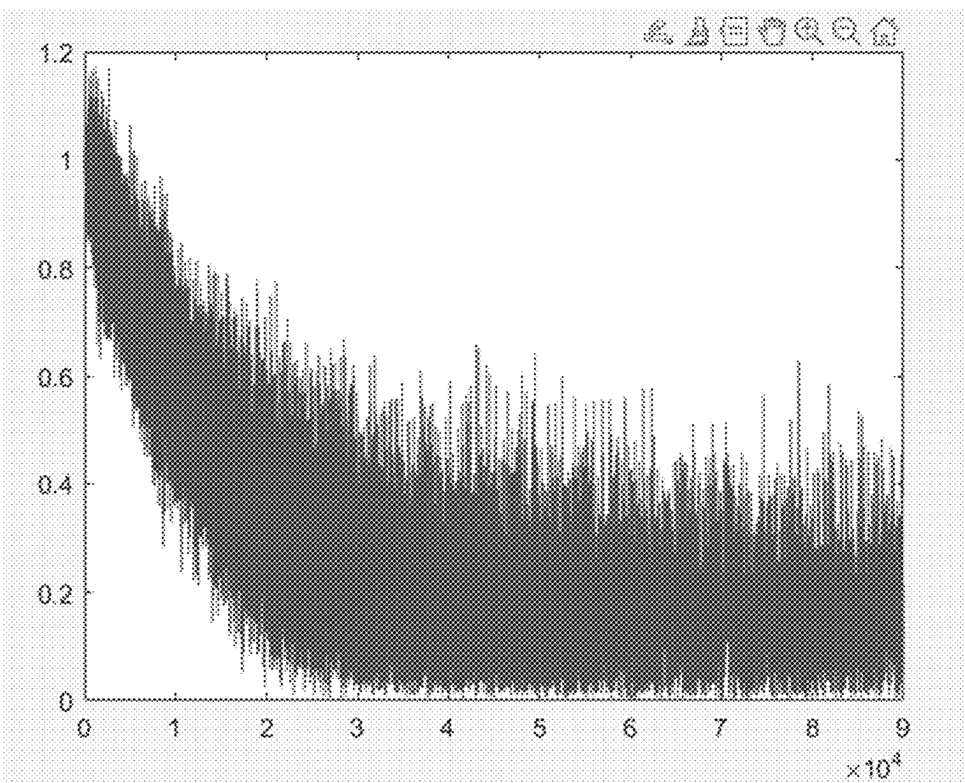


FIG. 106B

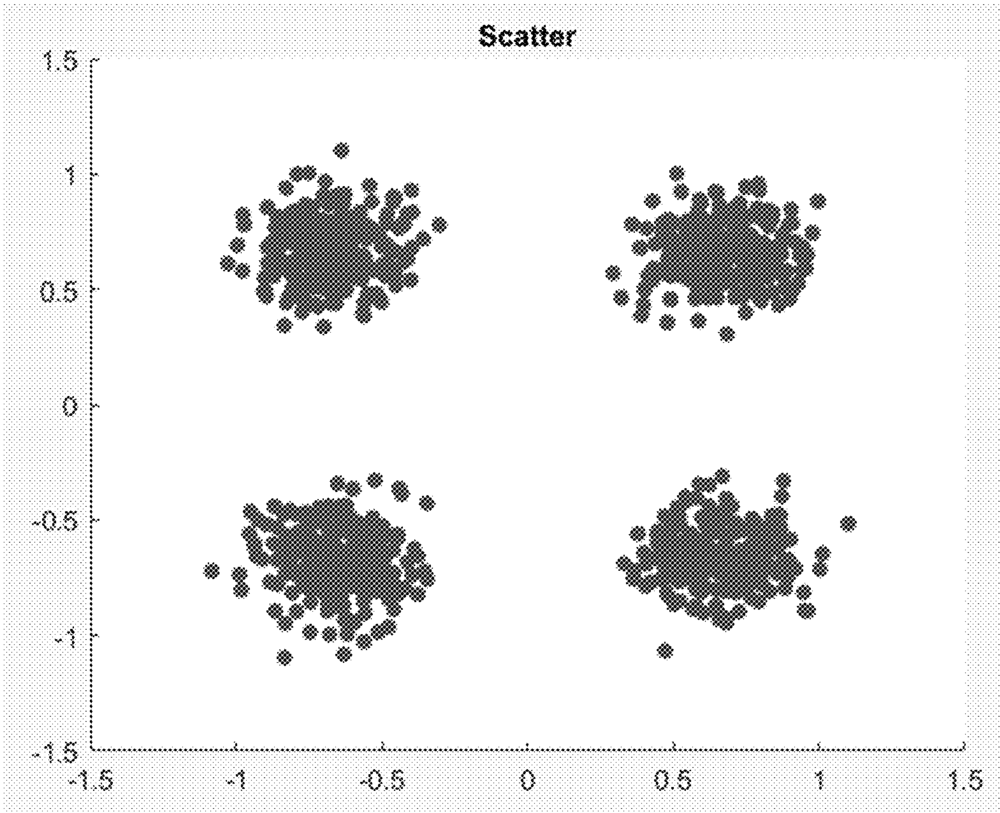


FIG. 106C

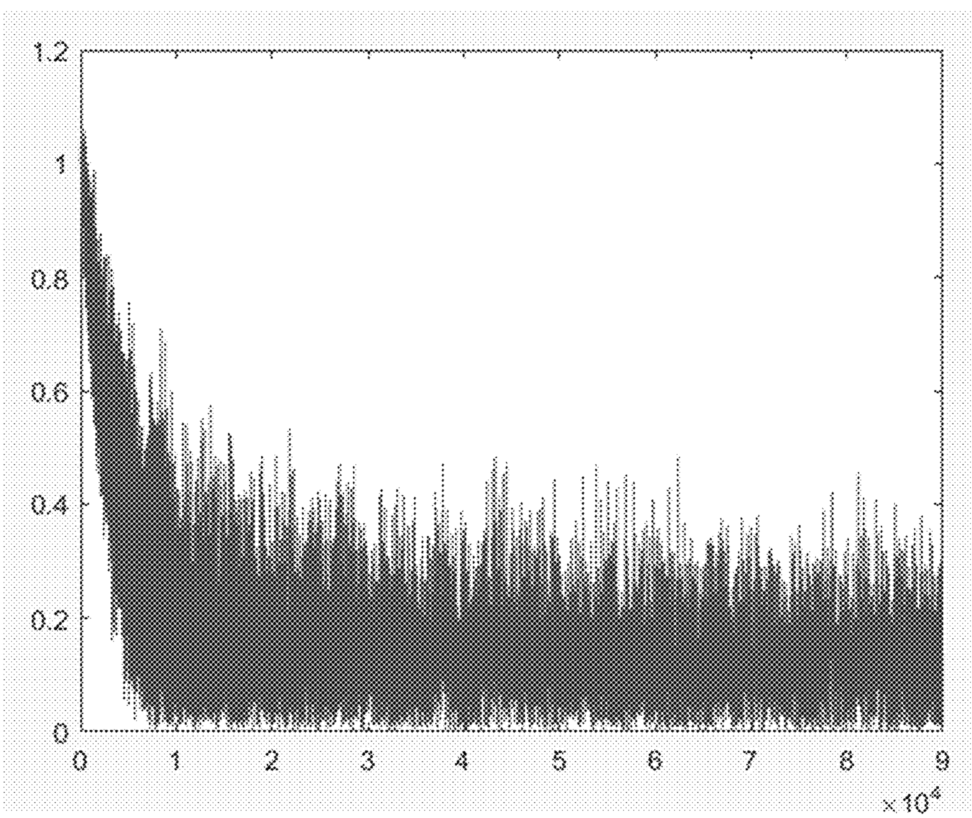


FIG. 106D

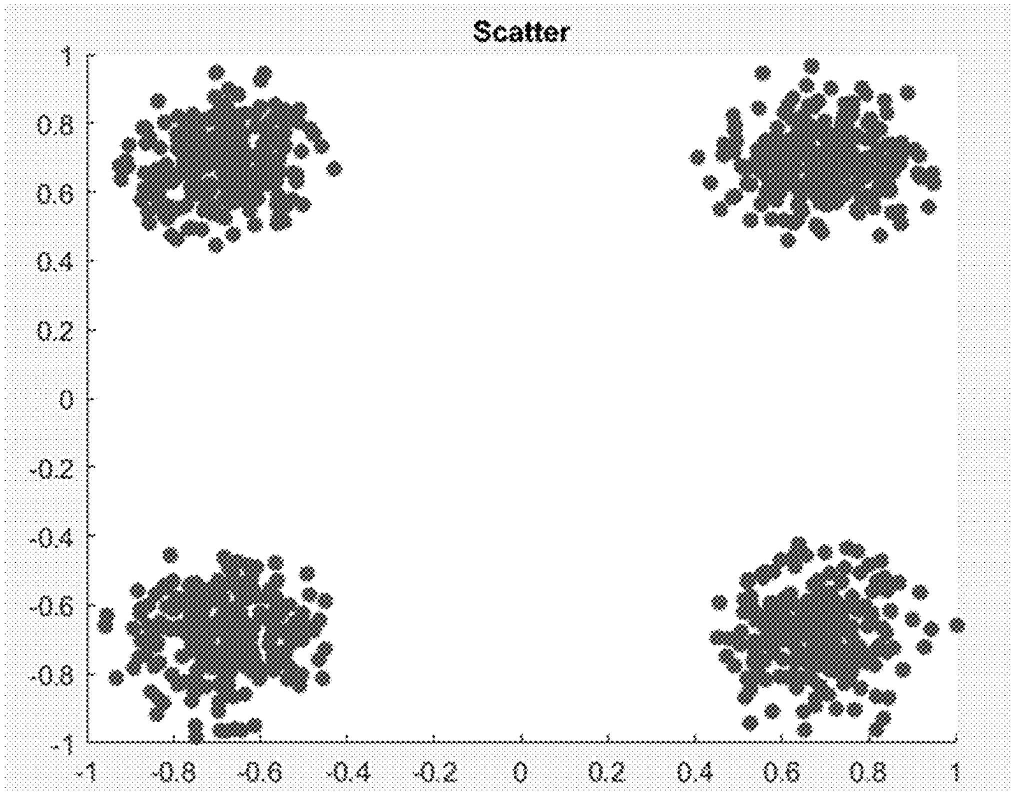


FIG. 106E

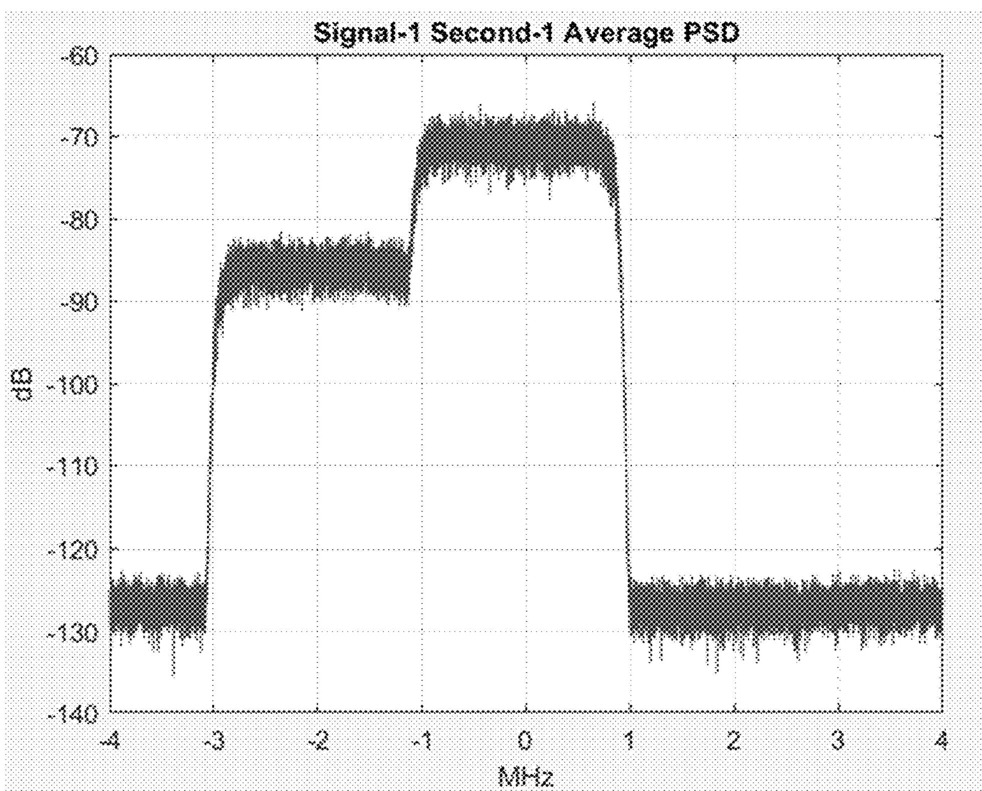


FIG. 107A

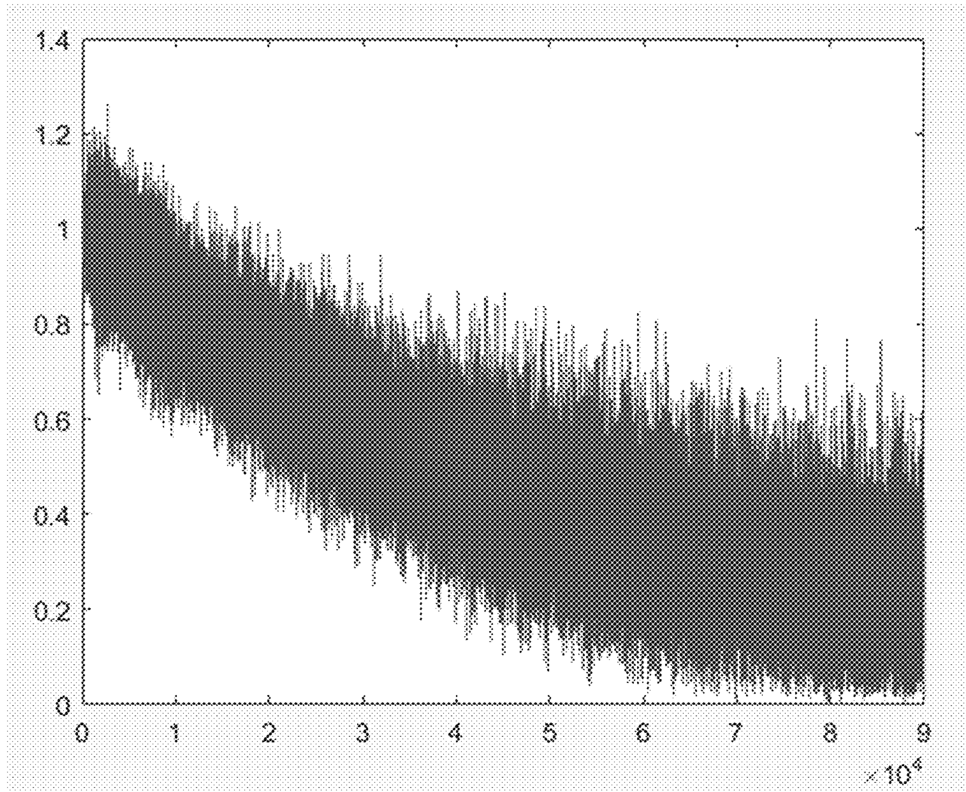


FIG. 107B

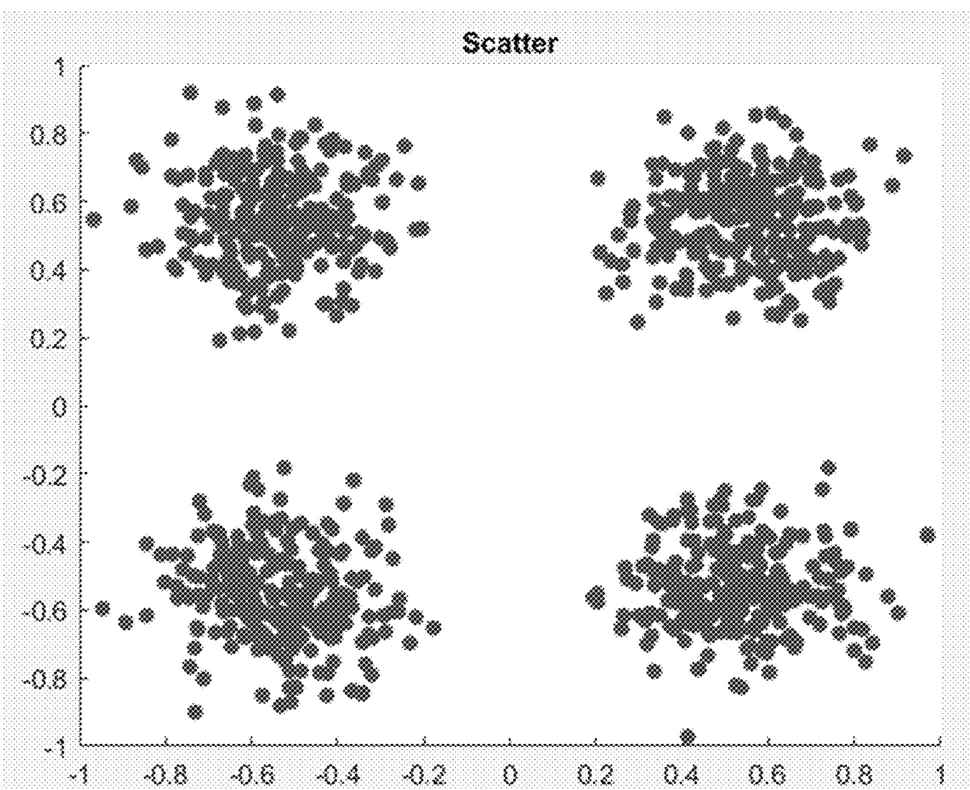


FIG. 107C

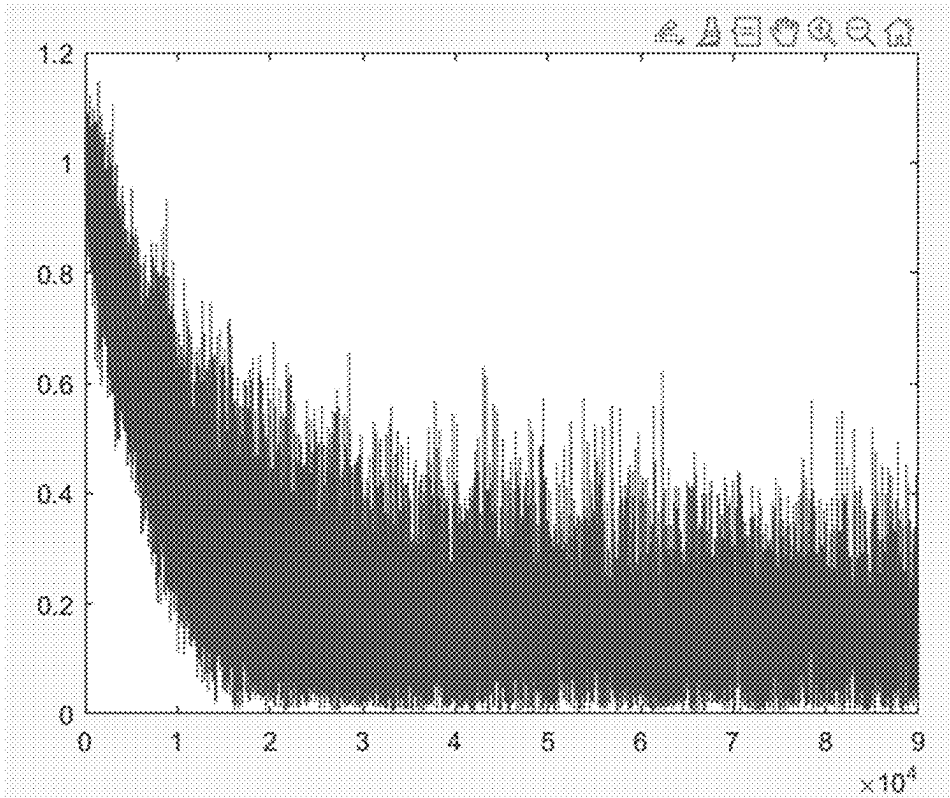


FIG. 107D

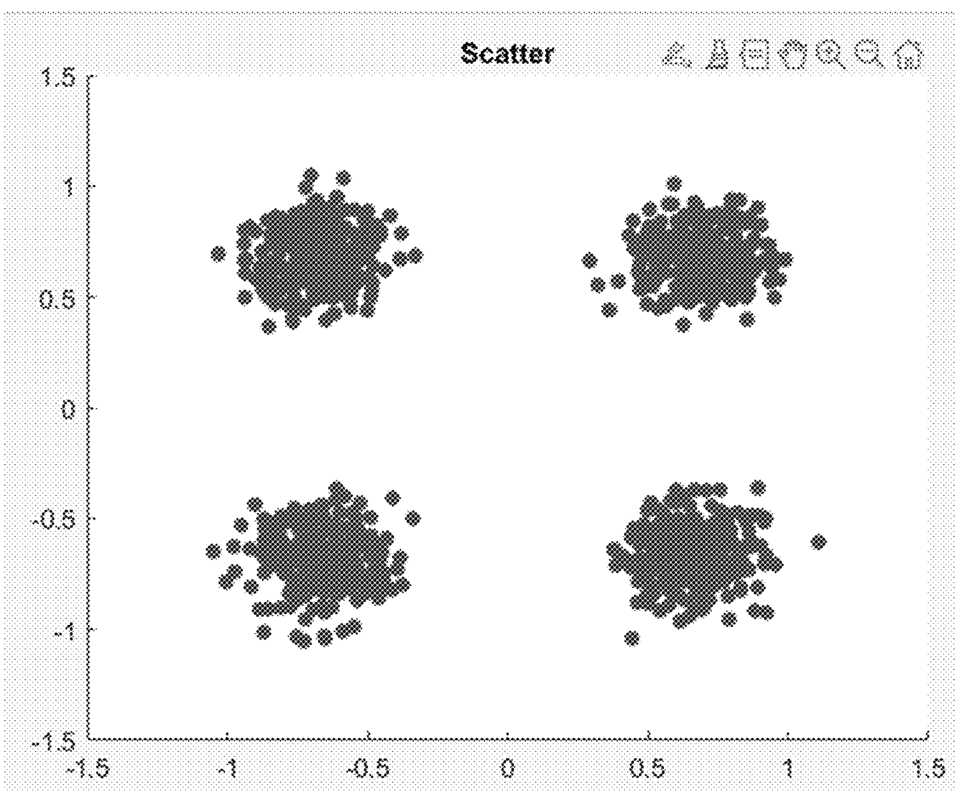


FIG. 107E

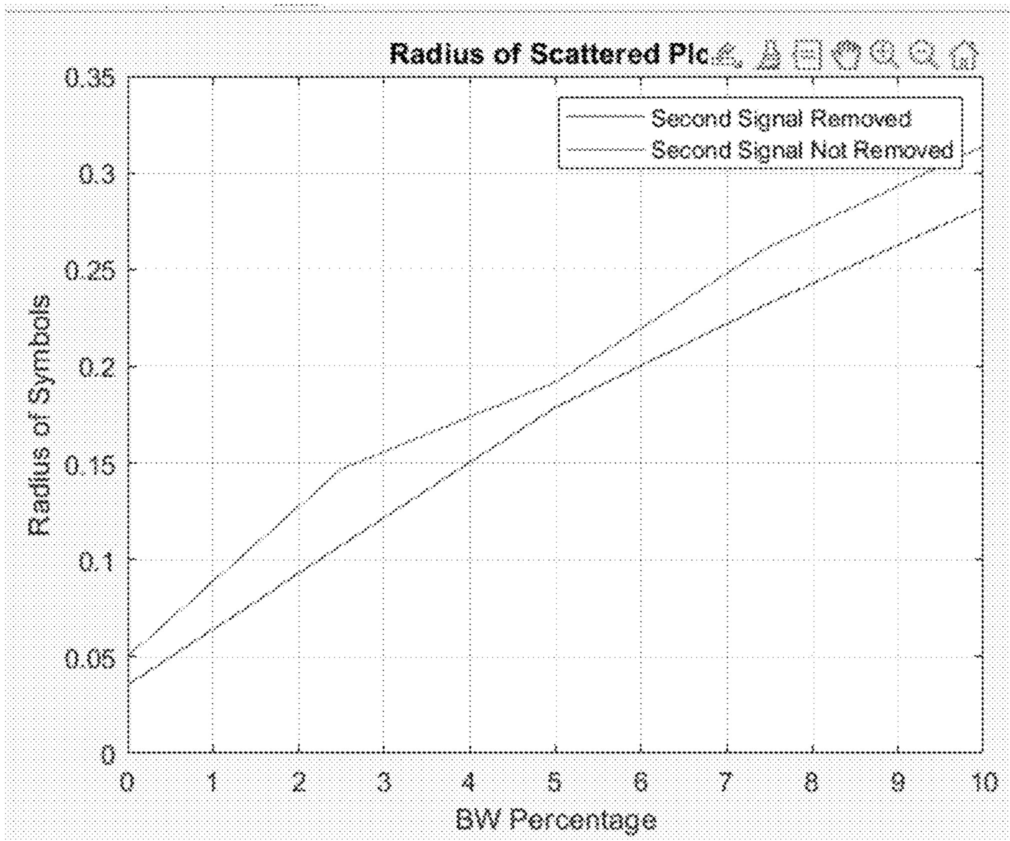


FIG. 108A

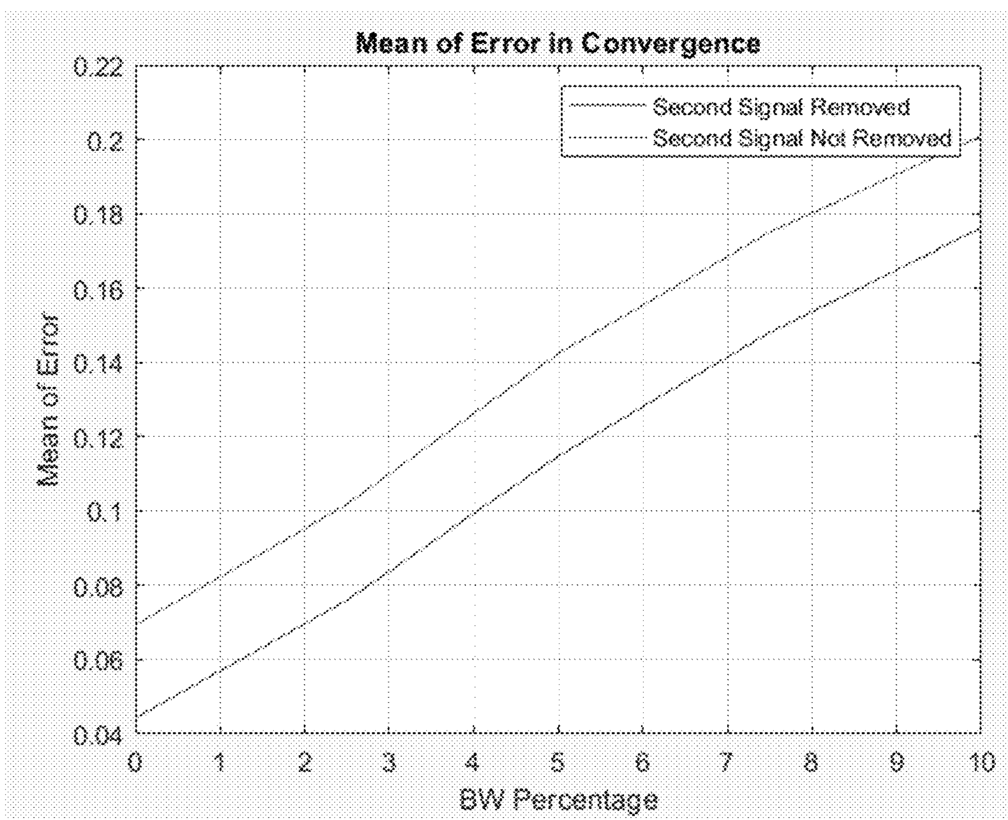


FIG. 108B

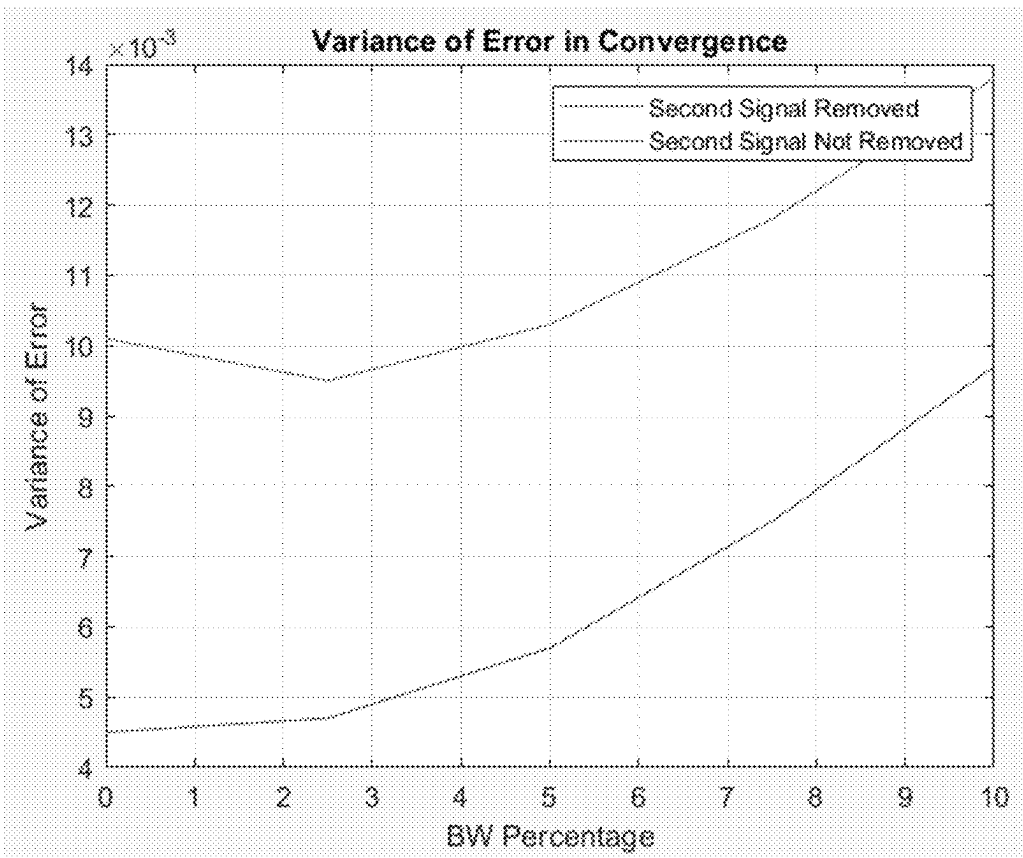

Variance of Error in Convergence
×10^-3
14
13
12
11
10
9
8
7
6
5
4
Variance of Error
Second Signal Removed
Second Signal Not Removed
0
1
2
3
4
5
6
7
8
9
10
BW Percentage

FIG. 108C

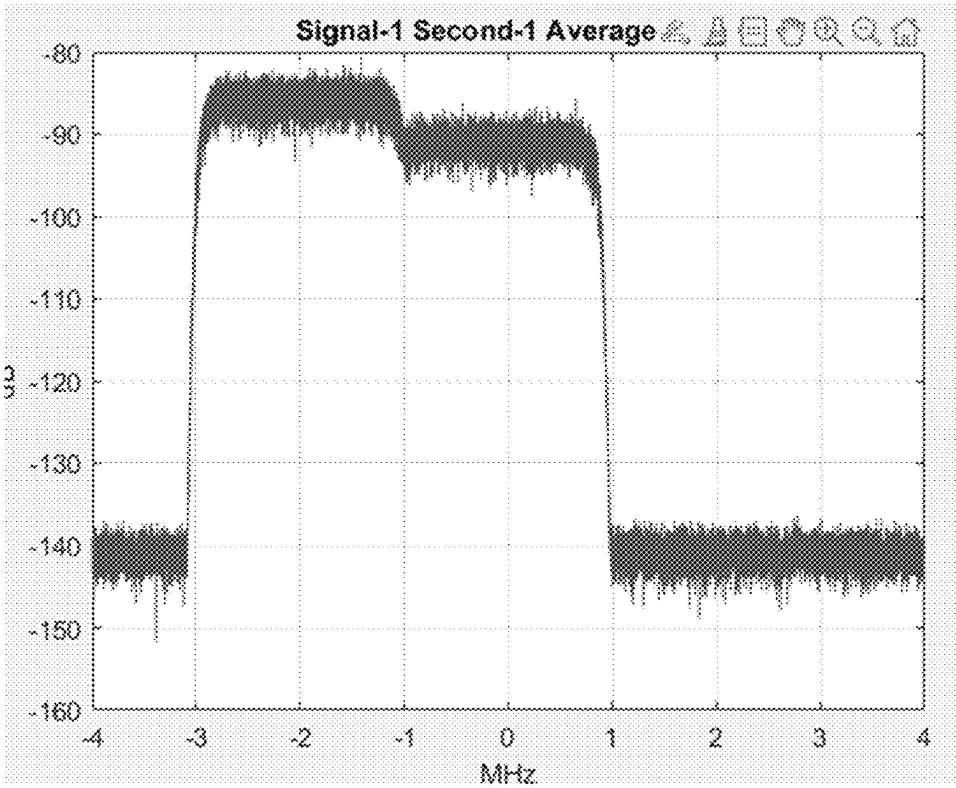


FIG. 109A

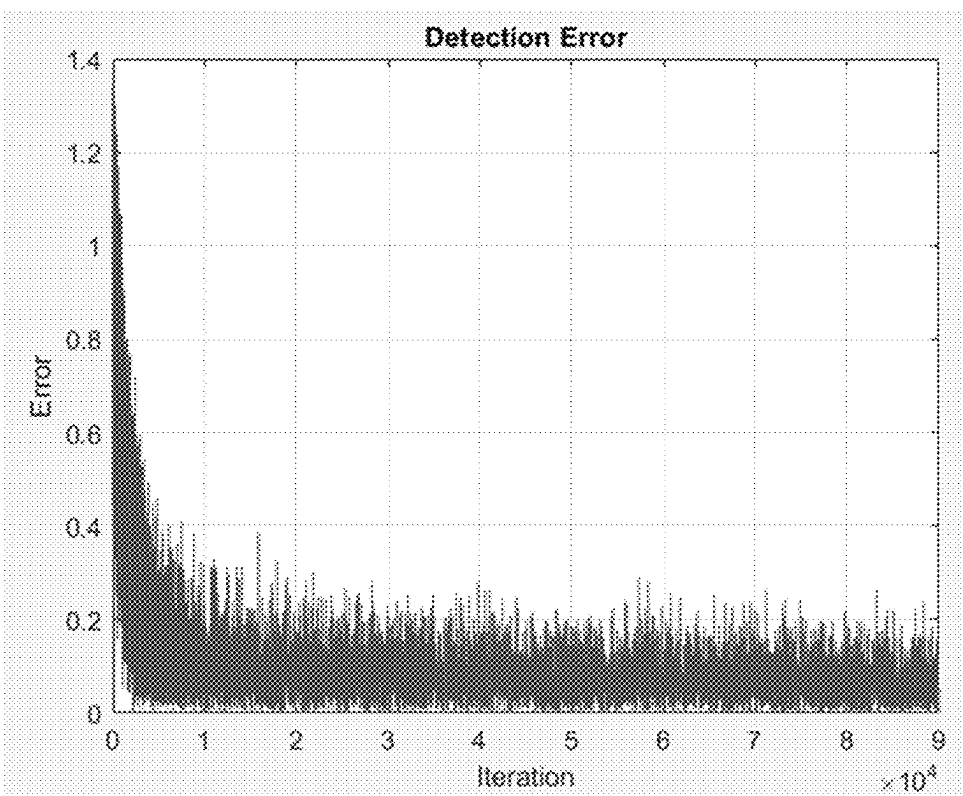


FIG. 109B

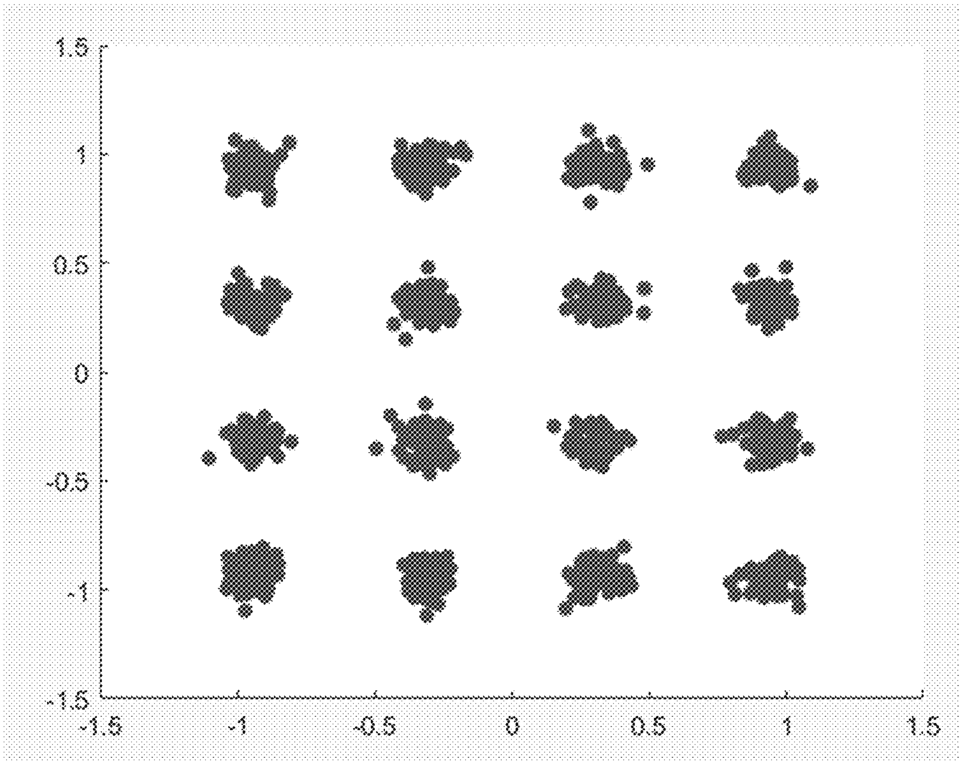


FIG. 109C

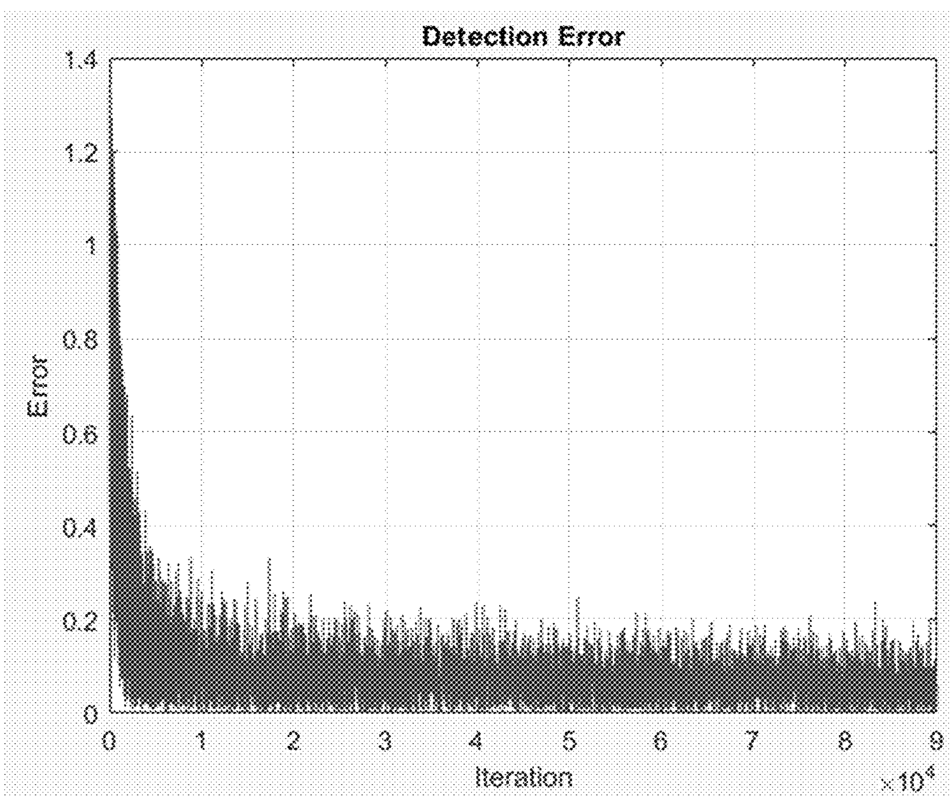


FIG. 109D

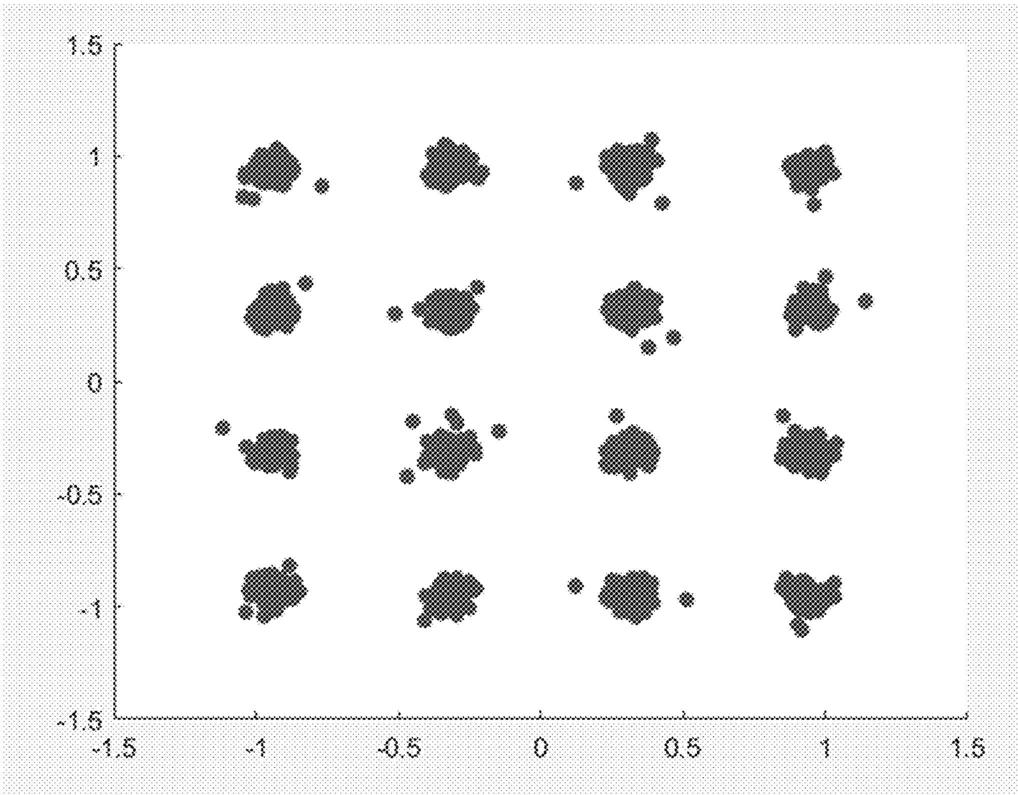


FIG. 109E

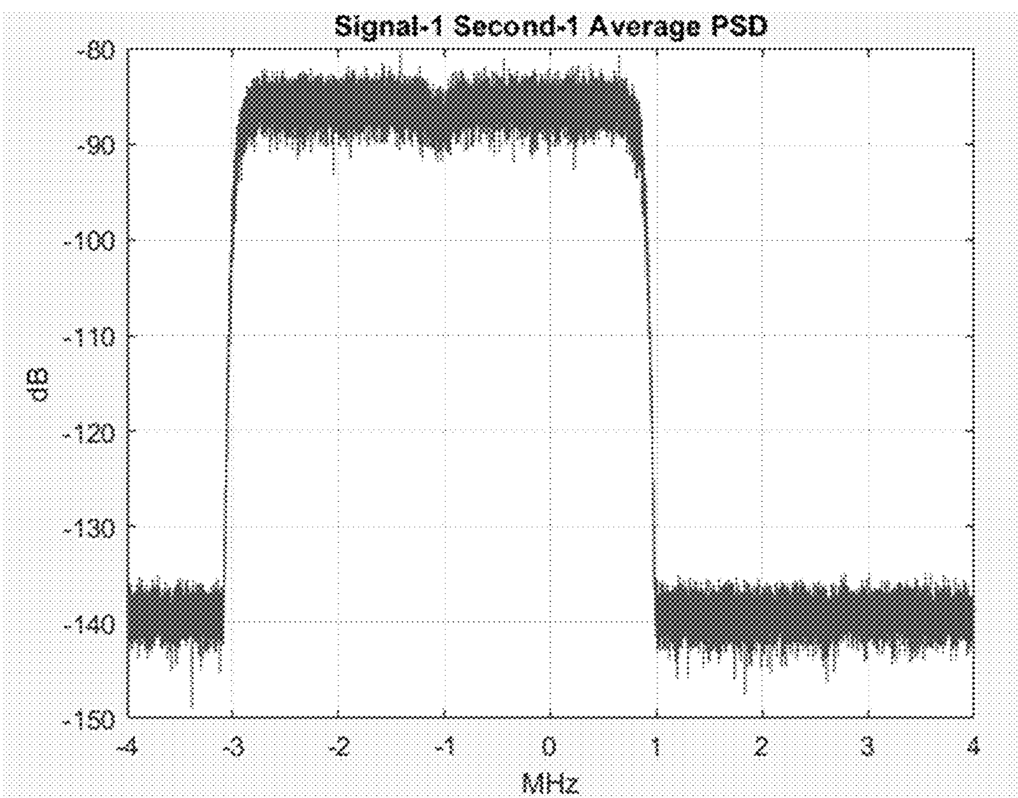


FIG. 110A

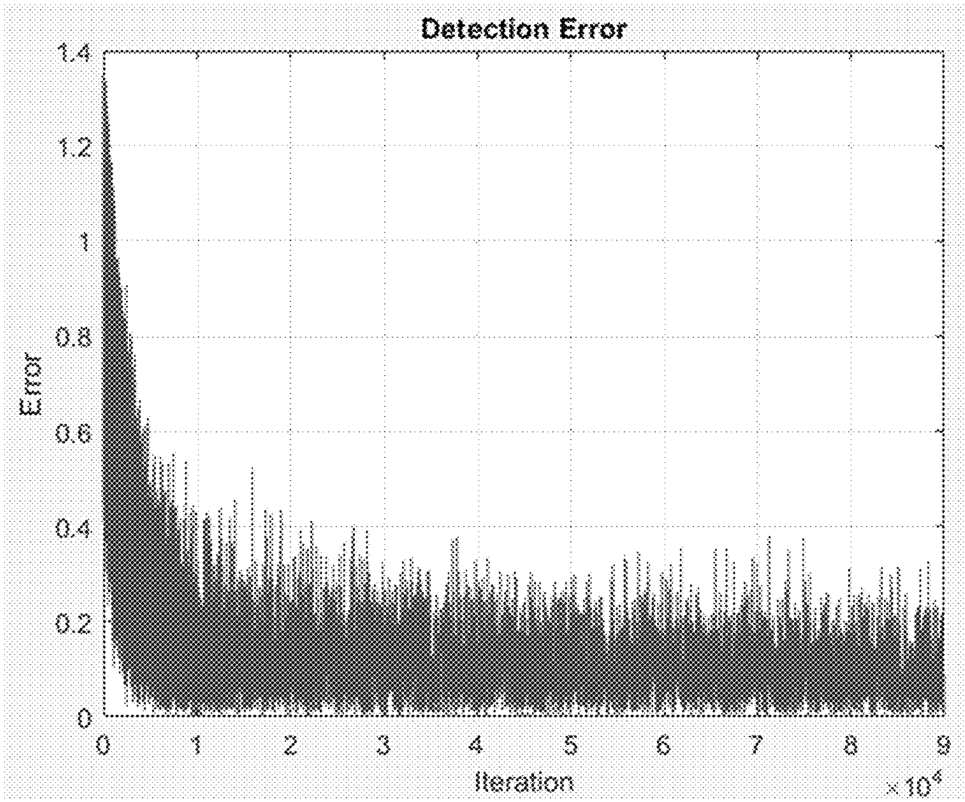


FIG. 110B

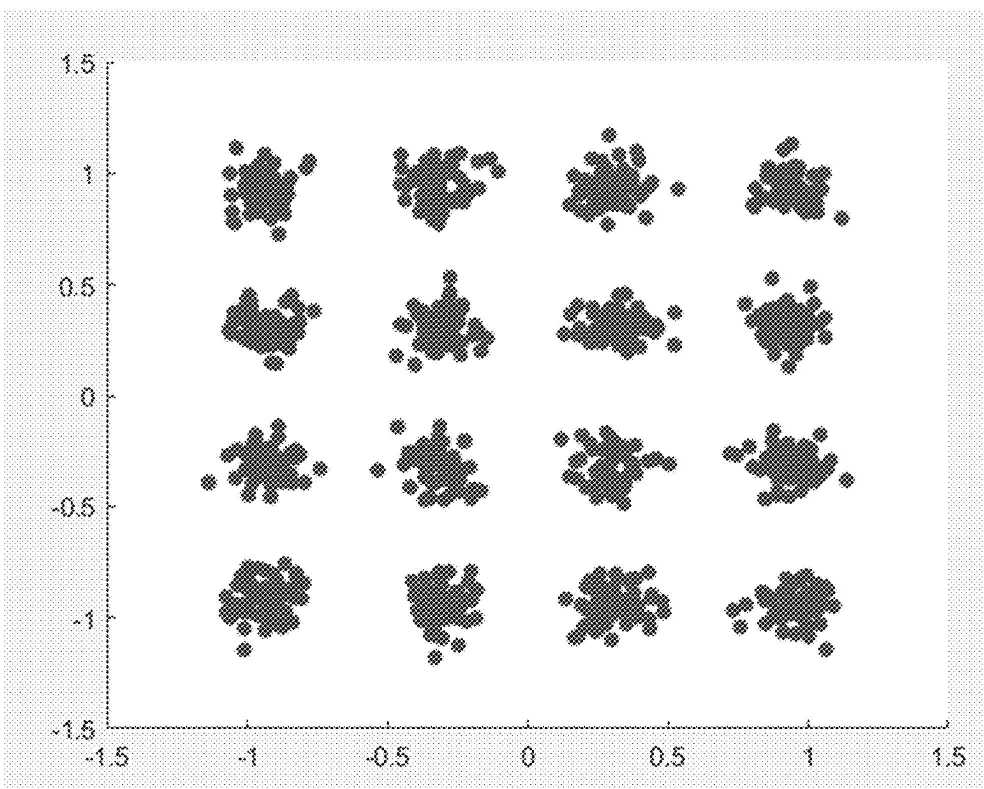


FIG. 110C

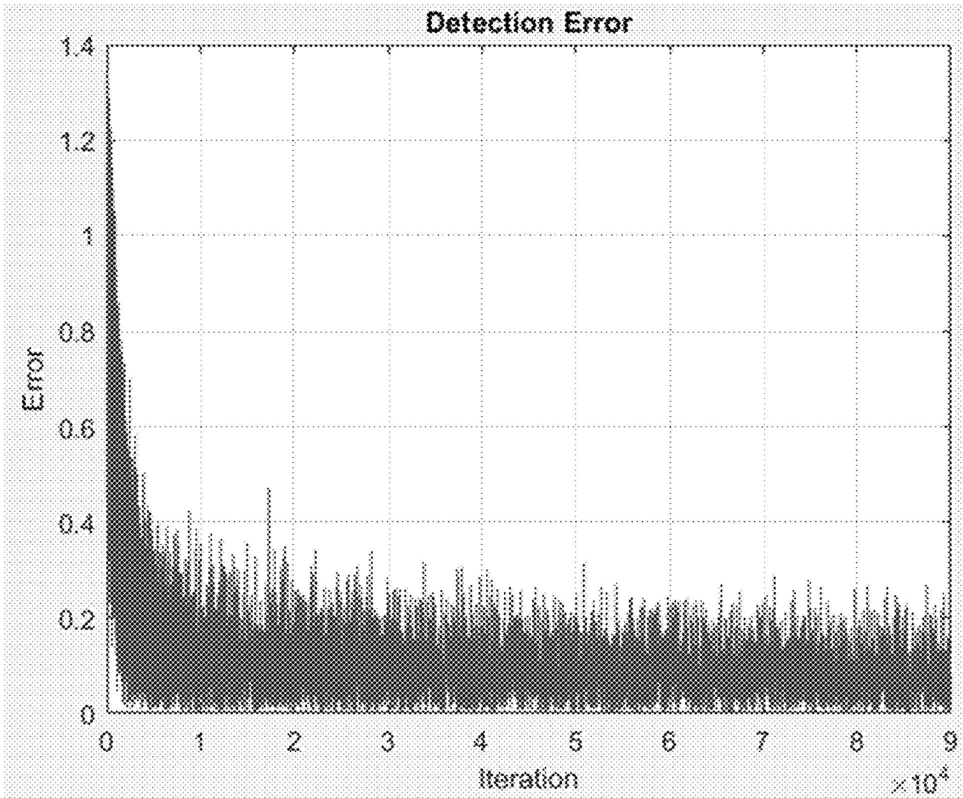


FIG. 110D

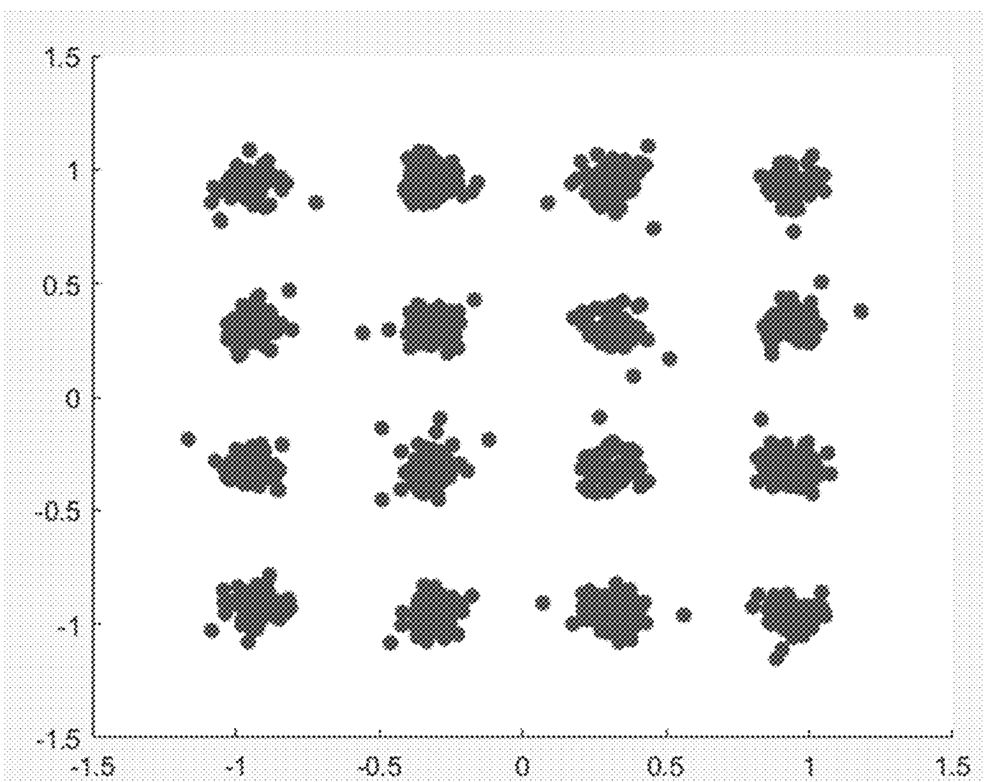


FIG. 110E

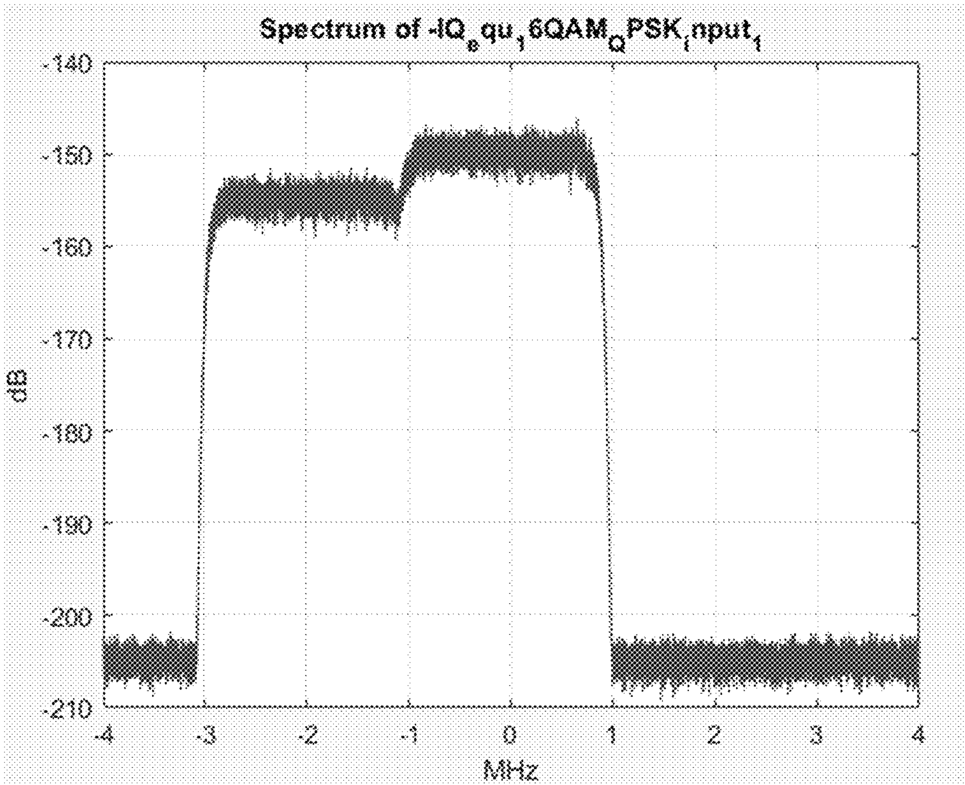


FIG. 111A

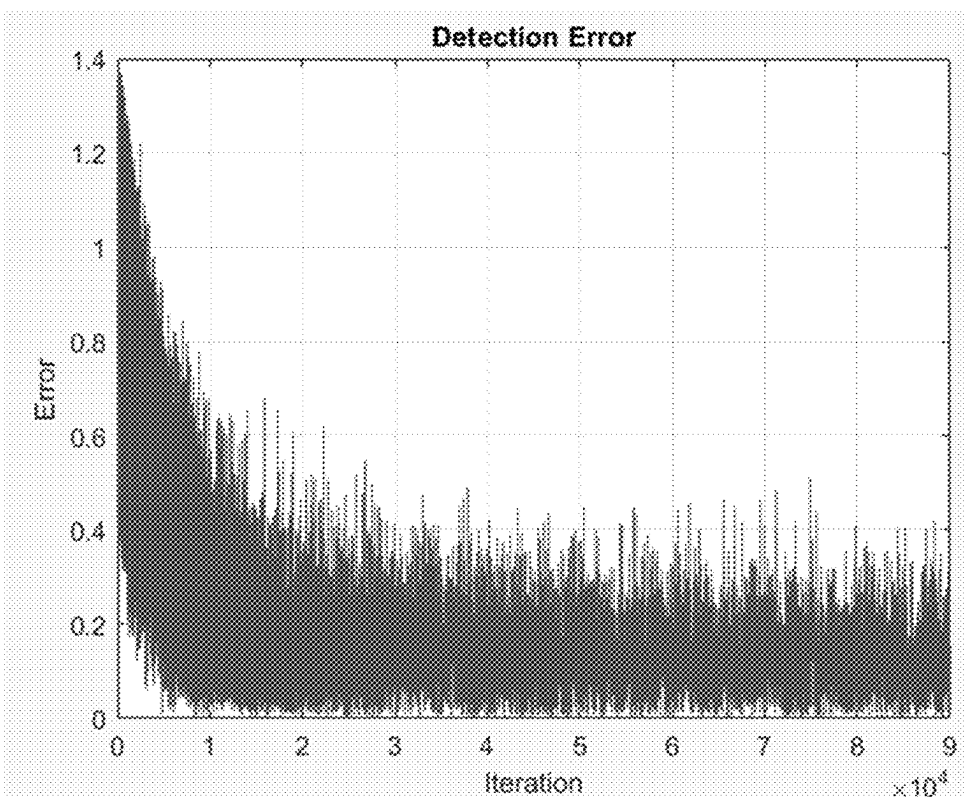


FIG. 111B

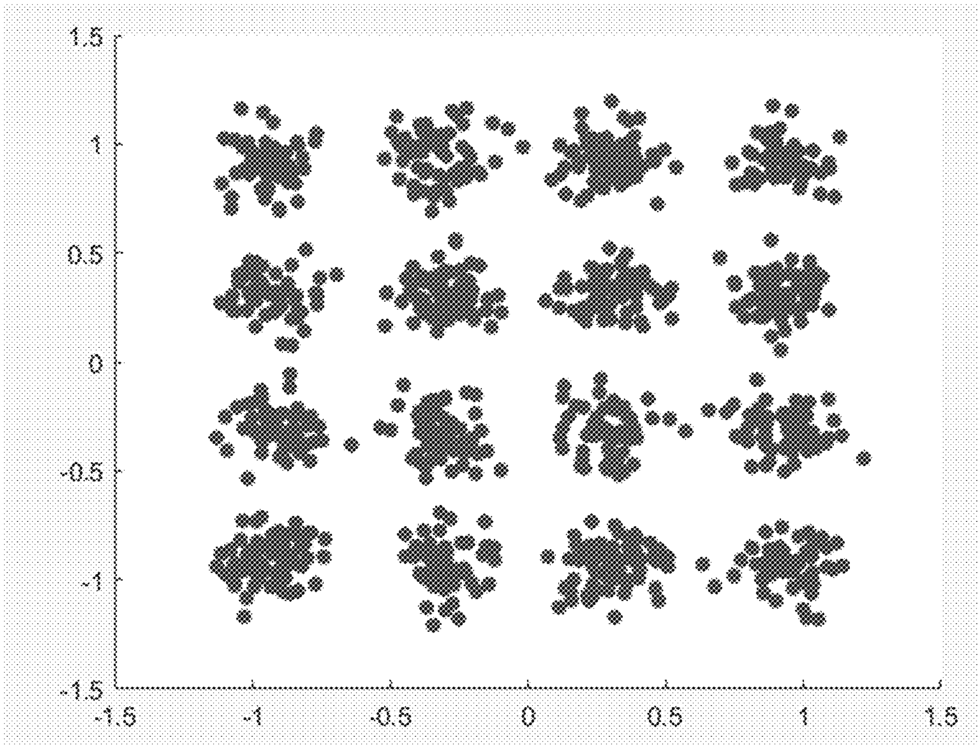


FIG. 111C

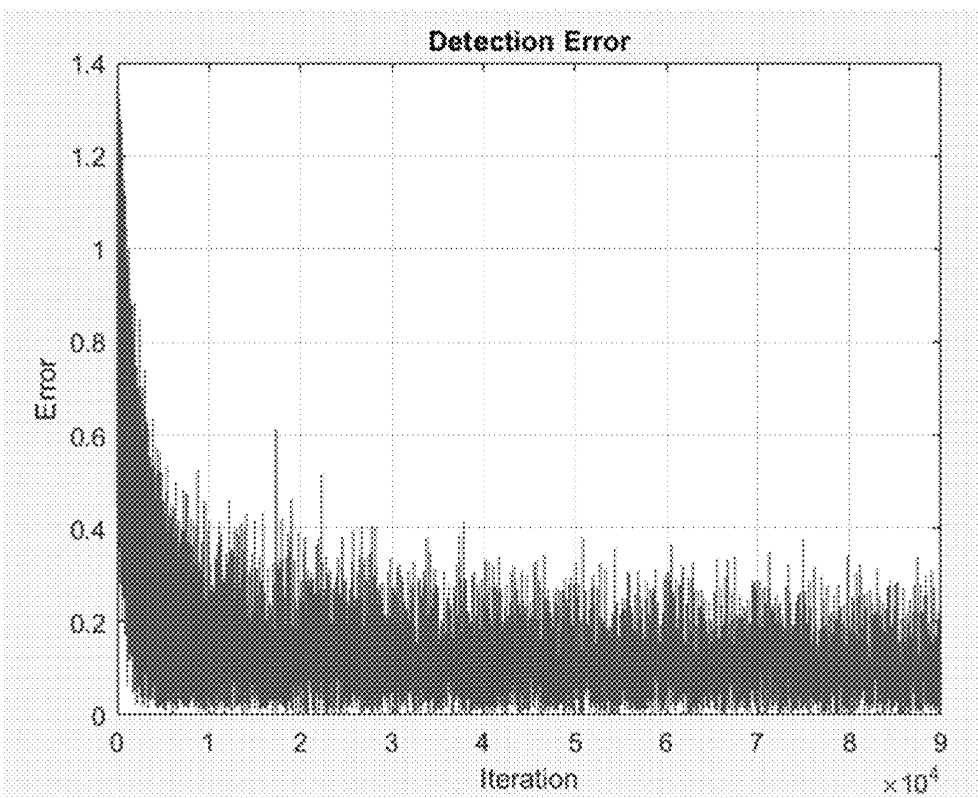


FIG. 111D

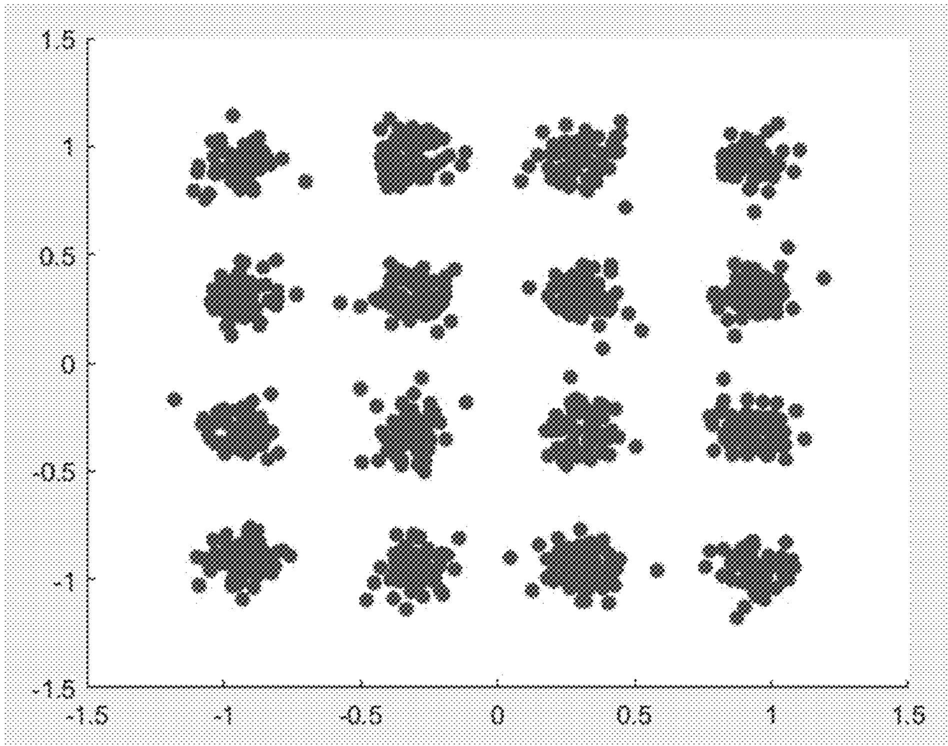


FIG. 111E

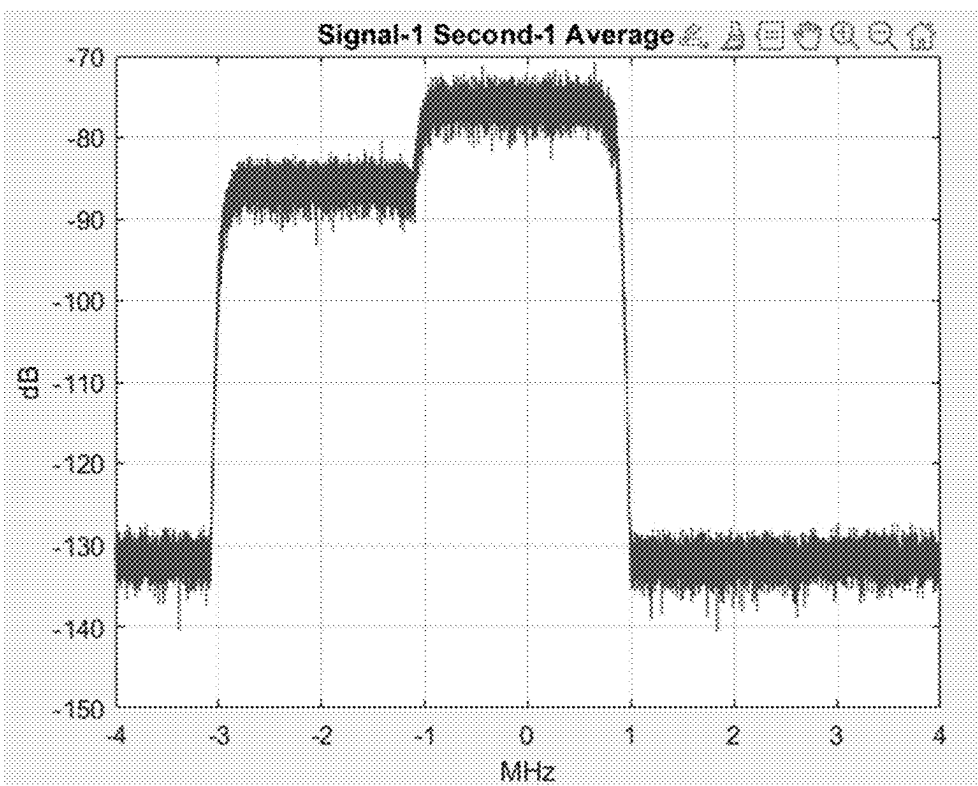


FIG. 112A

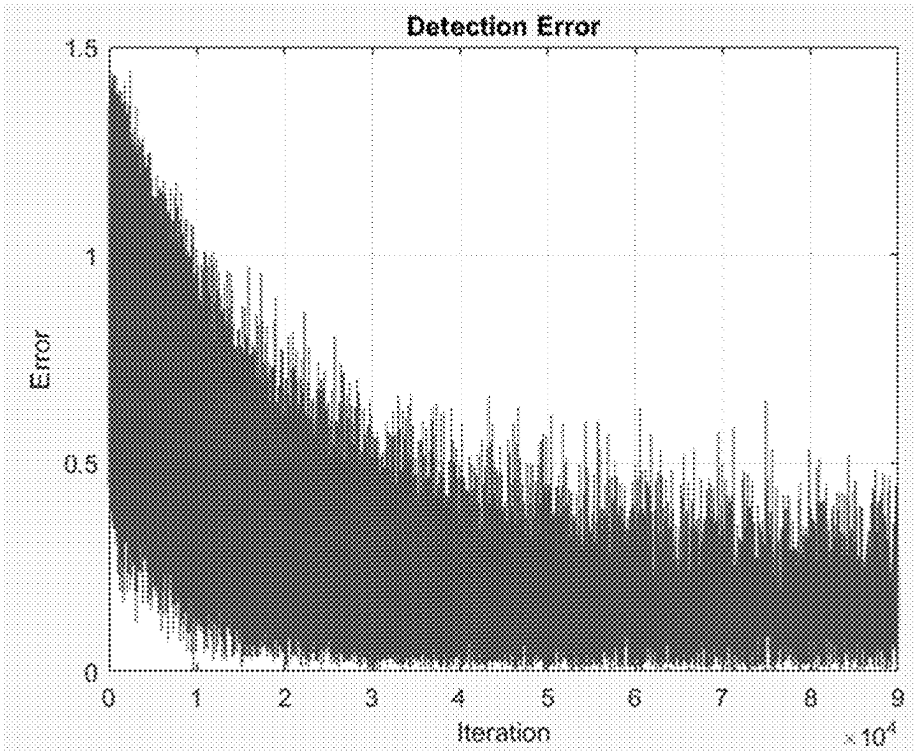


FIG. 112B

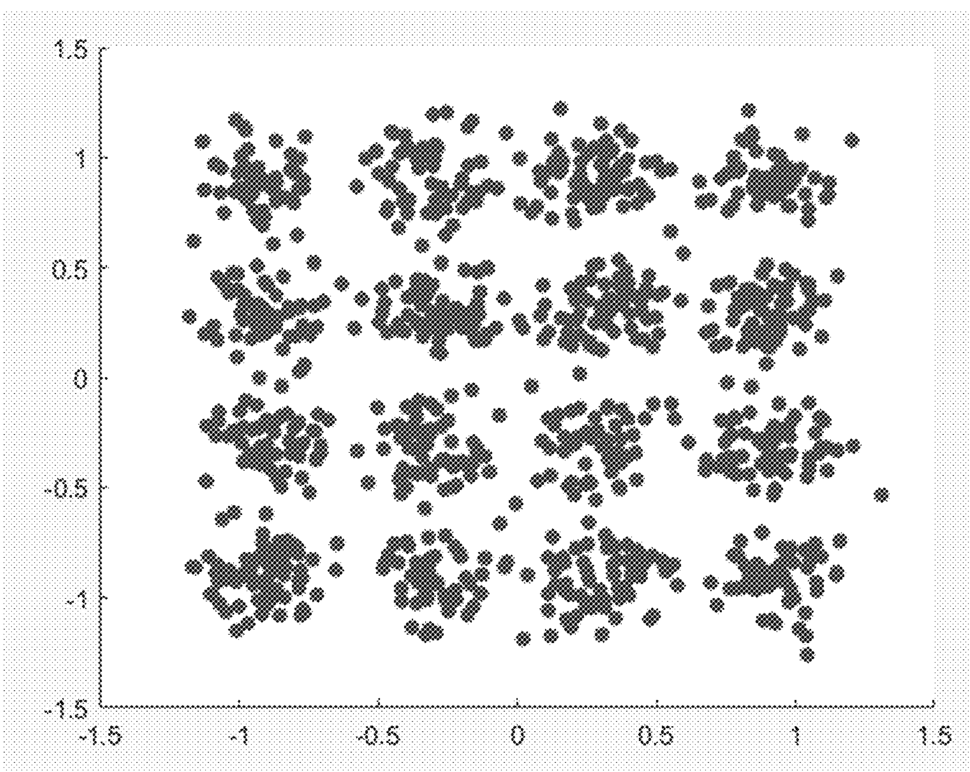


FIG. 112C

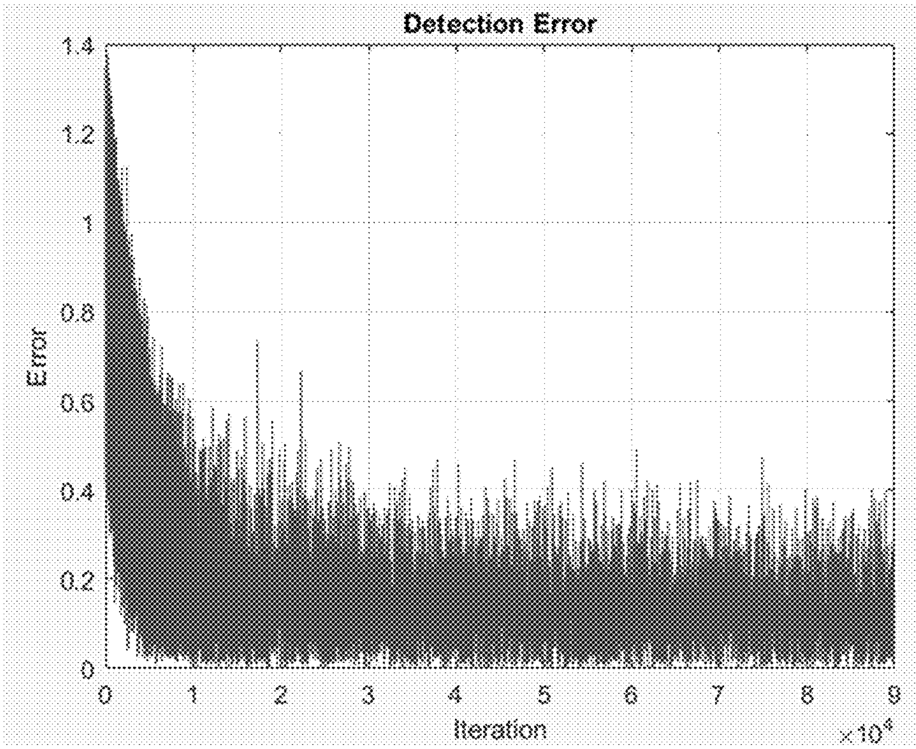


FIG. 112D

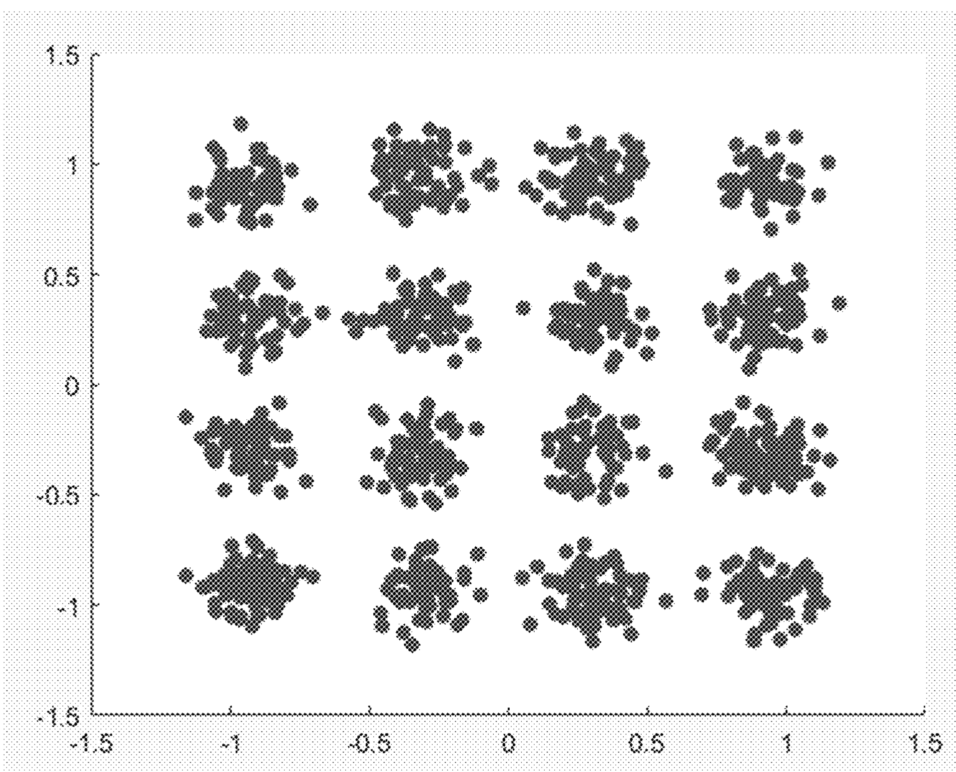


FIG. 112E

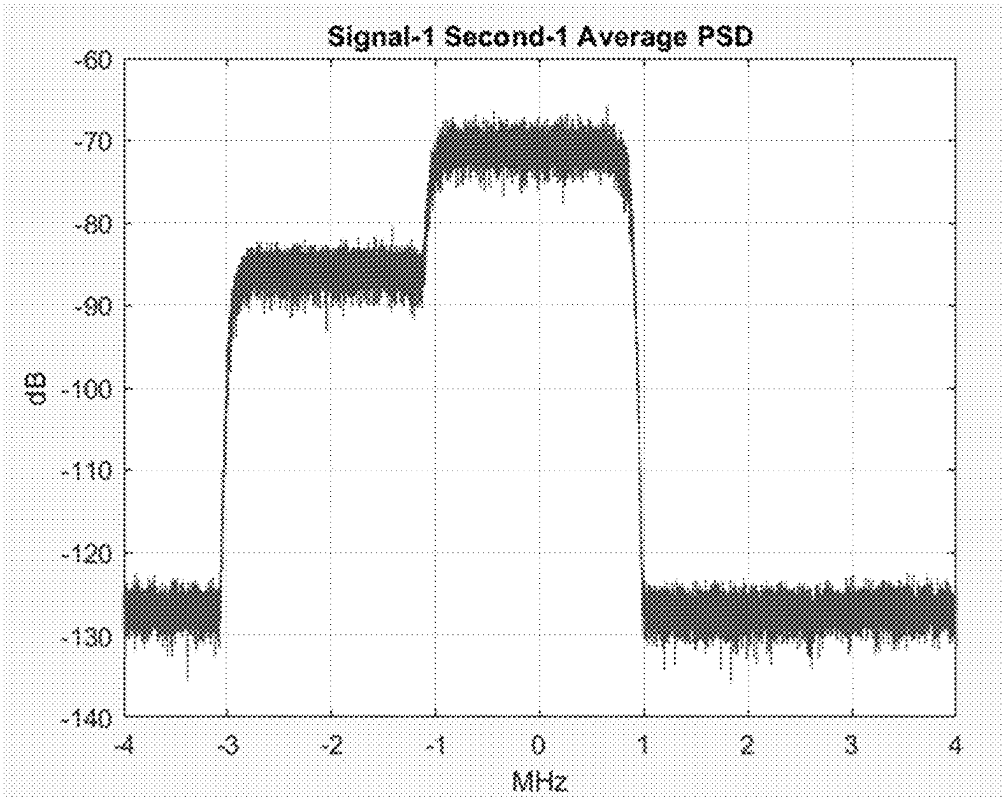


FIG. 113A

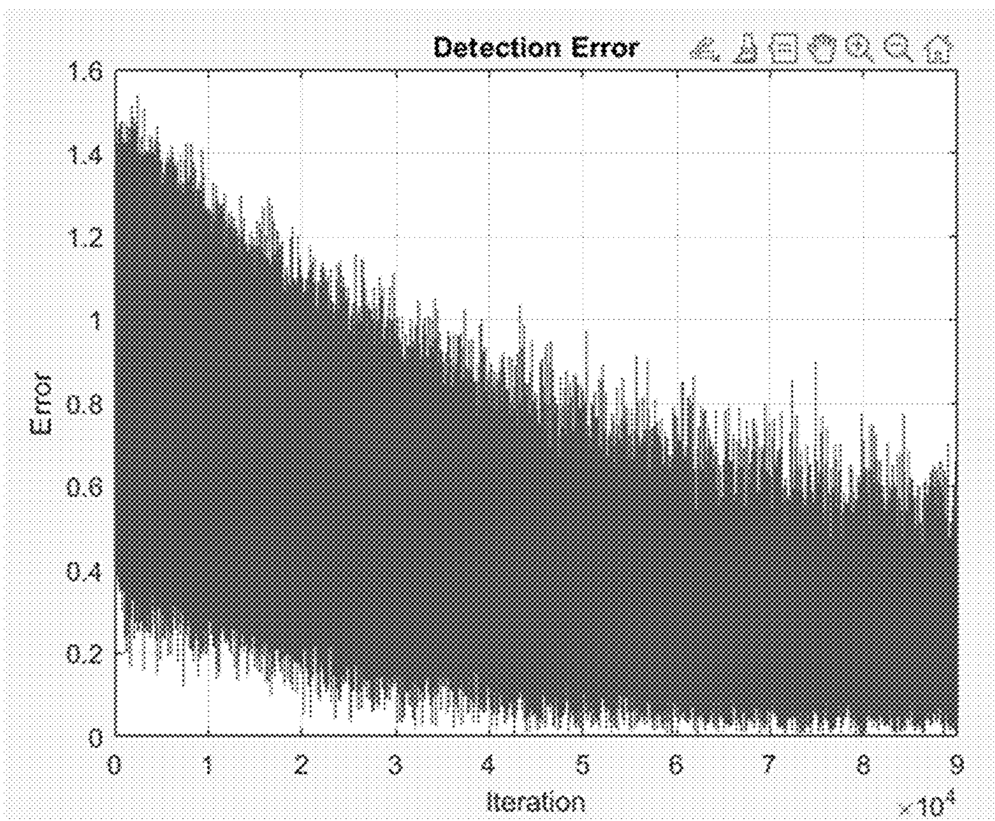


FIG. 113B

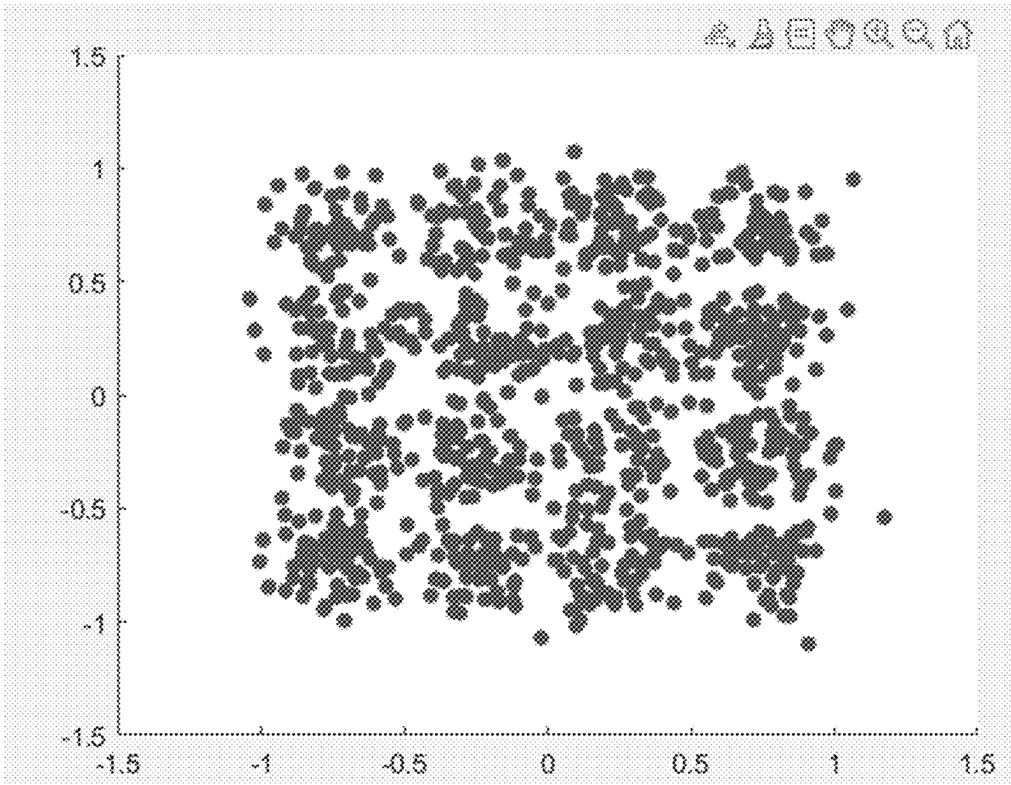


FIG. 113C

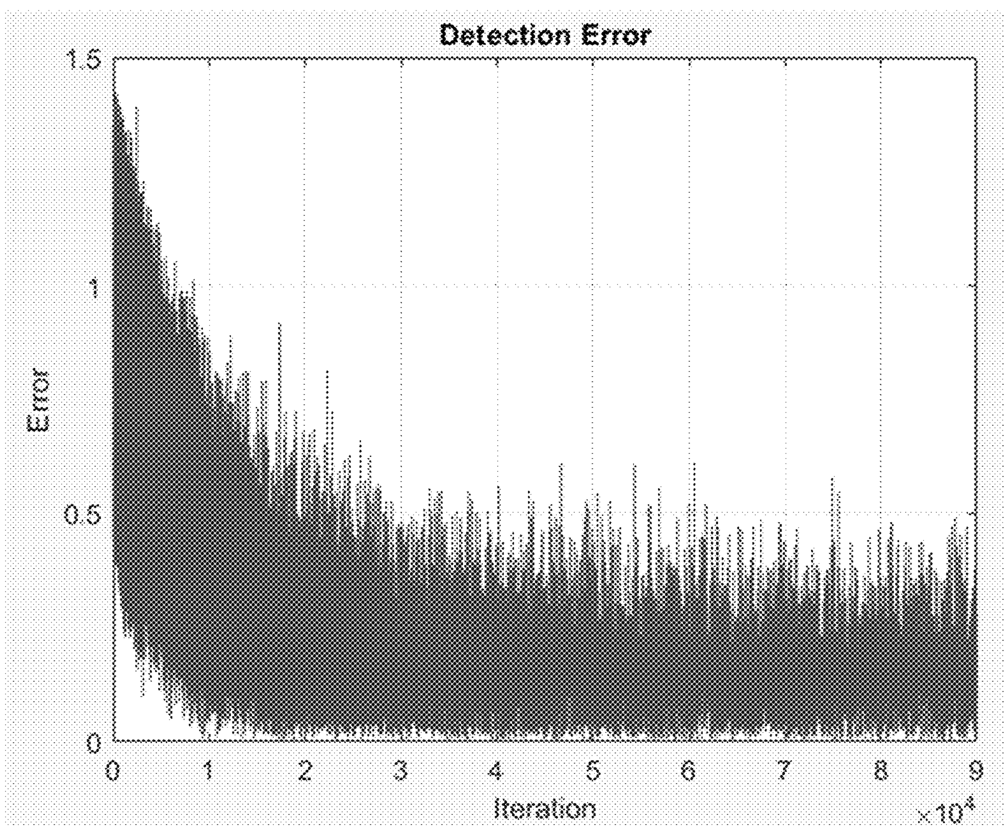


FIG. 113D

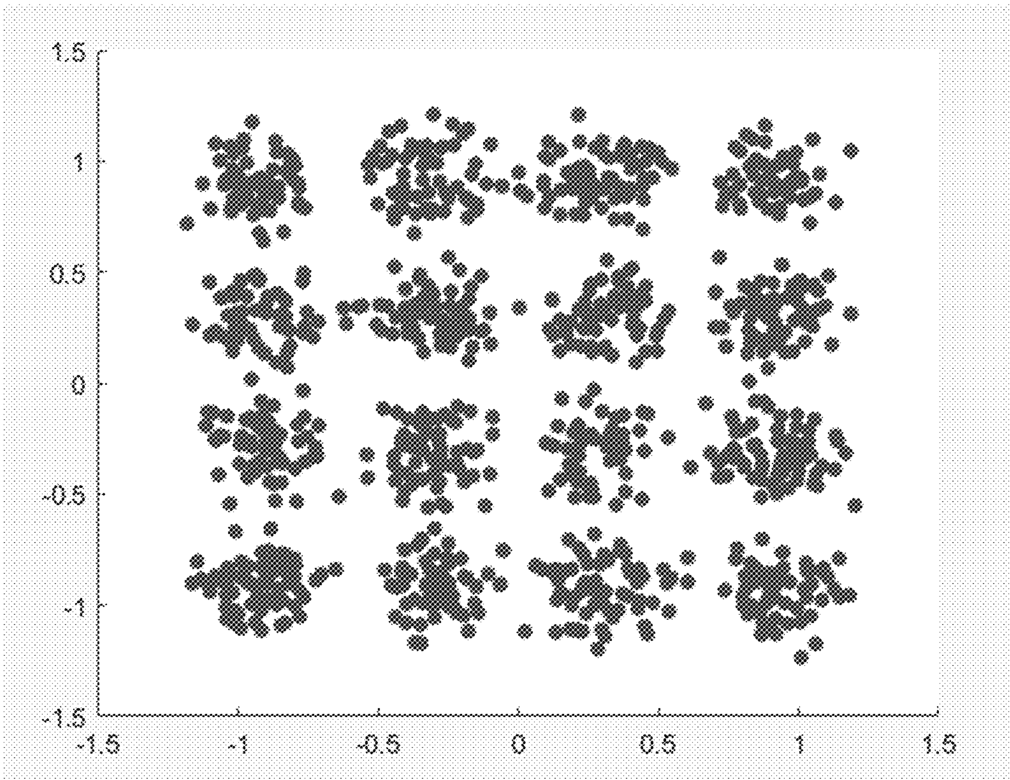


FIG. 113E

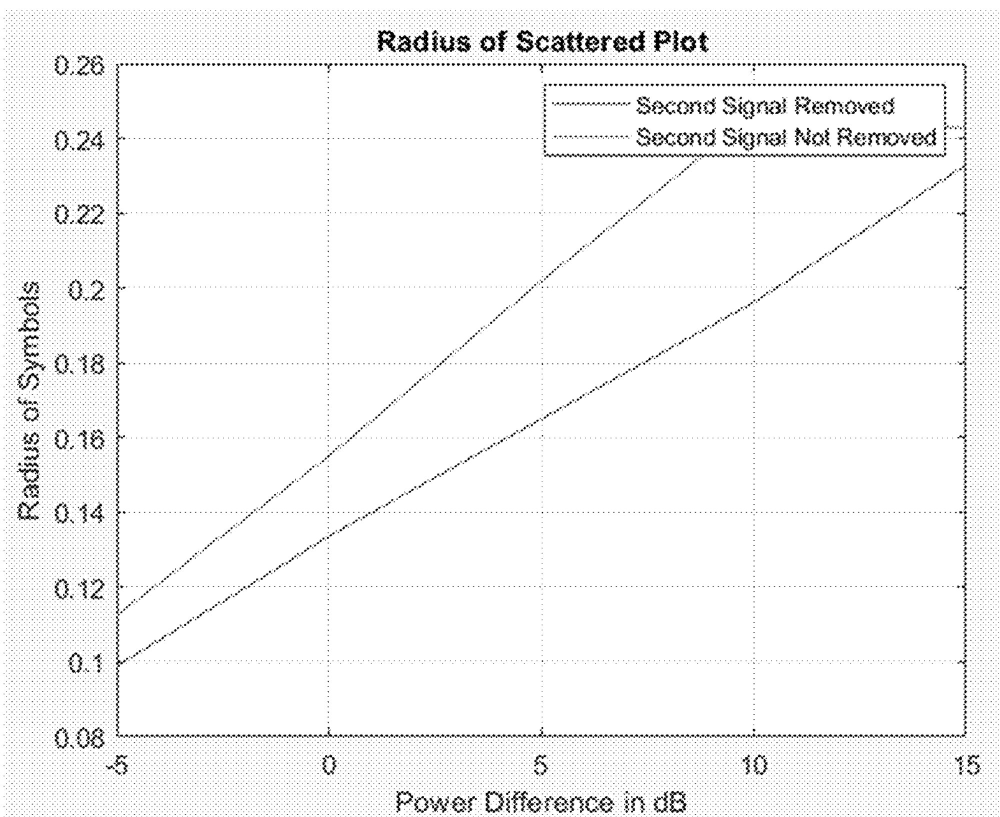


FIG. 114A

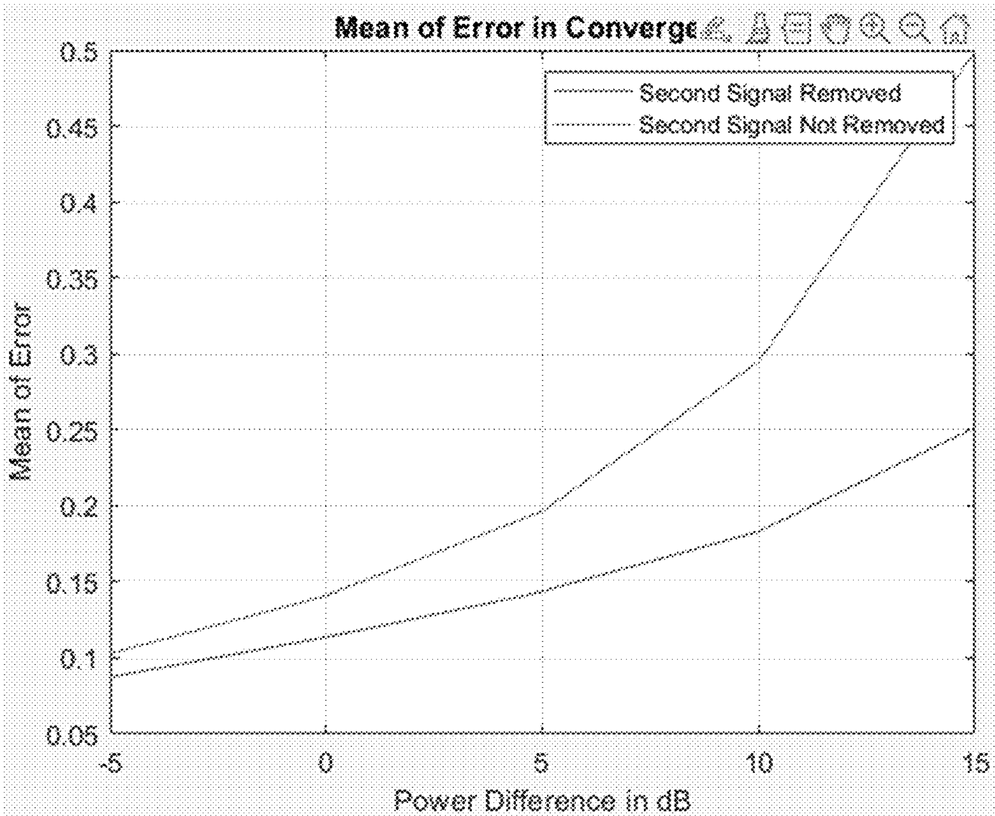


FIG. 114B

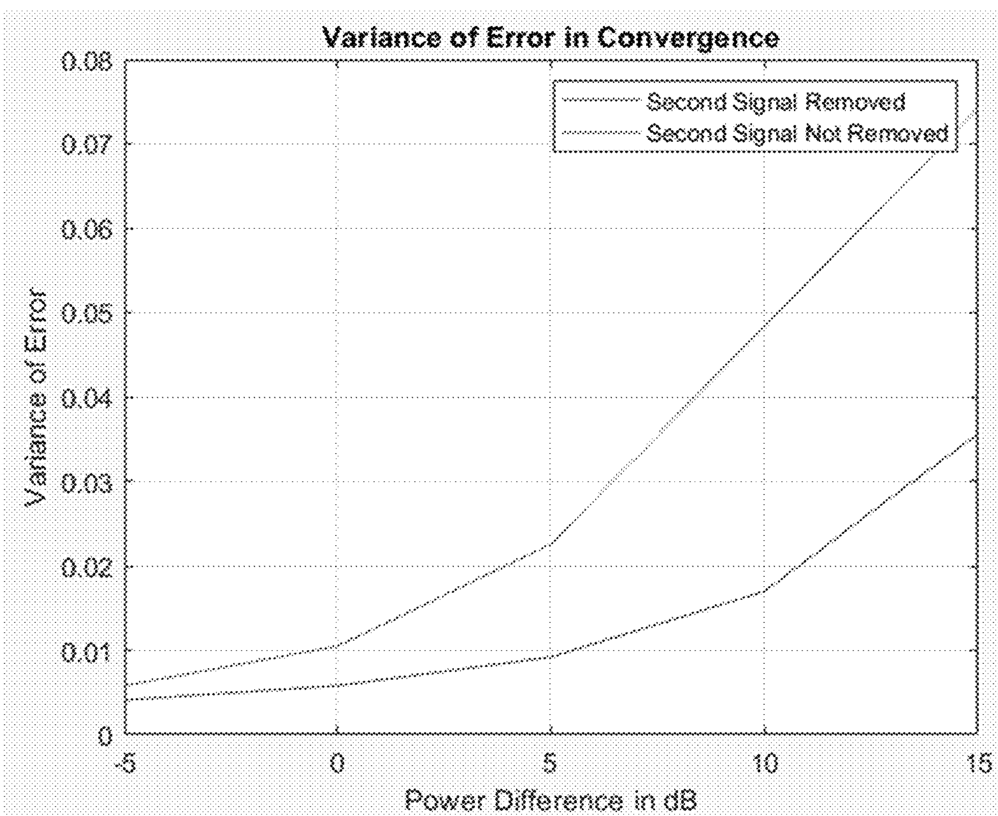


FIG. 114C

SYSTEM, METHOD, AND APPARATUS FOR PROVIDING OPTIMIZED NETWORK RESOURCES

CROSS REFERENCES TO RELATED APPLICATIONS

This application is related to and claims priority from the following U.S. patents and patent applications. This application is a continuation of U.S. patent application Ser. No. 18/802,740 filed Aug. 13, 2024, which is a continuation of U.S. patent application Ser. No. 18/799,623 filed Aug. 9, 2024, which is a continuation-in-part of U.S. patent application Ser. No. 18/789,220 filed Jul. 30, 2024, which is a continuation-in-part of U.S. patent application Ser. No. 18/738,760 filed Jun. 10, 2024, which is a continuation-in-part of U.S. patent application Ser. No. 18/646,330 filed Apr. 25, 2024, which is a continuation-in-part of U.S. patent application Ser. No. 18/417,659 filed Jan. 19, 2024, which is a continuation of U.S. patent application Ser. No. 18/411,817 filed Jan. 12, 2024, which is a continuation of U.S. patent application Ser. No. 18/405,531 filed Jan. 5, 2024, which is a continuation of U.S. patent application Ser. No. 18/526,329, filed Dec. 1, 2023, which is a continuation of U.S. patent application Ser. No. 18/237,970, filed Aug. 25, 2023, which is a continuation-in-part of U.S. patent application Ser. No. 18/086,115, filed Dec. 21, 2022, which is a continuation-in-part of U.S. patent application Ser. No. 18/085,904, filed Dec. 21, 2022, which is a continuation of U.S. patent application Ser. No. 18/085,791, filed Dec. 21, 2022, which is a continuation of U.S. patent application Ser. No. 18/085,733, filed Dec. 21, 2022, which is a continuation-in-part of U.S. patent application Ser. No. 17/901,035, filed Sep. 1, 2022, which claims priority to and the benefit of U.S. Provisional Patent Application No. 63/370,184, filed Aug. 2, 2022. Each of the above listed applications is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to spectrum analysis and management for electromagnetic signals, and more particularly for providing optimized network resources.

2. Description of the Prior Art

It is generally known in the prior art to provide wireless communications spectrum management for detecting devices and for managing the space. Spectrum management includes the process of regulating the use of radio frequencies to promote efficient use and gain net social benefit. A problem faced in effective spectrum management is the various numbers of devices emanating wireless signal propagations at different frequencies and across different technological standards. Coupled with the different regulations relating to spectrum usage around the globe effective spectrum management becomes difficult to obtain and at best can only be reached over a long period of time.

Another problem facing effective spectrum management is the growing need from spectrum despite the finite amount of spectrum available. Wireless technologies and applications or services that require spectrum have exponentially grown in recent years. Consequently, available spectrum has become a valuable resource that must be efficiently utilized.

Therefore, systems and methods are needed to effectively manage and optimize the available spectrum that is being used.

Prior art patent documents include the following:

U.S. Pat. No. 11,395,149 for System, method, and apparatus for providing dynamic, prioritized spectrum management and utilization by inventor Montalvo, filed Oct. 30, 2020 and issued Jul. 19, 2022, is directed to systems, methods, and apparatuses for providing dynamic, prioritized spectrum utilization management. The system includes at least one monitoring sensor, at least one data analysis engine, at least one application, a semantic engine, a programmable rules and policy editor, a tip and cue server, and/or a control panel. The tip and cue server is operable utilize the environmental awareness from the data processed by the at least one data analysis engine in combination with additional information to create actionable data.

U.S. Patent Publication No. 2018/0352441 for Devices, methods, and systems with dynamic spectrum sharing by inventors Zheng, et al., filed Jun. 4, 2018 and published Dec. 6, 2018, is directed to devices, methods, and systems with dynamic spectrum sharing. A wireless communication device includes a software-defined radio, a spectrum sensing sub-system, a memory, and an electronic processor. The software-defined radio is configured to generate an input signal, and wirelessly communicate with one or more radio nodes using a traffic data channel and a broadcast control channel. The spectrum sensing sub-system is configured to sense local spectrum information from the input signal. The electronic processor is communicatively connected to the memory and the spectrum sensing sub-system and is configured to receive the local spectrum information from the spectrum sensing sub-system, receive spectrum information from the one or more radio nodes, and allocate resources for the traffic data channel based on the local spectrum information and the spectrum information that is received from the one or more radio nodes.

U.S. Patent Publication No. 2018/0295607 for Method and apparatus for adaptive bandwidth usage in a wireless communication network by inventors Lindoff, et al., filed Oct. 10, 2017 and published Oct. 11, 2018, is directed to reconfiguration of a receiver bandwidth of the wireless device is initiated to match the second scheduling bandwidth, wherein the second scheduling bandwidth is larger than a first scheduling bandwidth currently associated with the wireless device, and wherein the first and second scheduling bandwidths respectively define the bandwidth used for scheduling transmissions to the wireless device.

U.S. Pat. No. 9,538,528 for Efficient co-existence method for dynamic spectrum sharing by inventors Wagner, et al., filed Oct. 6, 2011 and issued Jan. 3, 2017, is directed to an apparatus that defines a set of resources out of a first number of orthogonal radio resources and controls a transmitting means to simultaneously transmit a respective first radio signal for each resource on all resources of the set. A respective estimated interference is estimated on each of the resources of the set when the respective first radio signals are transmitted simultaneously. A first resource of the set is selected if the estimated interference on the first resource exceeds a first predefined level and, in the set, the first resource is replaced by a second resource of the first number of resources not having been part of the set. Each of the controlling and the estimating, the selecting, and the replacing is performed in order, respectively, for a predefined time.

U.S. Pat. No. 8,972,311 for Intelligent spectrum allocation based on user behavior patterns by inventors Srikanteswara, et al., filed Jun. 26, 2012 and issued Mar. 3, 2015, is directed to a platform to facilitate transferring spectrum rights is provided that includes a database to ascertain information regarding available spectrum for use in wireless communications. A request for spectrum use from an entity needing spectrum may be matched with available spectrum. This matching comprises determining a pattern in user requests overtime to optimize spectrum allocation. The Cloud Spectrum Services (CSS) process allows entities to access spectrum they would otherwise not have; it allows the end user to complete their download during congested periods while maintaining high service quality; and it allows the holder of rental spectrum to receive compensation for an otherwise idle asset.

U.S. Pat. No. 10,536,210 for Interference suppressing method and device in dynamic frequency spectrum access system by inventors Zhao, et al., filed Apr. 14, 2016 and issued Jan. 14, 2020, is directed to an interference suppressing method and device in a dynamic frequency spectrum access (DSA) system. The system includes: a frequency spectrum management device, a primary system including a plurality of primary devices, and a secondary system including a plurality of secondary devices. The method includes: transmitting position information of each of the secondary devices to the frequency spectrum management device; determining, by the frequency spectrum management device, a weight factor for a specific secondary device according to the received position formation; and performing a second-stage precoding, and in the second-stage precoding, adjusting, by using the weight factor, an estimated power of the specific secondary device leaking to the other secondary device.

U.S. Pat. No. 10,582,401 for Large scale radio frequency signal information processing and analysis system by inventors Mengwasser, et al., filed Apr. 15, 2019 and issued Mar. 3, 2020, is directed to a large-scale radio frequency signal information processing and analysis system that provides advanced signal analysis for telecommunication applications, including band capacity and geographical density determinations and detection, classification, identification, and geolocation of signals across a wide range of frequencies and across broad geographical areas. The system may utilize a range of novel algorithms for bin-wise processing, Rayleigh distribution analysis, telecommunication signal classification, receiver anomaly detection, transmitter density estimation, transmitter detection and location, geolocation analysis, telecommunication activity estimation, telecommunication utilization estimation, frequency utilization estimation, and data interpolation.

U.S. Pat. No. 10,070,444 for Coordinated spectrum allocation and de-allocation to minimize spectrum fragmentation in a cognitive radio network by inventors Markwart, et al., filed Dec. 2, 2011 and issued Sep. 4, 2018, is directed to An apparatus and a method by which a fragmentation probability is determined which indicates a probability of fragmentation of frequency resources in at least one network section for at least one network operating entity. Moreover, an apparatus and a method by which frequency resources in at least one network section are allocated and/or de-allocated, priorities of frequency resources are defined for at least one network operating entity individually, and allocating and/or de-allocating of the frequency resources for the at least one network operating entity is performed based on the priorities. For allocating and/or de-allocating of the frequency resources, also the fragmentation probability may be taken into account.

U.S. Patent Publication No. 2020/0007249 for Wireless signal monitoring and analysis, and related methods, systems, and devices by inventors Derr, et al., filed Sep. 12, 2019 and published Jan. 2, 2020, is directed to wireless signal classifiers and systems that incorporate the same may include an energy-based detector configured to analyze an entire set of measurements and generate a first single classification result, a cyclostationary-based detector configured to analyze less than the entire set of measurements and generate a second signal classification result; and a classification merger configured to merge the first signal classification result and the second signal classification result. Ensemble wireless signal classification and systems and devices the incorporate the same are disclosed. Some ensemble wireless signal classification may include energy-based classification processes and machine learning-based classification processes. Incremental machine learning techniques may be incorporated to add new machine learning-based classifiers to a system or update existing machine learning-based classifiers.

U.S. Patent Publication No. 2018/0324595 for Spectral sensing and allocation using deep machine learning by inventor Shima, filed May 7, 2018 and published Nov. 8, 2018, is directed to methods and systems for identifying occupied areas of a radio frequency (RF) spectrum, identifying areas within that RF spectrum that are unusable for further transmissions, and identifying areas within that RF spectrum that are occupied but that may nonetheless be available for additional RF transmissions are provided. Implementation of the method then systems can include the use of multiple deep neural networks (DNNs), such as convolutional neural networks (CNN's), that are provided with inputs in the form of RF spectrograms. Embodiments of the present disclosure can be applied to cognitive radios or other configurable communication devices, including but not limited to multiple inputs multiple output (MIMO) devices and 5G communication system devices.

U.S. Patent Publication No. 2017/0041802 for Spectrum resource management device and method by inventors Sun, et al., filed May 27, 2015 and published Feb. 9, 2017, is directed to a spectrum resource management device: determines available spectrum resources of a target communication system, so that aggregation interference caused by the target communication system and a communication system with a low right against a communication system with a high right in a management area does not exceed an interference threshold of the communication system with a high right; reduces available spectrum resources of the communication system with a low right, so that the interference caused by the communication system with a low right against the target communication system does not exceed an interference threshold of the target communication system; and updates the available spectrum resources of the target communication system according to the reduced available spectrum resources of the communication system with a low right, so that the aggregation interference does not exceed the interference threshold of the communication system with a high right.

U.S. Pat. No. 9,900,899 for Dynamic spectrum allocation method and dynamic spectrum allocation device by inventors Jiang, et al., filed Mar. 26, 2014 and issued Feb. 20, 2018, is directed to a dynamic spectrum allocation method and a dynamic spectrum allocation device. In the method, a centralized node performs spectrum allocation and transmits a spectrum allocation result to each communication node, so that the communication node operates at a corresponding spectrum resource in accordance with the spectrum allocation result and performs statistics of communication quality measurement information. The centralized node receives the communication quality measurement information reported by the communication node, and determines whether or not it is required to trigger the spectrum re-allocation for the communication node in accordance with the communication quality measurement information about the communication node. When it is required to trigger the spectrum re-allocation, the centralized node re-allocates the spectrum for the communication node.

U.S. Pat. No. 9,578,516 for Radio system and spectrum resource reconfiguration method thereof by inventors Liu, et al., filed Feb. 7, 2013 and issued, Feb. 21, 2017, is directed to a radio system and a spectrum resource reconfiguration method thereof. The method comprises: a Reconfigurable Base Station (RBS) divides subordinate nodes into groups according to attributes of the subordinate nodes, and sends a reconfiguration command to a subordinate node in a designated group, and the RBS and the subordinate node execute reconfiguration of spectrum resources according to the reconfiguration command; or, the RBS executes reconfiguration of spectrum resources according to the reconfiguration command; and a subordinate User Equipment (UE) accessing to a reconfigured RBS after interruption. The reconfiguration of spectrum resources of a cognitive radio system can be realized.

U.S. Pat. No. 9,408,210 for Method, device and system for dynamic frequency spectrum optimization by inventors Pikhletsky, et al., filed Feb. 25, 2014 and issued Aug. 2, 2016, is directed to a method, a device and a system for dynamic frequency spectrum optimization. The method includes: predicting a traffic distribution of terminal(s) in each cell of multiple cells; generating multiple frequency spectrum allocation schemes for the multiple cells according to the traffic distribution of the terminal(s) in each cell, wherein each frequency spectrum allocation scheme comprises frequency spectrum(s) allocated for each cell; selecting a frequency spectrum allocation scheme superior to a current frequency spectrum allocation scheme of the multiple cells from the multiple frequency spectrum allocation schemes according to at least two network performance indicators of a network in which the multiple cells are located; and allocating frequency spectrum(s) for the multiple cells using the selected frequency spectrum allocation scheme. This improves the utilization rate of the frequency spectrum and optimizes the multiple network performance indicators at the same time.

U.S. Pat. No. 9,246,576 for Apparatus and methods for dynamic spectrum allocation in satellite communications by inventors Yanai, et al., filed Mar. 5, 2012 and issued Jan. 26, 2016, is directed to a communication system including Satellite Communication apparatus providing communication services to at least a first set of communicants, the first set of communicants including a first plurality of communicants, wherein the communication services are provided to each of the communicants in accordance with a spectrum allocation corresponding thereto, thereby to define a first plurality of spectrum allocations apportioning a first predefined spectrum portion among the first set of communicants; and Dynamic Spectrum Allocations apparatus operative to dynamically modify at least one spectrum allocation corresponding to at least one of the first plurality of communicants without exceeding the spectrum portion.

U.S. Pat. No. 8,254,393 for Harnessing predictive models of durations of channel availability for enhanced opportunistic allocation of radio spectrum by inventor Horvitz, filed Jun. 29, 2007 and issued Aug. 28, 2012, is directed to a proactive adaptive radio methodology for the opportunistic allocation of radio spectrum is described. The methods can be used to allocate radio spectrum resources by employing machine learning to learn models, via accruing data over time, that have the ability to predict the context-sensitive durations of the availability of channels. The predictive models are combined with decision-theoretic cost-benefit analyses to minimize disruptions of service or quality that can be associated with reactive allocation policies. Rather than reacting to losses of channel, the proactive policies seek switches in advance of the loss of a channel. Beyond determining durations of availability for one or more frequency bands statistical machine learning also be employed to generate price predictions in order to facilitate a sale or rental of the available frequencies, and these predictions can be employed in the switching analyses The methods can be employed in non-cooperating distributed models of allocation, in centralized allocation approaches, and in hybrid spectrum allocation scenarios.

U.S. Pat. No. 6,990,087 for Dynamic wireless resource utilization by inventors Rao, et al., filed Apr. 22, 2003 and issued Jan. 24, 2006, is directed to a method for dynamic wireless resource utilization includes monitoring a wireless communication resource; generating wireless communication resource data; using the wireless communication resource data, predicting the occurrence of one or more holes in a future time period; generating hole prediction data; using the hole prediction data, synthesizing one or more wireless communication channels from the one or more predicted holes; generating channel synthesis data; receiving data reflecting feedback from a previous wireless communication attempt and data reflecting a network condition; according to the received data and the channel synthesis data, selecting a particular wireless communication channel from the one or more synthesized wireless communication channels; generating wireless communication channel selection data; using the wireless communication channel selection data, instructing a radio unit to communicate using the selected wireless communication channel; and instructing the radio unit to discontinue use of the selected wireless communication channel after the communication has been completed.

U.S. Pat. No. 10,477,342 for Systems and methods of using wireless location, context, and/or one or more communication networks for monitoring for, preempting, and/or mitigating pre-identified behavior by inventor Williams, filed Dec. 13, 2017 and issued Nov. 12, 2019, is directed to systems and methods of using location, context, and/or one or more communication networks for monitoring for, preempting, and/or mitigating pre-identified behavior. For example, exemplary embodiments disclosed herein may include involuntarily, automatically, and/or wirelessly monitoring/mitigating undesirable behavior (e.g., addiction related undesirable behavior, etc.) of a person (e.g., an addict, a parolee, a user of a system, etc.). In an exemplary embodiment, a system generally includes a plurality of devices and/or sensors configured to determine, through one or more communications networks, a location of a person and/or a context of the person at the location; predict and evaluate a risk of a pre-identified behavior by the person in relation to the location and/or the context; and facilitate one or more actions and/or activities to mitigate the risk of the pre-identified behavior, if any, and/or react to the pre-identified behavior, if any, by the person.

SUMMARY OF THE INVENTION

The present invention relates to spectrum analysis and management for electromagnetic signals, and more particularly for providing optimized network resources. Furthermore, the present invention relates to spectrum analysis and management for electromagnetic (e.g., radio frequency (RF)) signals, and for automatically identifying baseline data and changes in state for signals from a multiplicity of devices in a wireless communications spectrum, and for providing remote access to measured and analyzed data through a virtualized computing network. In an embodiment, signals and the parameters of the signals are identified and indications of available frequencies are presented to a user. In another embodiment, the protocols of signals are also identified. In a further embodiment, the modulation of signals, data types carried by the signals, and estimated signal origins are identified.

It is an object of this invention to prioritize and manage applications in the wireless communications spectrum, while also optimizing application performance.

In one embodiment, the present invention provides a system for dynamic spectrum utilization management in an electromagnetic environment comprising: at least one sensor unit operable to measure radiofrequency (RF) data, an RF analysis engine operable to extract physical layer data from the measured RF data, wherein the RF analysis engine is operable to analyze or process the extracted physical layer data from the measured RF data, wherein the at least one sensor unit and the RF analysis engine are provided in a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board for real time dynamic spectrum sharing for the electromagnetic environment, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board are provided on a single electronic device, wherein the single electronic device is operable to send the analyzed or processed extracted physical layer data to a distributed data unit (DDU), a centralized unit (CU), a radio unit (RU), and/or a Multi-Access Edge Computing (MEC) layer, and wherein the analyzed or processed extracted physical layer data is used by the DDU, the CU, the RU, and/or MEC layer to create actionable data for optimizing network resources.

In another embodiment, the present invention provides a system for dynamic spectrum utilization management in an electromagnetic environment comprising: at least one sensor unit operable to measure radiofrequency (RF) data, an RF analysis engine operable to provide physical layer data based on the measured RF data, a customer programmable statistical interface, and a Multi-Access Edge Computing (MEC) layer in a network slice or a subnetwork, wherein the MEC layer is in communication with a radio access network (RAN) and a core network, wherein the at least one sensor unit, the RF analysis engine, the customer programmable statistical interface are provided in a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board are provided on an electronic device, wherein the electronic device is operable to send the analyzed or processed extracted physical layer data to the MEC layer, and wherein the analyzed or processed extracted physical layer data is used by the MEC layer to create actionable data for optimizing network resources.

In yet another embodiment, the present invention provides an apparatus for dynamic spectrum utilization management in an electromagnetic environment comprising: an electronic device including a single chip, a single chipset, multiple chips, multiple chipsets, or a single circuit board, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes at least one sensor unit operable to measure radiofrequency (RF) data and an RF analysis engine operable to provide physical layer data based on the measured RF data, wherein the RF analysis engine is operable to analyze or process the extracted physical layer data from the measured RF data, wherein the electronic device is operable to send the analyzed or processed extracted physical layer data to a distributed data unit (DDU), a centralized unit (CU), a radio unit (RU), and/or a Multi-Access Edge Computing (MEC) layer, wherein the analyzed or processed extracted physical layer data is used by the DDU, the CU, the RU, and/or MEC layer to create actionable data for optimizing network resources.

These and other aspects of the present invention will become apparent to those skilled in the art after a reading of the following description of the preferred embodiment when considered with the drawings, as they support the claimed invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates one embodiment of a network.

FIG. **2** illustrates one embodiment of a RAN interface.

FIG. **3** illustrates one embodiment of a Multi-Access Edge Computing (MEC) layer.

FIG. **4** illustrates one embodiment of the at least one sensor unit operable to interface with the physical layer.

FIG. **5** illustrates possible functional splits between central and distributed units.

FIG. **6** illustrates another example of possible functional splits.

FIG. **7** illustrates 3GPP, Small Cell Forum (SCF), and O-RAN possible functional splits.

FIG. **8** illustrates an example of a traditional base station with a remote radio head (RRH).

FIG. **9** illustrates an example of a centralized RAN (C-RAN).

FIG. **10** illustrates one embodiment of an open, disaggregated RAN.

FIG. **11** illustrates one embodiment of several planes of operation described in the O-RAN Fronthaul specification.

FIG. **12** illustrates one embodiment of a fronthaul interface according to the O-RAN Fronthaul specification.

FIG. **13** illustrates one embodiment of the O-RU/SU part of the xRAN split.

FIG. **14** illustrates e-NB/g-NB architecture including an O-DU and a plurality of radio units (O-RUs).

FIG. **15** illustrates one embodiment of a Layer 1 split.

FIG. **16** is a table describing supported data flow for a single radio unit with a single component carrier.

FIG. **17** illustrates one example of dataflows between the O-DU and the O-RU excluding M-Plane dataflows.

FIG. **18** illustrates an example of the C-Plane and U-Plane packet exchange.

FIG. **19** is a table of default values used for the implementation of O-DU and O-RU/SU simulation with a mmWave scenario.

FIG. **20** is a table of default values used for the implementation of O-DU and O-RU/SU simulation with numerology 0.

FIG. **21** is a table of default values used for the implementation of O-DU and O-RU/SU simulation with numerology 1.

FIG. **22** illustrates one embodiment of an ORAN Fronthaul process.

FIG. **23** illustrates Configuration LLS-C1.

FIG. **24** illustrates Configuration LLS-C3.

FIG. **25** illustrates one embodiment of a native ethernet frame with VLAN.

FIG. **26** illustrates one embodiment of eCRPI header field definitions.

FIG. **27** illustrates bit allocations of ecpriRtcid/ecpriPcid.

FIG. **28** illustrates xRAN packet components for DL/UL IQ data messages.

FIG. **29** illustrates one embodiment of a common radio application header.

FIG. **30** illustrates one embodiment of a data section application header.

FIG. **31** illustrates one embodiment of an xRAN packet data payload.

FIG. **32** illustrates a table of section types and target scenarios.

FIG. **33** illustrates one embodiment of a radio application common header.

FIG. **34** illustrates a structure of a Section Type 0 message.

FIG. **35** illustrates a structure of a Section Type 1 message.

FIG. **36** illustrates an entire Section Type 1 message.

FIG. **37** illustrates a structure of a Section Type 3 message.

FIG. **38** illustrates an entire Section Type 3 message.

FIG. **39** illustrates a structure of a Section Type 5 message.

FIG. **40** illustrates a structure of a Section Type 6 message.

FIG. **41** illustrates the F1-C and F1-U protocol stacks.

FIG. **42** is a table of F1 interface functionalities.

FIG. **43** illustrates transfer of application data between the DU and CU-UP using the user plane of the F1-U.

FIG. **44** is a table of PDU Type 0 downlink user data.

FIG. **45** is a table of PDU Type 1 downlink delivery status.

FIG. **46** illustrates one embodiment of O-RAN defined nodes.

FIG. **47** illustrates one embodiment of an overall O-RAN architecture.

FIG. **47** also illustrates three control loops.

FIG. **48** illustrates disaggregated network functions in the O-RAN.

FIG. **49** illustrates an aggregated O-CU and O-DU, which form an E2 node.

FIG. **50** illustrates an aggregated near-RT RIC, O-CU-CP, and O-CU-UP.

FIG. **51** illustrates an aggregated near-RT RIC, O-CU-CP, O-CU-UP, O-DU, and O-RU.

FIG. **52** illustrates one embodiment of near-RT RIC internal architecture.

FIG. **53** illustrates a centralized near-RT RIC.

FIG. **54** illustrates a fully distributed near-RT RIC

FIG. **55** illustrates one embodiment of E2 interface architecture.

FIG. **56** illustrates a 3GPP 5G with the SBA on the left and the MEC system on the right.

FIG. **57** illustrates one embodiment of an integrated MEC deployment.

FIG. **58**A illustrates a MEC and the local UPF co-located with the base station.

FIG. **58**B illustrates a MEC co-located with a transmission node and optionally with a local UPF.

FIG. **58**C illustrates a MEC and the local UPF co-located with a network aggregation point.

FIG. **58**D illustrates a MEC co-located with the core network function (e.g., in the same data center).

FIG. **59** illustrates one embodiment of application mobility in an integrated MEC deployment.

FIG. **60** illustrates one embodiment of the MEC system operable to provide add-on services to at least one MEC application.

FIG. **61** illustrates one embodiment of the MEC system including a system level and distributed host level.

FIG. **62** illustrates one embodiment of a third-party cloud for MEC in a 5G network environment.

FIG. **63** illustrates one embodiment of a MEC host with and without a break-out to cloud.

FIG. **64** illustrates one embodiment of traffic steering to an alternative MEC host.

FIG. **65** illustrates one embodiment of a Distributed Autonomous Slice Management and Orchestration (DASMO).

FIG. **66** illustrates one embodiment of proposed generalized MEC architecture.

FIG. **67** illustrates one embodiment of DASMO extended with MEC.

FIG. **68** illustrates one embodiment of the system including resource optimization.

FIG. **69** illustrates one example of an RF environment.

FIG. **70** is a schematic diagram of a system of the present invention.

FIG. **71**A illustrates one embodiment of an interference template including interference metrics, adjacent channel measurements, and geolocation.

FIG. **71**B illustrates one embodiment of an interference template including additional evidence of external interference.

FIG. **72** illustrates one example of a graphical user interface (GUI) for a channel average power.

FIG. **73** illustrates one example of a GUI for channel availability.

FIG. **74** illustrates one embodiment of a system including an antenna subsystem, an RF conditioning subsystem, and at least one front end receiver.

FIG. **75** illustrates one embodiment of a system including a channelizer (e.g., a frequency domain programmable channelizer), a blind detection engine, a noise floor estimator, and an I/Q buffer.

FIG. **76** illustrates one embodiment of a system including at least one data analysis engine.

FIG. **77** illustrates one embodiment of a system including an FFT engine.

FIG. **78** illustrates one embodiment of a system including the systems from FIGS. **74**-**76**.

FIG. **79** illustrates one embodiment of a system including the systems from FIGS. **74**-**75** and **77**.

FIG. **80** shows typical functions in a RAN.

FIG. **81** illustrates a block diagram of a sensor unit and its communications with other components in a system of the present invention.

FIG. **82**A illustrates the ORAN functions partition according to an embodiment of the present invention.

FIG. **82**B illustrates two options for RF sensor functions that are implemented in the software embedded in the single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board of the present invention.

FIG. **83**A illustrates the downlink and uplink from fronthaul to MAC associated with the L1 physical layer.

FIG. **83**B illustrates the functionality of the present invention integrated into the physical layers.

FIG. **84**A illustrates different options for lower layer split architectures.

FIG. 84B illustrates a schematic of one embodiment of a 5G option 7-2 split implemented via software of the present invention.

FIG. 85 illustrates a block diagram of an RF environment with ORAN integration with an AI RAN Intelligent Controller (RIC).

FIG. 86 illustrates a block diagram comparing traditional wireless network optimization and network optimization utilizing RF awareness and AI.

FIG. 87A illustrates a block diagram of a cloud-based RAN implementation using AI/ML and its communications with other components in a system of the present invention.

FIG. 87B illustrated a block diagram of the distributed data unit operations and its communications with other components in a system of the present invention.

FIG. 88 illustrates a block diagram of interface points within 5G architecture according to one embodiment of the present invention.

FIG. 89 illustrates a block diagram of the RF awareness and analysis system.

FIG. 90 illustrates a block diagram of a MEC architecture type.

FIG. 91 illustrates a block diagram of the RF awareness platform.

FIG. 92 illustrates a block diagram of the RAN functions focusing on the CU interface.

FIG. 93A illustrates a block diagram of the RU and DU interface with RF awareness aggregation.

FIG. 93B illustrates a block diagram of the RU and DU interface with info aggregation.

FIG. 94 illustrates a block diagram of a wireless communication systems represented as an autoencoder.

FIG. 95 illustrates a block diagram of deep learning or machine learning (ML) techniques for physical layer L1 for 5G/6G.

FIG. 96 illustrates a diagram of a MIMO (Multiple Inputs Multiple Outputs) system with transmitters and receivers.

FIG. 97 illustrates a block diagram illustrating the channel function (H(t)) and background noise (N(t)) between transmitters and receivers.

FIG. 98 illustrates a diagram of a MIMO system with arrows illustrating the data from the transmitters to a receiver.

FIG. 99A illustrates a power spectral density (PSD) graph of case 1.

FIG. 99B illustrates the probability of error converging without second signal removal for case 1.

FIG. 99C illustrates IQ signals after the Equalizer iterations without second signal removal for case 1.

FIG. 99D illustrates the probability of error converging with second signal removal for case 1.

FIG. 99E illustrates IQ signals after the Equalizer iterations with second signal removal for case 1.

FIG. 100A illustrates a power spectral density (PSD) graph of case 2.

FIG. 100B illustrates the probability of error converging without second signal removal for case 2.

FIG. 100C illustrates IQ signals after the Equalizer iterations without second signal removal for case 2.

FIG. 100D illustrates the probability of error converging with second signal removal for case 2.

FIG. 100E illustrates IQ signals after the Equalizer iterations with second signal removal for case 2.

FIG. 101A illustrates a power spectral density (PSD) graph of case 3.

FIG. 101B illustrates the probability of error converging without second signal removal for case 3.

FIG. 101C illustrates IQ signals after the Equalizer iterations without second signal removal for case 3.

FIG. 101D illustrates the probability of error converging with second signal removal for case 3.

FIG. 101E illustrates IQ signals after the Equalizer iterations with second signal removal for case 3.

FIG. 102A illustrates a power spectral density (PSD) graph of case 4.

FIG. 102B illustrates the probability of error converging without second signal removal for case 4.

FIG. 102C illustrates IQ signals after the Equalizer iterations without second signal removal for case 4.

FIG. 102D illustrates the probability of error converging with second signal removal for case 4.

FIG. 102E illustrates IQ signals after the Equalizer iterations with second signal removal for case 4.

FIG. 103A illustrates a power spectral density (PSD) graph of case 5.

FIG. 103B illustrates the probability of error converging without second signal removal for case 5.

FIG. 103C illustrates IQ signals after the Equalizer iterations without second signal removal for case 5.

FIG. 103D illustrates the probability of error converging with second signal removal for case 5.

FIG. 103E illustrates IQ signals after the Equalizer iterations with second signal removal for case 5.

FIG. 104A illustrates a power spectral density (PSD) graph of case 6.

FIG. 104B illustrates the probability of error converging without second signal removal for case 6.

FIG. 104C illustrates IQ signals after the Equalizer iterations without second signal removal for case 6.

FIG. 104D illustrates the probability of error converging with second signal removal for case 6.

FIG. 104E illustrates IQ signals after the Equalizer iterations with second signal removal for case 6.

FIG. 105A illustrates a power spectral density (PSD) graph of case 7

FIG. 105B illustrates the probability of error converging without second signal removal for case 7.

FIG. 105C illustrates IQ signals after the Equalizer iterations without second signal removal for case 7.

FIG. 105D illustrates the probability of error converging with second signal removal for case 7.

FIG. 105E illustrates IQ signals after the Equalizer iterations with second signal removal for case 7.

FIG. 106A illustrates a power spectral density (PSD) graph of case 8.

FIG. 106B illustrates the probability of error converging without second signal removal for case 8.

FIG. 106C illustrates IQ signals after the Equalizer iterations without second signal removal for case 8.

FIG. 106D illustrates the probability of error converging with second signal removal for case 8.

FIG. 106E illustrates IQ signals after the Equalizer iterations with second signal removal for case 8.

FIG. 107A illustrates a power spectral density (PSD) graph of case 9.

FIG. 107B illustrates the probability of error converging without second signal removal for case 9.

FIG. 107C illustrates IQ signals after the Equalizer iterations without second signal removal for case 9.

FIG. 107D illustrates the probability of error converging with second signal removal for case 9.

FIG. 107E illustrates IQ signals after the Equalizer iterations with second signal removal for case 9.

FIG. **108**A illustrates the performance radius difference with and without the second signal removal.

FIG. **108**B illustrates the mean error in convergence difference with and without the second signal removal.

FIG. **108**C illustrates the variance error in convergence difference with and without the second signal removal.

FIG. **109**A illustrates a power spectral density (PSD) graph of case 10.

FIG. **109**B illustrates the probability of error converging without second signal removal for case 10.

FIG. **109**C illustrates IQ signals after the Equalizer iterations without second signal removal for case 10.

FIG. **109**D illustrates the probability of error converging with second signal removal for case 10.

FIG. **109**E illustrates IQ signals after the Equalizer iterations with second signal removal for case 10.

FIG. **110**A illustrates a power spectral density (PSD) graph of case 11.

FIG. **110**B illustrates the probability of error converging without second signal removal for case 11.

FIG. **110**C illustrates IQ signals after the Equalizer iterations without second signal removal for case 11.

FIG. **110**D illustrates the probability of error converging with second signal removal for case 11.

FIG. **110**E illustrates IQ signals after the Equalizer iterations with second signal removal for case 11.

FIG. **111**A illustrates a power spectral density (PSD) graph of case 12

FIG. **111**B illustrates the probability of error converging without second signal removal for case 12.

FIG. **111**C illustrates IQ signals after the Equalizer iterations without second signal removal for case 12.

FIG. **111**D illustrates the probability of error converging with second signal removal for case 12.

FIG. **111**E illustrates IQ signals after the Equalizer iterations with second signal removal for case 12.

FIG. **112**A illustrates a power spectral density (PSD) graph of case 13.

FIG. **112**B illustrates the probability of error converging without second signal removal for case 13.

FIG. **112**C illustrates IQ signals after the Equalizer iterations without second signal removal for case 13.

FIG. **112**D illustrates the probability of error converging with second signal removal for case 13.

FIG. **112**E illustrates IQ signals after the Equalizer iterations with second signal removal for case 13.

FIG. **113**A illustrates a power spectral density (PSD) graph of case 14.

FIG. **113**B illustrates the probability of error converging without second signal removal for case 14.

FIG. **113**C illustrates IQ signals after the Equalizer iterations without second signal removal for case 14.

FIG. **113**D illustrates the probability of error converging with second signal removal for case 14.

FIG. **113**E illustrates IQ signals after the Equalizer iterations with second signal removal for case 14.

FIG. **114**A illustrates the performance radius difference with and without the second signal removal for 16-QAM.

FIG. **114**B illustrates the mean error in convergence difference with and without the second signal removal for 16-QAM.

FIG. **114**C illustrates the variance error in convergence difference with and without the second signal removal for 16-QAM.

DETAILED DESCRIPTION

The present invention is generally directed to spectrum analysis and management for electromagnetic signals, and more particularly for providing methods for network resources optimization by providing at least one chip, chipsets, or circuit boards with functionality related to the physical layer (layer 1 of the OSI network model) by using data obtained from sensors capturing data from the electromagnetic environment. More particularly, the present invention provides for RF awareness via extraction of physical layer (layer 1) data via the software operable on a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board improves performance for modulation and/or demodulation, and beam forming for better RF awareness in real time for spectrum management, interference detection, and with low latency and high reliability, thereby enhancing 5-layer performance with equalizers, demodulators, and beam formation by reducing computation and/or improving the performance of these components or functions.

In one embodiment, the present invention provides a system for dynamic spectrum utilization management in an electromagnetic environment comprising: at least one sensor unit operable to measure radiofrequency (RF) data, an RF analysis engine operable to extract physical layer data from the measured RF data, wherein the RF analysis engine is operable to analyze or process the extracted physical layer data from the measured RF data, wherein the at least one sensor unit and the RF analysis engine are provided in a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board for real time dynamic spectrum sharing for the electromagnetic environment, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board are provided on a single electronic device, wherein the single electronic device is operable to send the analyzed or processed extracted physical layer data to a distributed data unit (DDU), a centralized unit (CU), a radio unit (RU), and/or a Multi-Access Edge Computing (MEC) layer, and wherein the analyzed or processed extracted physical layer data is used by the DDU, the CU, the RU, and/or MEC layer to create actionable data for optimizing network resources.

In another embodiment, the present invention provides a system for dynamic spectrum utilization management in an electromagnetic environment comprising: at least one sensor unit operable to measure radiofrequency (RF) data, an RF analysis engine operable to provide physical layer data based on the measured RF data, a customer programmable statistical interface, and a Multi-Access Edge Computing (MEC) layer in a network slice or a subnetwork, wherein the MEC layer is in communication with a radio access network (RAN) and a core network, wherein the at least one sensor unit, the RF analysis engine, the customer programmable statistical interface are provided in a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board are provided on an electronic device, wherein the electronic device is operable to send the analyzed or processed extracted physical layer data to the MEC layer, and wherein the analyzed or processed extracted physical layer data is used by the MEC layer to create actionable data for optimizing network resources.

In yet another embodiment, the present invention provides a system for dynamic spectrum utilization management in an electromagnetic environment comprising: at least one sensor unit operable to measure radiofrequency (RF) data and an RF analysis engine operable to provide physical layer data based on the measured RF data, wherein the RF analysis engine is operable to include an AI agent embedded in the engine. The AI agent includes a training model for automatic pattern recognition and/or pattern analysis. The training model recognizes patterns and trends in the RF environment and automatically adjusts detection parameters, signal detection bands, signal noise adjustments, interference parameters, and automatically detects and classifies signals. The AI agent is operable to record and store past information and use previous data and learned signals to automatically adjust and detect current and future signals in the RF environment. The AI agent adjusts parameters based upon customer goals and/or desired output. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In yet another embodiment, the present invention provides an apparatus for dynamic spectrum utilization management in an electromagnetic environment comprising: an electronic device including a single chip, a single chipset, multiple chips, multiple chipsets, or a single circuit board, wherein the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes at least one sensor unit operable to measure radiofrequency (RF) data and an RF analysis engine operable to provide physical layer data based on the measured RF data, wherein the RF analysis engine is operable to analyze or process the extracted physical layer data from the measured RF data, wherein the electronic device is operable to send the analyzed or processed extracted physical layer data to a distributed data unit (DDU), a centralized unit (CU), a radio unit (RU), and/or a Multi-Access Edge Computing (MEC) layer, wherein the analyzed or processed extracted physical layer data is used by the DDU, the CU, the RU, and/or MEC layer to create actionable data for optimizing network resources.

The system is operable to monitor the electromagnetic (e.g., RF) environment, analyze the electromagnetic environment, and extract environmental awareness of the electromagnetic environment. In a preferred embodiment, the system extracts the environmental awareness of the electromagnetic environment by including customer goals. In another embodiment, the system uses the environmental awareness with the customer goals and/or user defined policies and rules to extract actionable information to help the customer optimize the customer goals. The system combines and correlates other information sources with the extracted actionable information to enhance customer knowledge through dynamic spectrum utilization and prediction models.

In another embodiment, the at least one monitoring sensor includes at least one spectrum monitoring unit. Examples of monitoring units include those disclosed in U.S. Pat. Nos. 10,122,479, 10,219,163, 10,231,206, 10,237,770, 10,244,504, 10,257,727, 10,257,728, 10,257,729, 10,271,233, 10,299,149, 10,498,951, and 10,529,241, and U.S. Publication Nos. 20190215201, 20190364533, and 20200066132, each of which is incorporated herein by reference in its entirety. In one embodiment, the at least one spectrum monitoring unit includes a housing, at least one processor and memory, at least one receiver, and at least one sensor constructed and configured for sensing and measuring the electromagnetic environment.

FIG. **1** illustrates one embodiment of a network. The network (e.g., 5G network) includes both physical infrastructure and virtualized infrastructure. The physical infrastructure includes storage, computing resources, and networking resources. The virtualized infrastructure includes at least one radio access network (RAN), a multi-access edge computing (MEC) layer, and a core network. The core is operable to provide cellular and data services. The core provides network functions (NFs) and NF services. The core also is operable to provide network function virtualization (NFV) and software defined networking (SDN). NFV is operable to replace network functions (e.g., firewalls, load balancers, routers) with virtualized instances running as software. This eliminates the need to invest in many expensive hardware elements and can also accelerate installation times, thereby providing revenue generating services to the customer faster. The virtualized infrastructure further includes management and orchestration (MANO). The MANO is operable to coordinate network resources and network services. The MANO includes, but is not limited to, a NFV orchestrator (NFVO), a virtual network function manager (VNFM), and a virtual infrastructure manager (VIM). The virtualized infrastructure preferably also includes Operation Support Systems/Business Support Systems (OSS/BSS).

The present invention is operable to provide physical layer management operable to be optimized by slice or customer. This includes optimization of network resources based on physical layer measurements and/or slice or customer goals. The present invention is operable to aggregate a plurality of RAN resources associated with a slice or a customer subnetwork and optimize the plurality of RAN resources based on the RF environment and the quality of service (QoS) required by at least one application.

The network includes at least one network slice. Each network slice is administered by a mobile virtual network operator (MVNO). At least one tenant occupies each network slice (e.g., two tenants are operable to share a network slice) offered by the MVNO. At least one user equipment (UE) is connected to the network via 3rd Generation Partnership Project (3GPP) protocols and/or non-3GPP protocols using at least one radio access technology (RAT). The at least one RAT includes, but is not limited to, BLUETOOTH, WI-FI, Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Long-Term Evolution (LTE), 5G New Radio (NR), long range (LoRa), and/or Push-to-Talk (PTT). The UE includes, but is not limited to, a smartphone, a mobile device, a tablet, a computer, a router, an internet of things (IoT) transceiver, and/or any other user equipment transmitting and/or receiving wireless radiofrequency messages. In one embodiment, one or more of the at least one UE includes embedded sub-sensors and/or is operable to perform RF analysis.

The at least one RAT interfaces with a radio access network (RAN). The RAN is operable to provide network connectivity to the at least one UE using at least one radio frequency. The RAN is operable to communicate with a multi-access edge computing (MEC) layer. The MEC is operable to provide resource optimization per application. The MEC is operable to communicate with a core. The core is operable to provide aggregated traffic policies and/or quality of service (QoS) recommendations.

In one embodiment, at least one sensor unit (SU) is used with a network (e.g., 5G network) to provide RF awareness in spectrum bands as shown in FIG. **1**. In one embodiment, the spectrum bands include spectrum bands of interest and/or adjacent bands to the spectrum bands of interest. The at least one SU is preferably operable to share information with the RAN, the MEC, and/or the core. In one embodiment, information from the at least one sensor unit is passed to the RAN, the MEC, and/or the core of each slice in the network as shown in FIG. **1**. By interacting with the MEC, applications that require optimization of physical layer resources (e.g., low latency, high reliability, high bandwidth, spectrum sharing) are operable to be optimized by properly assigning resources based on RF environmental conditions as well as network resource availability. Advantageously, properly assigning resources allows for the applications to work properly. The at least one sensor unit interfaces with the RAN to communicate resource assignment recommendations for implementation. The sensors also interface with the core in each slice through an Access and Mobility Management Function (AMF) in the core to help aggregate resources for applications and services requiring special physical layer parameters.

In one embodiment, the at least one sensor unit is collocated with the at least one RU in the RAN. Alternatively, the at least one sensor unit is within an area of coverage of the access point's RU (e.g., between 10 m to 1 km depending on the area of coverage of a single access or base station). In one embodiment, the at least one sensor unit connects to at least one DU in the RAN through a data format as described infra.

In one embodiment, one or more of the at least one sensor unit is operable to use existing antennas of the RUs in the RAN. In one embodiment, the one or more of the at least one sensor unit is included as an RU board within the RU structure in the RAN. In one embodiment, the one or more of the at least one sensor unit is assigned an identifier (e.g., RU identifier number). In one embodiment, the identifier is assigned using 3GPP and/or ORAN standards. In one embodiment, one or more of remaining sensor units (e.g., sensor units not operable to use existing antennas of the RUs in the RAN) are distributed into the DUs and/or CUs of the RAN. In one embodiment, antennas are deployed within the coverage range of each access point or base station (e.g., if one or more of the at least one sensor unit is not operable to use existing antennas of the RUs in the RAN) and resulting data is passed to the MEC through the core orchestration connection.

In one embodiment, the present invention includes a RAN interface operable to provide resource allocation recommendations, a MEC interface operable to provide resource optimization per application, and/or a core interface operable to provide aggregated traffic policies and/or quality of service (QoS) recommendations.

The system is operable to provide at least one network resources optimization recommendation from the MEC to the core. In one embodiment, during network setup and through the orchestration layer (e.g., using the MANO functions), a MEC function is configured to receive CU information from each RAN in the customer subnet or slice containing the RF awareness information and/or pertinent actionable data, which is routed to the network optimization application software. In one embodiment, the network optimization application software includes decision gates. In one embodiment, the network optimization application software is run in the MEC as a third-party function. In one embodiment, the core and/or the MEC are reconfigured through the MANO and/or the MEC orchestrator to act on data provided by the network optimization application software and/or allow the MEC application to generate RAN commands to change appropriate RAN parameters.

FIG. **2** illustrates one embodiment of a RAN interface. The at least one sensor unit is operable to act like an additional radio unit (RU), and thus is operable to interact with a base station. In one embodiment, the base station includes, but is not limited to, a Node B (NB), an eNode B (evolved NB), a gNB-CU (a next generation node base station central unit), a gNB-DU (a next generation node base station distributed unit), a base transceiver station (BTS), a radio base station, a radio transceiver, a transceiver function, a basic service set (BSS), an extended service set (ESS), and/or an access point (AP) (e.g., a wireless access point). In one embodiment, the at least one sensor unit is operable to interface with the base station through Non-Access Stratum (NAS) and Access Stratum (AS) functional layer protocols. The at least one sensor unit is further operable to interface with the core through the AMF to help affect connection management and resource aggregations per application.

As previously described, a Multi-Access Edge Computing (MEC) layer is included in the slice to support cloud computing at the slice portion of the network as shown in FIG. **3**. The MEC allows for applications and/or cloud computing at the edge of the network. The MEC level includes at least one MEC Host. The at least one MEC Host preferably includes a MEC Platform, MEC applications, and/or MEC Virtualization Infrastructure. In one embodiment, the MEC applications are hosted on a MEC application server. The MEC application server is preferably operable to support multi-tenancy. The MEC applications are provided by at least one equipment vendor, at least one customer, at least one service provider, and/or at least one third party. The at least one MEC Host is operable to provide a virtualization environment to run the MEC applications. The MEC Platform includes, but is not limited to, a MEC Service, a service registry, traffic rules control, and/or domain name service (DNS) handling. The MEC Platform is operable to run the MEC applications using the MEC Virtualization Infrastructure. The MEC Host is preferably operable to interface with at least one other MEC Host, which includes at least one other MEC Platform.

The MEC Host is in network communication with MEC Host Level Management. The MEC Host Level Management preferably includes a MEC Platform Manager and/or a Virtualization Infrastructure Manager (VIM). The MEC Platform Manager is operable to provide MEC Platform element management, MEC application rules and requests management, and/or MEC application life-cycle management. The MEC Host Level Management is operable to interface with system level resources including, but not limited to, a device application, a Customer Facing Service (CFS) portal, a user application life-cycle management (LCM) proxy, an operations support system, and/or a MEC orchestrator.

In one embodiment, the at least one sensor unit interfaces with an optimization application in the MEC Host as another application with its associate service registry and management as shown in FIG. **3**.

In one embodiment, the at least one sensor unit interfaces with the MEC through the core (e.g., the 5G slice's core) or the NAF function from the CU interface. In one embodiment, network resource optimization and/or customer decision gates (e.g., for mission critical applications) are conducted in the MEC. In one embodiment, the network resource optimization and/or the customer decision gates are provided as at least one MEC application in the MEC platform. In one embodiment, the at least one MEC application is configured in the MEC management layers through virtual infrastructure management at the orchestration and MANO levels. In one embodiment, the MEC is compatible with 3GPP release 16. The present invention is compatible with additional 3GPP protocols and releases.

In one embodiment, the at least one sensor unit is operable to interface with the physical layer (e.g., base stations, radio units, antennas, associated antenna forming logic) as shown in FIG. **4**. In one embodiment, the at least one sensor unit is operable to share at least one antenna with a base station. The at least one antenna preferably covers at least one band of interest and/or at least one adjacent band to the at least one band of interest to obtain situational awareness. Additionally or alternatively, the at least one sensor unit includes at least one antenna. In one embodiment, the at least one sensor unit captures data related to the RF environment. The at least one sensor unit is operable to analyze data captured by the at least one antenna from the base station and/or the at least one sensor unit, thereby creating analyzed data.

In one embodiment, information from the base station antennas is passed to the at least one sensor unit. In one embodiment, the RAN follows the O-RAN standards or the 3GPP new RAN standards, which provide for an interface to pass data (e.g., metadata) from each antenna to the RUs. In one embodiment, the data includes, but is not limited to, an antenna number, parameters associated with the antenna number, a beam number, parameters associated with the beam number, and/or I&Q data. In one embodiment, the system is operable to act as another RU or RU software embedded application in the RAN. In one embodiment, a destination RU is selected. In one embodiment, identification of the destination RU (e.g., using bits) is done during configuration and/or orchestration to add an RU independent of the existing RUs in the RAN.

Analyzed data is passed to a statistical inference and machine learning (ML) engine. The statistical inference and ML engine utilizes statistical learning techniques and/or control theory to learn the electromagnetic environment and make predictions about the electromagnetic environment. The statistical inference and ML engine is preferably programmed according to customer goals regarding a customer application. The statistical inference and data analysis engine preferably identifies relevant information required by the customer application to reach the customer goals. Advantageously, this decreases the amount of analyzed data that must be processed. The relevant information is used along with network information to identify physical layer resources (e.g., antenna, resource blocks, modulation parameters, bandwidth, spectrum sharing, spectrum aggregation) required for each application to perform properly. An optimization of resource assignment is conducted. In one embodiment, the optimization of resource assignment is conducted in the MEC as an application. Alternatively, the optimization of resource assignment is conducted in the at least one sensor unit.

In one embodiment, the statistical inference and ML engine interfaces with the MEC using at least one application. In one embodiment, the present invention follows the MEC application interphase protocols to communicate with the MEC MANO layer. Advantageously, performing optimization in the MEC as an application provides the lowest network transportation latency due to its proximity to the RAN. Further, performing optimization in the MEC as an application provides the ability to add computation and storage resources during configuration through the MANO and orchestration layer.

In one embodiment, the optimization of resource assignment is conducted in the at least one sensor unit. Advantageously, if the optimization is performed in the at least one sensor unit, no interface is needed with the RU, DU, and/or CU of the RAN. All data is passed to the MEC and core of all slices of the customer subnetwork. The main advantage is minimizing latency at the cost of power and computation limitations (e.g., optimizations are operable to be performed for a limited number of customer goals). In one embodiment, if multiple RU and DU are aggregated in a single CU, the system requires a plurality of sensor units.

As previously described, in one embodiment, the at least one sensor unit is operable to share at least one antenna with the base station. In one embodiment, no antenna forming logic is used, and antenna outputs are provided in the analog domain if a splitter is used for the at least one antenna. Alternatively, antenna forming logic is used, and antenna outputs are shared with the at least one sensor unit by passing information (e.g., beam identifier along with the antenna forming logic analog output or digital output). The at least one sensor unit is operable to derive associated I & Q data for RF environment analysis. Additionally or alternatively, the at least one sensor unit includes at least one antenna. For example, if the at least one antenna from the base station is not operable to be shared and/or does not include the at least one band of interest, then the at least one sensor unit includes at least one antenna and is operable to provide antenna forming logic. In one embodiment, the radio unit is operable to share I & Q data (e.g., RF, IF, or baseband), and the at least one sensor unit is operable to consume the I & Q data. The I & Q data is preferably time-stamped. Additionally, the at least one sensor unit is preferably provided with any information specifying receiver beam information to obtain information including, but not limited to, beam azimuth, elevation, and/or beamwidth.

As previously described, the system is operable to optimize resources (e.g., in a 5G network). Resource optimization is typically done in the core, where aggregated key performance indicators (KPIs) from different access points are used to evaluate conditions of the network and inform the network management layer. In 5G networks, the RAN functions of the slice's core still use these KPIs for each slice in the customer subnetwork. MAC and IP layers are optimized based on customer network performance preference in the MANO layers of each subnetwork. The present invention is operable to provide RF awareness and actionable data, thus performing physical layer optimization (e.g., in the MEC) and making suggestions to the core about physical layer parameters. In one embodiment, the RF awareness information is filtered by the customer goals to provide actionable data for each customer goal or mission critical application. Priorities between applications are preferably configured during network set up or pushed down to the MEC through the MANO orchestration layer. The MEC is operable to service multiple slices, and each slice's core is operable to be configured to share information through the orchestration and management layers.

Standards for 5G networks include, but are not limited to, (1) 3GPP TS 36.201, Version 17.0.0 (Mar. 31, 2022); (2) 3GPP TS 36.211, Version 17.2.0 (Jun. 23, 2022); (3) 3GPP TS 36.212, Version 17.1.0 (Apr. 1, 2022); (4) 3GPP TS 36.213, Version 17.2.0 (Jun. 23, 2022); (5) 3GPP TS 36.214, Version 17.0.0 (Mar. 31, 2022); (6) 3GPP TS 36.216, Version 17.0.0 (Mar. 31, 2022); (7) 3GPP TS 36.201, Version 16.0.0 (Jul. 14, 2020); (8) 3GPP TS 36.211, Version 16.7.0 (Sep. 28, 2021); (9) 3GPP TS 36.212, Version 16.7.0 (Jan. 5, 2022); (10) 3GPP TS 36.213, Version 16.8.0 (Jan. 5, 2022); (11) 3GPP TS 36.214, Version 16.2.0 (Mar. 31, 2021); (12) 3GPP TS 36.216, Version 16.0.0 (Jul. 14, 2020); (13) 3GPP TS 38.321, Version 17.1.0 (Jul. 17, 2022); (14) 3GPP TS 38.321, Version 16.8.0 (Jul. 17, 2022); (15) 3GPP TS 23.501, Version 17.5.0 (Jun. 15, 2022); (16) 3GPP TS 23.501, Version 16.13.0 (Jun. 15, 2022); (17) 3GPP TS 23.558, Version 17.4.0 (Jun. 13, 2022); (18) 3GPP TS 28.531, Version 17.4.0 (Jun. 16, 2022); and (19) 3GPP TS

28.531, Version 16.12.0 (Dec. 23, 2021), each of which is incorporated herein by reference in its entirety.

FIG. **8** illustrates an example of a traditional base station with a remote radio head (RRH). The base station or base band unit (BBU) and the RRH connected via a high bandwidth fiber connection (i.e., fronthaul). Generally, current LTE macro cell sites include equipment positioned at the bottom of a tower and an RRH positioned at the top of the tower.

FIG. **9** illustrates an example of a centralized RAN (C-RAN). A plurality of RRHs is connected to a BBU pool via a plurality of fronthaul connections. Generally, the BBU pool is located a few miles from the RRH.

A plurality of protocol standards including, but not limited to, Common Public Radio Interface (CPRI), Open Base Station Architecture Initiative (OBSAI), and Open Radio Equipment Interface (ETSI-ORI), govern transport of data on the fronthaul. CPRI is the most used standard for LTE. Advantageously, CPRI allows for customization, so RAN vendors included a significant amount of proprietary customization. However, this proprietary customization led to a significant amount of interoperability issues between radio equipment and baseband processing equipment from different vendors. To resolve the interoperability issues, an open, disaggregated RAN has been proposed as shown in FIG. **10**.

Additionally, transporting LTE data rates using CPRI transport required significant fiber bandwidth, which is expensive and created deployment problems. As such, many vendors have determined that CPRI is not sufficient for fronthaul requirements. 5G applications often require low latency, which makes fiber bandwidth a significant issue. In some embodiments, 5G is operable to deliver at least 10 times up to at least 100 times faster data rates than LTE. In one embodiment, a 5G base station is operable to deliver a data rate of at least 10 Gpbs. In comparison, an LTE base station is operable to deliver a data rate of less than 1 Gbps.

5G deployments utilize enhanced CPRI (eCPRI) or radio over ethernet (RoE) for transport on the fronthaul between DUs and RUs. eCPRI is a fronthaul protocol defined by the CPRI Forum. The eCPRI protocol is operable to deliver higher data rates via compression techniques. RoE is protocol defined by the IEEE 1914.3 working group. The RoE protocol defines encapsulation and mappings of radio protocols via ethernet frames. Option 7-2 supports both eCPRI and RoE transport options. The partition of features is operable to change the information payload between RAN components.

The O-RAN Fronthaul specification addresses the issues with interoperability between the radio equipment and baseband processing equipment. The O-RAN Fronthaul specification defines several planes of operation, including a control plane (C-Plane), user plane (U-Plane), a synchronization plane (S-Plane), and a management plane (M-Plane) as shown in FIG. **11**. The C-Plane is operable to utilize message to define scheduling and coordination required to transfer control signal data (e.g., beamforming for 5G). The U-Plane is operable to utilize messages to define transfer of user data. The S-Plane provides timing and synchronization between the DU and the RU. The M-Plane is operable to provide management of the radio unit via messages.

FIG. **12** illustrates one embodiment of a fronthaul interface according to the O-RAN Fronthaul specification. The O-RAN fronthaul provides communication between the O-RAN distributed unit (O-DU) and the O-RAN radio unit (O-RU). In one embodiment, the system includes a sensor unit (SU) including multiple hardware and software components.

In one embodiment, the SU is integrated into the DU. In one embodiment, the SU appears like a PHY algorithm and appends data to the WLS-CU interface message.

Hardware components include two networking ports. The two networking ports are operable to communication to the fronthaul network and the backhaul and/or midhaul network. The two networking ports are also operable to receive precision time protocol (PTP) synchronization. A system timer is operable to provide timing to the gNB application. Software components include a PTP software (e.g., a Linux PTP) to synchronize to the system timer to a global time (e.g., GPS timer), a PTP4L program operable to synchronize an oscillator on a network interface controller (NIC) to the PTP grandmaster (GM), a Phyc2sys program to synchronize the system timer to the oscillator on the NIC, a data plane development kit (DPDK) operable to provide an interface to an ethernet port, and/or an xRAN library to provide U-Plane and C-Plane functionality. PHY uses the xRAN library to access an interface to the O-RU. PHY uses a set of MAC/PHY APIs and a shared memory interface (WLS) to communicate with an L2 application. The L2 application is operable to use the backhaul and/or midhaul networking port to connect to the CU. The xRAN library and PHY are operable to communicate control (C-Plane) information, transmission time interval (TTI) information, symbol timing information, and/or IQ data.

FIG. **13** illustrates one embodiment of the O-RU/SU part of the xRAN split. In one embodiment, the at least one sensor unit is embedded in the ORAN block.

FIG. **14** illustrates e-NB/g-NB architecture including an O-DU and a plurality of radio units (O-RUs). In one embodiment, at least one SU is included in the e-NB/g-NB. In one embodiment, more than one RU and/or more than one SU is operable to be supported with the same implementation of the xRAN library.

In one embodiment, the SU is a stand alone unit (e.g., not incorporated into the RUs and/or DUs as computing software additions). In one embodiment, the stand-alone unit does not interface with the DUs and/or RUs in the ORAN. In one embodiment, the stand-alone unit interfaces with the MEC and/or the core.

As previously described, the O-RAN Fronthaul specification provides a plurality of splits of Layer 1 functionality between the O-DU and O-RU. FIG. **15** illustrates one embodiment of a Layer 1 split.

FIG. **16** is a table describing supported data flow for a single radio unit with a single component carrier. The U-Plane includes DL frequency domain IQ data, UL frequency domain IQ data, and PRACH frequency domain IQ data. The C-Plane includes scheduling commands. The S-plane includes timing and synchronization.

FIG. **17** illustrates one example of dataflows between the O-DU and the O-RU excluding M-Plane dataflows.

FIG. **18** illustrates an example of the C-Plane and U-Plane packet exchange. The example shown in FIG. **18** does not include a Quality of Service (QoS) request.

The O-RAN Fronthaul specification defines a latency model of the fronthaul interface and interactions between the O-DU and the O-RU. The xRAN library is operable to support a defined transport method. The O-RAN Fronthaul specification further defines network transport requirements, and O-DU transmit and receive windows are based on the network transport requirements. Delay characteristics of at least one RU and/or at least one SU are determined within the timing domain framework (e.g., GPS time).

FIG. **19** is a table of default values used for the implementation of O-DU and O-RU/SU simulation with a mmWave scenario. FIGS. **20-21** are tables of default values used for the implementation of O-DU and O-RU/SU simulation with numerology 0 and numerology 1 examples, respectively, as defined in the O-RAN standard for Sub6 scenarios. The configuration is operable to be adjusted via configuration files for sample application and reference PHY.

FIG. **22** illustrates one embodiment of an ORAN Fronthaul process. The O-DU includes an O-DU network interface card (NIC), and the O-RU includes a O-RU NIC. The O-DU and the O-RU are connected between the O-DU NIC and the O-RU NIC.

In one embodiment, the xRAN library provides support for transporting In-band and Quadrature (IQ) samples between the O-DU and O-RU/SU within the xRAN architecture based on functional split option 7-2. The xRAN library defines xRAN packet formats operable to be used to transport radio samples via the fronthaul according to the O-RAN Fronthaul specification. Additionally, the xRAN library is operable to provide functionality to generate at least one xRAN packet, append IQ samples in a payload of the at least one xRAN packet, and/or extract IQ samples from the at least one xRAN packet.

FIG. **23** illustrates Configuration LLS-C1. Configuration LLS-C1 provides network timing distribution from the O-DU and to the O-RU via a point-to-point topology and a synchronized ethernet (SyncE).

FIG. **24** illustrates Configuration LLS-C3. Configuration LLS-C3 provides network timing distribution from the primary reference time clock/telecom grand master clock (PRTC/T-GM). A network of switches includes at least one ethernet switch.

The O-RAN Fronthaul specification defines a list of mandatory functionality. However, the list of mandatory functionality for the O-DU includes features that are not currently supported. See, e.g., Transport Layer and ORAN Fronthaul Protocol Implementation (2019), O-RAN Project Revision 70d9d920, available at https://docs.o-ran-sc.org/projects/o-ran-sc-o-du phy/en/latest/Transport-Layer-and-ORAN-Fronthaul-Protocol-Implementation_fh.html#section-type-3-structure (last accessed Mar. 20, 2022), which is incorporated herein by reference in its entirety. Table 5 of Transport Layer and ORAN Fronthaul Protocol Implementation (2019) lists ORAN Mandatory and Optional Feature Support. Table 6 of Transport Layer and ORAN Fronthaul Protocol Implementation (2019) lists levels of validation for xRAN functionality.

O-RAN Fronthaul data is operable to be transported over ethernet or IPv4/IPv6. However, current implementation of the xRAN library only supports ethernet with a virtual local area network (VLAN). FIG. **25** illustrates one embodiment of a native ethernet frame with VLAN.

The O-RAN Fronthaul specification defines the transport header based on the eCPRI specification. FIG. **26** illustrates one embodiment of eCRPI header field definitions. FIG. **27** illustrates bit allocations of ecpriRtcid/ecpriPcid.

In one embodiment, an xRAN packet includes compression. In one embodiment, an xRAN packet including compression includes a Compression Header after each Application Header. The O-RAN Fronthaul specification defines the Compression Header. Alternatively, the xRAN packet does not include compression. In one embodiment, the xRAN packet not including compression does not include the Compression Header.

FIG. **28** illustrates xRAN packet components for DL/UL IQ data messages. In one embodiment, octet M+9 through M+12 and octet M+17 through M+19 is specified as sensor data. In one embodiment, the sensor data includes a location and/or a directionality relative to the DU.

FIG. **29** illustrates one embodiment of a common radio application header. In one embodiment, the filterIndex=0, frameId=[0:99], subframeId=[0:9], slotId=[0:7], and symbolId=[0:13].

In one embodiment, the common radio application header is followed by an application header that is operable to be repeated for each data section within an eCPRI message. FIG. **30** illustrates one embodiment of a data section application header. In one embodiment, a single section is used for an ethernet packet where IQ samples startPrbu is equal to 0 and numPrbu is equal to the number of RBs used. The rb field is not normally used (value=0). In one embodiment, the present invention assigns the rb field a specific value of 1. The symInc field is not normally used (value=0). In one embodiment, the present invention assigns the symInc field a specific value of 1. Alternative configurations are compatible with the present invention. Advantageously, this format provides flexibility. For example, and not limitation, octet 9 allows up to 8 payload versions and 16 filter indexes to be set. In one embodiment, at least one payload version and/or at least one filter index is operable to pass UL sensor information (e.g., if the UE includes sensor capabilities). In another embodiment, the at least payload version and/or the at least one filter index is operable to pass UE parameter values that have been optimized in the DL.

An xRAN packet data payload includes a plurality of physical resource blocks (PRBs). In one embodiment, each PRB includes 12 IQ samples. In one embodiment, the xRAN packet data payload includes udCompParam to indicate that compression is enabled. FIG. **31** illustrates one embodiment of an xRAN packet data payload.

In one embodiment, a C-Plane message includes a first header layer and a second header layer. The first header layer includes a standard eCPRI header including a message type and the second header layer includes an application layer operable to provide control and synchronization.

FIG. **32** illustrates a table of section types and target scenarios.

FIG. **33** illustrates one embodiment of a radio application common header. The radio application common header is operable to be used for time reference.

FIG. **34** illustrates a structure of a Section Type 0 message. The Section Type 0 message is operable to indicate idle or guard periods from the O-DU to the open radio unit (O-RU).

FIG. **35** illustrates a structure of a Section Type 1 message. The Section Type 1 message is operable to The Section Type 1 message includes a user data compression header (udCompHdr) including IQ compression information.

FIG. **36** illustrates an entire Section Type 1 message. The entire Section Type 1 message includes the radio application common header, the radio application Section 1 header, and radio application Section 1 information.

FIG. **37** illustrates a structure of a Section Type 3 message. The Section Type 3 message includes the radio application common header, a timeOffset, a frameStructure, a cpLength, and the udCompHdr.

FIG. **38** illustrates an entire Section Type 3 message. The entire Section Type 3 message includes the radio application common header, the radio application Section 3 header, and radio application Section 3 information.

FIG. **39** illustrates a structure of a Section Type 5 message. The Section Type 5 message is operable to provide scheduling information for UEs.

FIG. **40** illustrates a structure of a Section Type 6 message. The Section Type 6 message is operable to provide UE channel information from the O-DU to the O-RU.

Communications between the DU and the CU are divided into control plane communications and user plane communications. The CU is the functional between control plane information and user plane information.

The F1 interface connects a gNodeB (gNB) CU to a gNB DU. The control plane of the F1 interface (F1-C) allows transfer of information between the CU and the DU, while the user plane of the F1 interface (F1-U) allows the transfer of user plane information (e.g., application data).

FIG. **41** illustrates the F1-C and F1-U protocol stacks. F1-C uses stream control transmission protocol (SCTP) over internet protocol (IP) and is defined in 3GPP TS 38.473, Version 16.8.0 (Dec. 23, 2021), which is incorporated herein by reference in its entirety. In contrast, F1-U uses GPRS tunneling protocol user plane (GTP-U) over user datagram protocol (UDP) over internet protocol (IP) for transport layer and is defined in 3GPP TS 38.425, Version 16.3.0 (Apr. 9, 2021), which is incorporated herein by reference in its entirety. GPRS Tunnelling Protocol (GTP) is a protocol to carry general packet radio service (GPRS) in 5G radio network.

The F1 interface is an open interface and general information about F1 is found in 3GPP TS 38.470, Version 16.5.0 (Jul. 1, 2021), which is incorporated herein by reference in its entirety. The F1 interface supports the exchange of signaling and data information between the endpoints. The F1 interface separates the control plane and the user plane. Additionally, the F1 interface separates the Radio Network Layer from the Transport Network Layer. The F1 interface allows for connection of a gNB-CU and a gNB-DU supplied by different manufacturers. The F1 interface enables exchange of user equipment (UE)-associated information and non-UE associated information.

FIG. **42** is a table of F1 interface functionalities. The F1 interface functionalities include, but are not limited to, interface management functions, system information (SI) management functions, UE context management functions, radio resource control (RRC) message transfer functions, paging functions, warning message transfer functions, remote interface management (RIM) functions, trace functions, load management functions, self-optimization support functions, positioning functions, and/or integrated access and backhaul (IAB) support functions. The interface management functions include, but are not limited to, reset procedures, error indication, F1 setup procedures, gNB-DU configuration updates, gNB-CU configuration updates, gNB-DU resource coordination, and/or gNB-status indication.

The reset procedures are operable to initialize or re-initialize F1AP UE contexts in event of a failure of the CU or the DU. In one embodiment, the failure occurs at the CU and a reset message is transmitted to the DU. The DU then releases all assigned F1 resources and related radio resources and responds with a reset acknowledge message. In one embodiment, the failure occurs at the DU and a reset message is transmitted to the CU. The CU releases all allocated F1 resources and responds with a reset acknowledge message.

The error indication procedure is operable to be initiated by the CU or the DU. In one embodiment, the error indication procedure is initiated by an error indication message. In one embodiment, the error indication message includes cause information and/or criticality diagnostic information.

The F1 setup procedures are operable to exchange application-level data for the CU and the DU to correctly interoperate. In one embodiment, the F1 setup procedure includes the DU initiating an F1 setup request to a CU, and the CU returning an F1 setup response message. In one embodiment, an SCTP connection is established between the CU and the DU before the F1 setup procedure is operable to be initiated. In one embodiment, the F1 setup request is operable to include an identification of the DU (e.g., name) and/or a set of cells served by the DU. In one embodiment, the F1 setup response is operable to provide a list of cells to be activated.

The gNB-DU configuration update is operable to update application-level configuration data for the gNB-DU and gNB-CU to interoperate correctly on the F1 interface. In one embodiment, the gNB-DU initiates the procedure by sending a gNB-DU configuration update message including updated configuration data (e.g., served cells to add, served cells to modify, served cells to delete, cells status). The CU returns a gNB-DU configuration update acknowledge message to the DU.

The gNB-CU configuration update is also operable to update application-level configuration data for the gNB-DU and gNB-CU to interoperate correctly on the F1 interface. In one embodiment, the gNB-CU initiates the procedure by sending a gNB-CU configuration update message including updated configuration data (e.g., cells to be activated, cells to be deactivated). The DU returns a gNB-CU configuration update acknowledge message to the CU.

The gNB-DU resource coordination procedure is operable to allow coordination of resource allocation between a gNB-CU and gNB-DU for spectrum sharing. In one embodiment, the gNB-CU initiates the procedure by sending a gNB-DU resource coordination request message to a gNB-DU to the DU. The DU returns a gNB-DU resource coordination response to the CU.

The gNB-DU status indication procedure is operable to inform the CU that the DU is overloaded to allow for overload reduction actions. In one embodiment, the gNB-DU initiates the procedure by sending a gNB-DU status indication message to the CU. The overload reduction actions are applied until an updated gNB-DU status indication message indicates that the DU is no longer overloaded.

The F1 interface includes a plurality of RRC message transfer procedures including, but not limited to, initial UL RRC message transfer, DL RRC message transfer, UL RRC message transfer, and/or RRC delivery report.

The initial UL RRC message transfer procedure is operable to send an initial RRC message from the gNB-DU to the gNB-CU. The DL RRC message transfer procedure is operable to send an RRC message from the gNB-CU to the gNB-DU. The UL RRC message transfer procedure is operable to send a UL RRC message transfer response from the gNB-DU to the gNB-CU. The RRC delivery report procedure is operable to send an RRC delivery report regarding successful delivery of messages from the gNB-CU to the gNB-DU.

The F1 interface includes a plurality of UE context management procedures including, but not limited to, UE context setup, UE context release request, UE context modification, UE inactivity notification, and/or notify.

The UE context setup procedure is operable to establish UE context. In one embodiment, the UE context is related to information including, but not limited to, SRB, DRB, BH RLC channel, and/or SL DRB configuration. The UE context setup procedure is operable to send a UE context setup request from the gNB-CU to the gNB-DU. The UE context setup procedure is operable to send a UE context setup response message from the gNB-DU to the gNB-CU.

The UE context modification procedure is operable to modify an established UE context (e.g., establish, modify, and/or release radio resources or sidelink resources). The UE context modification procedure includes a UE context modification request from the gNB-CU to the gNB-DU. The UE context modification procedure includes a UE context modification response.

The UE context modification required procedure is operable to modify the established UE context (e.g., modify and/or release radio bearer resources, sidelink radio bearer resources, and/or candidate cells). The UE context modification required procedure includes a UE context modification required message sent from the gNB-DU to the gNB-CU. The UE context modification required procedure includes a UE context modification confirm message sent from the gNB-CU to the gNB-DU.

The UE context release procedure is operable to enable the gNB-CU to order the release of an existing UE context. The UE context release procedure includes the gNB-CU sending a UE context release command to the gNB-DU. The UE context release procedure includes the gNB-DU sending a UE context release complete message to the gNB-CU.

The UE inactivity notification procedure is operable to indicate an inactivity status of a UE. In one embodiment, the gNB-DU sends a UE inactivity notification message to the gNB-CU.

The notify procedure is operable to allow the gNB-DU to inform the gNB-CU that a quality of service (QoS) is not operable to fulfilled or is operable to be fulfilled again. In one embodiment, the gNB-DU initiates the notify procedure by sending a notify message to the gNB-CU. In one embodiment, the notify message is operable to indicate alternative QoS parameters the gNB-DU is operable to fulfil.

In one embodiment, the F1 interface further includes a plurality of warning message transmission procedures including, but not limited to, a write-replace warning, a public warning system (PWS) cancel, a PWS restart indication, and/or a PWS failure indication.

The write-replace warning procedure is operable to start or overwrite the broadcasting of warning messages. In one embodiment, the gNB-CU initiates the write-replace warning procedure by sending a write-replace warning request message to the gNB-DU and the gNB-DU returns a write-replace warning response.

The PWS cancel procedure is operable to cancel broadcast of a warning message. In one embodiment, the gNB-CU initiates the PWS cancel procedure by sending a PWS cancel request to the gNB-DU and the gNB-DU returns a PWS cancel response.

The PWS restart indication procedure is operable to inform the gNB-CU that PWS information for at least one cell of the gNB-DU is available for reloading. In one embodiment, the gNB-DU initiates the PWS restart indication procedure by sending a PWS restart indication to the gNB-CU.

The PWS failure indication procedure is operable to inform the gNB-CU that ongoing PWS transmission of the gNB-DU has failed for at least one cell. In one embodiment, the gNB-DU sends a PWS failure indication message to the gNB-CU. The PWS failure indication message preferably includes identification of the at least one cell.

In one embodiment, the F1 interface includes a system information delivery procedure operable to command the gNB-DU to broadcast Other System Information (OSI). In one embodiment, the gNB-CU initiates the procedure by sending a system information delivery command to the DU.

In one embodiment, the F1 interface includes a paging procedure operable to providing paging information to allow a gNB-DU to page a UE. In one embodiment, the gNB-CU initiates the procedure by sending a paging message to the DU. The paging message includes an identity of the UE (e.g., RAN UE Paging Identity (I-RNTI), Core Network UE Paging Identity (S-TMSI)). In one embodiment, the paging message further includes a paging DRX to determine a final paging cycle for the UE, a paging priority, and/or a paging cell list.

FIG. **43** illustrates transfer of application data between the DU and CU-UP using the user plane of the F1-U. A Protocol Data Unit (PDU) Type 0 is transmitted from the CU to the DU, while a PDU Type 1 is transmitted from the DU to the CU. Application data is transferred via GTP-U tunnels, which are identified using a tunnel endpoint identifier (TEID). Each data radio bearer (DRB) has a tunnel.

The user plane protocol uses services of the transport network layer to provide control mechanisms for transfer of downlink data. The control mechanisms include, but are not limited to, flow control, detection of lost data packets, and/or delivery status updates (e.g., reporting successful delivery).

The CU-UP uses a PDU Type 0 frame format to track sequence numbers for each downlink data packet. In one embodiment, the sequence numbers are used by the DU to detect lost data packets. In one embodiment, the PDU Type 0 frame format is used to indicate discard instructions. FIG. **44** is a table of PDU Type 0 downlink user data.

The DU uses a PDU Type 1 frame format to report lost data packets and provide flow control. The PDU Type 1 frame format is preferably operable to indicate a sequence number of the highest successfully delivered PDCP sequence number, the desired buffer size for the data radio bearer, and/or the desired data rate. In one embodiment, the desired data rate indicates an amount of data in bytes for the DU to receive within a specified time interval (e.g., 1 second). In one embodiment, the cause value is operable to indicate a radio link outage and/or a radio link resume. FIG. **45** is a table of PDU Type 1 downlink delivery status.

See, e.g., (1) 3GPP TS 38.470 5G NG-RAN: F1 general aspects and principles, Version 16.5.0 (dated Jul. 1, 2021); (2) 3GPP TS 38.473 5GNG-RAN: F1 Application Protocol (F1AP), Version 16.8.0 (dated Dec. 23, 2021); and 3GPP TS 38.425 5G NG-RAN: NR user plane protocol, Version 16.3.0 (dated Apr. 9, 2021), each of which is incorporated herein by reference in its entirety.

FIG. **46** illustrates one embodiment of O-RAN defined nodes. The O-CU-CP, O-CU-UP, O-DU, and O-RU are defined by 3GPP and adapted by O-RAN specifications. The O-Cloud is a cloud computing platform formed of physical infrastructure elements operable to host O-RAN nodes (e.g., near RT-RIC, O-DU) and operable to host virtual network functions used by components (e.g., RICs). The O-RAN radio unit (O-RU) is operable to process radio frequencies received by the PHY layer. The O-DU is a logical node hosting protocols including, but not limited to, radio resource control (RLC), medium access control (MAC), and/or the physical interface (PHY). The O-CU includes the O-CU-CP and the O-CU-UP. The O-CU-CP includes radio resource control (RRC) and control plane components of Packet Data Convergence Protocol (PDCP). The O-CU-UP includes Service Data Adaptation Protocol (SDAP) and user plane components of PDCP. The near-RT RIC is operable to enable near-RT control and/or optimization of O-RAN components and resources. In one embodiment, the near-RT RIC includes artificial intelligence and/or machine learning. The non-RT RIC is operable to enable non-RT control and/or optimization of O-RAN components and resources. In one embodiment, the non-RT RIC is operable to provide policy-based management of the near-RT RIC. An xApp is an application operable to run on the near-RT RIC. In one embodiment, the xApp is independent of the near-RT RIC. The Service Management and Orchestration framework (SMO) is operable to manage the near-RT RIC, non-RT RIC, the O-Cloud, the O-CU, and/or the O-DU. Advantageously, different components are operable to be provided by different manufacturers.

FIG. **47** illustrates one embodiment of an overall O-RAN architecture. The A1 interface is defined between the non-RT RIC in the SMO and the near-RT RIC. The A1 interface provides at least three types of services including, but not limited to, policy management services, enrichment information services, and machine learning (ML) model management services. The E2 interface is operable to communicate with the base station (e.g., O-RU, O-DU, O-CU). At least one message (e.g., monitor, suspend, override, control) is operable to control the base station and actions are operable to executed (e.g., from xApps, from near-RT RIC). The E2 interface is operable to collect data and receive feedback from the base station (e.g., O-RU, O-DU, O-CU). The O1 and Open-Fronthaul M-plane interfaces are a Fault, Configuration, Accounting, Performance, Security (FCAPS) interface. The O1 and Open-Fronthaul M-plane interfaces are operable to exchange information (e.g., configuration, registration, security, performance, monitoring) with components including, but not limited to, the O-CU-CP, O-CU-UP, the O-DU, the O-RU, and/or the near-RT RIC. The O2 interface is operable to manage communications between the SMO and the O-Cloud (e.g., management of platform resources and workload).

FIG. **47** also illustrates three control loops. The first control loop is a real-time control loop. In one embodiment, actions in the real-time control loop occur in less than 10 ms. The second control loop is a near-real-time control loop. In one embodiment, actions in the near-real-time control loop occur between 10 ms and 1 s (e.g., functions such as Traffic Steering, Mobility Management, Interface Management). The third control loop is a non-real-time control loop. In one embodiment, actions in the non-real-time control loop occur in greater than 1 s (e.g., orchestration and optimization functions, incorporation of ML models).

FIGS. **48**-**51** illustrate example embodiments for the implementation of O-RAN architecture. Descriptions of O-RAN architecture are included in "O-RAN Architecture-Description 6.0", O-RAN.WG1.O-RAN-Architecture-Description-v06.00, O-RAN Alliance (March 2022), which is incorporated herein by reference in its entirety. In one embodiment, the E2 is a logical node terminating E2 interface. In one embodiment, the E2 node includes O-CU-CP, O-CU-UP, O-DU, or any combination specified by the O-RAN Alliance. The nodes are operable to be aggregated in a plurality of different ways including, but not limited to, (1) disaggregated network functions in the O-RAN, (2) aggregated O-CU-CP and O-CU-UP, (3) aggregated O-CU-CP, O-CU-UP, (4) aggregated near-RT RIC, O-CU-CP, and O-CU-UP, (5) aggregated O-CU-CP, O-CU-UP, O-DU, and O-RU, (6) aggregated O-DU and O-RU, or (7) aggregated near-RT RIC, O-CU-CP, O-CU-UP, O-DU, and O-RU.

FIG. **48** illustrates disaggregated network functions in the O-RAN. In the embodiment shown in FIG. **48**, the near-RT RIC has E2 connections to the O-CU-CP, the O-CU-UP, and the O-DU.

FIG. **49** illustrates an aggregated O-CU and O-DU, which form an E2 node. There is only one E2 connection from the near-RT RIC to the E2 node, and only one 01 connection from the SMO to the E2 node.

FIG. **50** illustrates an aggregated near-RT RIC, O-CU-CP, and O-CU-UP. The E2 interfaces to control the O-CU-CP and the O-CU-UP are contained within the E2 node. The E2 node has an E2 interface with the O-DU.

FIG. **51** illustrates an aggregated near-RT RIC, O-CU-CP, O-CU-UP, O-DU, and O-RU. The E2 interface is fully internal. A single O1 connection is present between the SMO and the E2 node, as well as an A1 connection between the non-RT RIC and the near-RT RIC.

The near-RT RIC hosts microservice-based applications known as xApps. xApps are operable to control a distributed collection of RAN components (e.g., eNB, gNB, CU, DU) via the E2 interface. The near-RT RIC also includes the A1 interface and the O1 interface to the non-RT RIC for the management and optimization of the RAN. Advantageously, this allows the near-RT RIC to utilize a plurality of RAN types (e.g., macro cells, small cells, massive MIMO) and/or a plurality of RAN data to manage and optimize the RAN. xApps are operable to utilize the E2 interface collect near-RT information. The near-RT RIC is operable to control E2 nodes via policies and data provided from the non-RT RIC via the A1 interface. The near-RT RIC includes machine learning (ML) models and is operable to provide loading balancing, handover control, interference management, and/or resource block management. The radio-network information base (R-NIB) is operable to determine a state of the network (e.g., in near RT) and transmit network state data to the RAN. In one embodiment, the network state data is used to train AI/ML models. In one embodiment, the AI/ML models are operable to facilitate radio resource management (RRM). In one embodiment, the non-RT RIC is operable to transmit trained models to the near-RT RIC via the A1 interface. The near-RT RIC is operable to execute the trained models to improve network conditions.

In one embodiment, the near-RT RIC operates in near-real time. In one embodiment, near-real time is greater than 10 ms and less than 1 s. In one embodiment, the near-RT RIC is operable to control and optimize RAN. In one embodiment, the near-RT RIC includes xApps. In one embodiment, the near-RT RIC is operable to perform radio resource management (e.g., via xApps).

The near-RT RIC is described in "O-RAN Near-Real-time RAN Intelligent Controller Architecture & E2 General Aspects and Principles 2.01", O-RAN.WG3.E2GAP-v02.01, O-RAN Alliance (March 2022), which is incorporated herein by reference in its entirety.

FIG. **52** illustrates one embodiment of near-RT RIC internal architecture. The near-RT RIC includes a plurality of functions hosted by xApps. The plurality of functions hosted by the xApps is operable to be executed at the near-RT RIC to provide services. Outcomes of the services are operable to be sent to the E2 nodes via the E2 interface. The database and the shared data layer are operable to allow reading and/or writing of information related to the RAN and/or UE. A conflict mitigation function is operable to resolve conflicts between at least two xApps. The xApp subscription management function is operable to merge subscriptions from a plurality of xApps. The security function is operable to provide security for the xApps. The management services function is operable to provide management (e.g., configuration, performance, lifecycle, fault) of xApps. The messaging infrastructure function is operable to provide messaging between internal functions of the near-RT RIC.

FIG. **53** illustrates a centralized near-RT RIC. In the centralized near-RT RIC, the entire gNB (e.g., via O-DU, O-CUs) and/or eNB are handled by the same near-RT RIC. Advantageously, this allows for the near-RT RIC to optimize operations and make overall decisions for an individual base station.

FIG. **54** illustrates a fully distributed near-RT RIC. In the fully distributed near-RT RIC, each E2 node is handled by a near-RT RIC entity including a plurality of near-RT RICs. Individual components of the E2 node (e.g., O-CU-CP, O-CU-UP, C-DU, and/or O-eNB) are optimized by one of the plurality of near-RT RICs.

Advantageously, the flexibility of implementation options allows for different components to be supplied and deployed by different companies. However, this requires more complexity in design of the E2 interface.

The E2 interface provides communication between the near-RT RIC and E2 nodes. The near-RT RIC (e.g., via the xApps) are operable to control functions inside the E2 nodes. E2 interface architecture is described in "O-RAN Near-Real-time RAN Intelligent Controller Architecture & E2 General Aspects and Principles 2.01", O-RAN.WG3.E2GAP-v02.01, O-RAN Alliance (March 2022), which is incorporated herein by reference in its entirety. The E2 interface is open and facilitates connectivity between the near-RT RIC and the E2 node supplied by different manufacturers. Further, the E2 interface facilitates exposure of selected E2 node data towards the near-RT RIC. The selected E2 node data includes, but is not limited to, configuration information (e.g., cell configuration, supported slices, public land mobile networks (PLMNs)), network measurements, and/or context information. The E2 interface further enables the near-RT RIC to control selected functions on the E2 node.

The E2 functions include, but are not limited to, near-RT RIC services and/or near-RT RIC support functions. The near-RT RIC services include, but are not limited to, REPORT, INSERT, CONTROL, and/or POLICY. The near-RT RIC support functions include, but are not limited to, interface management (e.g., E2 setup, E2 reset, E2 node configuration update, reporting of general error situations) and/or a near-RT RIC service update.

FIG. **55** illustrates one embodiment of E2 interface architecture. The near-RT RIC includes a database and at least one xApp. The database is operable to store data from the at least one xApp and the E2 node. The database is also operable to provide data to the at least one xApp. The near-RT RIC further includes an E2 termination function that is operable to terminate the E2 interface. The E2 includes at least one RAN function controlled by the near-RT RIC, an E2 agent, and other functions. In one embodiment, the E2 agent is operable to terminate the E2 interface. In one embodiment, the E2 agent is operable to forward and/or receive E2 messages. The at least one RAN function (e.g., Function (1), Function (N)) is controlled by the near-RT RIC and supports near-RT RIC services. In one embodiment, the other functions are RAN functions that do not support near-RT RIC services.

One of the major challenges with implementing 5G networks is reducing latency. Although networking slicing and RAN modifications reduce delays relative to 3G and 4G networks, it is not enough to meet the requirements with 5G. As a result, services need to move to the edge of the network. Advantageously, this moves application services and content closer to users, providing low latency, optimized content distribution, localized data caching, and/or integration with internet of things (IoT) devices.

The integration of ETSI Multi-access Edge Computing (MEC) and 5G is viewed as a solution to the difficulty of meeting the latency requirements. One critical issue for the MEC is the management of physical resources (e.g., via at least one application). The MEC is operable to assist in traffic routing and policy control.

ETSI ISG MEC (Industry Specification Group for Multi-access Edge Computing) is responsible for developing the technical standards for edge computing. The ETSI ISG MEC has published a set of specifications for the MEC including, but limited to, the following: (1) ETSI GS MEC 003 V1.1.1, "Mobile Edge Computing (MEC); Framework and Reference Architecture" (2016-03); (2) ETSI GS MEC 010-1 V1.1.1, "Mobile Edge Computing (MEC); Mobile Edge Management; Part 1: System host and platform management" (2017-10); (3) ETSI GS MEC 010-2 V1.1.1, "Mobile Edge Computing (MEC); Mobile Edge Management; Part 2: Application lifecycle, rules and requirements management" (2017-07); (4) ETSI GS MEC 011 V1.1.1, "Mobile Edge Computing (MEC); Mobile Edge Platform Application Enablement" (2017-07); (5) ETSI GS MEC 012 V1.1.1, "Mobile Edge Computing (MEC); Radio Network Information" (2017-07); (6) ETSI GS MEC 013 V1.1.1, "Mobile Edge Computing (MEC); Location API" (2017-07); (7) ETSI GS MEC 014 V1.1.1, "Mobile Edge Computing (MEC); UE Identity API" (2018-02); (8) ETSI GS MEC 015 V1.1.1, "Mobile Edge Computing (MEC); Bandwidth Management API" (2017-10); and (9) ETSI GS MEC 016 V1.1.1, "Mobile Edge Computing (MEC); UE Application Interface" (2017-09), each of which is incorporated herein by reference in its entirety. The set of specifications include management and orchestration (MANO) of MEC applications, application enablement application programming interfaces (API), service APIs, and the user equipment (UE) API. The MANO and application enablement functions are operable to provide service environments in edge data center. The service APIs are operable to provide network information to application. Advantageously, the MEC provides contextual information and real-time status of the environment through the APIs. The UE API is operable to facilitation UE interaction with the MEC system.

Edge computing is one of the key technologies involved in 5G to support low latency, mission critical services, and/or IoT devices. The MEC is operable to be mapped onto application functions (AFs) that are operable to use services and/or information provided by network functions based on configuration policies. Further, the MEC is operable to be deployed in a plurality of configurations, which provides flexibility to the system. The MEC is operable to include a plurality of applications. The plurality of applications is operable to provide a plurality of services including, but not limited to, streaming (e.g., movies, television), gaming, IoT, and/or V2X communication.

The system architecture for 5G is specified by 3GPP in 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; System architecture for the 5G System (5GS); Stage 2 (Release 17) v17.4.0 (dated March 2022), which is incorporated herein by reference in its entirety. One of the significant changes to the 5G system is the ability to use either a point-to-point paradigm or a service based architecture (SBA) between core network functions.

The SBA includes a plurality of network functions that are operable to consume and/or produce at least one service. In one embodiment, the SBA includes a request-response model and/or a subscribe-notify model. ETSI ISG MEC defined an API framework operable to be used MEC applications. Both the API framework and the SBA are operable to provide efficient use of services using functions including, but not limited to, registration, service discovery, availability notifications, de-registration, authentication, and/or authorization. FIG. **56** illustrates a 3GPP 5G with the SBA on the left and the MEC system on the right.

The network functions and corresponding services produced by the network functions are operable to be registered in a network resource function (NRF). Services produced by MEC applications are operable to registered in a service registry of the MEC platform. A list of available services is operable to be discovered from the NRF. In one embodiment, a service is accessible only via the NEF. In one embodiment, the NEF is operable to authorize access requests external to the domain. An Authentication Server Function (AUSF) is operable to perform procedures related to authentication. A Network Slice Selection Function (NSSF) is operable to assist in selecting suitable network slice instances for user and allocating Access Management Functions. A MEC application is operable to belong to at least one network slice configured in the core network.

The Policy Control Function (PCF) is operable to handle policies and rules. An AF (e.g., a MEC platform) is operable to request services from the PCF to impact traffic steering rules. The PCF is operable to be accessed directly or via the NEF.

The unified data management (UDM) is operable to provide services related to users and subscriptions. The UDM is operable to manage data for authentication, user registration, and data network profiles.

The user plane function (UPF) is operable to connect data from the RAN to the Internet and/or route traffic for user devices to a base station. In one embodiment, UPFs are controlled via a network exposure function (NEF) to policy control function (PCF) to session management function (SMF) route. In one embodiment, the UPF is included in the MEC.

FIG. **57** illustrates one embodiment of an integrated MEC deployment. In the embodiment shown in FIG. **57**, the MEC orchestrator is included in the MEC system as a system level entity that is operable to interact as an application function with the network exposure function (NEF). In one embodiment, the MEC orchestrator is operable to interact as an application function directly with network functions. The MEC includes a host level with a MEC platform operable to interact as an application function with the network functions.

The NEF is located between the core network and external third-party applications. The NEF is operable to manage external network data and external applications. The N6 reference point is located between the UPF and a data network. In one embodiment, the MEC is deployed at the N6 reference point. In one embodiment, the MEC host includes a plurality of MEC applications, a message broker as a MEC platform service, and/or a MEC platform service operable to steer traffic. In one embodiment, an Access and Mobility Management Function (AMF) is operable to provide mobility related procedures. In one embodiment, the AMF is operable to terminate RAN control plane and/or Non-Access Stratum (NAS) procedures, protect the integrity of signaling, manage registrations, manage connections, manage reachability, interface with the lawful interception function (e.g., for access and mobility events), provide authentication and/or authorization for the access layer, and/or host Security Anchor Functionality (SEAF). The SEAF is operable to act as a "middleman" during authentication between a UE and a network. In one embodiment, the AMF is operable to provide communication and/or reachability services for at least one network function. In one embodiment, the AMF is operable to allow subscriptions to receive notifications regarding mobility events.

A Session Management Function (SMF) is operable to provide a plurality of functions including, but not limited to, session management internet protocol (IP) address allocation and management; Dynamic Host Configuration Protocol (DHCP) services; selection, reselection, and/or control of the UPF; configuring traffic rules for the UPF; interception for session management events; charging; and/or support for roaming. The SMF is operable to provide service operations to allow MEC to manage Protocol Data Unit (PDU) session, control policy sessions and traffic rules, and/or subscribe to notification on session management events.

MEC hosts are deployed in the edge or central data network. The UPF is operable to steer user plane traffic towards MEC applications in the data network. The MEC management system is operable to orchestrate operation of MEC hosts and applications. The MEC management system is further operable to dynamically deploy MEC applications.

FIGS. **58**A-**58**D illustrate options for the physical location of MEC. FIG. **58**A illustrates a MEC and the local UPF co-located with the base station. FIG. **58**B illustrates a MEC co-located with a transmission node and optionally with a local UPF. FIG. **58**C illustrates a MEC and the local UPF co-located with a network aggregation point. FIG. **58**D illustrates a MEC co-located with the core network function (e.g., in the same data center). Advantageously, the MEC is operable to be deployed in a plurality of ways in different locations (e.g., near the base station, near the central data network).

The MEC is operable to provide traffic steering to route traffic to targeted applications in a slice or a distributed cloud. The M2 reference point between the data plane and the MEC platform is operable to provide traffic steering instructions (e.g., for applications, networks, services, etc.) to the data plane.

The Mp2 reference point between the MEC platform and the data plane of the virtualization infrastructure is used to instruct the data plane on how to route traffic among applications, networks, services, etc. The User Plane Function (UPF) is operable to route traffic to applications and/or network functions. An Application Function (AF) is operable to influence selection and/or re-selection of a UPF. The AF is also operable to configure rules to provide traffic steering to a data network.

The AF is operable to map Functional Entities (FE) of the MEC system. Traffic is not routed to a MEC application unless the MEC application is prepared to receive traffic and the MEC platform has configured the data plane to route traffic to the MEC application. A MEC FE is operable to interact with the PCF to request traffic steering. In one embodiment, the MEC FE transmits information identifying the traffic to be steered to the PCF. In one embodiment, the PCF is operable to analyze the request, form policies in response to the request (e.g., policies that apply to at least one PDU session), and/or provide routing rules to the SMF. In one embodiment, the SMF is operable to initiate configuration of the routing rules in a target UPF. If no target UPF exists, the SMF is operable to designate at least one UPF.

In one embodiment, data plane functionality of the MEC is governed by the UPF. In one embodiment, the UPF is influenced by the MEC via control plane interactions with core network functions. In one embodiment, the SMF is operable to configure the UPF with a plurality of options for traffic steering. In one embodiment, the SMF inserts an uplink classifier function (UL CL) in the data path (e.g., for IPv4, IPv6, IPv4v6, ethernet). In one embodiment, the UL CL includes traffic rules operable to forward uplink traffic towards at least one application and/or network function. In one embodiment, the UL CL is operable to merge traffic destined to at least one UE in the downlink direction.

In one embodiment, a PDU session uses IPv6 or IPv4v6. In one embodiment, the SMF is operable to use a multi-homing concept for traffic steering. In one embodiment, the SMF is operable to insert a branching point function in a target UPF and/or configure the target UPF to split uplink traffic to a location application instance and/or services in a central cloud based on source prefixes of the IP data packets.

Advantageously, the system is operable to enable traffic steering based on a plurality of parameters. In one embodiment, the system is operable to provide generic traffic rule setting. In another embodiment, the system is operable to provide specific traffic rule setting for at least one specific UE. In one embodiment, the plurality of parameters includes, but is not limited to, information to identify the traffic (e.g., DNN, S-NSSAI, AF-Service-Identifier), a reference identifier operable to provide preconfigured routing information, a list of DNASs, information about at least one UE, information regarding possibilities of relocating at least one application, a timeframe when a routing condition is valid, a geographic location when the routing condition is valid, a notification type for user plane management notification, and/or a transaction identifier for the AF. In one embodiment, the system is operable to allow MEC functional entities and/or a MEC orchestrator to monitor mobility events related to MEC application instances. In one embodiment, the MEC functional entities are operable to subscribe to user plane path management notifications from at least one SMF. In one embodiment, the user plane path management notifications are operable to initiate traffic configuration procedures and/or application relocation procedures.

The MEC system is operable to provide networking and computing at the edge of the network with low latency and high bandwidth. Providing services at the edge means that the system must be operable to provide UE mobility. For example, and not limitation, handheld devices (e.g., smartphones) and/or vehicles (e.g., including V2X communication) require mobility. As such, when the handheld devices and/or the vehicles move, a location of the edge application may no longer be optimal, which is why the system must be operable to provide UE mobility. In one embodiment, the application instance is changed from a first location to a second location. In one embodiment, user context is transferred from the first location to the second location for a stateful application.

In one embodiment, an application is a stateful service. In one embodiment, application mobility for the stateful services includes transferring and synchronizing a service state between a first application instance and a second application instance. Advantageously, this process provides service continuity. In one embodiment, the application is constructed and configured to allow multiple instances of the application to run concurrently. In one embodiment, the service state of the application is operable to be captured in the first application instance and transferred to the second application instance independent of operation of the instance itself. In one embodiment, the second application instance is operable to continue in a second MEC host without disruption of service when the UE disconnects from the first application instance in a first MEC host. Alternatively, the application is a stateless service. In one embodiment, the stateless service does not require transferring and synchronizing the service state between the first application instance and the second application instance. Advantageously, the system is operable to provide application mobility within the MEC system.

As previously described, in a preferred embodiment, the system is operable to provide application mobility. In one embodiment, service to a UE resumes when a user's context and/or application instance is relocated from a first MEC host to a second MEC host. FIG. **59** illustrates one embodiment of application mobility in an integrated MEC deployment.

In one embodiment, application mobility features include a plurality of procedures. In one embodiment, the plurality of procedures includes, but is not limited to, application mobility enablement, detection of UE movement, validation of application mobility, user context transfer, application instance relocation, and/or post-post processing of application relocation. In one embodiment, implementation of the plurality of procedures is dependent on characteristics of the application, characteristics of the environment, and/or capabilities of the system (e.g., MEC host, MEC orchestrator, MEC application).

In one embodiment, application mobility is triggered by detection of UE movement from a first serving cell to a second serving cell. In one embodiment, application mobility involves the NEF and/or MEC functional entities. In one embodiment, the MEC functional entities are operable to subscribe to relevant event notification. In one embodiment, the MEC platform subscribes to radio network information produces by the Radio Network Information Service (RNIS). In one embodiment, the radio network information is operable to identify at least one UE moving from the first serving cell to the second serving cell. In one embodiment, the radio network information is operable to determine whether the at least one UE is moving from a first service area of a first MEC host to a second service area of a second MEC host.

In one embodiment, the NEF is operable to expose capability information and/or services operable to be provided by core network functions to at least one external entity. In one embodiment, the at least one external entity includes at least one application function (AF) (e.g., MEC system functional entities). In one embodiment, SBA enables an authorized AF to directly access a network function. In one embodiment, services are exposed over NEF. In one embodiment, the services exposed over NEF include, but are not limited to, monitoring, provisioning, and/or policy and charging.

In one embodiment, monitoring provides for an external entity to request and/or subscribe to UE related events of interest. In one embodiment, the UE related events of interest include, but are not limited to, a roaming status of a UE, loss of connectivity of the UE, reachability of the UE, and/or location related events (e.g., location of a specific UE, identification of a UE in a geographical area). In one embodiment, the AMF and/or the UDM are operable to provide information about the UE related events of interest (e.g., predicted UE movement, communication characteristics).

In one embodiment, provisioning provides for an external entity to provision expected UE behavior in the system (e.g., predicted UE movement, communication characteristics).

In one embodiment, policy and charging is operable to handle quality of service (QoS) and charging policy for UE based requests from at least one external party. In one embodiment, policy and charging facilitates sponsored data services. In one embodiment, Policy and Charging Control (PCC) is governed by the Policy Control Function (PCF). In one embodiment, the PCC is supported by at least one NF.

FIG. **59** illustrates an example of 5G capability exposure to the MEC system. In the embodiment shown in FIG. **59**, the MEC orchestrator is an AF and is operable to provide centralized functions for managing computing resources and operation of MEC hosts. The MEC orchestrator is operable to provide orchestration of MEC application running on the MEC hosts. In one embodiment, the MEC orchestrator is operable to interact with the NEF and/or network functions to provide monitoring, provisioning, and/or policy and charging. In one embodiment, the MEC host is deployed at the edge of the RAN. In one embodiment, the MEC platform is directly exposed to the CUs and/or the DUs of the RAN. Advantageously, this provides real-time radio information related to UEs, limiting latency and bandwidth consumption.

In one embodiment, the MEC system is operable to provide add-on services to at least one MEC application by leveraging network capability information from the RAN as shown in FIG. **60**. In one embodiment, the MEC platform and/or a MEC application is operable to determine a location of a UE using real-time signal information. In one embodiment, the MEC platform and/or the MEC producing application is operable to use the location to expose the UE to a MEC service consuming application via a MEC location service. In one embodiment, the location is operable to be transmitted to the 5G network. In one embodiment, the location is operable to be provided to the NEF to be used in predicting UE location. In one embodiment, the location is operable to be used to provide optimization of service and/or location-based services (LBSs) (e.g., location-based marketing) to the UE.

In one embodiment, the Mx2 reference point is positioned between the device application and the User Application Lifecycle Management proxy as shown in FIG. **61**. In one embodiment, the system includes a UE Application API over the Mx2 reference point. In one embodiment, the UE Application API is operable to allow the device application to request at least one lifecycle management action in the MEC system (e.g., requesting a list of available MEC applications, instantiation of at least one MEC application, termination of at least one MEC application). In one embodiment, the UE Application API is operable to allow the device application to receive at least one notification of a change in the MEC application's IP address. The MEC applications instantiated in a MEC host in response to a request via a device application are referred to as user applications.

In one embodiment, the UE Application API is operable to assist the MEC system with application and/or context relocation. In one embodiment, the UE Application API is operable to assist the MEC system with application relocation between a first MEC system and a second MEC system. In one embodiment, the UE Application API is operable to assist the MEC system with application relocation between the MEC system and a cloud system.

In one embodiment, MEC services are provided by at least one Mobile Network Operator (MNO). Additionally or alternatively, the MEC services are provided by at least one third party. In one embodiment, the at least one third party is a cloud service provider, a venue owner, a facility owner, a management company, a cell tower provider, a neutral host vendor, and/or a fleet management company. In one embodiment, the at least one MNO leases or buys edge cloud services from the at least one third party.

FIG. **62** illustrates one embodiment of a third-party cloud for MEC in a 5G network environment. The Network Exposure Function (NEF) is operable to be used an entry point into the 5G network for at least one authorized third party. The at least one authorized third party is operable to configure application traffic in the user plane and direct the application traffic to at least one MEC application in a local data network (LDN). The NEF is also operable to provide network information (e.g., mobility information, radio resource information) to the MEC system. The NEF is operable to handle control functions to manage MEC operations (e.g., for the at least one authorized third party). Advantageously, this provides separation between the MNO and the at least one authorized third party.

Traffic on the user place is directed to MEC applications via configuration and placement of UPF functions. The configuration and placement of the UPF functions is operable to be influenced (e.g., by third party cloud service providers) via a control interface exposed through the NEF.

MEC enables serverless computing by hosting Function as a service (FaaS) at the edge and integrating with a cloud service provider. FaaS is operable to be implemented via at least one cloud wrapper MEC application running on at least one MEC host. A MEC service application is operable to manage local resources.

FIG. **63** illustrates one embodiment of a MEC host with and without a break-out to cloud.

Traffic is operable to be sent back to an IoT device, sent to a cloud service provider from a cloud wrapper MEC application, or transferred to an alternate MEC application with sufficient resources. The MEC application and/or the MEC service is operable to indicate to the AF to initiate traffic steering to an alternative MEC host with sufficient resources. In one embodiment, the indication includes traffic rule activation over an application enablement API.

FIG. **64** illustrates one embodiment of traffic steering to an alternative MEC host.

MEC is operable to support enterprise applications and provide enterprise connectivity. For example, and not limitation, MEC-based applications are expected to benefit a plurality of industry sectors (e.g., traffic management, healthcare, government entities). Network slicing and flexibility of UPF deployment are operable to enable the enterprise applications for the plurality of industry sectors.

In one embodiment, a network includes ultra-reliable low latency communications (URLLC) including local processing (e.g., in an edge cloud). Advantageously, the URLLC provides benefits for IoT devices. In one embodiment, the edge cloud is used in Massive IoT (e.g., hundreds to billions of connected devices or sensors). Network slicing provides dedicated resources for tenants (e.g., for IoT). Additional information is included in ETSI, MEC in 5G networks, ETSI White Paper No. 28, ISBN No. 979-10-92620-22-1 (June 2018), which is incorporated herein by reference in its entirety.

In one embodiment, the MEC provides traffic steering and policy control information of applications. In one embodiment, information is exchanged between the MEC and the network exposure function (NEF). See, e.g., ETSI: ETSI GS MEC 002 Multi-access Edge Computing (MEC); Phase 2: Use Cases and Requirements, v2.1.1. ETSI MEC ISG (October 2018), which is incorporated herein by reference in its entirety.

In one embodiment, the system includes an NFV MANO as part of the management and orchestration domain. In one embodiment, the NFVO and/or the VFNM are operable to provide life cycle management of the MEC platform and/or the MEC applications. In one embodiment, the NFV infrastructure (NFVI) is operable to deploy the MEC applications, the MEC platforms, and/or the MEC platform managers.

In one embodiment, a slice is included in the MEC. In one embodiment, the MEC Platform (MEP) and the MEC Platform Management (MEPM) entities are operable to be shared by more than one slice. In one embodiment, each slice includes a MEP and a MEPM. In one embodiment, the MEC includes a MEC Applications Orchestrator (MEAO) and/or a virtualized MEPM (MEPM-V). In one embodiment, each slice is isolated from other slices.

In one embodiment, the MEC includes procedures for migration and/or service continuity of applications. In one embodiment, the procedures include, but are not limited to, MEC host pre-allocation based on UE movement prediction and/or creation of relocation groups. In one embodiment, the relocation groups include at least one MEC host pre-configured to run at least one application. Advantageously, pre-configuring the at least one MEC host to run the at least one application reduces deployment time required for a handover. See, e.g., ETSI: ETSI GR MEC 018, Multi-access Edge Computing (MEC); End to End Mobility Aspects, v1.1.1 ETSI MEC ISG (October 2017), which is incorporated herein by reference in its entirety.

In one embodiment, the MEC is defined as a separate orchestration domain. In one embodiment, the MEC is implemented on the same NFVI and VNFs. In one embodiment, the MEC is hosted by the ETSI NFV MANO stack of the VNF domain. The MEC is operable to reduce latency, offload computation, scale data, and/or offload some network functions.

In one embodiment, the system is operable to perform network slicing. In one embodiment, the network slicing is based on an ETSI NFV MANO architecture. In one embodiment, the network slicing is operable to support tenant-oriented operations and interfaces. In one embodiment, the network slicing includes at least one embedded in-slice manager.

In one embodiment, the system includes a Distributed Autonomous Slice Management and Orchestration (DASMO), which is illustrated in FIG. **65**. DASMO is described in S. Kukliński and L. Tomaszewski, "DASMO: A scalable approach to network slices management and orchestration," NOMS 2018-2018 IEEE/IFIP Network Operations and Management Symposium, 2018, pp. 1-6, doi: 10.1 109/NOMS.2018.8406279, which is incorporated herein by reference in its entirety. In one embodiment, a slice includes a core. The core includes a plurality of functions and/or at least one functional block. In one embodiment, the plurality of functions includes, but is not limited to, application virtual network functions (A-VNFs), control virtual network functions (C-VNFs), management virtual network functions (M-VNFs), and/or support virtual network functions (S-VNFs). In one embodiment, the at least one function includes a Slice Manager (SM) and/or a Slice Operation Support (SOS). In one embodiment, the SM is operable to implement M-VNFs. In one embodiment, the SOS is operable to implement S-VNFs.

The SM includes connections to Embedded Element Managers (EEMs) of VNFs implemented within a slice. The EEMs are operable to provide slice-level management support, VNF monitoring, actuating, and/or autonomic control loops. In one embodiment, the SM is operable to provide a real-time feedback loop. In one embodiment, the real-time feedback loop is compatible with a Monitor-Analyze-Plan-Execute (MAPE) model. In one embodiment, the SM further provides accounting, KPI monitoring and reporting, and/or configuration support as tenant-oriented functions. In one embodiment, the SM includes an interface to the global OSS/BSS. In one embodiment, SOS functions are operable to provide slice-level operations including, but not limited to, slice selection, subscription, authentication, and/or stitching of sub-slices.

In one embodiment, the SM is centrally located within the slice management plane. In one embodiment, the SM is linked to Embedded Element Managers (EEMs) of VNFs implemented within a slice. In one embodiment, the EEMs are compatible with ETSI NFV concepts of an Element Manager (EM). In one embodiment, the EEMs are operable to include

Advantageously, the in-slice management (ISM) concept is scalable. For example, and not limitation, orchestration is operable to be scaled using recursive orchestration (e.g., "MANO in MANO"). Further, this ISM concept is compatible with DASMO. In one embodiment, slicing architecture of the MEC is based on a plurality of factors including, but not limited to, limited geographic scope, specificity of services, flexible architecture, implementation of MEC applications as part of slice AP, and/or tight integration of MEC APIs.

FIG. **66** illustrates one embodiment of proposed generalized MEC architecture. In one embodiment, the VNFs are implemented in a VNF space. In one embodiment, the VNFs utilize a common NFVI managed by a VIM. In one embodiment, the NFVI is a single-domain. Alternatively, the NFVI is a multi-domain. In one embodiment, the VNFs have EMs (shown in gray dots) connected to the OSS/BSS (shown using gray arrows). The MEC Apps include management functions. In one embodiment, the management functions are embedded in the applications. The VNFs and the Ems are connected to at least one VNFM. The at least one VNFM is operable to provide life cycle management of MEC applications and VNFs. In one embodiment, all interactions with the NFV MANO stack are provided by an OSS-NFVO interface. In one embodiment, at least one MEC reference point is internalized. In one embodiment, the OSS/BSS opens the Mx1 interface and/or the Mx2 interface to the customer domain.

In one embodiment, the system includes a MEP-MEP-V (Variant 1). In FIG. **66**, the "VNF space" is operable to be renamed as "5G Network" using Variant 1. Alternatively, the system includes a MEP/MEPM-V shared by multiple networks (Variant 2). In Variant 2, the MEP-MEPM-V are dedicated and external to 5G networks. In one embodiment, the system is operable to provide network privacy via externalized MEP relative to connected networks (e.g., in Variant 2). In one embodiment, the system is operable to provide inter-application privacy.

Moving network functions to the edge of a distributed network decreases latency and increases performance but reduces control and management of the system overall. Distributed networks generally do not use centralized management due to the inefficiencies created by transporting data to a centralized location.

FIG. **67** illustrates one embodiment of DASMO extended with MEC. Each VNF has a corresponding EEM, which is required in DASMO. Each corresponding EEM is connected to the SM. The MEAO and the User App LCM proxy are located in the SM. The SM is operable to provide routing of data. The MEP and the MEPM-V are located in the SOS.

The DASMO architecture is also operable to support multi-domain sliced networks. In one embodiment, the global OSS/BSS includes Multi-Domain Management and Orchestration Support functions including a Multi-Domain Slice Configurator (MDSC) and/or a Multi-Domain Orchestrator ("Umbrella NFVO"). In one embodiment, the MDSC is operable to monitor the end-to-end slice and/or coordinate reconfiguration of the end-to-end slice. In one embodiment, the MDSC is operable to configure local SOS entities for inter-domain operations.

In one embodiment, the system is operable to provide horizontal end-to-end slice stitching to enable operations in a multi-domain environment. In one embodiment, the system utilizes Inter-Domain Operations Support (IDOS) to provide the horizontal end-to-end slice stitching. In one embodiment, the IDOS is operable to provide exchange of information between neighboring domains. In one embodiment, the Mp3 reference point is operable to control information transfer between MEPs. In one embodiment, the information transfer is via IDOS.

In one embodiment, the system includes service APIs exposed to MEC applications by the MEP. In one embodiment, the service APIs include, but are not limited to, Radio Network Information, Location, UE Identity, and/or Bandwidth Management. In one embodiment, the service APIs are provided via the Mp2 reference point.

In one embodiment, the MEC is where the RF environmental information and the customer goals are used to optimize the customer utilization of spectrum and RF environment. The RF environmental information collected and analyzed in the RU, DU, and/or CU are first combined with customer goals to filter and use only relevant data (e.g., actionable data) to optimize customer utilization of the RF environment and spectrum.

In the RU, DU, and/or CU, the environment is collected, aggregated, and analyzed to obtain RF environmental awareness information. This is represented in a vector ensemble class (SD) for each signal in the RF environment. If N signals are detected in the RF environment, then this ensemble is operable to be represented by the following group:

$$SD_t = \bigcup_{i=1}^{N} S_{c_i}$$

where S_{c_i} is the ith detected signal information. The detected signal information includes, but is not limited to, a center frequency (f_{c_i}), a bandwidth (BW_i), a power (P_i), a signal to noise ratio (SNR_i), a signal to total noise and interference ratio ($SNIR_i$), a modulation type (M_i), a type of signal (T_i), a location of signal or angle of arrival relative to the RU (L_i), an antenna index (A_i), an arrival rate (ar_i), a time of arrival of signal i to antenna index j ($TOA_{i,j}$), a priority latency (PL_i), an interaction vector (I_{v_i}) (e.g., list of signals that the ith signal interacts with), customer jth actionable data or information (ADI_j), a lower frequency component of signal i (f_{L_i}), an upper frequency component of signal i (f_{U_i}), and/or a time duration of the ith signal (TD_i). S_{c_i} is operable to be represented by the following, among other environmental RF awareness metadata:

$$S_{c_i} = \left[f_{c_i}, BW_i, P_i, SNR_i, SNIR_i, M_i, T_i, L_i, A_i, ar_i, TOA_{i,j}, PL_i, I_{v_i}, ADI_j, f_{L_i}, TD_i, \ldots\right]$$

The signal information is then analyzed for all signals in the capture environment. Statistical information (e.g., simple statistics) of the signals are obtained, and possible interactions are analyzed $\{I_{v_i}\}$. The customer goals are analyzed and actionable data is extracted on SD for the customer. This operation is operable to be performed for a plurality of customers simultaneously (e.g., using the vectors described herein).

As seen in FIG. **68**, the CU passes the set SD containing all information available for each signal in the environment to the MEC application. The following steps are performed. First, each signal in the SD is analyzed for possible interactions. For example, and not limitation:

a) Center frequency: $f_{c_i}=f_{c_j}\pm\Delta_i$

b) For the jth signal: $f_{L_i}\leq f_{L_j}<f_{L_i}+BW_i$

c) For the jth signal: $f_{L_i}<f_{L_i}+BW_j<f_{U_i}$

If these conditions are satisfied, then i and j interact and power levels are checked for lower estimate of $SNIR_i$ contribution of that interaction for the signal i and s_j is added to IV_i.

Once all possible interaction between signals in the SD_t are detected, a new set is created by adding the set $\{IV_i\}_i^v$ to SD_t. The resulting set $\overline{SD_t}$ is then combined with the customer goals index vector $\{CG_{i=1}\}_i^M$, which is a vector of binary values {0,1}, where 1 in the Kth index denotes the SC_i. K index $\forall_i$ is used for further analysis to satisfy the customer goals:

$$CG_j = [a_1 \quad a_2 \quad \ldots \quad a_{IL}]$$

where $a_j \in \{0,1\}$ and IL is the length of SC_j $\forall_i$. This result is the ADI_i, which is the actionable data information for customer i.

The customer goal index vector for the jth customer is obtained by a semantic engine. The semantic engine is operable to associate information required for each goal requested and assign a one or a zero to each index in SC_i. In a preferred embodiment, a one is assigned if the information is relevant and a zero is assigned if the information is not relevant. Alternatively, a zero is assigned if the information is relevant and a one is assigned if the information is not relevant. This is performed in the relevant statistical logic function. Additionally, this function uses a constraint vector

$$\left.h_{c_p}\right]_{p=1}^{M}$$

is generated if and only if information about the network resources (e.g., both transmitter and receiver of each node on the network) are known and part of the customer goals information supplied to the function (e.g., during initialization or setup). This constraint vector is used to set order of importance for the usage of each resource. Each customer goal generates a unique set of constraint vectors. An additional factor influencing this constraint vector includes, but is not limited to, the granularity at which the network resources are operable to be accessed. In general, the optimization is operable to be expressed as follows:

$$J_{ru} = \min_{ru}\left[G(ADI_t) + \lambda_C^T A(ru) - CGV\right]$$

where ru is the resource unit, $G(\cdot)$ is a function defined by customer goals, $A(\cdot)$ is a function defined by the customer goals and the available resource units in the network, and

CGV is the optimal values reflecting the customer goals under ideal circumstances. G(·), A(·), and CGV are dictated by the customer goals and network resource knowledge, which are a priori information (e.g., loaded during initialization or set up).

Before proceeding with examples of customer goals, the network resources available for optimization must first be established. The following examples begin with simple examples and move to more comprehensive examples relevant to current 4G, 5G, and new 6G networks.

Example 1

The first example includes a customer goal to minimize interference for a transmitted signal (s_2).

FIG. **69** illustrates one example of an RF environment. In the example shown, a first signal (s_1) is a QPSK signal having a power P_1 with f_{1L}=3 MHz, f_{1U}=6 MHz, BW_1=3 MHz, L_1=0°, TOA_1=15 samples, SNR_1=20, $SNIR_1$=9.2 dB, M_1=3 (QPSK), A_1=1, ar_1=1, P_{L_1}=0 dB, I_{v_1}=[2], and TD_1=1. A second signal (s_2) is the customer signal, which is a QPSK signal having a power P_2 similar to P_1 with f_{2L}=4 MHz, f_{2U}=11 MHz, BW_2=7 MHz, L_2=0°, TOA_2=40 samples, SNR_2=20, $SNIR_2$=2.92 dB, M_2=3 (QPSK), A_2=1, ar_2=1, P_{L_2}=0 dB, I_{v_1}=[1,3], and TD_2=1. A third signal (s_3) is a 16-QAM signal having a power P_3 that is 3 dB above P_1 and P_2 with f_{3L}=9 MHz, f_{3U}=13 MHz, BW_3=4 MHz, L_3=0°, TOA_3=20 samples, SNR_3≈23, $SNIR_3$≈18 dB, M_3=16 (16-QAM), A_3=1, ar_3=1, P_{L_3}=0 dB, I_{v_3}=[2], and TD_3=1. A fourth signal (s_4) is a BPSK signal having a power P_4 that is 1 dB above P_1 and P_2 with f_{4L}=4 MHz, f_{4U}=12 MHz, BW_4=8 MHz, L_4=30°, TOA_4=100 samples, SNR_4≈21 dB, $SNIR_4$≈37 dB, M_4=1 (BPSK), A_4=1, ar_4=1, P_{L_4}=0 dB, I_{v_4}=[Ø], and TD_4=1.

The customer goal is to minimize interference, then actionable data relevant to customer 2 is included in the following vector:

$$ADI_2 = \left[s_{c_2}, M_1, M_3, P_1, P_3, f_{1U}, f_{1L}, f_{3U}, f_{3L}, BW_1, BW_3, L_1, L_3\right]$$

Optimization according to the goal of reducing overall SINR for signal 2 and reducing interference while only controlling the parameters associated with signal s_2 provides the following equation:

$$G = SINR \text{ for } s_2 \text{ based on } ADI_2$$

First, if BW_2 is operable to be adjusted (e.g., no throughput constraint), then G is operable to be calculated as follows:

$$G(ADI_2) = 10\log\left[\frac{P_2}{N_2 + (f_{1U} - f_{2L})\frac{P_1}{BW_1} + (f_{2U} - f_{3L})\frac{P_3}{BW_3}}\right]$$

The A(·) function is calculated as:

$$A_2(\cdot) = SNR_2 + SINR_2$$

and CVG_2 is calculated as follows:

$$CGV_2 = SNR_2$$

The optimization is given as follows:

$$J_{ru} = \min_{RU_2}[G(ADI_2) + \lambda(SNR_2 + SINR_2 - SNR_2)]$$

where $\min_{RU_2}$ is minimized over all parameters (e.g., P_2, f_{2L}, f_{2U}, BW_2, etc.). This results in the following equation (eq. A):

$$J_{ru} = \min_{RU_2}\left[10\log\left[\frac{P_2}{N_2 + (f_{1U} - f_{2L})\frac{P_1}{BW_1} + (f_{2U} - f_{3L})\frac{P_3}{BW_3}}\right] + \lambda(SNR_2 + SINR_2 - SNR_2)\right]$$

If there is no constraint on BW_2 (and throughput, assuming M_2 remains constant), then $f_{2L}=f_{1U}$ and $f_{2U}=f_{3L}$, $SINR_2$ becomes SNR_2. Thus, the above cost function is minimized to zero and interference is removed from s_2.

However, if BW_2 has a constraint of BW_2=7 MHz, then the above expression is minimized relative to P_2 by making P_2 as large as possible. Typically, there are constraints on P_{max} for each signal. For example, and not limitation, if P_{2max}=10 dBm, P_1=5 dBm, and P_3=8 dBm, the cost function becomes:

$$\text{Cost} = [1+\lambda]\left[10\log_{10}\left(\frac{10^{\left(\frac{10}{10}\right)}}{\frac{10^{\left(\frac{10}{10}\right)}}{100} + 10\left(\frac{5(2)}{30}\right) + 10\left(\frac{8(2)}{40}\right)}\right)\right] = 5.98 \text{ dB}$$

Example 2

The second example includes optimizing over the customer transmitting signal 4 (s_4) as well as customer 2 transmitting s_2. The goal of customer 4 is to maximize throughput given a power constraint of P_{4max}=8 dBm.

In this case, the cost function has the previous cost function as its first component and the second component is provided in the following equation:

$$\max_{RU_4}(f_{4U} - f_{4L}) + \lambda[BW_4 - BW_{4max}] \text{ where } BW_{4max} = 15 \text{ MHz}$$

Thus, the component cost function becomes:

$$C_{total} = eq\ A + \max_{RU_4}(f_{4U} - f_{4L}) + \lambda[BW_4 - 15]$$

s_4 is at AOA of 30° compared to s_1, s_2, and s_3, which are at 0°. Thus, the spatial filtering separates both signals. Therefore, the two components of the compound cost function are operable to be treated as two optimizations because I_{v_4}=[Ø] and I_{v_2}=[1,3], so it does not contain s_4. Therefore, in this example, the second optimization results in f_{4U}=15 MHz and f_{4L}=0 MHz for BW_4=BW_{max}=15 MHz.

Example 3

The third example includes utilization of spectrum in the Citizens Broadband Radio Service (CBRS) band (3.4 to 3.55 GHz) for private wireless networks. A private wireless network provides a private cellular network for use by a customer. In one embodiment, the private wireless network uses cellular infrastructure both for the customer access point and user equipment (e.g., based on 4G LTE or 5G protocols). In one embodiment, the private wireless network uses spectrum in the CBRS band in the unlicensed portion of the 150 MHz (the General Authorized Access (GAA) portion). In one embodiment, the private wireless network uses Spectrum Access System (SaS) allocation methodology. In one embodiment, the allocation is based on information stored in at least one database. In one embodiment, the information includes information about at least one network access point (e.g., all network access points) for the private wireless network. In one embodiment, the information includes, but is not limited to, transmitter power, static location, bandwidth requirements, protocol used, priority of service, and/or other quality of service requirements supported. In one embodiment, the system includes propagation models to estimate spectrum utilization by at least one user in at least one user location by at least one CBRS registered device (e.g., all CBRS registered devices).

In one embodiment, the allocation of spectrum is based on propagation models estimation of spectrum utilization. However, as a number of CBRS registered devices increases and a number of private wireless networks grows, the propagation modeling will become more computationally complex and less flexible (e.g., exponential computational growth will make this prohibitive). As the number of services used in the private network and the number of private networks increases, interference will increase between services trying to use the same and/or adjacent frequencies. Thus, there is a need to track interference events affecting a mission critical service provided by a private wireless network.

The present invention is operable to detect and/or track at least one interference events. Information about the at least one interference event is operable to be provided to the SaS to allow for a more effect reallocation of the spectrum among CBRS network users. In one embodiment, one or more of the at least one interference event is parameterized based on at least one intended service requirement. In one embodiment, the present invention uses RF environmental information (e.g., channel spectrum utilization by at least one other signal), not signals associated with the intended service or signals associated with the signal itself (e.g., S_{c_i}).

In one embodiment, interference between an intended service's signal and at least one signal affecting the intended service's signal is defined to select a channel in the CBRS band that is optimal for the service intended. In one embodiment, in a similar case to the first example discussed above, the channel is selected to minimize the interference to the intended service by using RF environmental information from the interference signals to predict their spectrum utilization and recommend to the network operator the channel with less interference to the intended service.

In one embodiment, interference event information and/or recommended spectrum preference for the private wireless network are provided to the SaS. In one embodiment, the interference event is reported to the SaS.

FIG. **71**A illustrates one embodiment of an interference template including interference metrics, adjacent channel measurements, and geolocation.

FIG. **71**B illustrates one embodiment of an interference template including additional evidence of external interference. The interference template preferably includes the interference metrics, the adjacent channel measurements, the geolocation, and the additional evidence of external interference.

FIGS. **72-73** represent an example of the quality of the channels, after processing by the analytical engine, associated with the CBRS spectrum. This allows the private wireless network operator the ability to request the best channel for their mission critical applications. The figures represent a GUI for interference detection and minimization as well as a spectrum utilization optimization display for the private wireless operator in the CBRS band.

FIG. **72** illustrates one example of a graphical user interface (GUI) for a channel average power. In the example shown in FIG. **72**, channelized trend analysis is shown over a 10 second interval. Other time intervals are compatible with the present invention (e.g., using the time aggregation feature). In one embodiment, the GUI is operable to display a plurality of channel center frequencies and select one or more frequencies from the plurality of channel center frequencies. In one embodiment, the one or more frequencies are displayed using a plurality of colors (e.g., a first frequency is displayed using a first color, a second frequency is displayed using a second color, etc.).

FIG. **73** illustrates one example of a GUI for channel availability. In one embodiment, the GUI provides selection between a plurality of RF scenarios (e.g., a first environment, a second environment, a third environment, etc.). In one embodiment, the GUI provides selection of channel status (e.g., all, unoccupied channels, occupied channels). In one embodiment, the channel status is displayed using a plurality of colors (e.g., a first channel status is displayed using a first color, a second channel status is displayed using a second color). In the example shown in FIG. **73**, the occupied channels are displayed in red and the unoccupied channels are displayed in green. In one embodiment, the GUI provides selection of a requested bandwidth and provides an option to reset the requested bandwidth. In one embodiment, the selection is between a set of fixed values. Alternatively, the selection is adjustable (e.g., via manual input). In one embodiment, the GUI provides a selection of requested reliability (e.g., low, medium, high) and provides an option to reset the requested reliability. In one embodiment, a requested Effective Radiated Power (ERP) is selectable (e.g., via manual input).

System Configuration

The system is operable to be implemented through a plurality of configurations of hardware and/or software. For example, and not limitation, the components described in the description and figures herein are operable to be included in a plurality of configurations of hardware and/or software. Examples of system components are found in U.S. Pat. No. 11,395,149, filed Oct. 30, 2020, U.S. Pat. No. 11,638,160, filed Nov. 11, 2022, U.S. Pat. No. 11,653,213, filed Nov. 22, 2022, U.S. Pat. No. 11,665,547, filed Nov. 23, 2022, U.S. Patent Publication No. 2023/0110731, filed Dec. 8, 2022, U.S. Pat. No. 11,700,533, filed Dec. 21, 2022, U.S. Pat. No. 11,711,726, filed Dec. 21, 2022, and U.S. Pat. No. 11,751,064, filed Dec. 21, 2022, each of which is incorporated herein by reference in its entirety.

In one embodiment, the hardware includes, but is not limited to, at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA), at least one system on a chip (SoC), at least one system in a package (SiP), at least one application-specific integrated circuit (ASIC), at least one multi-chip package (MCP), at least one logic circuit, at least one logic chip, at least one programmable logic controller (PLC), at least one programmable logic device (PLD), at least one transistor, at least one switch, at least one filter, at least one amplifier, at least one antenna, at least one transceiver, and/or similar hardware elements. In one embodiment, components of the system are combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board (e.g., a plurality of SoCs mounted on the single circuit board). In one embodiment, the hardware is referred to as a circuit or a system of multiple circuits configured to perform at least one function in an electronic device. In one embodiment, the circuit or the system of multiple circuits is operable to execute at least one software and/or at least one firmware program to perform at least one function in the system. The combination of the hardware and the at least one software and/or the at least one firmware program is operable to be referred to as circuitry.

In one embodiment, the software is operable to be executed by at least one processor. In one embodiment, the at least one processor includes, but is not limited to, at least one central processing unit (CPU), at least one graphics processing unit (GPU), at least one data processing unit (DPU), at least one neural processing unit (NPU), at least one crosspoint unit (XPU), at least one application processor, at least one baseband processor, at least one ultra-low voltage processor, at least one embedded processor, at least one reduced instruction set computer (RISC) processor, at least one complex instruction set computer (CISC), at least one advanced RISC machine (ARM) processor, at least one digital signal processor (DSP), at least one field programmable gate array (FPGA), at least one application-specific integrated circuit (ASIC), at least one programmable logic controller (PLC), at least one programmable logic device (PLD), at least one radio-frequency integrated circuit (RFIC), at least one microprocessor, at least one microcontroller, at least one single-core processor, at least one multi-core processor (e.g., a dual-core processor, a triple-core processor, a quad-core processor, etc.), and/or at least one multithreaded processor. In one embodiment, one or more of the at least one processor includes a special-purpose processor and/or a special-purpose controller constructed and configured to execute one or more components in the system. For example, but not limitation, the at least one processor is operable to include an INTEL ARCHITECTURE CORE-based processor, an INTEL microcontroller-based processor, an INTEL PENTIUM processor, an ADVANCED MICRO DEVICES (AMD) ZEN ARCHITECUTRE-based processor, a QUALCOMM SNAPDRAGON processor, and/or an ARM processor.

In one embodiment, one or more of the at least one processor includes and/or is in communication with at least one memory (e.g., volatile and/or non-volatile memory). The at least one memory includes, but is not limited to, random-access memory (RAM), dynamic random-access memory (DRAM), static random-access memory (SRAM), synchronous dynamic random-access memory (SDRAM), magnetoresistive random-access memory (MRAM), phase-change memory (PRAM), read-only memory (ROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), flash memory, solid-state memory, optical drive, magnetic hard drive, and/or any other suitable type of memory. In one embodiment, the at least one memory includes electronic, magnetic, optical, electromagnetic, infrared, holographic, micromechanical, phase change, resistance change, chemical, and/or semiconductor systems, devices, and/or apparatuses. In one embodiment, the at least one memory includes at least one shared memory. In one embodiment, the at least one memory includes at least one single die package (SDP), at least one dual die package (DDP), at least one quad die package (QDP), and/or at least one octo die package (ODP). In one embodiment, the at least one shared memory is operable to be accessed by a plurality of processing elements. In one embodiment, one or more of the at least one memory is operable to store data and/or processor-executable code. In one embodiment, the data and/or processor-executable code is loaded in response to execution of a function by one or more of the at least one processor. In one embodiment, the at least one processor is operable to read data from and/or write data to the at least one memory.

One or more of the at least one processor is operable to execute computer-executable instructions (e.g., program code, software, firmware, operating system) stored in one or more of the at least one memory. The computer-executable instructions are operable to be written in any computer language and/or combination of computer languages (e.g., Python, Ruby, Java, C++, C, assembly, etc.). The computer-executable instructions are operable to include at least one instruction (e.g., one instruction, a plurality of instructions). The computer-executable instructions are operable to be stored in one or more of the at least one memory. In one embodiment, the computer-executable instructions are distributed between a plurality of the at least one memory. In one embodiment, the computer-executable instructions are organized as at least one object, at least one procedure, and/or at least one function. In one embodiment, one or more of the at least one processor is operable to execute machine learning, artificial intelligence, and/or computer vision algorithms.

In one embodiment, the system includes at least one secure execution environment. In one embodiment, the at least one processor includes a secure-embedded controller, a dedicated SoC, and/or a tamper-resistant chipset or microcontroller. In one embodiment, the at least one secure execution environment further includes at least one tamper-resistant or secure memory. In one embodiment, the at least one secure execution environment includes at least one secure enclave. The at least one secure enclave is operable to access, process, and/or execute data stored within the at least one secure enclave.

In one embodiment, the system further includes at least one power supply (e.g., battery, power bus), at least one power controller, and/or at least one power manager. For example, and not limitation, the at least one power manager is operable to save power and/or provide thermal management. In one embodiment, the at least one power manager is operable to adjust a power supply voltage in real time and/or in near-real time, control production of thermal energy, and/or provide other power management. In one embodiment, the at least one power manager includes a power management integrated circuit (PMIC). In one embodiment, the PMIC provides power via at least one voltage rail to one or more system components (e.g., at least one processor, etc.). In one embodiment, the system includes dynamic clock and voltage scaling (DCVS). For example, and not limitation, the at least one processor is operable to be adjusted dynamically (e.g., in real time, in near-real time) in response to operating conditions.

In one embodiment, the system includes at least one interface operable to exchange information between at least two components or devices. In one embodiment, the at least one interface includes, but is not limited to, at least one bus, at least one input/output (I/O) interface, at least one peripheral component interface, and/or similar interfaces.

In one embodiment, the system includes at least one communication interface operable to provide communications between at least two components or devices. For example, and not limitation, the at least one communication interface is operable to provide communications between the system and a remote device (e.g., an edge device) and/or between a first component of the system (e.g., the RF awareness subsystem) and a second component of the system (e.g., data analysis engine). In one embodiment, the at least one communication interface is any communication circuit or device operable to transmit and/or receive data over a network. The at least one communication interface is operable to transmit and/or receive data via wired or wireless communications. In one embodiment, the at least one communication interface includes WI-FI, WORLDWIDE INTEROPERABILITY FOR MICROWAVE ACCESS (WIMAX), Radio Frequency (RF) communication including RF identification (RFID), NEAR FIELD COMMUNICATION (NFC), BLUETOOTH including BLUETOOTH LOW ENERGY (BLE), ZIGBEE, Infrared (IR) communication, cellular communication, satellite communication, Universal Serial Bus (USB), Ethernet communications, communication via fiber-optic cables, coaxial cables, twisted pair cables, and/or any other type of wireless or wired communication. In one embodiment, the at least one communication interface further includes at least one wire, at least one cable, and/or at least one printed circuit board trace.

The following documents include additional information about chipsets, SoCs, VLSIs, and/or components thereof. U.S. Pat. Nos. 9,170,957; 9,300,320; 9,330,736; 9,354,812; 9,386,521; 9,396,070; 9,400,295; 9,443,810; 9,467,453; 9,489,305; 9,542,333; 9,552,034; 9,552,163; 9,558,117; 9,575,881; 9,588,804; 9,612,615; 9,639,128; 9,640,242; 9,652,026; 9,658,671; 9,690,364; 9,690,710; 9,699,683; 9,703,493; 9,734,013; 9,734,073; 9,734,878; 9,747,038; 9,747,209; 9,748,847; 9,749,962; 9,778,871; 9,785,371; 9,819,357; 9,823,846; 9,846,612; 9,858,637; 9,921,909; 9,928,168; 9,928,924; 9,940,109; 9,959,075; 9,973,431; 9,983,930; 10,019,602; 10,048,316; 10,061,644; 10,090,040; 10,101,756; 10,121,001; 10,140,223; 10,157,008; 10,162,543; 10,169,262; 10,247,617; 10,296,069; 10,310,757; 10,359,803; 10,387,333; 10,454,487; 10,482,943; 10,509,588; 10,558,369; 10,579,516; 10,586,038; 10,591,965; 10,591,975; 10,628,308; 10,707,753; 10,713,189; 10,725,932; 10,769,073; 10,783,252; 10,817,224; 10,878,880; 11,115,176; 11,139,830; 11,249,134; 11,360,897; 11,416,049; 11,452,001; 11,463,141; 11,489,608; 11,490,457; 11,493,970; 11,493,980; 11,493,986; and 11,494,248 and U.S. Patent Publication Nos. 20150138714, 20160105549, 20160269185, 20160270134, 20160338137, 20170078890, 20170079012, 20170127411, 20170164220, 20170181134, 20170187886, 20180007627, 20180020365, 20180020462, 20180059863, 20180063820, 20180063869, 20180069651, 20180069664, 20180070219, 20180083684, 20180098370, 20180109346, 20180124685, 20180146487, 20180146494, 20180152819, 20180152950, 20180159668, 20180159935, 20180205438, 20180206108, 20180206260, 20180206269, 20180212733, 20180213425, 20180213498, 20180219605, 20180219662, 20180220386, 20180220399, 20180227958, 20180241458, 20180242224, 20180254805, 20180254851, 20180254853, 20180255576, 20180263013, 20180269945, 20180270860, 20180279408, 20180288715, 20180294924, 20180302868, 20180302900, 20180309928, 20180316409, 20180316453, 20180324826, 20180338281, 20180352564, 20180376474, 20180376531, 20190007812, 20190013901, 20190013908, 20190020451, 20190021026, 20190021053, 20190021105, 20190036552, 20190037429, 20190041223, 20190043968, 20190044066, 20190044794, 20190045390, 20190045581, 20190052317, 20190068352, 20190074887, 20190081679, 20190086955, 20190132089, 20190132860, 20190141679, 20190149379, 20190149434, 20190150017, 20190150155, 20190150157, 20190158331, 20190174423, 20190182696, 20190208507, 20190215907, 20190230550, 20190239093, 20190239212, 20190239245, 20190239286, 20190246377, 20190257916, 20190261361, 20190261453, 20190261454, 20190268061, 20190268128, 20190268935, 20190268970, 20190273569, 20190288811, 20190289668, 20190296790, 20190296877, 20190297662, 20190306737, 20190319699, 20190319868, 20190326959, 20190327024, 20190327117, 20190327621, 20190334611, 20190349272, 20190356463, 20190364456, 20190364556, 20190373667, 20190379492, 20190387401, 20190387424, 20190387577, 20190394719, 20190394741, 20200008088, 20200014483, 20200015128, 20200022218, 20200029392, 20200045618, 20200077414, 20200092876, 20200092946, 20200112943, 20200119893, 20200128579, 20200136777, 20200163156, 20200178288, 20200196186, 20200236572, 20200260526, 20200260527, 20200274666, 20200280466, 20200281021, 20200296155, 20200382190, 20200389836, 20200389917, 20210007023, 20210014656, 20210058206, 20210058748, 20210058785, 20210058946, 20210076389, 20210076397, 20210099976, 20210112528, 20210135803, 20210144517, 20210144624, 20210168577, 20210176762, 20210176769, 20210219166, 20210258811, 20210266915, 20210297204, 20210307051, 20210314954, 20210328739, 20210345163, 20210345395, 20210352655, 20210360563, 20210378041, 20210385865, 20210392673, 20210392714, 20210400584, 20210409335, 20220014286, 20220022019, 20220022167, 20220030475, 20220038164, 20220039032, 20220060905, 20220108092, 20220110018, 20220116334, 20220123849, 20220124043, 20220286972, 20220287083, 20220300418, 20220317901, 20220318343, 20220332350, 20220343241, 20220345863, and 20220353732, each of which is incorporated herein by reference in its entirety.

FIG. **74** illustrates one embodiment of a system **7100** including an antenna subsystem, an RF conditioning subsystem, and at least one front end receiver. In one embodiment, the system **7100** further includes an AGC double loop subsystem. In one embodiment, the system **7100** further includes at least one power supply, at least one power controller, and/or at least one power manager. In one embodiment, the system **7100** further includes at least one processor and/or at least one memory. As previously described, the system **7100** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7100** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

FIG. **75** illustrates one embodiment of a system **7200** including a channelizer (e.g., a frequency domain programmable channelizer), a blind detection engine, a noise floor estimator, and an I/Q buffer. In one embodiment, the system **7200** further includes an FFT engine and/or a classification engine. In another embodiment, the FFT engine is included as a separate system (FIG. **77**). In one embodiment, the system **7200** further includes at least one power supply, at least one power controller, and/or at least one power manager. In one embodiment, the system **7200** further includes at least one processor and/or at least one memory. As previously described, the system **7200** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7200** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

In another embodiment, the channelizer includes an embedded AI agent. The AI agent includes an automatic training model for automatic pattern recognition and/or pattern analysis. The training model recognizes pattern and trends in the RF environment and automatically adjusts signal band parameters, channel frequency ranges, signal noise adjustments, interference parameters, and/or splits a wideband input signal into multiple narrower frequency bands/channels. The AI agent records and stores past channel information and uses previous data and learned information to automatically adjust the channels and/or bands used. The AI agent adjusts parameters based upon customer goals and/or desired output. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing. In one embodiment, the AI agent is operable to predict future trends in the RF environment and automatically adjust signal band parameters, channel frequency ranges, signal noise adjustments, interference parameters, and/or split a wideband input signal into multiple narrower frequency bands/channels. The AI agent is operable to provide pattern recognition, pattern analysis, and predictive capabilities in real time or near real time and autonomously without human intervention.

In yet another embodiment, the blind detection engine includes an embedded AI agent. The AI agent includes a training model for automatic pattern recognition and/or pattern analysis. The training model recognizes patterns and trends in the RF environment and automatically adjusts detection parameters, signal detection bands, signal noise adjustments, and/or interference parameters, and automatically detects and classifies/categorizes signals of interest. The AI agent records and extracts relevant features from a signal to use and implement in the training model to improve performance over time by automatically adjusting detection parameters to more accurately and efficiently detect current and future signals in the RF environment. The AI agent adjusts parameters based upon customer goals and/or desired output. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In yet another embodiment, the noise floor estimator includes an embedded AI agent. The AI agent includes a training model for automatic improvement of pattern recognition and/or pattern analysis. The training model recognizes patterns and trends by using past and/or current signal data in the RF environment and automatically adjusts noise detection parameters. The AI agent extracts relevant features from a signal for implementation in the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently classify noise in the electromagnetic environment. The AI agent adjusts parameters based upon customer goals and/or network requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In yet another embodiment, the I/Q buffer includes an embedded AI agent. The AI agent includes a training model for automatic improvement of pattern recognition and/or pattern analysis. The training model recognizes patterns and trends by using past and/or current processed signals and automatically adjusts data requirements limits for the buffer based on previous predictive trends. The AI agent extracts relevant features from previously processed signals and signal volume for implementation in the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently adapt to the anomalies and changes in electromagnetic environment. The AI agent adjusts parameters based upon customer goals and/or network requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In yet another embodiment, the FFT engine includes an embedded AI agent. The AI agent includes a training model for automatic pattern recognition and/or pattern analysis. The training model recognizes patterns and trends by using past and/or current signal data in the RF environment and automatically adjusts parameters, signal detection bands, signal noise adjustments, channel interference parameters, and automatically detects and classifies/categorizes signals of interest. The AI agent records and extracts relevant features from a signal to use and implement in the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently monitor the performance of the system in real-time and predict potential faults or degradation. The AI agent adjusts parameters based upon customer goals and/or dynamically adjusts the allocation of resources based on demand and/or quality of service (QoS) requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In yet another embodiment, the classification engine includes an embedded AI agent. The AI agent includes a training model for automatic improvement of pattern recognition and/or pattern analysis. The training model recognizes patterns and trends by using past and/or current signal data in the RF environment and automatically adjusts parameters, signal detection bands, signal noise adjustments, channel interference parameters, and automatically detects and classifies/categorizes signals of interest. The AI agent records and extracts relevant features from a signal for implementation in the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently classify signals and/or noise in the electromagnetic environment. The AI agent adjusts parameters based upon customer goals and/or network requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

In another embodiment, the geolocation engine includes an embedded AI agent. The AI agent includes a training model for automatic improvement of pattern recognition and/or pattern analysis. The geolocation engine with the embedded AI agent is operable to provide for 3D pattern recognition for geolocation of signals using congruent observables, including data obtained from other engines or components of the system or network. The training model recognizes patterns and trends by using past and/or current signal data in the RF environment. The AI agent records and extracts relevant features from a signal for implementation into the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently identify geolocation of signal sources in the electromagnetic environment. The AI agent adjusts parameters based upon customer goals and/or network requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

The AI agents of the present invention provide for pattern recognition, prediction, and optimization of L1, L2, and/or L3 functions and network parameters for these layers. RF awareness information provides for improvements on protocol signal decoding. The present invention also provides for improved signal detection in low signal to noise ratio using CSC. In one embodiment, the AI agents of the present invention are operable to provide for pattern comparison and then inference analysis. Inference analysis includes statistical inference analysis in one embodiment, which is operable to include utilization of statistical learning techniques and/or control theory to learn the electromagnetic environment and make predictions about the electromagnetic environment. In one embodiment, the AI agents of the present invention provide for faster analysis than the use of neural networks, and neural networks are not used for pattern recognition, pattern analysis, inference analysis, or predictions. The AI agents provide for autonomous decision making and autonomous optimization of L1, L2, and L3 functions, as well as the RAN, in real time or near real time based on data provided from RF awareness functionality of the present invention. The AI agents are operable to be integrated with components of third-party platforms for autonomous and real time or near real time pattern recognition, pattern analysis, inference analysis, or predictions.

FIG. **76** illustrates one embodiment of a system **7300** including at least one data analysis engine. In one embodiment, the system **7300** includes a semantic engine and an optimization engine. In one embodiment, the system further includes at least one power supply, at least one power controller, and/or at least one power manager. In one embodiment, the system **7300** is operable to provide actionable data about the electromagnetic environment (e.g., RF environment). In one embodiment, the system **7300** further includes at least one processor and/or at least one memory. As previously described, the system **7300** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7300** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

In yet another embodiment, the data analysis engine includes an embedded AI agent. The AI agent includes a training model for automatic pattern recognition and/or pattern analysis. The training model recognizes patterns and trends by using past and/or current signal data in the RF environment and automatically adjusts parameters, signal detection bands, signal noise adjustments, channel interference parameters, and automatically analyzes signals of interest. The AI agent records and extracts relevant features from a signal to use and implement in the training model to improve performance over time by automatically adjusting parameters to more accurately and efficiently monitor and optimize the performance of the system in real-time and predict future signals, signal patterns, system degradation, and/or congestion in the electromagnetic environment. The AI agent adjusts parameters based upon customer goals and/or dynamically adjusts the allocation of resources based on demand and/or quality of service (QoS) requirements. The AI agent is operable to include a machine learning algorithm, a neural network, and/or natural language processing.

FIG. **77** illustrates one embodiment of a system **7400** including an FFT engine. As previously described, the system **7400** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7400** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

FIG. **78** illustrates one embodiment of a system **7500** including the systems from FIGS. **74-76**. In one embodiment, the system **7500** further includes at least one power supply, at least one power controller, and/or at least one power manager. In one embodiment, the system **7500** further includes at least one processor and/or at least one memory. As previously described, the system **7500** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7500** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

FIG. **79** illustrates one embodiment of a system **7600** including the systems from FIGS. **74-75** and **77**. In one embodiment, the system **7600** further includes at least one power supply, at least one power controller, and/or at least one power manager. In one embodiment, the system **7600** further includes at least one processor and/or at least one memory. As previously described, the system **7600** is operable to be configured using hardware and/or software. For example, and not limitation, the system **7600** is operable to be combined in a single chip, a single chipset, multiple chips, multiple chipsets, or provided on a single circuit board. In one embodiment, the single chip, the single chipset, the multiple chips, the multiple chipsets, or the single circuit board includes additional hardware (e.g., at least one very-large-scale integration (VLSI) circuit, at least one field programmable gate array (FPGA)).

In one example, provided for example and not limitation, the present invention includes the system **7100** in a system on a chip (SoC) and the system **7200** in a custom VLSI and/or FPGA chipset.

Alternative combinations are compatible with the present invention.

The present invention advantageously provides for providing multiple applications and data analysis capabilities that traditionally have been provided on multiple network devices or devices remote from a local electronic device including a processor and a memory connected to an electromagnetic network, such as an RF network, on a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board on the local electronic device. This provides for acceleration of the RF awareness at the physical layer into the RAN. Essentially, every communications device having such a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board transforms every device comprising them into a sensor for the RF spectrum, I.e., every device with such a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board and RF awareness functions operable thereon provides RF data for real-time, dynamic spectrum measurement and monitoring for shared spectrum management and dynamic spectrum sharing to optimize utilization based on the distributed sensors and the single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board having RF awareness via software operable thereon. RF awareness functions include, but are not limited to, any function or method used to analyze or process RF data, such as FFT, Noise Floor Extension (NFE), blind detection, blind classification, and a priori detection. Providing this functionality for communications devices advantageously provides for point-to-point communication about the RF environment, especially for congested and contested environments, e.g., in dynamic spectrum sharing environments. The RF awareness functions are embedded in the RAN for providing actionable data, geolocation, INQ, time, spatial, frequency in space to create environmental awareness based on the data provided by the at least one sensor and RF awareness captured and processed on the single chip, single chipset, multiple chips, multiple chipsets, or single circuit board; and the MEC provides for optimization parameters. The systems and methods of the present invention provide for approximately 40% less computation (about 60% faster) related to real time dynamic RF spectrum environment awareness processing by the software embedded in the single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board, and the data is passed directly to the MEC. The systems and methods of the present invention also provide for uplink from distributed handheld communications devices or other communications equipment to the base station, and from the base station back to the distributed handheld communications devices having the single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board with RF awareness functionality included therein.

The present invention with the RF awareness via extraction of physical layer (layer 1) data via the software operable on a single chip, a single chipset, multiple chips, multiple chipsets, or on a single circuit board improves performance for modulation and/or demodulation, and beam forming for better RF awareness in real time for spectrum management, interference detection, and with low latency and high reliability, thereby enhancing 5-layer performance with equalizers, demodulators, and beam formation by reducing computation and/or improving the performance of these components or functions. Specifically, the present invention provides improved performance of receiver beamforming, as well as improved performance of demodulation functions, including improved performance of equalizers, improved interference detection and mitigation, and symbol demodulations. This results in low latency and high reliability for a variety of services.

The single chip, single chipset, multiple chips, multiple chipsets, or on a single circuit board including software operable for RF sensing provides for a duty cycle, a sample rate, etc. with computations per stream, calculated assuming 4 or 8 streams. Surprising results showed that FFT using 4 streams and 1 second per stream is accelerated at the physical layer (layer 1) and reduced calculations provide for up to 1000 times more sampling in real time. This is due to the relatively small computations required for the present invention.

FIG. **80** shows typical functions in a RAN, including all the options proposed in 3GPP release 15 for decomposing the RAN's functions:

Option 1 (RRC/PCDP 1A like split, RRC in CU while PDCP, RLC, MAC, Phy, in DU and RF in RU).

Option 2 (PDCP/RLC spilt User plane only (like option 3) RRC, PDCP are in CU. RLC, MAC, and Phy in DU).

Option 3 (High RLC/Low RLC split two sub approaches based on real time need vs non-real time, segmentation or ARQ).

Option 4 (RLC-MAC split, RRC, PDCP and RLC in the CU and MAC, PHY in DU).

Option 5 (Intra MAC split, Phy and Lower MAC in DU while High layer MAC RLC and PDCP in CU).

Option 6 (Mac-Phy Split, RRC, PDCP, RLC and MAC in CU, Phy in DU, RF configuration data pass to CU).

Option 7 (Intra Phy split with three distinct possible implementations including Option 7, Option 7a, and Option 7x).

Option 8 (Phy RF split RF in RU, Phy in DU and all other functions in the CU).

Regarding FIG. **81**, the sensor unit has three (3) major subfunctions: RF capture (I&Q), RF environment analysis (channelizer, detection, classification, identification, geolocation, and associated ML algorithm to get RF awareness), and customer programmable and data analysis (customer actionable data). The present invention provides for several options for interfaces with the RAN, including all RF capture being split between RU and DU (depending on the split option used); RF environment analysis being split between DU and CU (depending on the split, and some basic data analysis (only for channel interference) will be in the CU). Most of the customer inputs for programmable and data analysis functions are provided for in the MEC and/or the core. Alternatively, all RF data capture is operable to be conducted in the RU, with aggregation of multiple RU captures being performed in the DU portion of the RAN.

FIG. **82**A illustrates the ORAN functions partition according to an embodiment of the present invention. There is a concentration of how to implement RF awareness functionality, including but not limited to data capture, analysis, actionable data, and process optimization with the Layer 1/Layer 2/Layer 3 (L1/L2/L3) and Core/MEC function partitions in the new 5G architecture. The present invention provides for L1 and L2 functions migrating from external software to software embedded in the single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board providing for new physical layer (L1) interactions including data capture, I&Q conditioning (including FFT, NFE, channelization, enveloped processing classification), BB demodulation public protocol synchronization, channel extraction and correlation to classification observables, identification observables, geolocation observables, and data link layer (L2) aggregation of multiple L1 data from several RU per DU. Network layer (L3) functions remain mostly implemented in external software in the present invention. The systems and methods also provide for aggregation of multiple DU's for L2 data to the CU for providing actionable data extracted according to service from aggregated RF awareness data. The Core and MEC include software applications providing for network resource optimization according to service and policies that are predetermined or based on customer-derived inputs.

FIG. **82**B illustrates two options for RF sensor functions that are implemented in the software embedded in the single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board including front end analysis features comprising I&Q conditioning and rendering for time, spatial, frequency, and signal space via FFT, NFE, channelization (blind and a priori), a priori detection, utilization mask (occupancy over time), anomaly detection and flagging, moments-blind classification, and partial beam forming. Implementations suitable for both approaches (Option 1: Look Aside; and Option 2: In-Line) provide for acceleration of L1 RAN functions. Option 1: Look Aside provide for easy implementation to follow data flow from the CPU to accelerator functions where RF awareness functions are considered one of at least one accelerator functions and use the same data flow. It advantageously allows for all devices to perform basic sensing analysis functions in the same architecture, integration of data from L1 upper to L2 for higher RF sensing functions classification, identification, geolocation, anomaly detection, and prediction of supportable service, and provides for aggregation of multiple RU/DU units. Option 2: In-Line provides an alternative wherein the front-end analysis features are incorporated into the conventional L1-Physical layer functions by sharing intermediate computation, for example for each RU, while in the accelerator the antenna and resource including demapping, mimo BF is being performed, the ADC I&Q samples are tagged with the antenna, and conducting a partial beam forming computation. While the filtering and FFT is being done in preparation for data demodulation, there is computing of the average FFT, the NFE, and conducting channelization of the I&Q samples. While demodulation is being performed, anomaly detection and classification of channels is being computed and determined. The partial results of the above computation are then passed along with the PUSCH, PDSCH, and PARCH channel data to help provide RF environmental information to the MAC layer implemented in the DUs. There is a partial results data flow as part of transport block information.

Computation complexity generally varies by sensors sub-function and estimated multiple/add/accumulator core required in a GPU/CPU/FPA type of cores.

FIG. **83**A illustrates the downlink and uplink from fronthaul to MAC associated with the L1 physical layer according to one embodiment of the present invention.

FIG. **83**B illustrates the functionality of the present invention integrated into the physical layers.

FIG. **84**A illustrates different options for lower layer split architectures. Different split architectures determine gNodeB architecture. Functional partitions are shown between RU and DU. The split between RU and DU affects timing and latency.

FIG. **84**B illustrates a schematic of one embodiment of a 5G option 7-2 split implemented via software of the present invention. This option includes implementing functionality such as pre-coding, FFT/IFFT, and resource element (RE) mapping/de-mapping on a node between RU and DU or on RU. These functions are low-PHY functions. High-PHY functions are performed on DU. High-PHY functions include modulation, demodulation, scrambling, and encode/decode.

FIG. **85** illustrates a block diagram of an RF environment with ORAN integration with an AI RAN Intelligent Controller (RIC). The diagram shows integrated RF awareness in communication with the RIC, O-RU, O-DU, O-CU, and the Core Network, all of which are operable to include an AI agent. Alternatively, the present invention includes an AI agent in just the RIC. RF awareness for dynamic spectrum management is operable to be provided by one or more sensor units of the present invention, which are operable to be a separate device or integrated with any component of the present invention, including in centralized units, distributed units, radio units, or at the core network. The current invention is operable to use AI and/or RF awareness to communicate with different RAN stacks and/or simulation using digital twin platforms to optimize performance. Emulation of the RF environment is operable to use stacks on the loop. RF awareness functions and AI implementation in L1, L2 and L3 ORAN also include the best partition of GPU vs CPU processing for implementations and/or implementation of optimal services to enable multiple payloads per function to support multiple services.

FIG. **86** illustrates a block diagram comparing traditional wireless network optimization and network optimization utilizing RF awareness and AI. The present invention utilizes RF awareness and AI to optimize support of emerging services (mobile/streaming/VR gaming, AR and VR training, Telemedicine, Logistics autonomous delivery and tracking of goods, Autonomous Vehicles, Metaverse etc.) with dynamic optimization of network resources in shared RF environments. The system utilizes Large Language Models (LLMs) to improve operational efficiencies and reduce operational cost through enhanced observations from RAN, and Localized core functions and Machine Learning (ML) for data pattern recognition, prediction, optimization of RAN functions. Combined with RF environment awareness and associated tools, the present invention provides for actionable observables and optimization of service performance. The present invention provides for low duty cycle high reliability Internet of Things traffic, as well as high machine to machine (M2M) low throughput sensor fusion traffic. The present invention also provides for validation of sensor fusion based on pattern recognition provided by AI agents or other AI/ML components combined with the RF awareness information provided by the components and systems of the present invention, or "zero trust sensor fusion."

FIG. **87**A illustrates a block diagram of a cloud-based RAN implementation using AI/ML and its communications with other components in a system of the present invention. The cloud-based RAN/virtual RAN (vRAN) utilizes cloud-based AI/ML software implemented in the vRAN which receives RF data from the radio unit (RU). Integration of chipsets of the present invention with the radio units provides for RF sensor functions implemented in software embedded in a single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board. The virtual implementation provides observability and intelligence to collect data and optimize the network in real time. A vRAN is operable to include a configuration where a baseband unit from a traditional RAN is substituted by commercial off the shelf hardware, with the rest of the RAN operations being executed using special purpose hardware according to one definition under the present invention. Alternatively, a vRAN includes a configuration where the RAN is implemented according to the O-RAN architecture with functional partitions (RU, DU, and CU), with some of the functions (ex: DU and CU) being implemented in software in the cloud. In another alternative, the vRAN includes a configuration in which radio units of the RAN are not able to be located in the same general location and/or the configuration of the RAN being reconfigurable to provide for a virtual radio unit coverage area. The present invention is operable to support ORAN architecture for these vRANs as well as other configurations which are considered vRANs.

FIG. **87**B illustrates a block diagram of the distributed data unit operations and its communications with other components in a system of the present invention. The diagram shows additional detail for the distributed data unit block also shown in FIG. **87**A and illustrates the GPU and CPU in the inline GPU accelerator. Both the GPU and CPU provide for RF awareness so the system controls the optimization of the entire system with use of the inline GPU accelerator.

FIG. **88** illustrates a block diagram of interface points within a 5G architecture according to one embodiment of the present invention. The system includes the interaction between the physical infrastructure embedded use equipment (UE) and the virtual infrastructure with RAN interface resource allocation, MEC resource optimization, and aggregated traffic policies and QoS recommendations.

FIG. **89** illustrates a block diagram of the entire RF awareness and analysis system. The block diagram shows the flow from the antenna subsystem and all the data processing systems the information goes through. Each of the different processing blocks and/or engines are operable to have an AI agent embedded in the component/engine that automatically adjusts the parameters of the component/engine over time based on the customers goals, policies, and/or KPI's.

Database 2 (DB2) as shown in the figure is a repository that contains all data related to the services being optimized, as well as alarm data for the customer. This database is distinct from the one containing actionable data and decisions, as it is larger and includes data shared with the customer. The Visualization System displays outputs for the customer, such as plots of spectrum utilization, signal properties, optimization parameters, and their statistics, along with any specific reports required by the customer. The Demod Bank represents a series of parallel demodulation functions applied post-signal classification, such as LTE downlink demodulation for identified LTE signals, and P25 or DMR demodulation for classified push-to-talk signals.

FIG. **90** illustrates a block diagram of a MEC architecture type where the objective/policies, third party data, network parametrization and actionable data all go into the inference reasoner for partitioning and filtering of the data. In one embodiment, the inference reasoner utilizes an AI agent to perform the partitioning/filtering of the data based on the customers goals, policies, and/or KPIs. The AI agent is also operable to utilize a service parameter optimizer to filter or partition the data or make recommendation to do so based on the service requirements on a per service basis. The AI agent is also operable to utilize environment observables, events/alarms, and new KPIs to adjust and filter the data. The MEC Host Level Management serves as the operating system for the MEC, providing interfaces for system-level operation managers for configuration and flow control. It also allocates computational resources for each function within the MEC. The MEC Platform Manager orchestrates these functions, while the Visualization Infrastructure and Manager handle planning, configuration, and reporting of MEC operations back to the network.

FIG. **91** illustrates a block diagram of the RF awareness platform. The system captures the RF environment using radio receivers and antenna to acquire time, frequency, spatial, signal spec, and other mission objectives from the RF environment. This data is the put into I,Q vectors and analyzed utilizing detection (mask creation, anomalies, and/or blind detection), classification, identification, learning using machine learning (ML)

FIG. **92** illustrates a block diagram of the RAN functions focusing on the CU interface. FIGS. **93**A and B offer an in-depth comparison of the interface and functionality differences between the two figures, with a focus on the DGS RF awareness functions and their integration with L1 RAN processing.

In FIG. **93**A, the interface is presented at a high level, providing a general overview of the RF awareness functions of the present invention. It outlines the basic flow and interaction with the L1 RAN processing but does not delve into the specifics of each function.

FIG. **93**B provides a granular view of the RF awareness functions. The Analog to Digital Converter (ADC) functions are critical for converting the analog Beamformed (BF) signals from the Radio Unit's (RU) RF front end into I&Q samples. This is particularly important in the uplink processing of a Multiple Input Multiple Output (MIMO) system, where Direct Down Conversion (DDC) is performed to extract I&Q information, which is then prepared for Digital Up Conversion (DUC) in the downlink. The Fast Fourier Transform (FFT) for uplink and Inverse FFT (IFFT) for downlink are computed on an average basis over several subframes (each of 10 ms). This averaging process helps estimate the power spectral density of the captured bandwidth, which is typically wider than the baseband (BB) bandwidth. Additionally, it aids in estimating the actual noise floor of the captured bandwidth.

Blind Detection and Channelization involve both blind and a priority hypothesis-based detection of signals within the captured bandwidth. It works in conjunction with the blind moment-based classification to provide the RAN with insights into all signals present, their basic properties, and interactions. This information is valuable for the channel estimation and equalization functions of the RAN L1 processing. The Utilization Mask and Anomaly Detections functions are utilized to enhance the MIMO detection and Demodulation functions of the RAN L1 processing. The utilization mask highlights unexpected signals in the environment, which, along with anomaly detections, helps mitigate interference and false data that could degrade performance. This along with other awareness processing (geolocation, pattern identification and demodulation banks as well as characteristic correlation filters) is used for identifying signal patterns that are indicative of service performances for different services and other relevant information for customer service optimization.

FIG. **94** illustrates a block diagram of a wireless communication systems represented as an autoencoder. The diagram shows the classical 5G architecture with an encoder and modulation before the channel, with demodulation and decoding on the receiver side. The current invention uses AI/ML approaches and neural networks that improve encoding/decoding and modulation/demodulation for both accuracy and speed. The present invention also discloses 6G architecture that fully incorporates AI/ML with the use of a neural transmitter which takes over the encoding/decoding and modulation/demodulation on both the front and back end. This approach allows for greater speed and control over the entire RF interference environment.

FIG. **95** illustrates a block diagram of deep learning or machine learning (ML) techniques for physical layer L1 for 5G/6G. The present invention pertains to a novel approach for enhancing the performance of the physical layer (L1) within 5G O-RAN and vRAN architectures through the utilization of artificial intelligence (AI), specifically machine learning (ML) and deep learning (DL) techniques. Unlike conventional methods that rely on controlled RF environments, the present invention addresses the complexities introduced by congested or shared spectra, where multiple signals operate beyond the control of the RAN operator. These environments often result in deviations unaccounted for during the training of ML and DL algorithms used in L1 processing.

In the context of wireless communication networks, the physical layer consists of transmitters and receivers responsible for signal propagation and message estimation. The present invention builds upon foundational concepts such as the autoencoder framework, originally introduced by Claude Shannon and further explored by the DL community. DL techniques, including neural transmitter and receiver implementations, are applied to RANs to enhance L1 processing capabilities.

To effectively employ DL techniques, a comprehensive understanding of channel behavior and conditional probabilities is crucial. The present invention operates under key assumptions, including the RAN operator's control over transmitted signals and the exploitability of embedded reference signals. Non-controlled signals are treated as additive white Gaussian noise. While traditional tap delay line/clustered delay line (TDL/CDL) models serve as the basis for DL training, adjustments are made for multiple-input multiple-output (MIMO) systems to accommodate various transmitters and receiver antenna beams.

The present invention introduces an innovative RF awareness-based AI system, which represents a departure from conventional DL approaches, particularly in congested or shared RF environments. By extracting comprehensive RF environment data, the system predicts performance requirements and utilizes a hybrid ML approach, combining RF awareness, support vector techniques, and convolutional neural networks (CNNs) to optimize spectrum utilization and enhance L1 function performance.

Various embodiments of the present invention encompass a range of RF awareness-based AI applications, including signal detection, interference prediction, and optimization of RF environment sampling. Importantly, the present invention is readily deployable in current 4G RANs and seamlessly integrates into evolving 5G O-RAN and vRAN architectures. By embedding these techniques into various RAN components, including remote units (RU), distributed units (DU), central units (CU), radio intelligent controllers (RIC), and multi-access edge computing (MEC) components, operators achieve optimal spectrum utilization and service performance in challenging RF environments.

FIG. **96** illustrates a diagram of a MIMO (Multiple Inputs Multiple Outputs) system with transmitters and receivers. MIMO is a communication model, widely used in applications such as WiFi or cellular networks, which increases communication throughput by utilizing multiple transmitting and receiving antennas. In this invention, as shown in the figure each user has a specific set of antennas assigned to them, such that the total number of transmitters is greater than the number of receivers, and such that each user is assigned more transmitters than receivers. When using a MIMO model, each receiving antenna receives a combination of all transmitted waves. The receiver then subtracts all the unwanted transmissions, as well as compensates for the channel function.

In one embodiment, the present invention utilizes a massive MIMO 5G/6G system because of the high number of antennas typically included in a station. The use of this massive MIMO system dramatically increases the capacity and spectral efficiency of the wireless network. By serving multiple users simultaneously with the same frequency resources, massive MIMO significantly boosts the capacity of the network. The large number of antennas allows for more precise beamforming, directing signals more accurately to users and reducing interference which provides for improved spectral efficiency. Enhanced reliability and coverage are provided through use of the array of antennas which provide better signal quality and coverage, especially in challenging environments. By focusing the transmission energy towards the users, massive MIMO is able to reduce the overall energy consumption, providing for increases in energy efficiency.

Some of the direct implantations or optimizations by a massive MIMO system include beamforming, channel estimation and feedback, and signal processing. Using the large antenna array, the base station forms narrow beams directed at specific users, enhancing signal strength and reducing interference, thereby providing for improvements in beamforming. Accurate channel state information (CSI) is crucial for effective beamforming and spatial multiplexing. Users typically provide CSI feedback to the base station, providing for improvements in channel estimation and feedback. Signal Processing is improved using advanced algorithms to process the signals from many antennas, managing interference and optimizing performance.

One of the potential drawbacks of massive MIMO systems are the computational requirements, and therefore energy requirements, of the system. To address this issue the present invention provides for calculations that ease the computation required for constant RF awareness information on the inputs and outputs. These calculations, along with AI/ML implementation and edge computing, ease some of the computational and energy requirements of the system while still vastly improving a systems efficiency and output while minimizing interference.

FIG. **97** illustrates a block diagram illustrating the channel function (H(t)) and background noise (N(t)) between transmitters and receivers. When transmitting data, the transmitted waveform goes through multiple steps as it makes its way to a receiving antenna. The transmitter first encodes the raw data into a transmittable waveform. Then, as the wave travels, it is affected by a multitude of factors (interference, distance falloff, echoing, multipath travel), which are all modeled by a channel function H(t). Additionally, each receiving antenna captures some amount of background noise N(t), which for the purposes of this explanation, is modeled as purely additive Gaussian white noise. Finally, the receiver has its own decoder function to return the waveform back to its digital representation.

FIG. **98** illustrates a diagram of a MIMO system with arrows illustrating the data from the transmitters to a receiver. The following calculations give a mathematical explanation for the MIMO system disclosed in the current invention operable to work with AI algorithms and AI agents to minimize interference based on the noise generated by the multiple transmitter and receiver systems currently employed in 5G/6G systems.

The total received waveform by one receiver is the summation of all transmitted waves, with the channel function applied, plus the additive noise.

$$y_1(t) = x_1 * h_{11}(t) + n_1(t) + x_2(t) * h_{21}(t) + \ldots + x_n(t) * h_{n1}(t)$$

By splitting this into the part applied by user 1 transmissions, and the part applied by all other users' transmissions:

$$\sum_{j=1}^{N_t} x_j(t) * h_{j,k}(t) = \sum_{j=1}^{N_{u_1}} x_j(t) * h_{j,k}(t) + \sum_{l=n_{u_1}+1}^{N_t} x_j(t) * h_{l,k}(t)$$

By defining a matrix calculation, which represents the contribution of all transmitted waves at a receiver:

$$\sum_{e=1}^{N_{u_1}} X_e(t) * h_{j,k}(t) = \begin{bmatrix} h_{1,k}(t)^p & h_{2,k}(t)^p & \ldots & h_{N_{u_1}}(t)^p \end{bmatrix} \begin{bmatrix} X_1^T(t)^p \\ \vdots \\ X_{N_{u_1}}^T(t)^p \end{bmatrix}$$

The superscript 'p' notation shows that the function depends on the time factor of the channel function convolution but is essentially a nomenclature formality. Also note that the summation for the convolution is also implied. Now generalize the entire system Y(t) into a matrix calculation.

$$\begin{bmatrix} y_1(t) \\ \vdots \\ y_{nR}(t) \end{bmatrix} = \begin{bmatrix} h_{11}(t)^p & h_{12}(t)^p & \ldots & h_{1,n_t}(t)^p & \\ \vdots & & & & \\ h_{n_{R,1}}(t)^p & \ldots & & \ldots & h_{n_1 n_t}(t)^p \end{bmatrix} \begin{bmatrix} x_1(t)^p \\ \vdots \\ x_{n_t}(t)^p \end{bmatrix} + \begin{bmatrix} N_1(t) \\ \vdots \\ N_R(t) \end{bmatrix}$$

Simplified as: $Y(t)=H^p X^p(t)+N(t)$. H^P then decomposes into two separate matrices:

$$H^p = \left[H^p_{N_R \times N^p_{u_1}} \middle| H^p_{N_R \times P(N_t - N_{u_1})} \right].$$

Where the first matrix represents the influence on all receiving antennas by user 1, and the second matrix represents the other users' influence on all receiving antennas.

MIMO in Reality

All the assumptions indicated above are not always satisfied, especially where multiple users are transmitting simultaneously using single antennas or beam-forming transformations. In this case, the RF environment can be represented as follows: $N_t > N_r$ and users only control a subset of the number of transmitters: User 1 of RF enviro. u_1 controls N_{u1} transmitter antennas. User 2 u_2 controls N_{u2} transmitter antennas . . . u_m controls N_{um} transmitter antennas so that $N_t = \Sigma_{e=1}{}^m X_{u_e} > N_{r_1}$ (number of receiver antennas for user 1) X is then decomposed into sub vectors. Now to consider more realistic problems of the RF environment of a MIMO system for multipoint user transmitters to a single point receiver: Where there are m users transmitting with each user using

$$\left. N_{u_e} \right\}_{e=1}^{m}$$

transmitting antennas. There is one receiver user point with N_r receiver antennas. N_{u1} transmitter antennas are controlled by u_1 and N_{r1} receiver antennas also. Other users are not influenced or controlled by user 1.

Basic information theory: $H(X)=-E_x[\log(P(X))]$: entropy of all users. Where H(X)—entropy of vector of random variables—is the amount of information needed to fully describe each random variable. Conditional Entropy involving two random variables:

$$H\left(\frac{x_1}{x_2}\right) = -E_{x_1,x_2}\left[\log\left(P\left(\frac{x_1}{x_2}\right)\right)\right] = -\int_{x1}\int_{x2} P(x_1, x_2) \log\left(P\left(\frac{x_1}{x_2}\right)\right) dx_1\, dx_2$$

Where $P(x_1, x_2)$ is the joint PDF of the two functions, and $P(x_1/x_2)$ is the conditional PDF of x_1 given x_2.

Joint Entropy:

$$H(x_1, x_2) = -E_{x_1,x_2}[\log(P(x_1, x_2))] = -\int_{x1}\int_{x2} P(x_1, x_2) \log(P(x_1, x_2))\, dx_1\, dx_2$$

Bayes Rule for entropy:

$$H\left(\frac{x_1}{x_2}\right) = H\left(\frac{x_2}{x_1}\right) + H(x_1) - Hx_2,$$

Proof: Since,

$$P\left(\frac{x_1}{x_2}\right) = \frac{P(x_1, x_2)}{P(x_2)} = \frac{P\left(\frac{x_2}{x_1}\right)}{P(x_2)} \text{ Therefore,}$$

$$H\left(\frac{x_1}{x_2}\right) = -E\left[\log\left(P\left(\frac{x_1}{x_2}\right)\right)\right] =$$

$$-E\left[\log\left[\frac{P\left(\frac{x_1}{X_1}\right)P(x-1)}{P(x_2)}\right]\right] = -E\left[\log\left(P\left(\frac{x_2}{x_1}\right)\right)\right] - E\log(x_1) + E[\log(P(x_2))]$$

Chain rule of entropy:

$$H(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} H\left(\frac{x_i}{x_{i-1}}, \ldots, x_1\right),$$

Mutual Information $I(x_1,$

$$x_2):\ I(x_1, x_2) = E_{x_1,x_2}\left[\log\left(\frac{P(x_1, x_2)}{P(x_1)P(x_2)}\right)\right] = H(x_1) + H(x_1) - H(x_1, x_2)$$

also, $I(x_1, x_2)=I(x_2, x_1)\geq 0$. Equals 0 if x_1 and x_2 are independent, random processes.

Kullback-Liebler (KL) divergence is used to measure of the difference between two probability distributions. To find divergence from $P(x_1)$ to $P(x_1/x_2)$, so by definition:

$$D_{KL}\left(P\left(\frac{x_1}{x_2}\right) \| P(x_1)\right) = \int_{X_1} P\left(\frac{x_1}{x_2}\right) \log\left(\frac{P\left(\frac{x_1}{x_2}\right)}{P(x_1)}\right) dx,$$

to interpret this divergence measurement as the amount of extra information needed to describe $P(x_1/x_2)$ to use $P(x_1)$, or the information gain when updating the belief from a priori $P(x_1)$ to a posterior $P(x_1/x_2)$, or information gained about x_1 when observing x_2.

Applying Information Theory to MIMO Communication Recall:

$$Y(t)=\begin{bmatrix} y_1(t) \\ \vdots \\ y_{nR}(t) \end{bmatrix}\begin{bmatrix} \sum_{j=1}^{N_t} x_j(t)*h_{j,1}(t)+n_1(t) \\ \sum_{j=1}^{N_t} x_j(t)*h_{j,N_R}(t)+n_{N_R}(t) \end{bmatrix}$$

Notice that user 1 controls only $x_1 \ldots X_{Nu1}$ transmitter antennas. So,

$$\sum_{j=1}^{N_t} x_j(t)*h_{j,k}(t)=\sum_{j=1}^{N_{u_1}} x_j(t)*h_{j,k}(t)+\sum_{l=n_{u_1}+1}^{N_t} x_l(t)*h_{l,k}(t)$$

Thus to express the convolution as a vector dot product . . . let $x_e(t)^p=[x_e(t), \ldots, x_e(t-p)$ (a time vector, dims. $1\times p$) and $h_{i,j}(t)^P=[h_{i,j}(t), \ldots, h_{i,j}(t-p)$ (a time vector) such that $X_e(t)^p * h_{i,j}(t)^p=h_{i,j}(t)^p \cdot X_e^{\,T}(t)^p$ (dot product), so:

$$\sum_{e=1}^{N_{u_1}} X_e(t)*h_{j,k}(t)=\begin{bmatrix} h_{1,k}(t)^p & h_{2,k}(t)^p & \ldots & h_{N_{u_1}}(t)^p \end{bmatrix}\begin{bmatrix} X_1^T(t)^p \\ \vdots \\ X_{N_{u_1}}^T(t)^p \end{bmatrix}$$

Therefore for Y(t):

$$\begin{bmatrix} y_1(t) \\ \vdots \\ y_{nR}(t) \end{bmatrix}=\begin{bmatrix} h_{11}(t)^p & h_{12}(t)^p & \cdots & h_{1,n_t}(t)^p & \\ \vdots & & & & \\ h_{n_{R,1}}(t)^p & \cdots & & \cdots & h_{n_1 n_t}(t)^p \end{bmatrix}\begin{bmatrix} x_1(t)^p \\ \vdots \\ x_{n_t}(t)^p \end{bmatrix}+\begin{bmatrix} N_1(t) \\ \vdots \\ N_R(t) \end{bmatrix}$$

So $Y(t)=H^pX^p(t)+N(t)$, where H^p can decompose as

$$H^p=\left[H^p_{N_R\times N^p_{u_1}}\;\middle|\;H^p_{N_R\times P(N_t-N_{u_1})}\right]$$

where the first matrix is user 1's influence on N_R receiver antennas, and the second matrix is the other user's influence.

Now, considering mutual information I(Y, X) and the conditional entropy H(Y/X)

$$H(Y,X)=H\left(Y/\left[x_1, x_2, \ldots, x_{N_{u_1}}/x_{N_{u_1}+1}, \ldots, x_{N_t}\right]\right)+H\left(\left[x_1, x_2, \ldots, x_{N_{u_1}}/x_{N_{u_1}+1}, \ldots, x_{N_t}\right]\right) \text{ and, } I(Y,X)=H(X)-H\left(\frac{X}{Y}\right)=H(Y)-H(Y,X)+H\left(x_1, \ldots, x_{N_{u_1}}/x_{N_{u_1}+1}, \ldots, x_{N_t}\right)$$

$$H\left(x_1, \ldots, x_{N_{u_1}}/x_{N_{u_1}+1}, \ldots, x_{N_t}\right)$$

is the extra information the other users give to Y about $x_1 \ldots x_{Nu1}$ for user 1.

Minimizing Divergence of Pseudo Inverse (W) Using Kullback Leibler (KL) Divergence

By the definition of Conditional Entropy:

$$\left(H\left(x_1 \ldots x_{n_{u_1}}/x_{n_{u_1}+1} \ldots x_{n_t}\right)=\int_{x_1}\cdots\int_{x_{n_t}} P\left(x_1 \ldots x_{n_{u_1}}/x_{n_{u_1}+1} \ldots x_{n_t}\right)\log\left[P\left(x_1 \ldots x_{n_{u_1}}/x_{n_{u_1}+1} \ldots x_{n_t}\right)\right]dx_1 \ldots dx_{n_t}\right)$$

This conditional entropy represents the lost capacity user u_1 experiences due to the presence of other users in the MIO system. It also represents the extra information that other users and other signals give to improve the classification and detection of signals associated with user 1. This is the property that will be exploited.

Considering the multi-user MIMO system, expressed as: $Y(t)=H^pX^p(t)+N(t)$ where

$$H^p=\left[H^p_{N_R\times N^p_{u_1}}\;\middle|\;H^p_{N_R\times P(N_t-N_{u_1})}\right]$$

and where the first portion of the decomposition refers to channel inter-symbol interference due to channel conditions acting on user 1, and the second portion of the decomposition represents the interference the channel brings due to the presence of other users in the system. Therefore, the interference on Y(t) due to other users is given by: ((INTF)=

$$H^p_{n_R\times(n_t-n_{u_1})}X^p_{(n_t-n_{u_1})\times 1}X^p_{(n_{u_1})\times 1}\Big).$$

Then, to properly equalize the received signals for user u_1, to minimize this interference. Most equalizers assume this interference is not present, the only thing they need to equalize is the channel conditions acting on user 1 alone. To obtain a good estimate for

$$X^p_{(n_{u_1})\times 1}$$

to compensate for the channel effect on the signal associated with user u_1.

Typically, an equalizer will act upon $Y(t)^p$ and output $\widehat{X^p}(t)$. There are several options for such an equalizer (zero forcing, minimum mean square error, successive cancellation, maximum likelihood, envelope base). However, in a multi-user MIMO case, these equalizers cannot properly compensate for INTF due to the presence of other users. Thus, to minimize the INTF contribution before or during conventional equalization. To minimize this contribution in a hybrid manner, where our detection capabilities give us estimates of the properties of each other signal associated with other users u_{nt-nu1} in the RF environment. A feed forward branch is used and subtract the INTF contribution from Y(t) before the conventional equalization.

So thus, the conventional equalizer acts only on

$$Y^P(t) - W\hat{X}^P_{(n_t-n_{u_1})\times 1},$$

which should approximate the received signal when only user u1 is present in the environment.

For this estimate to be correct,

$$\left(\hat{X}(t)^p_{(n_t-n_{u_1})\times 1} \approx X(t)^p_{(n_t-n_{u_1})\times 1}\right),$$

and W approximately the pseudo-inverse of

$$\left(H^p_{n_R\times(n_t-n_{u_1})}\right).$$

Note that to get W close to the pseudo inverse, use of the estimate

$$\left(H^p_{n_R\times(n_t-n_{u_1})}\right),$$

which will require its own conventional equalizer; but in reality, this is not required since an initial value of W is obtained from the properties of the observed signals associated with other users $u_2 \ldots u_{nt}$.

The equation:

$$\hat{X}(t)^p_{(n_t-n_{u_1})\times 1}\Big)$$

by W, such that:

$$\left((INTF) = H^p_{n_R\times(n_t-n_{u_1})} X(t)^p_{(n_t-n_{u_1})\times 1} \approx W\hat{X}^p_{(n_t-n_{u_1})\times 1}\right),$$

Recall that

$$\left(Y(t) = \left[H^p_{\{n_R\times n_{\{u_1\}}\}} \,\middle|\, H^p_{\{n_R\times(n_t-n_{\{u_1\}})\}}\right]\left[\frac{x_1 \;\ldots\; x_{\{n_{\{u_1\}}\}}}{x_{\{n_{\{u_1\}}+1\}} \;\ldots\; x_{\{n_t\}}}\right] + N(t)\right)$$

Nomenclature:

$$H_1 = H^p_{\{n_R\times n_{\{u_1\}}\}}$$

(the channel effects on user 1 alone)

$$H_2 = H^p_{\{n_R\times(n_t-n_{\{u_1\}})\}}$$

(the channel effects on user 1 caused by interference by other users)

$$X_1 = \begin{bmatrix} x_1 \\ \vdots \\ x_{\{n_{\{n_1\}}\}} \end{bmatrix} X_2 = \begin{bmatrix} x_{\{n_{\{n_1\}}+1\}} \\ \vdots \\ x_{\{n_t\}} \end{bmatrix},\ Y(t) = [H_1 \,|\, H_2]\left[\frac{X_1}{X_2}\right] + N(t)$$

so therefore, $Y(t)=H_1X_1+H_2X_2+N(t)$ where H_2X_2 represents the interference from other users.

Let's call the equalizer equation as the matrix Q ($n_{u1}\times n_R$ dim.) containing the equalizer's impulse response. Then, $Z=Y-W\hat{X}_2 \ldots QZ$=output of equalizer. EQ output=$(Q(Y-W\hat{X}_2)=Q(H_1X_1+H_2X_2-W\hat{X}_2+N(t))$. Now consider the error vector X_1- output of equalizer:

$$(\text{error}=X_1-QH_1X_1-QH_2X_2+QW\hat{X}_2-QN(t),=(I-QH_1)X_1-Q(H_2X_2-W\hat{X}_2)-QN(t)$$

Note that a zero forcing equalizer will try to force this error to zero.

If $W\hat{X}_2\approx H_2X_2$ and $Q(N(t))$ is small, then a zero forcing equalizer will try to make $QH_1=I$ which implies the optimal value of Q should be the pseudo inverse of H_1: $(Q_{opt_{ZF}}=(H_1{}^*H_1)^{-1}H_1{}^H)$, where A^H is the conjugate transpose of A. In this case the use of conventional MIMO zero-forcing EQ case. If $(W\hat{X}_2/\approx H_2X_2)$ and $Q(N(t))$ is not small, the ZF equalizer will have a residual(?) due to noise and due to the interference of other users, and most likely it will not converge.

Let us consider: $\arg\min_Q E\|Q(Y(t)-W\hat{X}_2)-X_1\|^2$=the MSE=(error vector)^H(error vector).

$$\text{Error vector} = Q\big(Y(t)-W\hat{X}_2\big) - X_1,$$

$$MSE \approx \left[Q\big(Y(t)-W\hat{X}_2\big)-X_1\right]^H\left[Q\big(Y(t)-W\hat{X}_2\big)-X_1\right],\ \Bigg(\frac{d(MSE)}{dQ} = \left[\frac{d}{dQ}(\text{error vector})^T\right](\text{error vector})+(\text{error vector})^H\frac{d(\text{error vector})}{dQ}\Bigg)$$

$$\text{error vector} = (I-QH_1)X_1 - Q\big(H_2X_2-W\hat{X}_2\big) - QN(t)$$

$$\frac{d(\text{error vector})}{dQ} = H_1X_1 - \big(H_2X_2-W\hat{X}_2\big) - N(t)$$

$$\frac{d(\text{error vector})^H}{dQ} = H_1^HX_1^H - \big(H_2X_2-W\hat{X}_2\big)^H - N^H(t).$$

Set d(MSE)/dQ to 0 to find inflection point of the equalizer equation and minimize error:

$$[(I-QH_1)X_1 - Q(H_2X_2-W\widehat{X_2}) - QN(t)]\left(X_1^TH_1^T - (H_2X_2-W\widehat{X_2})^T - N^T\right)(I-QH_1)X_1\left[X_1^TH_1^T - (H_2X_2-W\widehat{X_2})^T - N^T\right] - Q\left[(H_2X_2 - W\widehat{X_2}+N)\left(X_1^TH_1^T - \left(H_2X_2-W\widehat{X_2}\right)^T - N^T\right)\right].$$

Leads to, if $H_2X_2\approx WX_2$, the typical MMSE MIMO equalizer setup which is known to be: $Q_{opt}\approx H_1{}^H(H_1H_1H-I_{nr}K)^{-1}$ where

$$K = \frac{\sigma_n^2}{\sigma_{u_1}^2},\ \sigma_n^2 = E\big(N^TN\big),\ \text{and}\ \sigma_{u_1}^2 = E\big(X_1^TX_1\big).$$

Otherwise, if $H_2X_2-W\hat{X}_2 \not\approx 0$, then the typical equalizer will have a substantial residual that could be influential on the convergence of the equalizer if X_2 has some correlation with X_1 (in other words, if $H(X_1/X_2)$—the conditional entropy of X_1 given X_2— is non-zero). Note that if X_2 and X_1 are uncorrelated, then there are no penalties on throughput and the typical equalizer will converge as long as the power of user 1 is larger than the power of spurious signals (noise and power of other signals uncorrelated to user 1).

Thus, the goal is to set W such that $H_2X_2 \approx W X_2$. This is accomplished through both processes H_2X_2 and $W\hat{X}_2$ to be defined by their pdf and consider how close their pdfs are—thus, to consider: $D_{KL}(P(H_2X_2)\|P(H_2X_2/W\hat{X}_2))=H(H_2X_2/WX_2)-H(H_2X_2)$.
Thus, to minimize this Kullback-Liebler divergence; therefore, minimize. $H(H_2X_2/W\hat{X}_2)$ using

$$\arg\max \lim_{N\to\infty} -\frac{1}{N}\sum_{i=1}^{N}\log P\left(H_2X_2/W\hat{X}_2\right).$$

For X_2 being random Gaussian processes based on the Gaussian normal distribution

$$pdf(H_2X_2) \propto 0\frac{1}{\det(H_2R_{X_1X_2}H_2)}e^{-\frac{1}{2}\left[(H_2X_2)^T\left(H_2^TR_{X_1X_2}H_2\right)^{-1}H_2X_2\right]}$$

$$pdf(W\overline{X_2}) \propto \frac{1}{\det\left(W^TR_{\hat{X}_2\hat{X}_2}W\right)}e^{-\frac{1}{2}\left[\left(W\hat{X}_2\right)^T\left(W^TR_{X_2X_2}W\right)^{-1}W\hat{X}_2\right]}$$

$$D_{KL} = E_{H_2X_2}\left[\log\left(\frac{pdf(H_2X_2)}{pdf\left(W\hat{X}_2\right)}\right)\right]$$

$$\left[KL \Rightarrow E_{pdf(H_2X_2)}\log\left(\sqrt{\frac{dct\left(W_2^TR_{x_2x_2}W_2\right)}{dct\left(H_2^TR_{x_2x_2}H_2\right)}}\right)+\log\left(e^{-\frac{1}{2}(H_2X_2)^T\left(H_2^TR_{x_2x_2}H_2\right)^{-1}H_2X_2}\right)-\log\left(e^{-\frac{1}{2}\left(W\hat{X}_2\right)^T\left(W^TR_{x_2x_2}W\right)^{-1}W\hat{X}_2}\right)\right]\Bigg]$$

$$\left[KL \Rightarrow \frac{1}{2}E_{pdf(H_2X_2)}\left[\log\left(\frac{dct\left(W_2^TR_{x_2x_2}W_2\right)}{dct\left(H_2^TR_{x_2x_2}H_2\right)}\right)-\frac{1}{2}(H_2X_2)^T\left(H_2^TR_{x_2x_2}H_2\right)^{-1}H_2X_2+\frac{1}{2}\left(W\hat{X}_2\right)^T\left(W^TR_{x_2x_2}W\right)^{-1}W\hat{X}_2\right]\right]$$

$$\left[KL \Rightarrow E_{pdf(H_2X_2)}\left[\log\left(\frac{\frac{1}{\sqrt{dct\left(H_2^TR_{x_2x_2}H_2\right)}}e^{-\frac{1}{2}(H_2X_2)^T\left(H_2^TR_{x_2x_2}H_2\right)^{-1}H_2X_2}}{\frac{1}{\sqrt{dct\left(W_2^TR_{x_2x_2}W_2\right)}}e^{-\frac{1}{2}\left(W\hat{X}_2\right)^T\left(W^TR_{x_2x_2}W\right)^{-1}W\hat{X}_2}}\right)\right]\right]$$

$$(H_2X_2)^T\left(H_2^TR_{x_2x_2}H_2\right)^{-1}H_2X_2$$

Notice how the equation is scalar. Thus,

$$(H_2X_2)^T(H_2^TR_{x_2x_2}H_2)^{-1}H_2X_2=\text{trace}[(H_2X_2)^T(H_2^TR_{x_2x_2}H_2)^{-1}H_2X_2]$$

Recalling $\text{trace}[Z^T(A)Z]=\text{trace}[ZZ^T A]$, therefore,

$$E_{pdf(H_2X_2)}\left[(H_2X_2)^T\left(H_2^TR_{X_2X_2}H\right)^{-1}H_2X_2\right] =$$
$$E_{pdf(H_2X_2)}\left[\text{trace }\left[H_2X_2(H_2X_2)^T\left(H_2^TR_{X_2X_2}H_2\right)^{-1}\right]\right] =$$
$$\text{trace }\left[E_{pdf(H_2X_2)}\left(H_2X_2(H_2X_2)^T\left(H_2^TR_{X_2X_2}H_2\right)^{-1}\right)\right] =$$
$$\text{trace }\left[E_{pdf(H_2X_2)}\left[H_2X_2(H_2X_2)^T\right]\left(H_2^TR_{X_2X_2}H_2\right)^{-1}\right]$$

This proves that: $E_{pdf(H_2X_2)}[(H_2X_2)(H_2X_2)^T]=H_2^TR_{x_2x_2}H_2$ thus,

$$\frac{1}{2}\text{ trace }\left[E_{pdf(H_2X_2)}\left[H_2X_2(H_2X_2)^T\right]\left(H_2^TR_{X_2X_2}H_2\right)^{-1}\right] =$$
$$\frac{1}{2}\text{ trace }\left[H_2^TR_{X_2X_2}H_2\left(H_2^TR_{X_2X_2}H_2\right)^{-1}\right] = \frac{1}{2}\text{ trace }\left[I_{n_t-n_{u_1}}\right] = \frac{1}{2}\left(n_t-n_{u_1}\right).$$

Now consider the 3rd term in the KL distance equation

$$E_{pdf(H_2X_2)}[(W\hat{X}_2)^T(W^TR_{\hat{X}_2\hat{X}_2}W)^{-1}W\hat{X}_2]= \ldots$$

By properties of Gaussian noise,

$$E_x[(x-m)^TA(x-m)]=(m-E(x))^TA(m-E(x))+\text{trace}(AR_{xx})$$

Thus, $E_{pdf(H_2X_2)}[(W\hat{X}_2)^T(W^TR_{\hat{X}_2\hat{X}_2}W)^{-1}W\hat{X}_2]=\text{trace}[(W^TR_{\hat{X}_2\hat{X}_2}W)^{-1}H_2^TR_{\hat{X}_2\hat{X}_2}H_2]$

Combining all three terms gives,

$$D_{KL} =$$
$$\frac{1}{2}\left[\log\left(\frac{\det\left(WR_{\hat{X}_2\hat{X}_2}W\right)}{\det\left(H_2^TR_{X_2X_2}H_2\right)}\right)-\frac{n_t-n_{u_1}}{2}+\text{trace }\left(W^TR_{\hat{X}_2\hat{X}_2}W\right)^{-I}H_2^TR_{\hat{X}_2\hat{X}_2}H_2\right]$$

Our goal is then to pick W such that the Kullback-Leibler distance is minimized—thus,

$$\text{minimize }\min_{W\,trace}\left[\left(W^TR_{\hat{X}_2\hat{X}_2}W\right)^{-1}H_2R_{\hat{X}_2\hat{X}_2}H_2\right]$$

The above simplifies to: $\text{trace}[(W^TW)^{-1}(H_2^TH_2)]$, which minimizes when $W=H_2$.
If $x_2 \ldots x_{nt}$ are not uncorrelated, finding R_{X2X2} corresponds to calculating their cross-correlating coefficients between all other signals associated with other users not controlled by user 1. Therefore,

$$\hat{R}_{\hat{X}_2\hat{X}_2} = \begin{matrix} e_{22} & e_{23} & \cdots & e_{2n_t} \\ e_{32} & e_{33} & \cdots & e_{3n_t} \\ \vdots & . & \ddots & \vdots \\ e_{n_t2} & . & . & e_{n_tn_t} \end{matrix}$$

$e_{ij} \triangleq \text{correlation}(\hat{x}_i\hat{x}_j)$; where there is an estimate of how much signal x_2 associated with user u_2 is correlated with any other user's signal. Thus, if the cross-correlation coefficients are showing that the signals are uncorrelated and $H_2=0$, then back to the original problem. If the signals are correlated with $H_2\neq 0$, then our cancellation approach before equalization will improve. The performance of the equalizer by reducing INTF gain given;

$$(INTF) = H^P_{n_R\times(n_t-n_{u1})}X^P_{(n_t-n_{u1})\times 1}.$$

Implementation of this signal noise prediction and cancellation approach previously described is operable to be combined with an AI algorithm, ML algorithm, AI agent, and RF awareness functionality of the present invention. The combination of the equalizer with an AI system will allow for rapid equalization of signals and the minimization of the signal noise associated in real-time as the signal/RF environment changes.

The Information gained from the other user's signals is combined with other RF awareness parameters described throughout the present invention and analyzed using an

AI/ML algorithm or AI agent to optimize a signal based upon the clients desired outcome and service to best deal with the current interference the RF environment presents.

Implementation of the AI agents and RF awareness functionality of the present invention for a vRAN is operable to be supported by several steps. The physical layer is set up through creation of an RF environmental emulator to provide RF environment conditions to test RAN performance in a controlled fashion with progressive complexities, such as the level and type of signals, congestion, and service sharing scenarios representing the various types of virtual configurations. Various transmitters providing for the various services to be represented in the RF environment under consideration are emulated in this step. The collected I&Q capture is augmented with a parametric RF environment to generate an aggregated RF environment in which the vRAN is configured to operate. RF awareness technology and partitions of this technology support vRAN implementations. RF awareness is operable to be accomplished through a sensor unit including an AI agent as a standalone unit. Points of interface for the RF awareness software, hardware, and AI agents are defined with the RAN resource scheduler, RIC, MEC, and other components of the present invention.

AI agents and RF awareness are integrated with RU and DU interfaces, with a common interface from RUs being defined to facilitate processing of data. RU interface definitions are operable to be ORAN basic standard definitions, with augmentation of RU baseband information providing access to an analog stream before filtering or access to a beam stream, access to pre-filtering an IMF analog signal on an ADC path, definition of a custom payload within a FH/IF interface, and use of an RF emulator to facilitate testing scenarios. Common interfaces to be used for RU/DU and DU/CU includes identification of one or more software functions to be used in the DU for processing each RU stream, while defining DU functions that could benefit from RF awareness or AI agent functionality and their interfaces. The software is then integrated and tested using RF emulator signals.

RF awareness and AI agent or ML technology is then integrated into the CU, with the definition of the number of Dus being aggregated in the CU for processing. Separation of information and interfaces between O-CU-CP and O-CU-UP and SMO or RIC is provided. Test cases including customer goals and policies are defined to create actionable data and payloads using O2 interfaces. Data aggregation services per DU and data filtering to provide for actionable data are integrated. The payload for A1/O1 and E1 interfaces are also defined.

Network parameters are then operable to be optimized per service integration. According to previously defined use test cases, alarms and an optimized parameters feedback interface is defined within a MEC or RIC configuration. A RAN network parameterization is selected to support. Test case service policies are refined, and the software including AI agents and/or RF awareness software are integrated and tested in the vRAN.

In one embodiment, RF awareness functions and AI/ML functions including functions performed by the at least one AI agent are not hosted in the cloud because of the additional latency introduced with this configuration. Furthermore, hosting this functionality in the cloud requires leveraging the RU bypass in O-RAN standards, which is not widely adopted. RF awareness functions and AI/ML functions including functions performed by the at least one AI agent are operable to be provided for in hardware dongles on one or more devices, which is particularly useful in private wireless use cases. AI agents of the present invention are operable to consider customer goals and data sets for autonomous and real time or near real time pattern recognition, pattern analysis, inference analysis, predictions, optimization of network parameters in L1, L2, and/or L3, and optimization of networks.

The following exemplary cases (cases 1-4) show an example implementation of the rapid equalization equations of signals and the minimization of the signal noise associated in real-time as the signal/RF environment changes as described above with respect to FIGS. **96-98**. The following use cases and the results of the equalizer shown in FIG. **99**A-**103**C show the equalizer improvement of an equalizer with the preemptive removal of the second signal based upon the entropy calculated from the outside information that is affecting the primary signal of interest as is described under FIGS. **96-98**. The equalizer in the data analysis engine improves the interference and/or noise from a signal through the removal of this second signal based upon the correlation of two signal therefore the performance of the equalizer improves by reducing INTF gain. In the example use cases 1-4, two quadrature phase shift keying (QPSK) signals are an explanatory use case with another more complex modulation type operable to provide more information for the second signal removal calculation, therefore more effectively improving the effectiveness of the equalizer.

Case 1

Case 1 shows two quadrature phase shift keying (QPSK) signals with a 2 MHz bandwidth (BW) with one signal centered at −2 MHz and the second signal centered at +0.5 MHz. This case represents no overlap in two signals of substantially equal bandwidth and power. FIG. **99**A illustrates the power spectral density (PSD) graph for case 1, showcasing the distribution of power across various frequency components of the signal. FIG. **99**B depicts the probability of error convergence without removing the second signal for case 1, demonstrating how the error rate changes over time. FIG. **99**C shows the in-phase and quadrature (IQ) signals after multiple iterations of the equalizer, still without the removal of the second signal, highlighting the impact on signal clarity. FIG. **99**D shows the probability of error convergence with the second signal removed, comparing to FIG. **99**B we see a quicker decrease in error with a quicker convergence to zero indicating an improved error rate. FIG. **99**E illustrates the IQ signals after the equalizer iterations with the second signal removed, showing a clearer signal which is shown by a smaller radius and/or tighter correlation of dots as compared to FIG. **99**C. This use case of non-overlapping signals there is a significant improvement for the use case of correlated signals. This would apply to any correlated signal and other modulation types with more complex modulation types showing a greater improvement than is seen in cases 1-4. The equalizer has a significantly lower error and tighter IQ signal groping proving a more effective equalization or cancellation of interference and/or distortion.

Case 2

For case 2, FIG. **100**A displays the PSD graph, detailing the power distribution for two quadrature phase shift keying (QPSK) signals with a 2 MHz bandwidth, centered at −2 MHz and +0.1 MHz, respectively, with minimal overlap. FIG. **100**B shows the probability of error convergence without second signal removal, while FIG. **100**C illustrates the IQ signals post-equalizer iterations without second signal removal. FIG. **100**D shows the probability of error convergence with the second signal removed, and FIG. **100**E shows the IQ signals after the equalizer iterations with the second signal removed, reflecting improved signal quality. In both the probability of error and IQ signal there is significant improvement in the equalization for compensation for signal distortion and reducing interference based upon the second signal being removed based upon the correlation and conditional entropy of the signal.

Case 3

For case 3, FIG. **101**A shows the PSD graph for two QPSK signals, each with a 2 MHz bandwidth, centered at −2 MHz and −0.1 MHz, representing a 5% overlap. FIG. **101**B shows the probability of error convergence without removing the second signal, and FIG. **101**C illustrates the IQ signals after the equalizer iterations without second signal removal. FIG. **101**D shows the probability of error convergence with the second signal removed, and FIG. **101**E shows the IQ signals after the equalizer iterations with the second signal removed, indicating a clearer signal.

Case 4

For case 4, FIG. **102**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth, centered at −2 MHz and −0.2 MHz, indicating a 10% overlap. FIG. **102**B shows the probability of error convergence without removing the second signal, while FIG. **102**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **102**D shows the probability of error convergence with the second signal removed, and FIG. **102**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity.

FIGS. **108**A-C illustrate the performance improvement of cases 1-4 by calculating the radius of the IQ plots, the mean error in convergence, and variance of error is convergence for each case that represent a bandwidth (BW) overlap percentage of zero to ten percent with the second signal removed and without. The data from the second signal removed is plotted as one line and the second signal not removed or a traditional equalizer as another to show the improvements in the radius of the IQ plots, the mean error in convergence, and variance of error is convergence that the second signal removal of the equalizer has for different use cases of overlapping BW or substantially adjacent QPSK signals.

FIG. **108**A illustrates the performance radius difference with and without the second signal removal, highlighting the impact and significant improvement on signal performance. FIG. **108**B presents the mean error in convergence difference with and without the second signal removal, showing the improvement in mean error rate with the removal of the second signal in addition to the equalizer the significant improvement of mean error with the removal of the second signal is shown. FIG. **108**C depicts the variance error in convergence difference with and without the second signal removal, showing a significant reduction in variance error. When the two signals are correlated the preemptive cancellation approach before equalization will improve the performance of the equalizer by reducing INTF gain given as previously discussed under FIG. **98**.

Case 5

For case 5, FIG. **103**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −35 dB power, which substantially indicates a 5% overlap. FIG. **103**B shows the probability of error convergence without removing the second signal, while FIG. **103**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **103**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **103**B. FIG. **103**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **103**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal. This signal removal in the equalizer is operable to be done where at least one signal is removed from at least other signal. The preemptive signal removal based upon the interference of the second signal information is operable to include the removal of multiple signals from one or more signals of interest.

Case 6

For case 6, FIG. **104**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −30 dB power, which substantially indicates a 5% overlap. FIG. **104**B shows the probability of error convergence without removing the second signal, while FIG. **104**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **104**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **104**B. FIG. **104**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **104**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 7

For case 7, FIG. **105**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −25 dB power, which substantially indicates a 5% overlap. FIG. **105**B shows the probability of error convergence without removing the second signal, while FIG. **105**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **105**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **105**B. FIG. **105**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **105**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 8

For case 8, FIG. **106**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −20 dB power, which substantially indicates a 5% overlap. FIG. **106**B shows the probability of error convergence without removing the second signal, while FIG. **106**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **106**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **106**B. FIG. **106**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **106**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 9

For case 9, FIG. **107**A illustrates the PSD graph for two QPSK signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −15 dB power, which substantially indicates a 5% overlap. FIG. **107**B shows the probability of error convergence without removing the second signal, while FIG. **107**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **107**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **107**B. FIG. **107**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **107**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 10

For case 10, FIG. **103**A illustrates the PSD graph for two 16-QAM signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −35 dB power, which substantially indicates a 5% overlap. FIG. **109**B shows the probability of error convergence without removing the second signal, while FIG. **109**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **109**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **109**B. FIG. **109**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **109**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal. This signal removal in the equalizer is operable to be done where at least one signal is removed from at least other signal. The preemptive signal removal based upon the interference of the second signal information is operable to include the removal of multiple signals from one or more signals of interest.

Case 11

For case 11, FIG. **110**A illustrates the PSD graph for two 16-QAM signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −30 dB power, which substantially indicates a 5% overlap. FIG. **110**B shows the probability of error convergence without removing the second signal, while FIG. **110**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **110**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **110**B. FIG. **110**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **110**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 12

For case 7, FIG. **111**A illustrates the PSD graph for two 16-QAM signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −25 dB power, which substantially indicates a 5% overlap. FIG. **111**B shows the probability of error convergence without removing the second signal, while FIG. **111**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **111**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **111**B. FIG. **111**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **111**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 13

For case 13, FIG. **112**A illustrates the PSD graph for two 16-QAM signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −20 dB power, which substantially indicates a 5% overlap. FIG. **112**B shows the probability of error convergence without removing the second signal, while FIG. **112**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **112**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **112**B. FIG. **112**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **112**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

Case 14

For case 14, FIG. **113**A illustrates the PSD graph for two 16-QAM signals with a 2 MHz bandwidth (BW), with one centered at −2 MHz and −30 dB power and the second centered at −0.1 MHz and −15 dB power, which substantially indicates a 5% overlap. FIG. **113**B shows the probability of error convergence without removing the second signal, while FIG. **113**C depicts the IQ signals after the equalizer iterations without second signal removal. FIG. **113**D shows the probability of error convergence with the second signal removed which shows a substantial improvement with the probability of error decreasing and converging to zero more quickly than FIG. **113**B. FIG. **113**E shows the IQ signals after the equalizer iterations with the second signal removed, demonstrating enhanced signal clarity. The decreased radius or tighter grouping of the four IQ signals than shown in FIG. **113**C demonstrates the effectiveness of the equalizer with the preemptive second signal removal based upon the determined interference of the second signal.

The improved equalizer of the present invention with the signal removal is operable to improve the noise or interference of at least one signal from at least another signal as was previously discussed and shown in FIGS. **98**-**114**. The improved equalizer is operable to be used wherever there are at least two signal that cause interference and/or noise with the other and with any modulation type including but not limited to BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), 8-PSK (8-Phase Shift Keying), 16-PSK (16-Phase Shift Keying), DPSK (Differential Phase Shift Keying), 16-QAM (16-Quadrature Amplitude Modulation), 32-, 64-QAM, 128-QAM, 256-QAM, 512-QAM, 1024-QAM, 2-FSK (2-Frequency Shift Keying), 4-FSK, GFSK (Gaussian Frequency Shift Keying), MSK (Minimum Shift Keying), CPFSK (Continuous Phase Frequency Shift Keying), 2-ASK (2-Amplitude Shift Keying), 4-ASK, OOK (On-Off Keying), OFDM (Orthogonal Frequency-Division Multiplexing), DMT (Discrete Multi-Tone), DSSS (Direct Sequence Spread Spectrum), FHSS (Frequency Hopping Spread Spectrum), O-QPSK (Offset Quadrature Phase Shift Keying), GMSK (Gaussian Minimum Shift Keying), TCM (Trellis-Coded Modulation), PAM (Pulse Amplitude Modulation), PPM (Pulse Position Modulation), PWM (Pulse Width Modulation), MIMO Modulation, CDMA (Code Division Multiple Access), and/or SC-FDMA (Single-Carrier Frequency Division Multiple Access).

FIGS. **114**A-C illustrate the performance improvement of cases 10-14 by calculating the radius of the IQ plots, the mean error in convergence, and variance of error is convergence for each case that each represent a different power difference in dB between two 16-QAM signals from −5 to 15 dB. The data from the second signal removed is plotted as one line and the second signal not removed or a traditional equalizer as another to show the improvements in the radius of the IQ plots, the mean error in convergence, and variance of error is convergence which show substantial improvement with all three metrics with second signal removal of the equalizer has for different use cases of varying power difference of the two signals with the most improvement being shown by the largest power difference in dB of 15. The −5 db power difference shows less improvement but still a substantial improvement in the radius of the IQ plots, the mean error in convergence, and variance of error is convergence.

FIG. **114**A illustrates the performance radius difference with and without the second signal removal, highlighting the impact and significant improvement on signal performance. FIG. **114**B presents the mean error in convergence difference with and without the second signal removal, showing the improvement in mean error rate with the removal of the second signal in addition to the equalizer the significant improvement of mean error with the removal of the second signal is shown. FIG. **114**C depicts the variance error in convergence difference with and without the second signal removal, showing a significant reduction in variance error. When the two signals are correlated the preemptive cancellation approach before equalization will improve the performance of the equalizer by reducing INTF gain given as previously discussed under FIG. **98**.

In one embodiment, the equalizer engine of the present invention improves the detection of at least one signal from the removal of at least one second signal based on the cancellation approach described used before equalization will improve the performance of the equalizer by reducing INTF gain described under FIG. **98**. The equalizer is operable to improve the modulation error ratio (MER) by decreasing the error of the at least one signal. This MER improvement or raising of the MER can be shown in cases 1-14 with a decrease in the cloud or radius of the IQ signal graph that shows a decrease in the noise mixed with the RF signal that causes the impairments to the plotting of the signal on the IQ graph which is indicative of interference or distortion of the signal. The preemptive cancelation of at least one second signal shows more improvement for more complex modulation types that provide more information as shown with greater improvement from 16-QAM over the improvement of 4-QAM (QPSK). In another embodiment, the equalizer is operable to be in communication with the data analysis engine and/or AI agent. The data analysis engine is operable to include the equalizer in order to mitigate interference of at least one signal. The equalizer is operable to communicate with the AI agent to receive future predictions of the RF environment, customer goals, actionable data and/or RF signal parameters learn the RF environment and changes over time. The equalizer is able to use information from the RF environment and AI agent to account for changes in both the RF environment and changes in customer goal and/or services.

The present invention provides supports multiple services and associated protocols, and provides data to support understanding of how the RF environment is used to optimize its utilization by multiple, disparate services concurrently. It is operable for time, frequency, space, signals and service goals for multiple services, including frequencies used by services and adjacent bands, multiple protocols, signal characteristics and interactions, and utilization statistics in real time based on the data provided from the sensors, and software embedded in the single chip, single chipset, multiple chips, multiple chipsets, or on the single circuit board. The RF environment and impact on 5G services and other services is based on goals and utilization policies that are automatically implemented for signals in the environment and their characteristics, including interference and coexistence information and validation of utilization policies, including error sources consideration. The optimization of network resources supports coexistence to share the RF environment for multiple services based on the service goals and coexistence policies, thus providing for dynamic spectrum sharing (DSSMS) based on the service needs and policies implemented in an autonomous, scalable basis in real time.

The system of the present invention is operable to utilize a plurality of learning techniques including, but not limited to, machine learning (ML), artificial intelligence (AI), deep learning (DL), neural networks (NNs), artificial neural networks (ANNs), support vector machines (SVMs), Markov decision process (MDP), and/or natural language processing (NLP). The system is operable to use any of the aforementioned learning techniques alone or in combination.

Further, the system is operable to utilize predictive analytics techniques including, but not limited to, machine learning (ML), artificial intelligence (AI), neural networks (NNs) (e.g., long short term memory (LSTM) neural networks), deep learning, historical data, and/or data mining to make future predictions and/or models. The system is preferably operable to recommend and/or perform actions based on historical data, external data sources, ML, AI, NNs, and/or other learning techniques. The system is operable to utilize predictive modeling and/or optimization algorithms including, but not limited to, heuristic algorithms, particle swarm optimization, genetic algorithms, technical analysis descriptors, combinatorial algorithms, quantum optimization algorithms, iterative methods, deep learning techniques, and/or feature selection techniques.

Additionally, the system is operable to employ control theory concepts and methods. This enables the system to determine if every data set processed and/or analyzed by the system represents a sufficient statistical data set.

Location data is created in the present invention using one or more hardware and/or software components. By way of example and not limitation, location data is created using the Global Positioning System (GPS), low energy BLUETOOTH based systems such as beacons, wireless networks such as WIFI, Radio Frequency (RF) including RF Identification (RFID), Near Field Communication (NFC), magnetic positioning, and/or cellular triangulation. By way of example, location data is determined via an Internet Protocol (IP) address of a device connected to a wireless network. A wireless router is also operable to determine identities of devices connected to the wireless network through the router, and thus is operable to determine the locations of these devices through their presence in the connection range of the wireless router.

FIG. **70** is a schematic diagram of an embodiment of the invention illustrating a computer system, generally described as **800**, having a network **810**, a plurality of computing devices **820**, **830**, **840**, a server **850**, and a database **870**.

The at least one server **850** is constructed, configured, and coupled to enable communication over a network **810** with a plurality of computing devices **820**, **830**, **840**. The at least one server **850** includes a processing unit **851** with an operating system **852**. The operating system **852** enables the server **850** to communicate through network **810** with the remote, distributed user devices. Database **870** is operable to house an operating system **872**, memory **874**, and programs **876**.

In one embodiment of the invention, the system **800** includes a network **810** for distributed communication via a wireless communication antenna **812** and processing by at least one mobile communication computing device **830**. Alternatively, wireless and wired communication and connectivity between devices and components described herein include wireless network communication such as WI-FI, WORLDWIDE INTEROPERABILITY FOR MICROWAVE ACCESS (WIMAX), Radio Frequency (RF) communication including RF identification (RFID), NEAR FIELD COMMUNICATION (NFC), BLUETOOTH including BLUETOOTH LOW ENERGY (BLE), ZIGBEE, Infrared (IR) communication, cellular communication, satellite communication, Universal Serial Bus (USB), Ethernet communications, communication via fiber-optic cables, coaxial cables, twisted pair cables, and/or any other type of wireless or wired communication. In another embodiment of the invention, the system **800** is a virtualized computing system capable of executing any or all aspects of software and/or application components presented herein on the computing devices **820**, **830**, **840**. In certain aspects, the computer system **800** is operable to be implemented using hardware or a combination of software and hardware, either in a dedicated computing device, or integrated into another entity, or distributed across multiple entities or computing devices.

By way of example, and not limitation, the computing devices **820**, **830**, **840** are intended to represent various forms of electronic devices including at least a processor and a memory, such as a server, blade server, mainframe, mobile phone, personal digital assistant (PDA), smartphone, desktop computer, netbook computer, tablet computer, workstation, laptop, and other similar computing devices. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit implementations of the invention described and/or claimed in the present application.

In one embodiment, the computing device **820** includes components such as a processor **860**, a system memory **862** having a random access memory (RAM) **864** and a read-only memory (ROM) **866**, and a system bus **868** that couples the memory **862** to the processor **860**. In another embodiment, the computing device **830** is operable to additionally include components such as a storage device **890** for storing the operating system **892** and one or more application programs **894**, a network interface unit **896**, and/or an input/output controller **898**. Each of the components is operable to be coupled to each other through at least one bus **868**. The input/output controller **898** is operable to receive and process input from, or provide output to, a number of other devices **899**, including, but not limited to, alphanumeric input devices, mice, electronic styluses, display units, touch screens, gaming controllers, joy sticks, touch pads, signal generation devices (e.g., speakers), augmented reality/virtual reality (AR/VR) devices (e.g., AR/VR headsets), or printers.

By way of example, and not limitation, the processor **860** is operable to be a general-purpose microprocessor (e.g., a central processing unit (CPU)), a graphics processing unit (GPU), a microcontroller, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA), a Programmable Logic Device (PLD), a controller, a state machine, gated or transistor logic, discrete hardware components, or any other suitable entity or combinations thereof that can perform calculations, process instructions for execution, and/or other manipulations of information.

In another implementation, shown as **840** in FIG. **70**, multiple processors **860** and/or multiple buses **868** are operable to be used, as appropriate, along with multiple memories **862** of multiple types (e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core).

Also, multiple computing devices are operable to be connected, with each device providing portions of the necessary operations (e.g., a server bank, a group of blade servers, or a multi-processor system). Alternatively, some steps or methods are operable to be performed by circuitry that is specific to a given function.

According to various embodiments, the computer system **800** is operable to operate in a networked environment using logical connections to local and/or remote computing devices **820**, **830**, **840** through a network **810**. A computing device **830** is operable to connect to a network **810** through a network interface unit **896** connected to a bus **868**. Computing devices are operable to communicate communication media through wired networks, direct-wired connections or wirelessly, such as acoustic, RF, or infrared, through an antenna **897** in communication with the network antenna **812** and the network interface unit **896**, which are operable to include digital signal processing circuitry when necessary. The network interface unit **896** is operable to provide for communications under various modes or protocols.

In one or more exemplary aspects, the instructions are operable to be implemented in hardware, software, firmware, or any combinations thereof. A computer readable medium is operable to provide volatile or non-volatile storage for one or more sets of instructions, such as operating systems, data structures, program modules, applications, or other data embodying any one or more of the methodologies or functions described herein. The computer readable medium is operable to include the memory **862**, the processor **860**, and/or the storage media **890** and is operable be a single medium or multiple media (e.g., a centralized or distributed computer system) that store the one or more sets of instructions **900**. Non-transitory computer readable media includes all computer readable media, with the sole exception being a transitory, propagating signal per se. The instructions **900** are further operable to be transmitted or received over the network **810** via the network interface unit **896** as communication media, which is operable to include a modulated data signal such as a carrier wave or other transport mechanism and includes any delivery media. The term "modulated data signal" means a signal that has one or more of its characteristics changed or set in a manner as to encode information in the signal.

Storage devices **890** and memory **862** include, but are not limited to, volatile and non-volatile media such as cache, RAM, ROM, EPROM, EEPROM, FLASH memory, or other solid state memory technology; discs (e.g., digital versatile discs (DVD), HD-DVD, BLU-RAY, compact disc (CD), or CD-ROM) or other optical storage; magnetic cassettes, magnetic tape, magnetic disk storage, floppy disks, or other magnetic storage devices; or any other medium that can be used to store the computer readable instructions and which can be accessed by the computer system **800**.

In one embodiment, the computer system **800** is within a cloud-based network. In one embodiment, the server **850** is a designated physical server for distributed computing devices **820**, **830**, and **840**. In one embodiment, the server **850** is a cloud-based server platform. In one embodiment, the cloud-based server platform hosts serverless functions for distributed computing devices **820**, **830**, and **840**.

In another embodiment, the computer system **800** is within an edge computing network. The server **850** is an edge server, and the database **870** is an edge database. The edge server **850** and the edge database **870** are part of an edge computing platform. In one embodiment, the edge server **850** and the edge database **870** are designated to distributed computing devices **820**, **830**, and **840**. In one embodiment, the edge server **850** and the edge database **870** are not designated for distributed computing devices **820**, **830**, and **840**. The distributed computing devices **820**, **830**, and **840** connect to an edge server in the edge computing network based on proximity, availability, latency, bandwidth, and/or other factors.

It is also contemplated that the computer system **800** is operable to not include all of the components shown in FIG. **70**, is operable to include other components that are not explicitly shown in FIG. **70**, or is operable to utilize an architecture completely different than that shown in FIG. **70**. The various illustrative logical blocks, modules, elements, circuits, and algorithms described in connection with the embodiments disclosed herein are operable to 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 (e.g., arranged in a different order or partitioned in a different way), but such implementation decisions should not be interpreted as causing a departure from the scope of the present invention.

Certain modifications and improvements will occur to those skilled in the art upon a reading of the foregoing description. The above-mentioned examples are provided to serve the purpose of clarifying the aspects of the invention and it will be apparent to one skilled in the art that they do not serve to limit the scope of the invention. All modifications and improvements have been deleted herein for the sake of conciseness and readability but are properly within the scope of the present invention.

The invention claimed is:

1. A system for spectrum management in an electromagnetic environment comprising:

a Multi-Access Edge Computing (MEC) layer in a network slice, wherein the MEC layer is in communication with a radio access network (RAN) and a core network; and

at least one data analysis engine in the MEC layer configured to analyze the measured data from the electromagnetic environment to create analyzed data; and

an artificial intelligence (AI) agent in communication with the at least one data analysis engine;

wherein the at least one data analysis engine uses an equalizer to reduce signal interference and/or signal noise of at least one signal based on information from at least one other signal for preemptive removal of the at least one other signal before equalization;

wherein the at least one signal and the at least one other signal have an overlapping bandwidth;

wherein the AI agent is configured to make predictions about the electromagnetic environment based on the analyzed data and/or a previous analyzed dataset from the data analysis engine; and

wherein the equalizer is configured to use the predictions about the electromagnetic environment for the reduction of the signal interference and/or the signal noise of the at least one signal in real-time as the electromagnetic environment changes.

2. The system of claim **1**, wherein the network slice is administered by a mobile virtual network operator (MVNO).

3. The system of claim **1**, wherein the equalizer reduces the signal interference and/or the signal noise of the at least one signal using a Kullback Leibler (KL) Divergence value.

4. The system of claim **1**, wherein the AI agent is configured to utilize at least one AI or machine learning (ML) algorithm to make the predictions about the electromagnetic environment.

5. The system of claim **1**, wherein slicing architecture of the MEC layer is based on a plurality of factors including geographic scope, specificity of services, flexible architecture, and/or implementation of MEC applications as part of a slice access point.

6. The system of claim 1, wherein the AI agent is configured to provide at least one recommendation to optimize L1, L2, and/or L3 network parameters in real-time.

7. The system of claim 1, wherein the at least one signal has a quadrature phase shift keying (QPSK) modulation type, and the equalizer improves a modulation error ratio (MER) of the QPSK modulation type by the reduction of the signal interference for the at least one signal.

8. The system of claim 1, wherein the equalizer utilizes information theory.

9. The system of claim 1, further comprising at least one radio unit, distributed unit, and/or central unit, wherein at least one of the at least one radio unit, distributed unit, and/or central unit includes the AI agent.

10. A system for spectrum management in an electromagnetic environment comprising:

a Multi-Access Edge Computing (MEC) layer in a network slice, wherein the MEC layer is in communication with a radio access network (RAN) and a core network;

at least one data analysis engine in the MEC layer operable to analyze measured data from the electromagnetic environment to create analyzed data; and

an artificial intelligence (AI) agent in communication with the at least one data analysis engine;

wherein the at least one data analysis engine uses an equalizer to reduce signal interference and/or distortion of at least one signal based on information from at least one other signal for preemptive removal of the at least one other signal before equalization;

wherein the at least one signal and the at least one other signal have an overlapping bandwidth;

wherein the at least one signal has a quadrature phase shift keying (QPSK) modulation type;

wherein the AI agent is configured to make predictions about the electromagnetic environment based on the analyzed data and/or a previous analyzed dataset from the data analysis engine;

wherein the equalizer is configured to use the predictions about the electromagnetic environment for equalization and mitigation of signal noise of the at least one signal in real-time as the electromagnetic environment changes; and

wherein the MEC layer is configured to use the predictions about the electromagnetic environment to create actionable data for optimizing network resources.

11. The system of claim 10, wherein the AI agent is configured to provide at least one recommendation for optimization of L1, L2, and/or L3 parameters.

12. The system of claim 10, wherein the AI agent is configured to provide at least one recommendation to optimize performance over time based on a training model.

13. The system of claim 10, wherein the AI agent is configured to provide for validation of sensor fusion based on pattern recognition.

14. The system of claim 10, wherein the actionable data is based on customer goals.

15. The system of claim 10, wherein the equalizer utilizes information theory.

16. A system for spectrum management in an electromagnetic environment comprising:

a Multi-Access Edge Computing (MEC) layer in a network slice, wherein the MEC layer is in communication with a radio access network (RAN) and a core network;

at least one data analysis engine in the MEC layer configured to analyze measured data from the electromagnetic environment to create analyzed data; and

an artificial intelligence (AI) agent in communication with the at least one data analysis engine; wherein the at least one data analysis engine uses an equalizer to reduce signal interference and/or distortion of at least one signal based on information from at least one other signal for preemptive removal of the at least one other signal before equalization;

wherein the at least one signal and the at least one other signal have an overlapping bandwidth;

wherein the at least one signal has a quadrature phase shift keying (QPSK) modulation type;

wherein the AI agent is configured to make predictions about the electromagnetic environment based on the analyzed data and/or a previous analyzed dataset from the data analysis engine;

wherein the equalizer is configured to use the predictions about the electromagnetic environment for the equalization and mitigation of signal noise of the at least one signal in real-time as the electromagnetic environment changes; and

wherein the AI agent is configured to provide at least one recommendation for optimization of network parameters based on at least one customer goal.

17. The system of claim 16, wherein the equalizer reduces the signal interference and/or the distortion of at least one signal using a Kullback Leibler (KL) Divergence value.

18. The system of claim 16, wherein the at least one recommendation includes an optimization of L1, L2, and/or L3 network parameters in real-time.

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