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

(10) **Patent No.: US 9,973,943 B2**
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(54) **WIRELESS NETWORK CONFIGURATION USING PATH LOSS DETERMINATION BETWEEN NODES**

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(73) Assignee: **AIRSPAN NETWORKS INC.**, Boca Raton, FL (US)

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(30) **Foreign Application Priority Data**

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Oct. 30, 2015 (GB) 1519273.5

(51) **Int. Cl.**
H04W 24/02 (2009.01)
G01S 19/53 (2010.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04W 24/02*** (2013.01); ***F16M 11/06*** (2013.01); ***G01S 3/043*** (2013.01); ***G01S 3/14*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H04W 24/02
See application file for complete search history.

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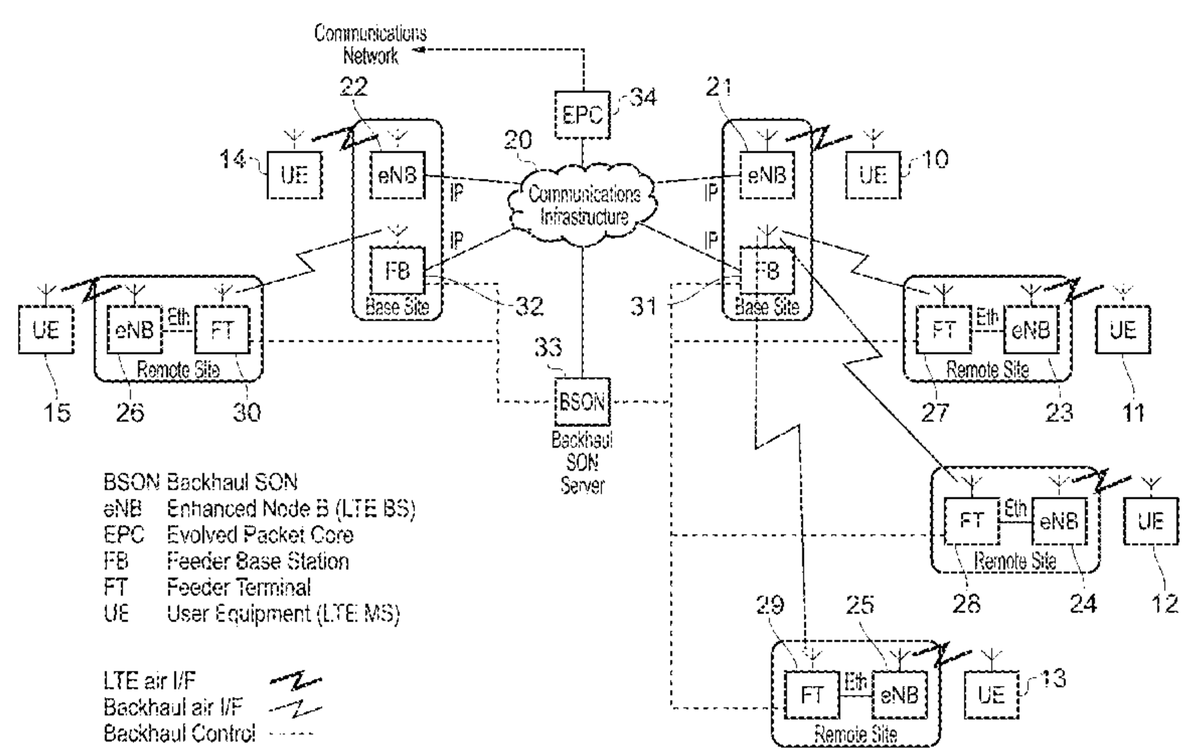
Primary Examiner — Gerald A Smarth
(74) *Attorney, Agent, or Firm* — Haynes Beffel & Wolfeld LLP

(57) **ABSTRACT**

A method and corresponding apparatus are provided for network configuration selection in a wireless network comprising a plurality of nodes. A subset of the nodes are configured to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node. Measurement reports are received from the subset of nodes, each measurement report comprising a signal source angle and a received signal strength. A path loss is determined in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs. Then a directional configuration is selected for a directional antenna of each node of the subset of nodes for data transmission in dependence on the set of path losses.

13 Claims, 39 Drawing Sheets



(51) **Int. Cl.**

G01S 3/14	(2006.01)
G01S 5/02	(2010.01)
H01Q 1/02	(2006.01)
H01Q 3/04	(2006.01)
H01Q 3/24	(2006.01)
H01Q 3/26	(2006.01)
H01Q 21/06	(2006.01)
H01Q 21/08	(2006.01)
H01Q 21/20	(2006.01)
H01Q 21/28	(2006.01)
H01Q 25/00	(2006.01)
H04B 7/06	(2006.01)
H04B 7/08	(2006.01)
H04W 28/02	(2009.01)
H04W 88/04	(2009.01)
H05K 7/20	(2006.01)
H04L 12/24	(2006.01)
H04L 29/08	(2006.01)
H04W 4/00	(2018.01)
H04W 16/28	(2009.01)
H04W 40/22	(2009.01)
H04W 72/08	(2009.01)
H04W 24/10	(2009.01)
H01Q 1/24	(2006.01)
H01Q 1/50	(2006.01)
H01Q 3/10	(2006.01)
H04W 72/04	(2009.01)
G01S 3/04	(2006.01)
G01S 19/24	(2010.01)
H01Q 1/36	(2006.01)
H01Q 1/42	(2006.01)
H01Q 3/12	(2006.01)
H01Q 21/00	(2006.01)
H01Q 1/12	(2006.01)
H01Q 3/02	(2006.01)
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H04B 7/0456	(2017.01)
F16M 11/06	(2006.01)
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H04W 24/08	(2009.01)
H04W 28/24	(2009.01)
H04W 48/06	(2009.01)
H04W 84/04	(2009.01)
H04W 84/02	(2009.01)
H04W 88/08	(2009.01)

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

CPC ***G01S 5/0247*** (2013.01); ***G01S 19/24*** (2013.01); ***G01S 19/53*** (2013.01); ***H01Q 1/02*** (2013.01); ***H01Q 1/1207*** (2013.01); ***H01Q 1/1228*** (2013.01); ***H01Q 1/246*** (2013.01); ***H01Q 1/36*** (2013.01); ***H01Q 1/42*** (2013.01); ***H01Q 1/50*** (2013.01); ***H01Q 3/02*** (2013.01); ***H01Q 3/04*** (2013.01); ***H01Q 3/10*** (2013.01); ***H01Q 3/12*** (2013.01); ***H01Q 3/24*** (2013.01); ***H01Q 3/26*** (2013.01); ***H01Q 3/2611*** (2013.01); ***H01Q 3/36*** (2013.01); ***H01Q 21/00*** (2013.01); ***H01Q 21/065*** (2013.01); ***H01Q 21/08*** (2013.01); ***H01Q 21/205*** (2013.01); ***H01Q 21/24*** (2013.01); ***H01Q 21/28*** (2013.01); ***H01Q 25/002*** (2013.01); ***H01Q 25/005*** (2013.01); ***H04B 7/0456*** (2013.01); ***H04B 7/0617*** (2013.01); ***H04B 7/0621*** (2013.01); ***H04B 7/0691*** (2013.01); ***H04B 7/0695*** (2013.01); ***H04B 7/086*** (2013.01); ***H04B 7/088*** (2013.01); ***H04B 7/0874*** (2013.01); ***H04L 41/0806*** (2013.01); ***H04L 41/0816*** (2013.01); ***H04L 43/0829*** (2013.01); ***H04L 67/18*** (2013.01); ***H04L 67/34*** (2013.01); ***H04W 4/001*** (2013.01); ***H04W 16/28*** (2013.01); ***H04W 24/08*** (2013.01); ***H04W 24/10*** (2013.01); ***H04W 28/0236*** (2013.01); ***H04W 28/0268*** (2013.01); ***H04W 28/0284*** (2013.01); ***H04W 28/24*** (2013.01); ***H04W 40/22*** (2013.01); ***H04W 48/06*** (2013.01); ***H04W 72/042*** (2013.01); ***H04W 72/085*** (2013.01); ***H04W 88/04*** (2013.01); ***H05K 7/20*** (2013.01); *H01Q 1/1257* (2013.01); *H04B 7/0817* (2013.01); *H04W 84/02* (2013.01); *H04W 84/045* (2013.01); *H04W 88/08* (2013.01)

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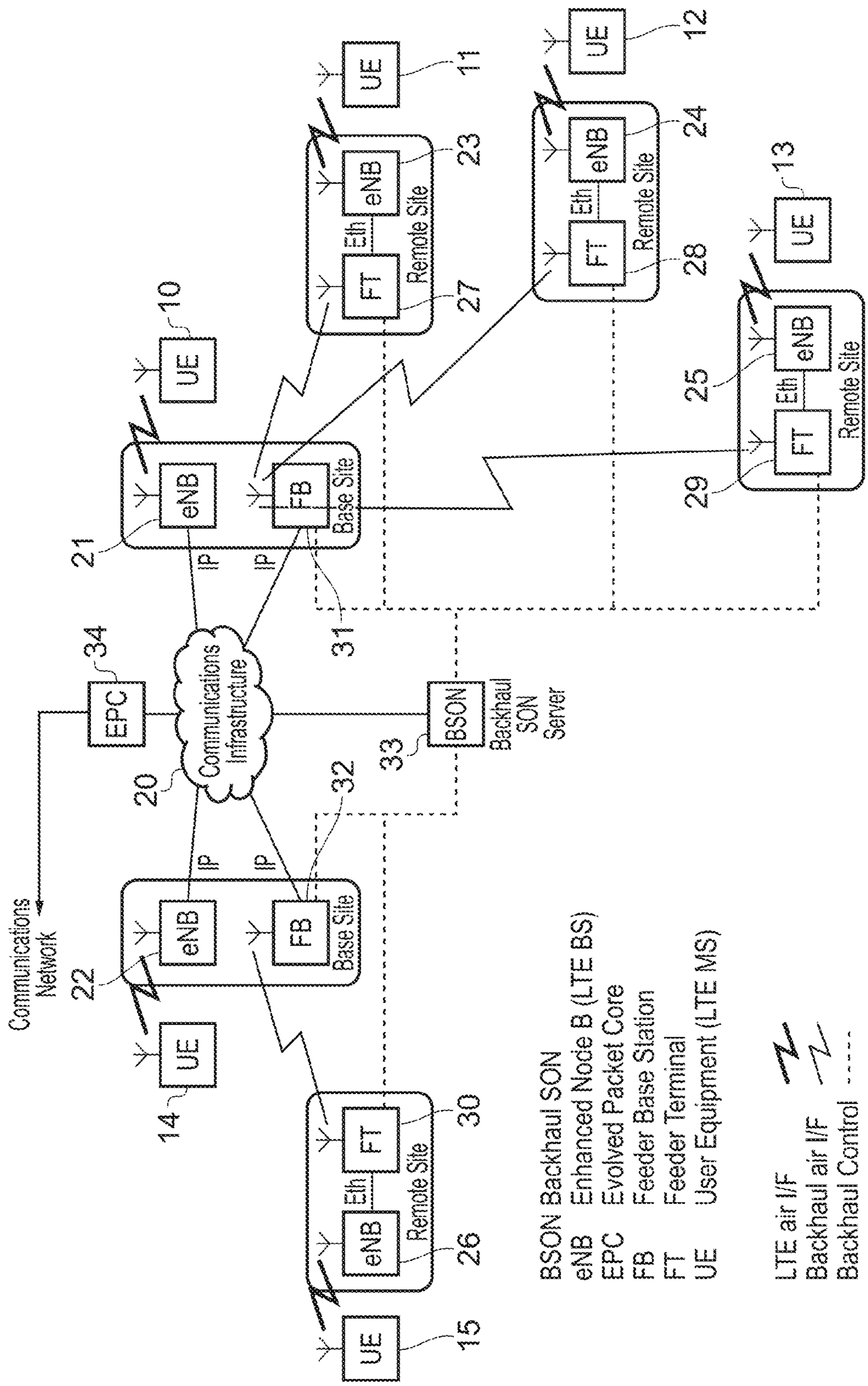
Communications Network
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34
Communications Infrastructure
20
BSON
Backhaul SON Server
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32
31
IP
IP
IP
IP
eNB
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FB
Base Site
UE
10
eNB
22
FB
Base Site
UE
14
FT
Eth
eNB
Remote Site
UE
15
26
30
FT
Eth
eNB
23
Remote Site
UE
11
27
FT
Eth
eNB
24
Remote Site
UE
12
28
FT
Eth
eNB
25
Remote Site
UE
13
29
BSON Backhaul SON
eNB Enhanced Node B (LTE BS)
EPC Evolved Packet Core
FB Feeder Base Station
FT Feeder Terminal
UE User Equipment (LTE MS)
LTE air I/F
Backhaul air I/F
Backhaul Control

FIG. 1

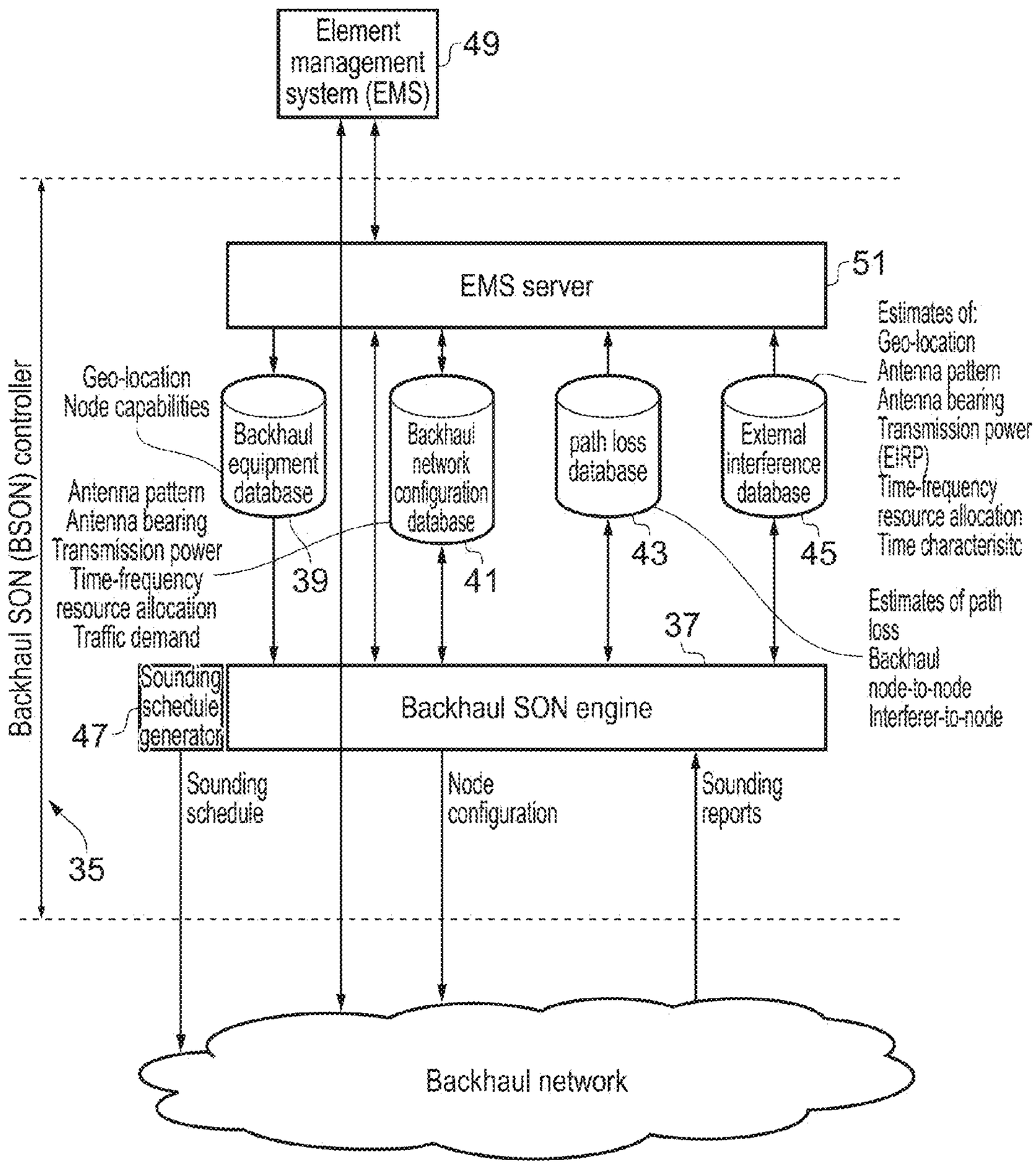

Element management system (EMS)
49
EMS server
51
Backhaul SON (BSON) controller
Geo-location
Node capabilities
Backhaul equipment database
Backhaul network configuration database
path loss database
External interference database
Estimates of:
Geo-location
Antenna pattern
Antenna bearing
Transmission power (EIRP)
Time-frequency resource allocation
Time characterisitc
Antenna pattern
Antenna bearing
Transmission power
Time-frequency resource allocation
Traffic demand
39
41
43
45
37
Estimates of path loss
Backhaul node-to-node
Interferer-to-node
Sounding schedule generator
47
Backhaul SON engine
Sounding schedule
Node configuration
Sounding reports
35
Backhaul network

FIG. 2

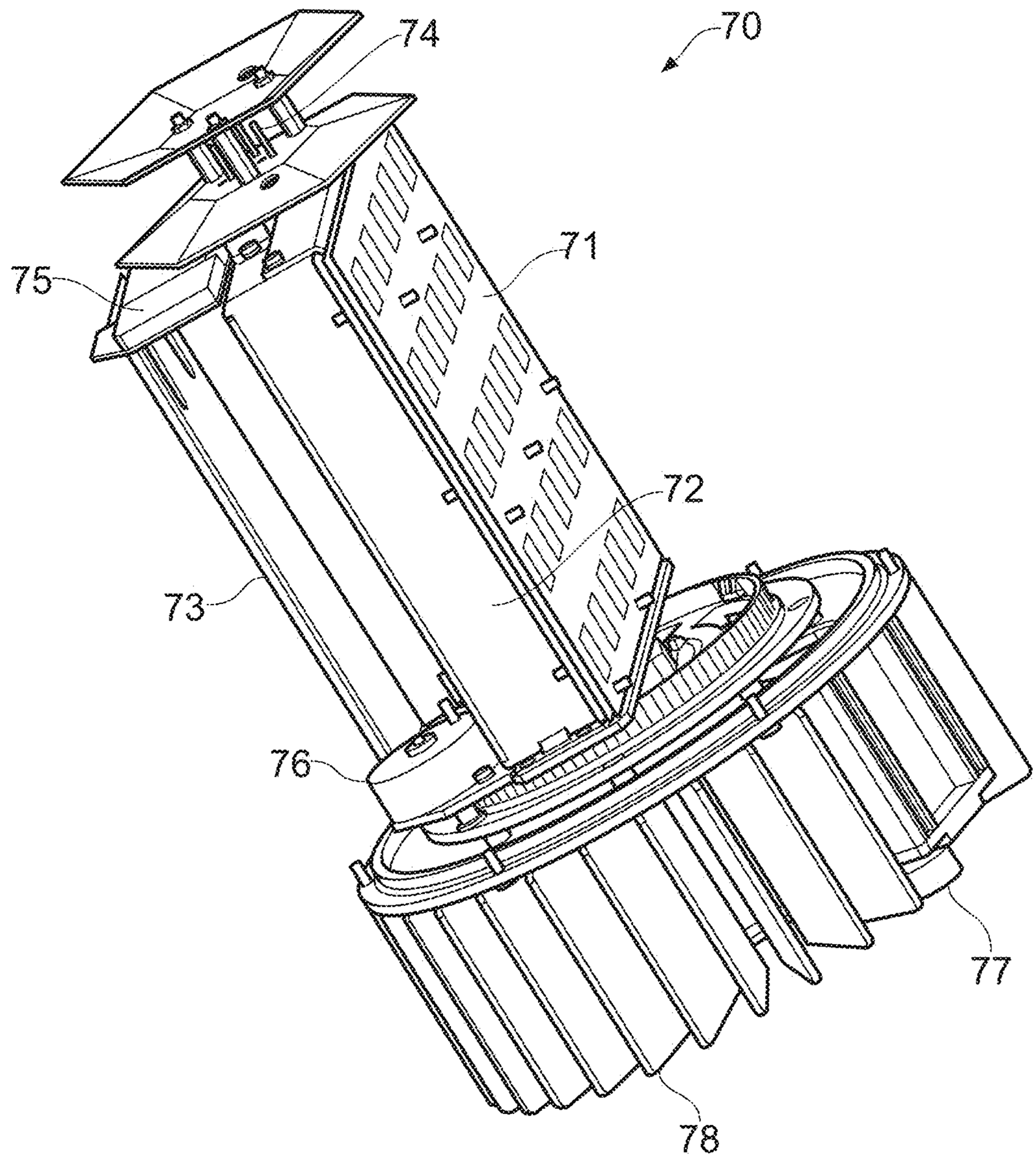
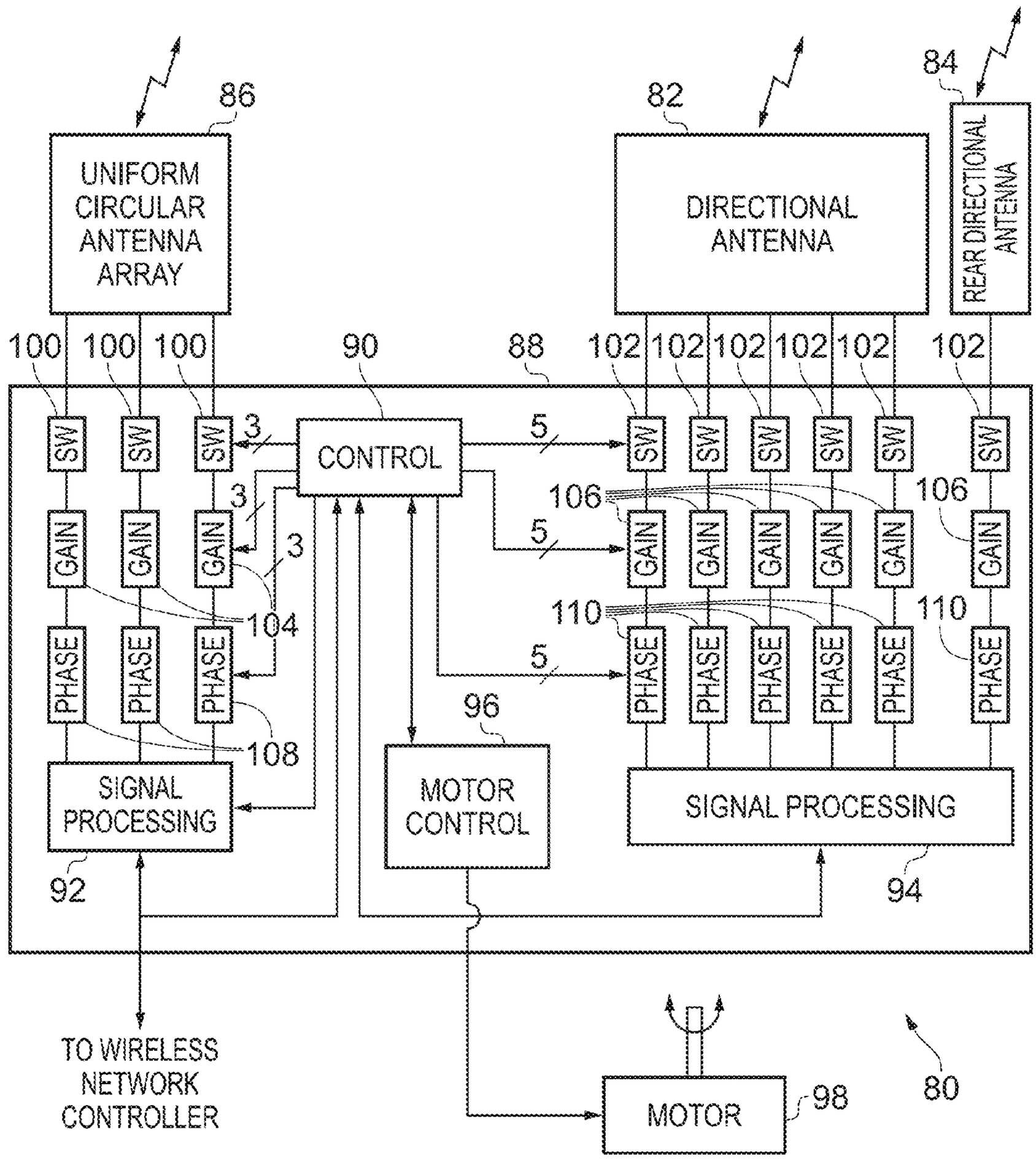


FIG. 3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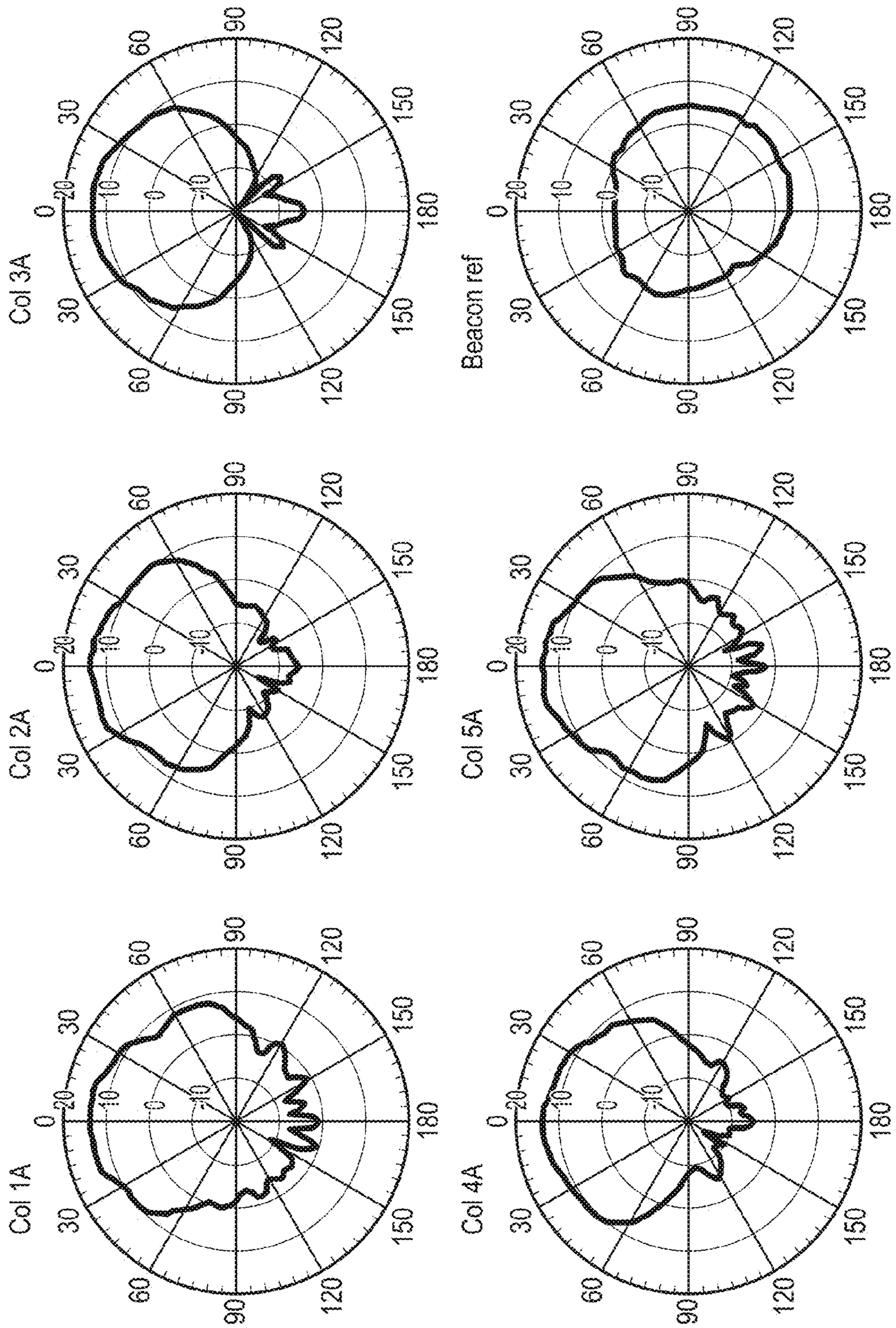
UNIFORM CIRCULAR ANTENNA ARRAY
82
DIRECTIONAL ANTENNA
84
REAR DIRECTIONAL ANTENNA
100
90
88
102
SW
CONTROL
3
5
106
GAIN
104
110
PHASE
108
96
SIGNAL PROCESSING
MOTOR CONTROL
92
94
TO WIRELESS NETWORK CONTROLLER
MOTOR
98
80

FIG. 4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Col 2A
Col 3A
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Col 5A
Beacon ref
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150
180
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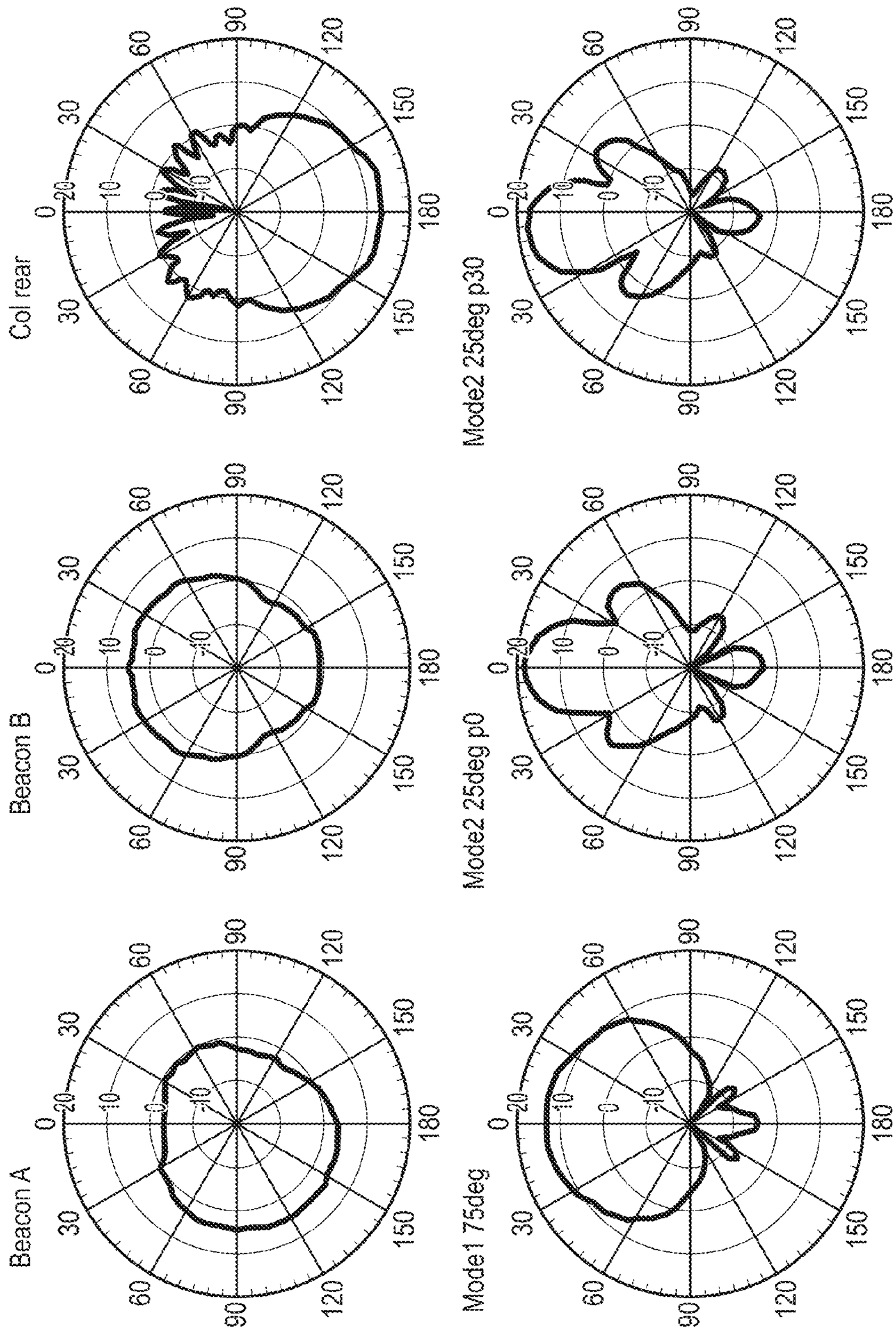
10
0
-10

FIG. 5



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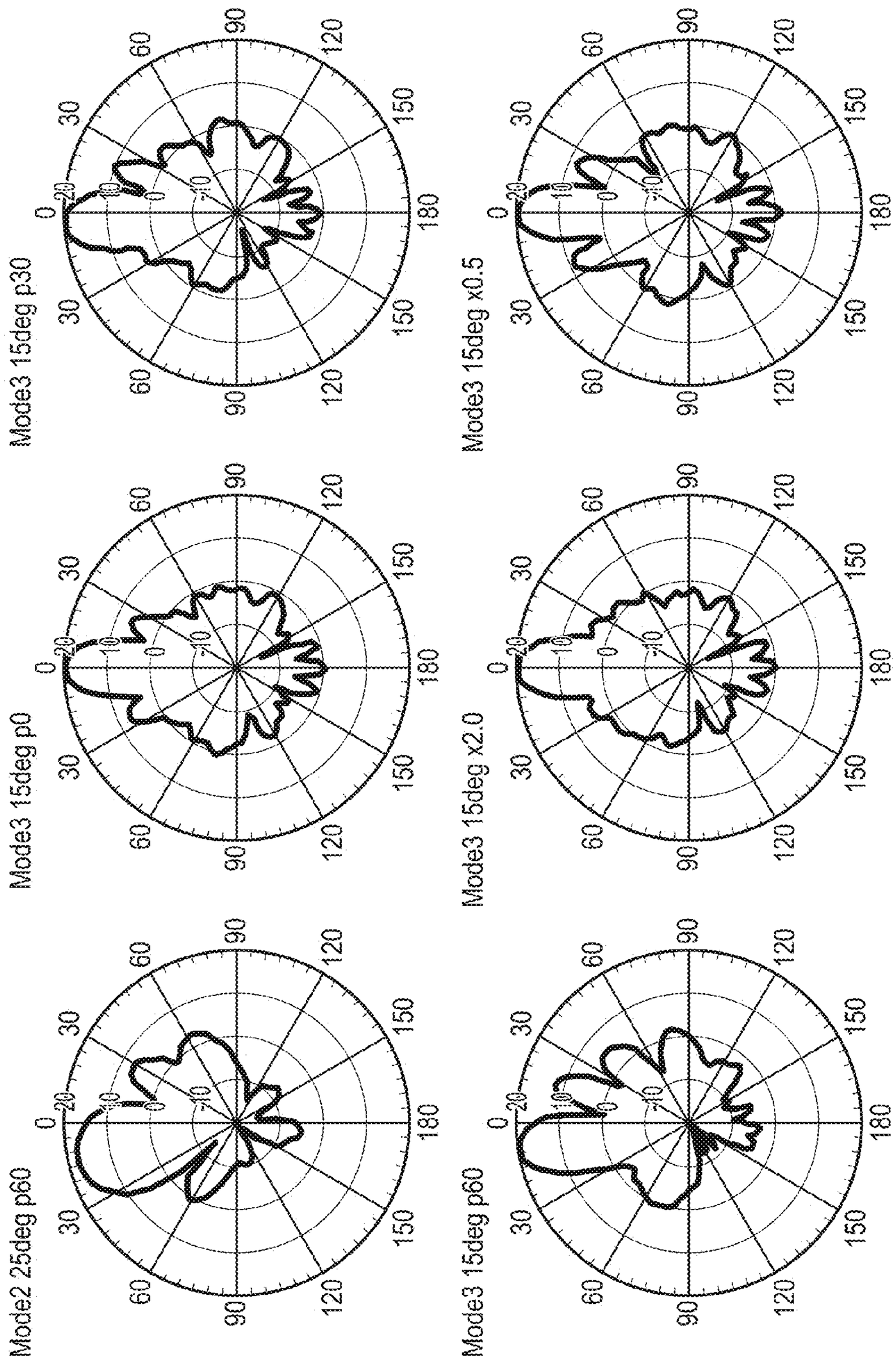

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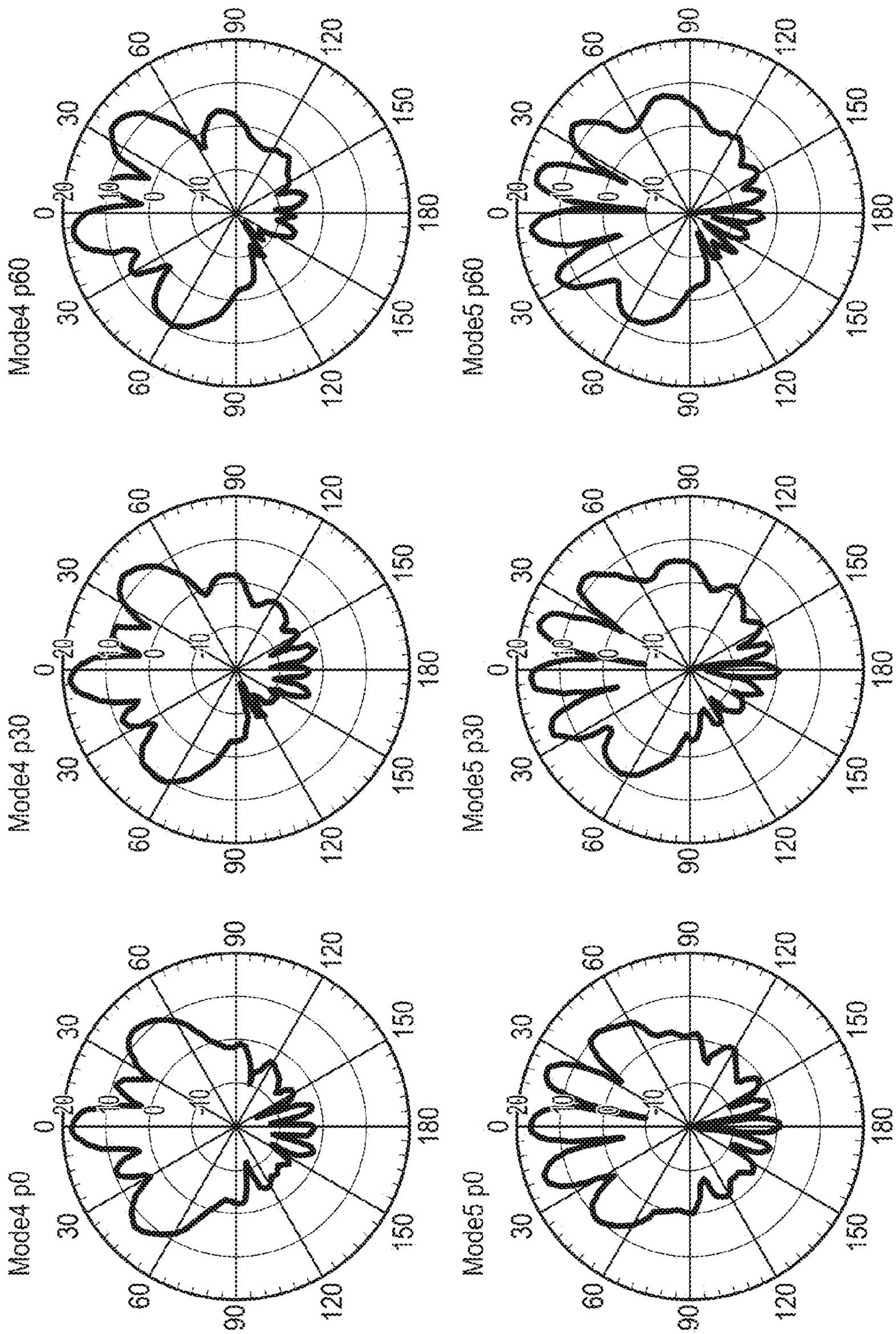

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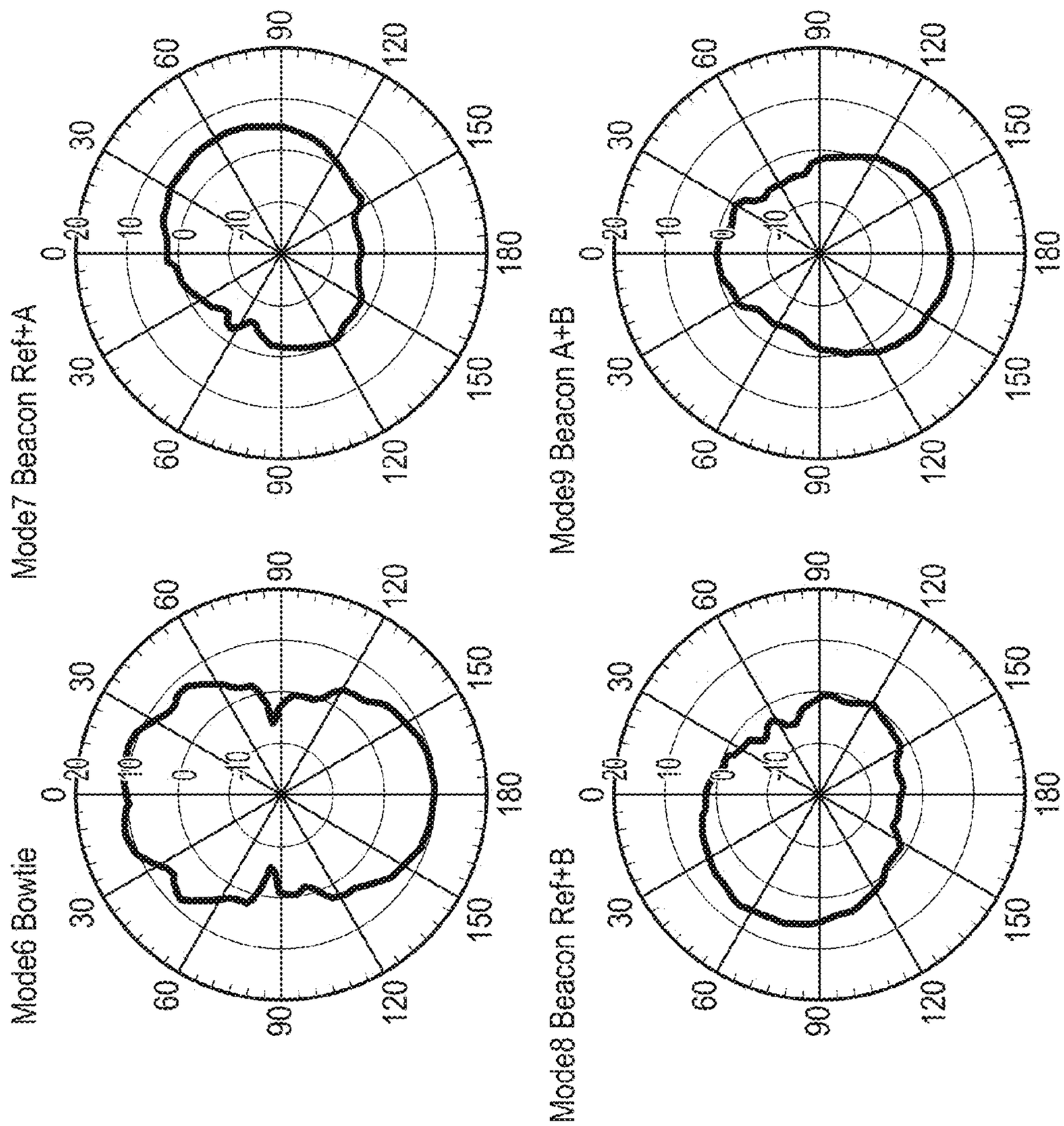

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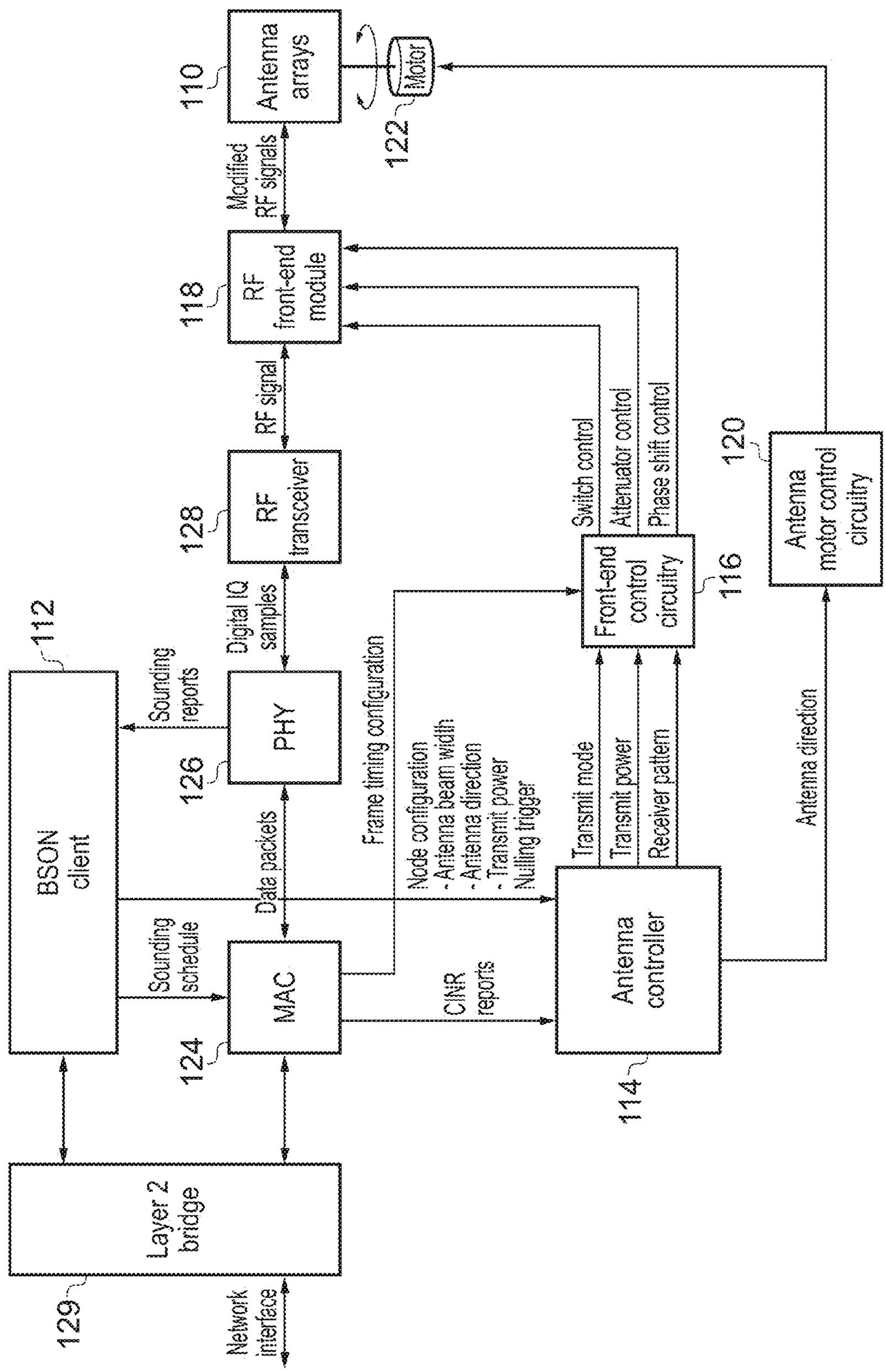

110
Antenna arrays
Motor
122
Modified RF signals
118
RF front-end module
RF signal
128
RF transceiver
Digital IQ samples
112
BSON client
Sounding reports
PHY
126
Data packets
Frame timing configuration
Node configuration
- Antenna beam width
- Antenna direction
- Transmit power
Nulling trigger
Switch control
Attenuator control
Phase shift control
120
Antenna motor control circuitry
Front-end control circuitry
116
Transmit mode
Transmit power
Receiver pattern
Antenna direction
Sounding schedule
MAC
124
CINR reports
Antenna controller
114
Layer 2 bridge
129
Network interface

FIG. 6

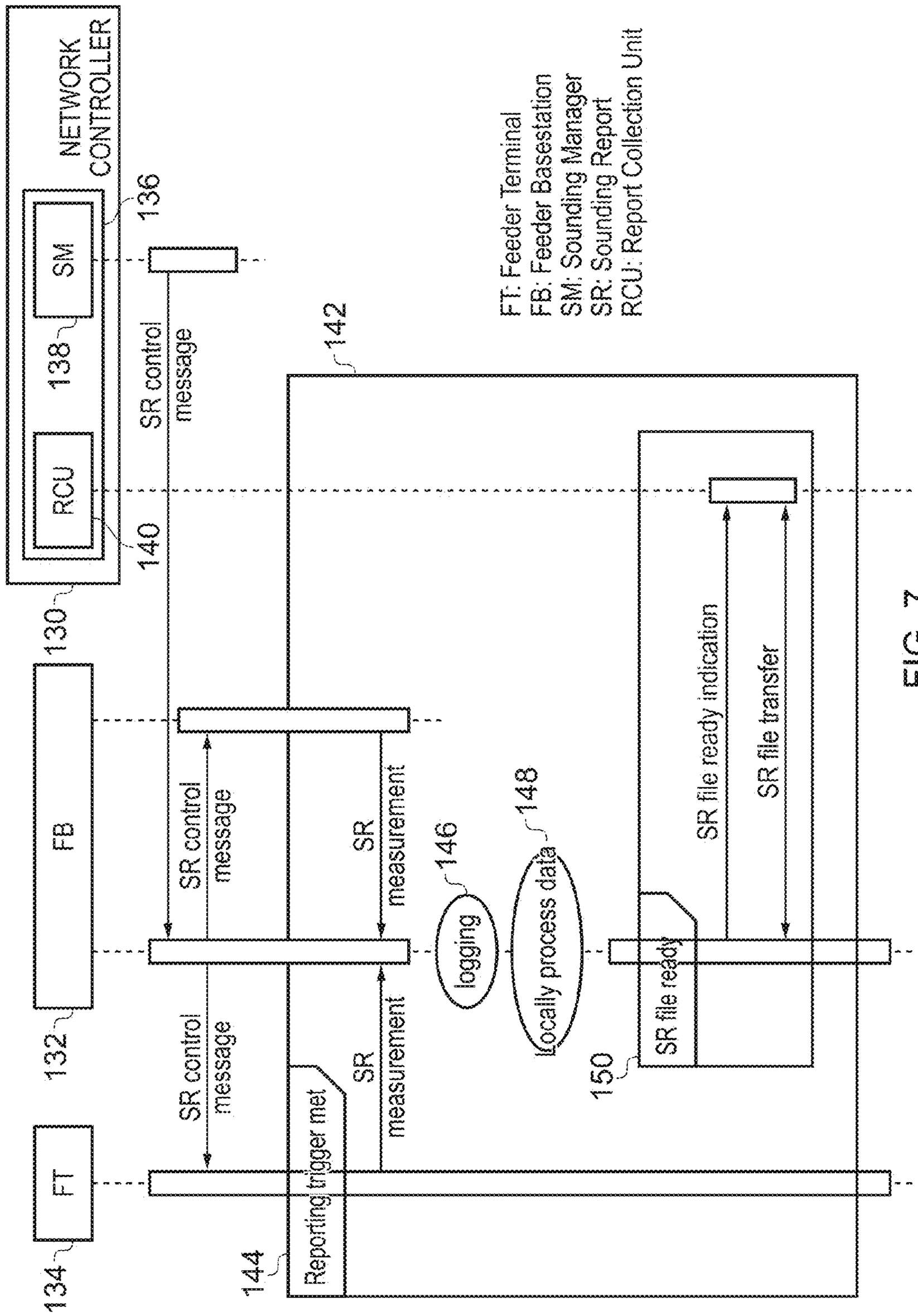
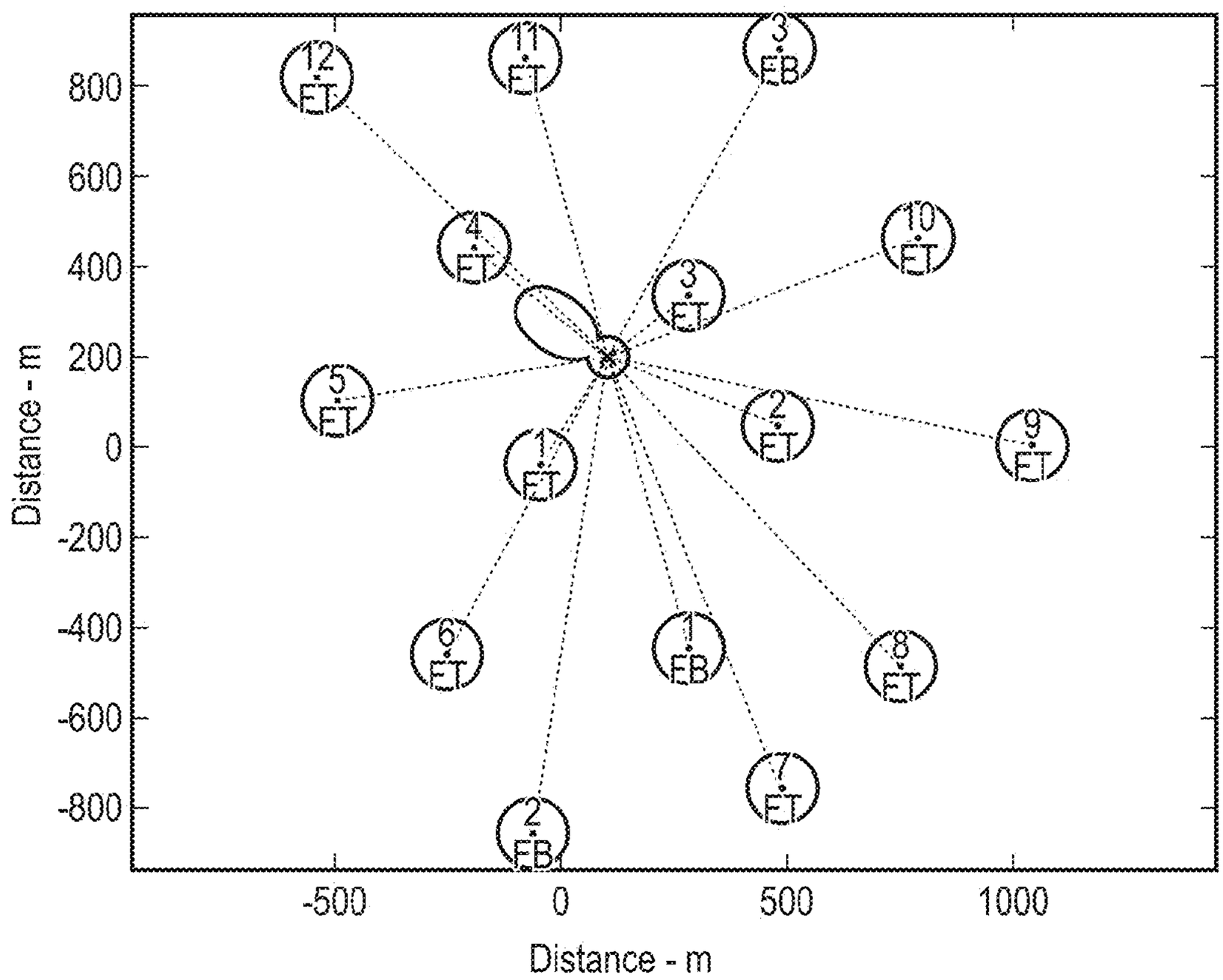

NETWORK CONTROLLER
SM
RCU
130
138
140
136
142
FT: Feeder Terminal
FB: Feeder Basestation
SM: Sounding Manager
SR: Sounding Report
RCU: Report Collection Unit
SR control message
FB
132
FT
134
SR control message
SR control message
SR measurement
SR measurement
logging
146
Locally process data
148
Reporting trigger met
144
SR file ready
150
SR file ready indication
SR file transfer

FIG. 7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0
-200
-400
-600
-800
Distance - m
-500
0
500
1000
Distance - m

FIG. 8

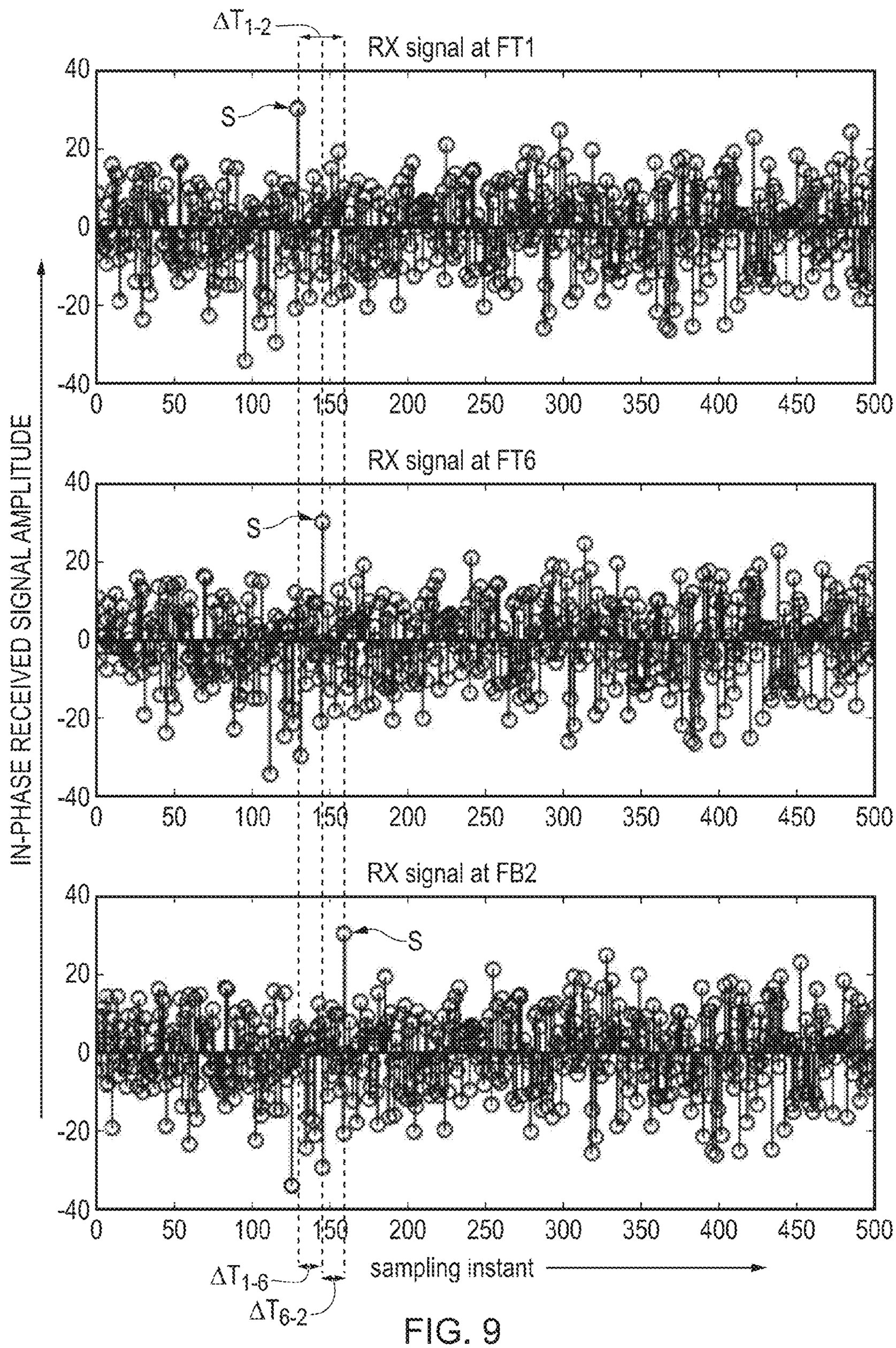

ΔT1-2
RX signal at FT1
S
RX signal at FT6
S
RX signal at FB2
S
IN-PHASE RECEIVED SIGNAL AMPLITUDE
40
20
0
-20
-40
0
50
100
150
200
250
300
350
400
450
500
sampling instant
ΔT1-6
ΔT6-2

FIG. 9

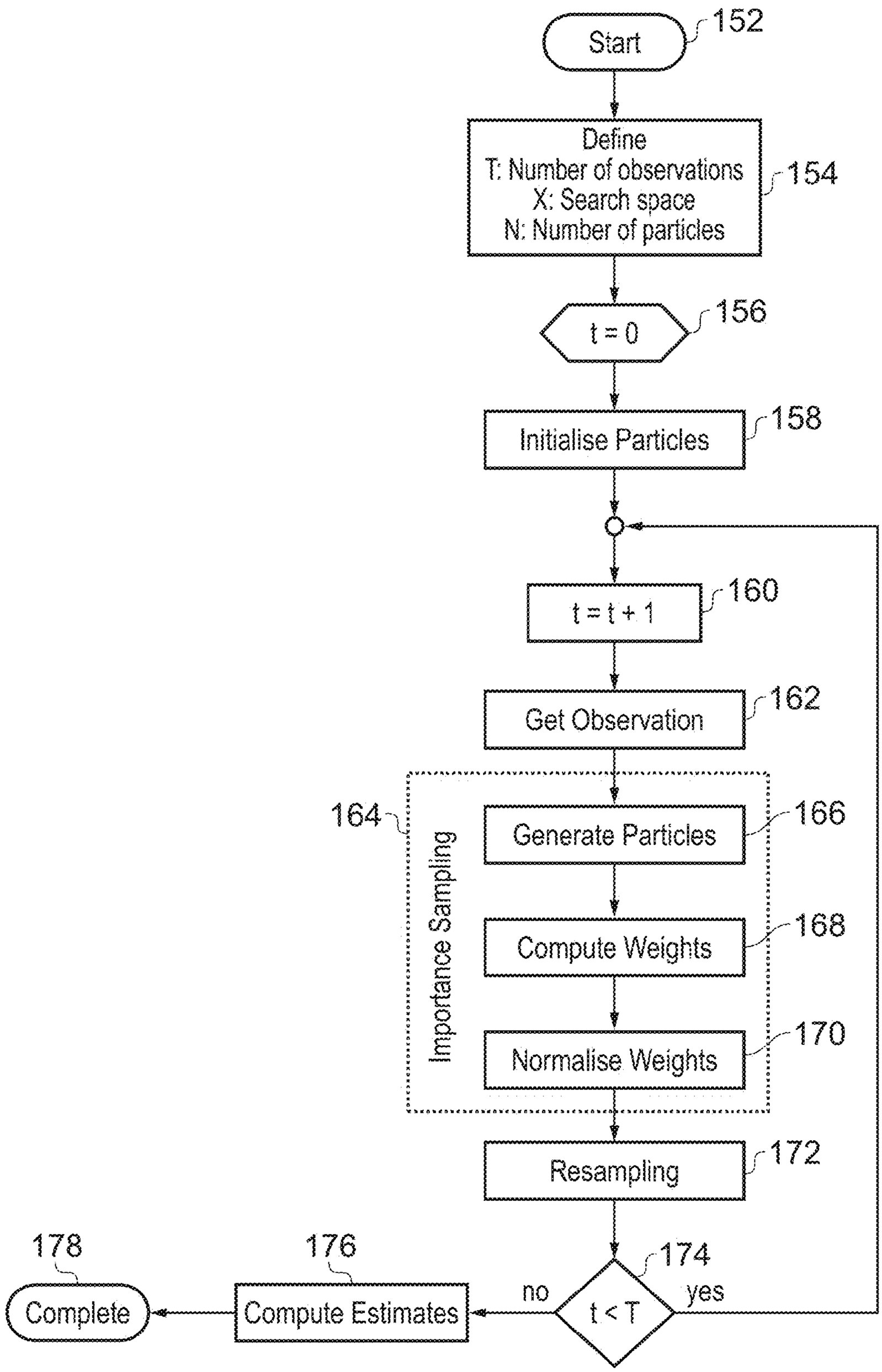

Start
152
Define
T: Number of observations
X: Search space
N: Number of particles
154
t = 0
156
Initialise Particles
158
t = t + 1
160
Get Observation
162
164
Importance Sampling
Generate Particles
166
Compute Weights
168
Normalise Weights
170
Resampling
172
174
t < T
no
yes
176
Compute Estimates
178
Complete

FIG. 10

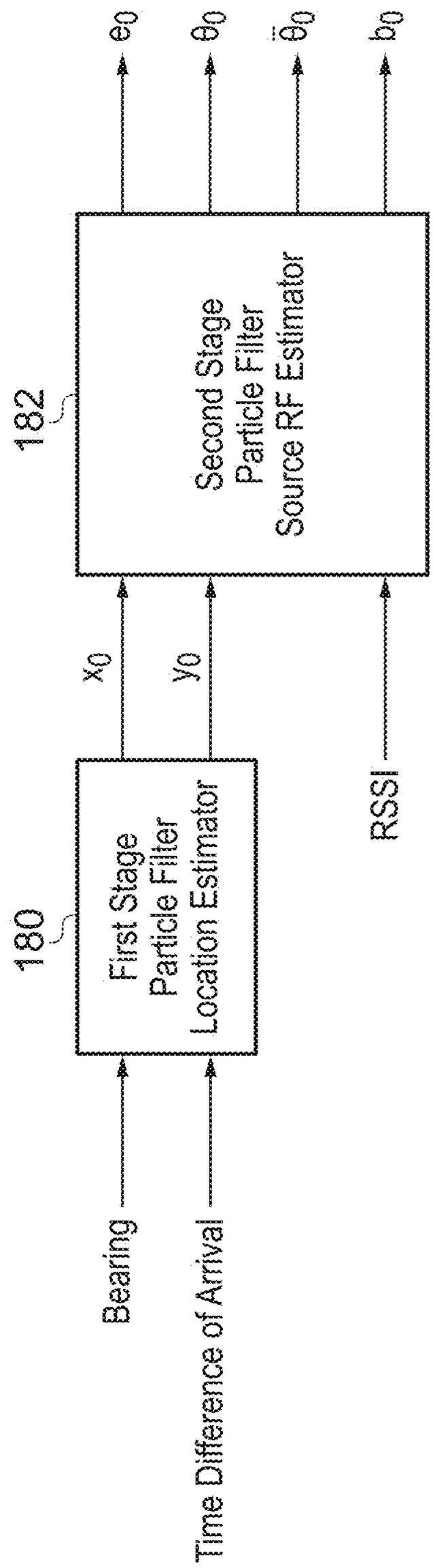

Bearing
Time Difference of Arrival
180
First Stage
Particle Filter
Location Estimator
x_0
y_0
RSSI
182
Second Stage
Particle Filter
Source RF Estimator
e_0
θ_0
$\dot{\theta}_0$
b_0

FIG. 11

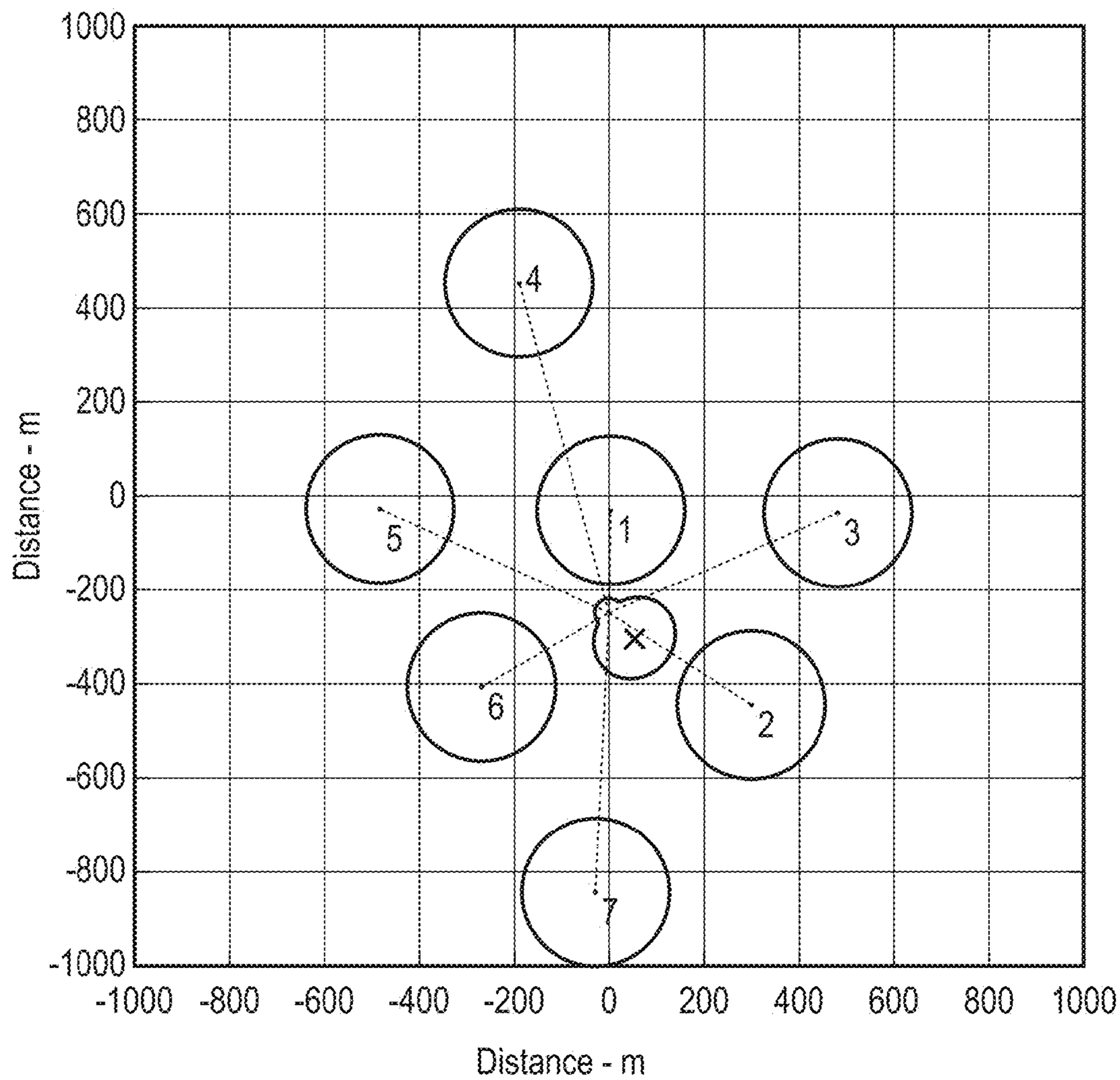

1000
800
600
400
200
0
-200
-400
-600
-800
-1000
Distance - m
-1000 -800 -600 -400 -200 0 200 400 600 800 1000
Distance - m
1
2
3
4
5
6
7

FIG. 12

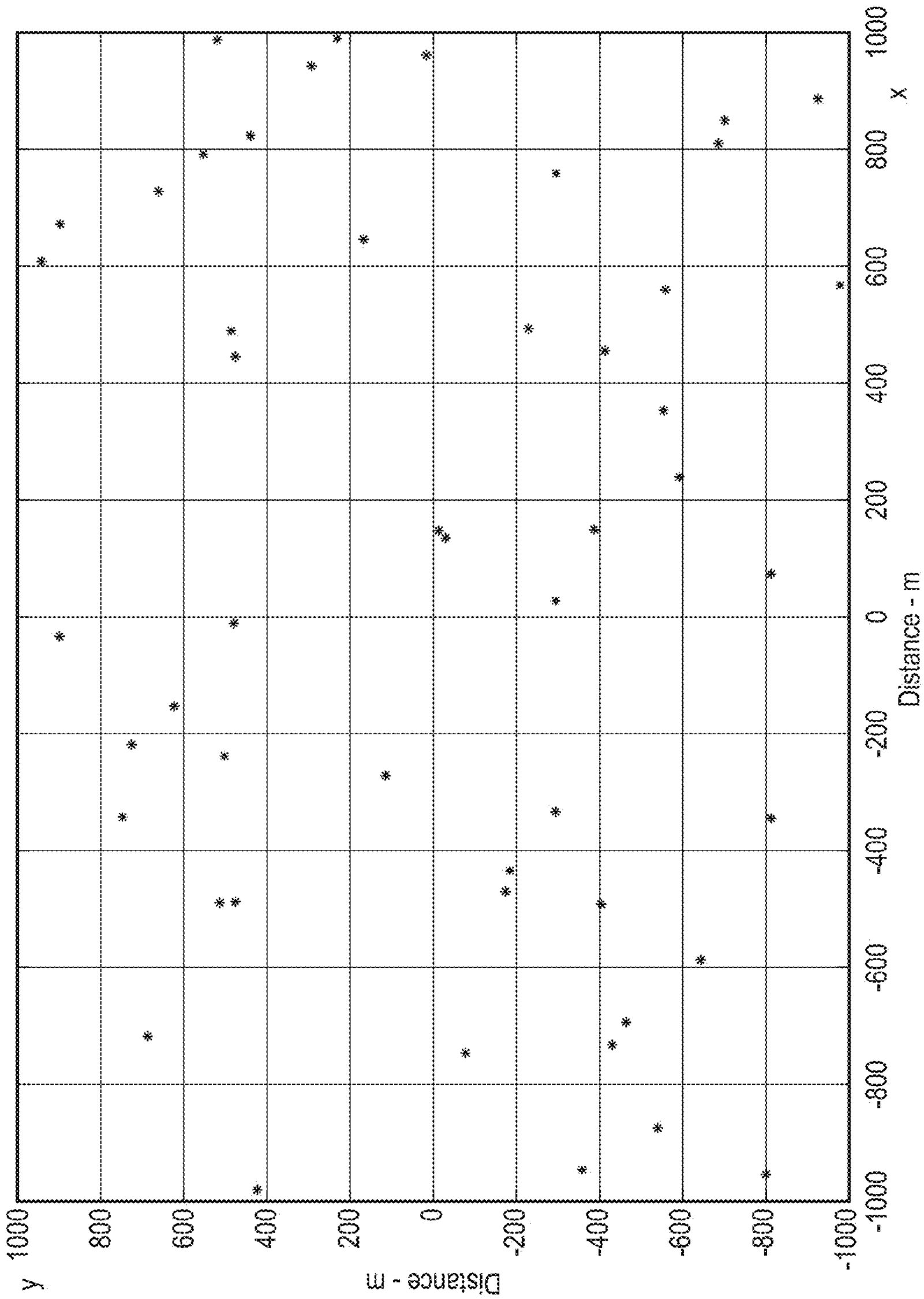

y
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
Distance - m
x
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
Distance - m

FIG. 13

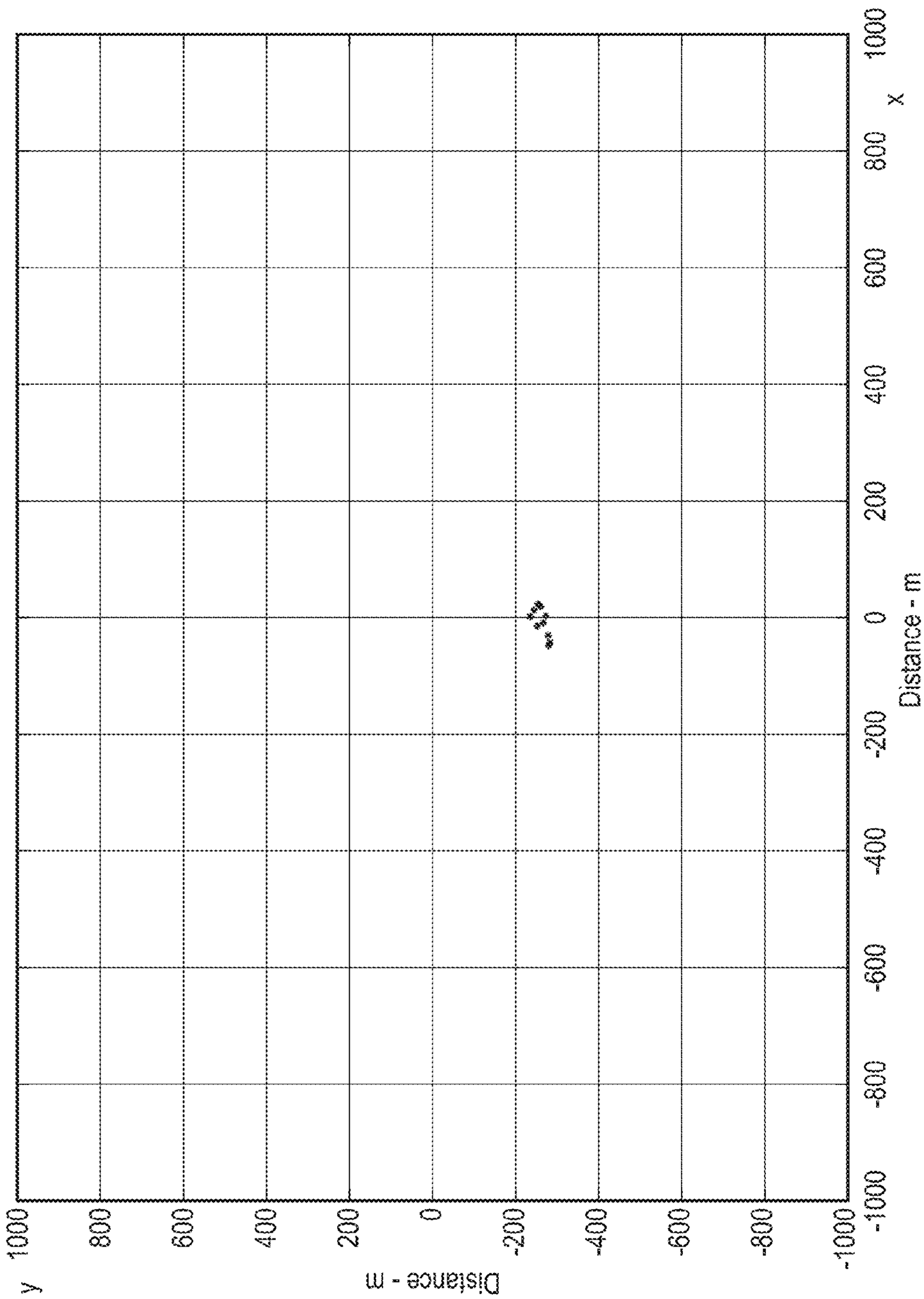

y
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
Distance - m
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
x
Distance - m

FIG. 14

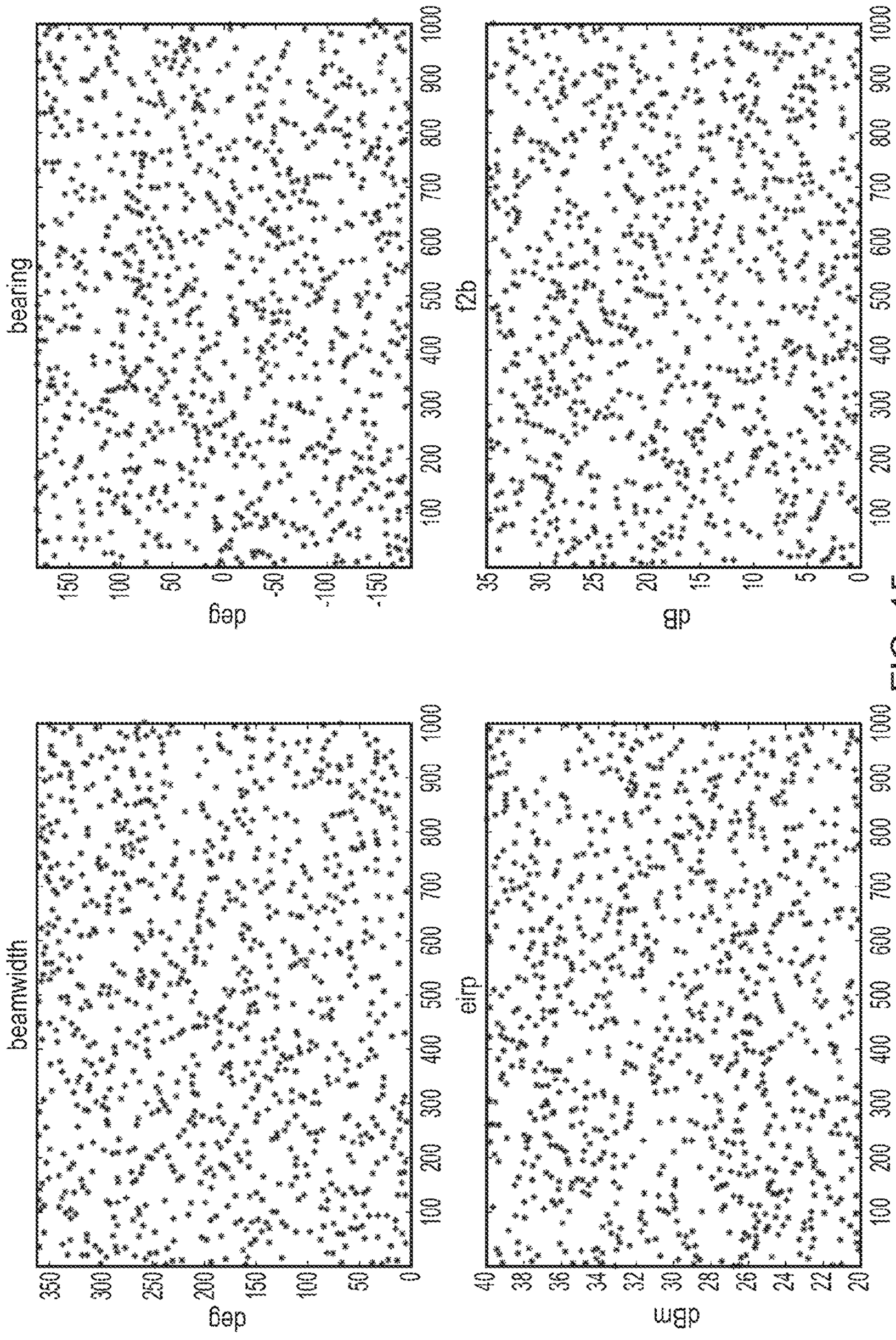


FIG. 15

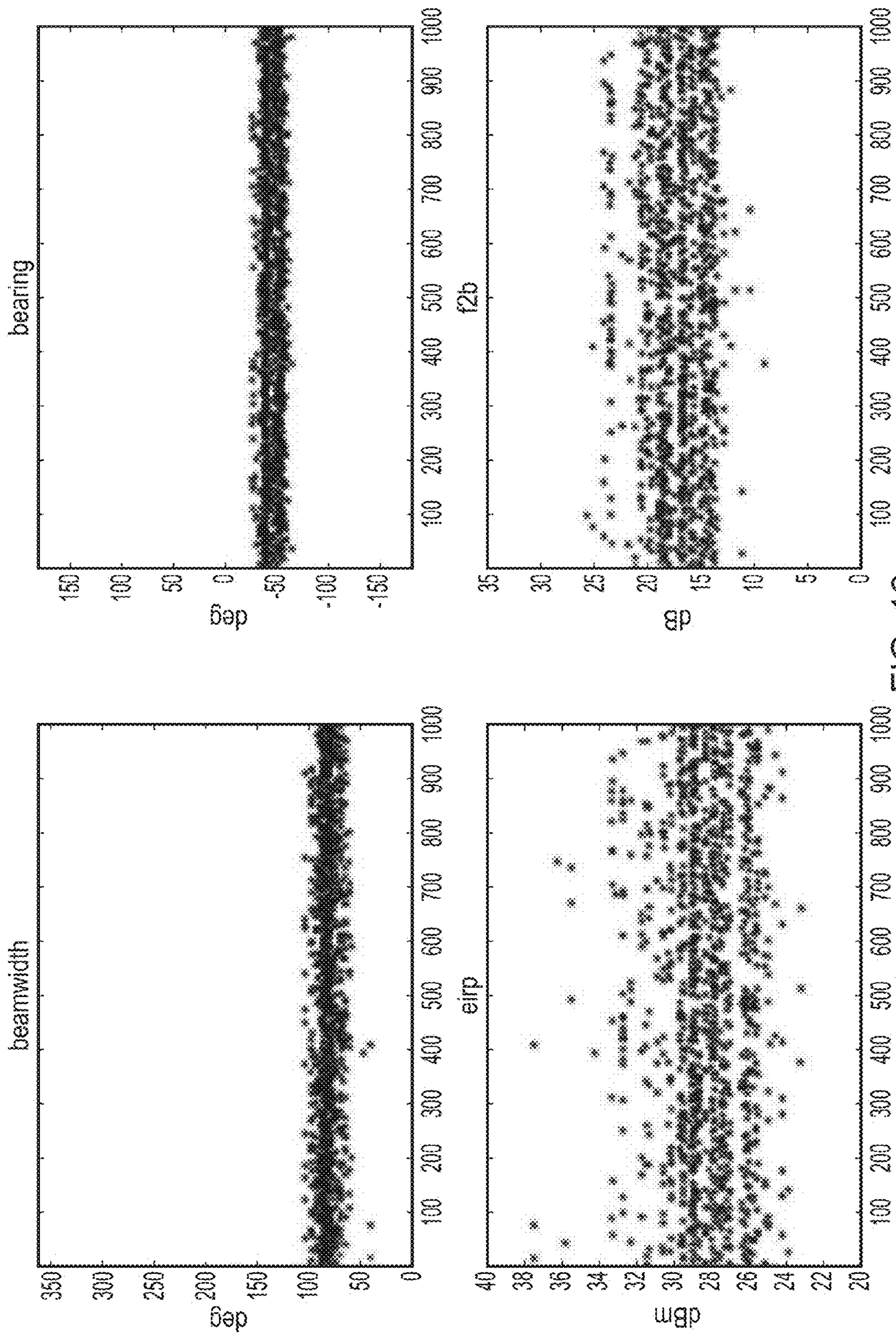


FIG. 16

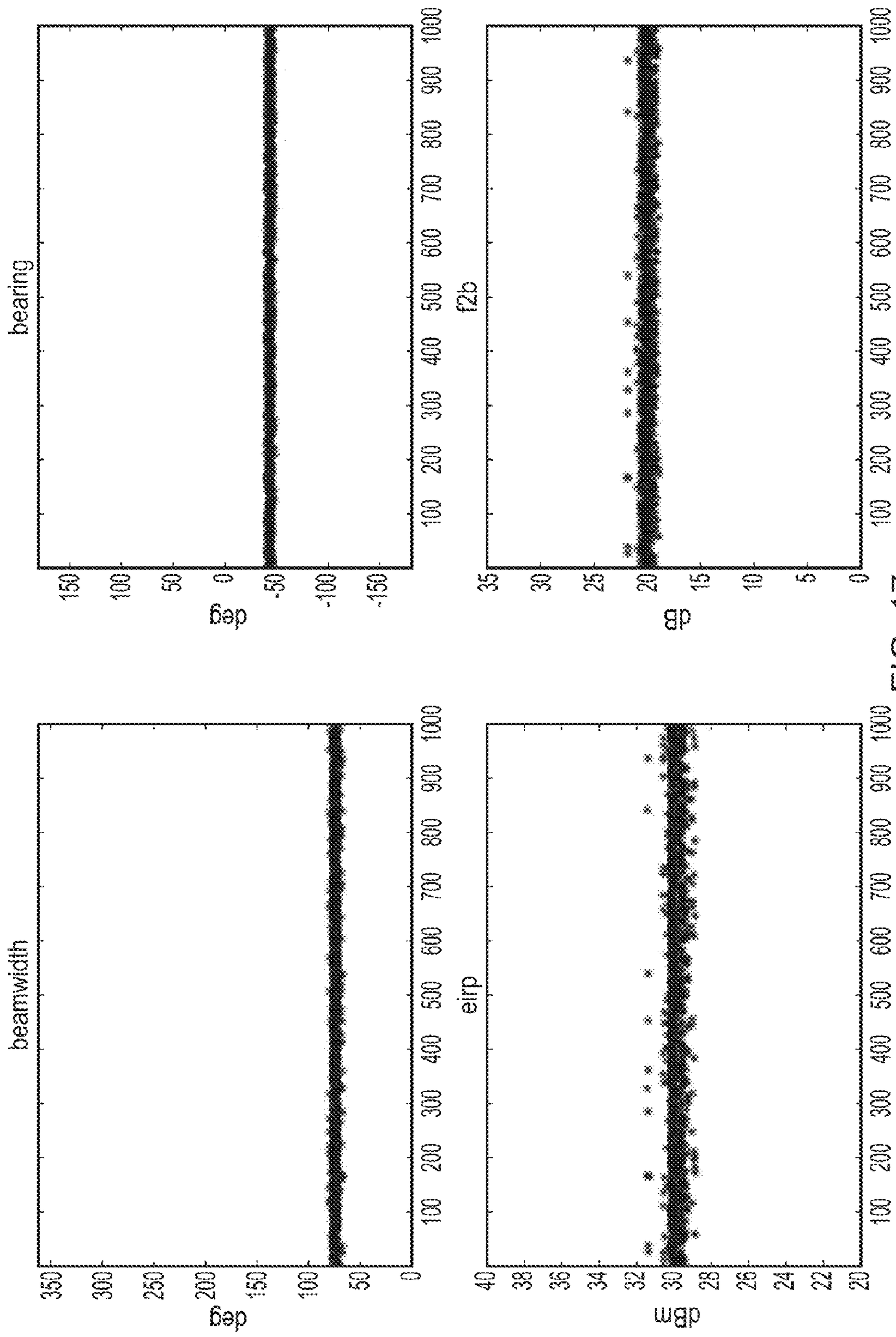

bearing
deg
150
100
50
0
-50
-100
-150
100 200 300 400 500 600 700 800 900 1000
f2b
db
35 30 25 20 15 10 5 0
beamwidth
deg
350 300 250 200 150 100 50 0
100 200 300 400 500 600 700 800 900 1000
eirp
dBm
40 38 36 34 32 30 28 26 24 22 20
100 200 300 400 500 600 700 800 900 1000

FIG. 17

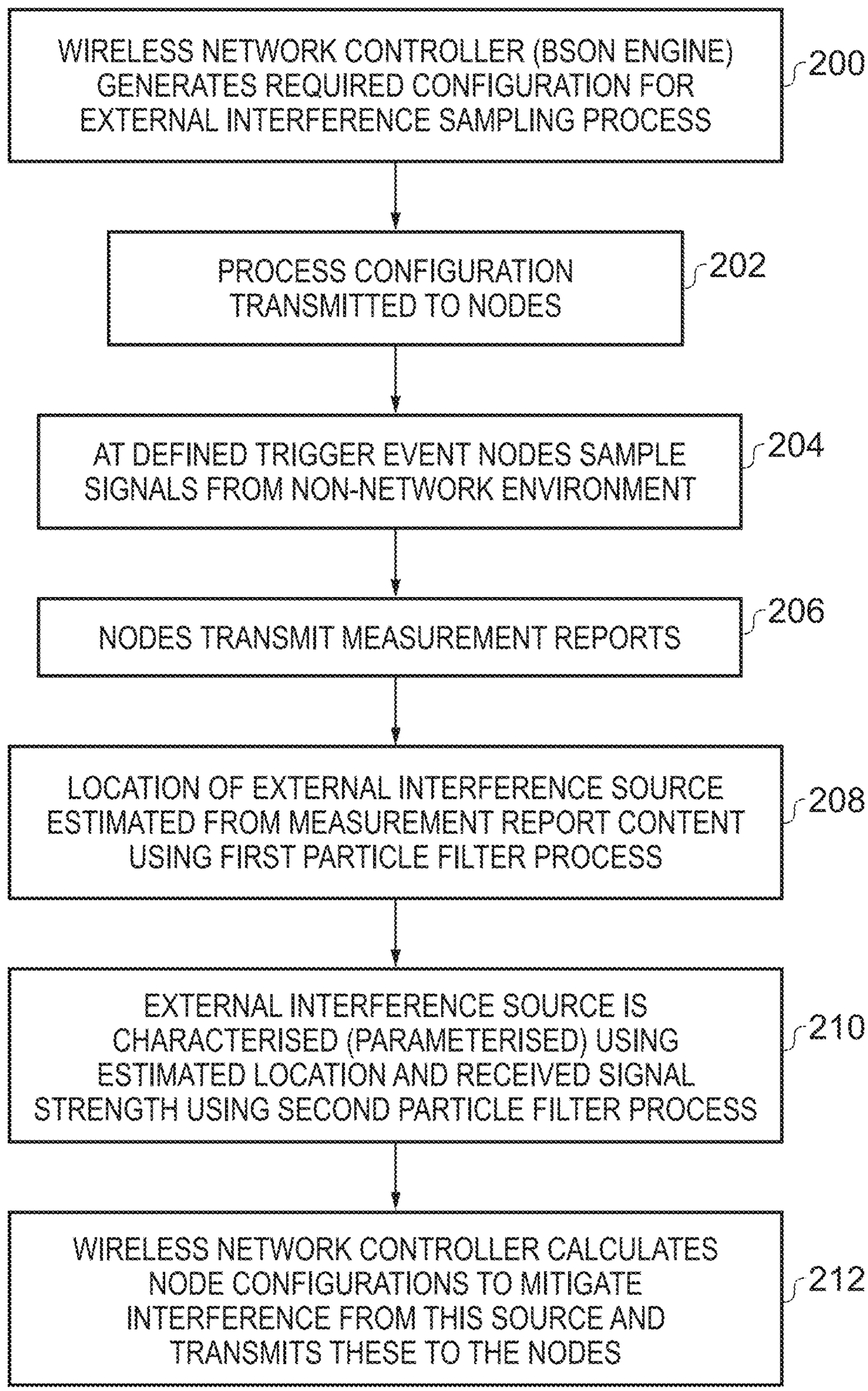

WIRELESS NETWORK CONTROLLER (BSON ENGINE) GENERATES REQUIRED CONFIGURATION FOR EXTERNAL INTERFERENCE SAMPLING PROCESS
200
PROCESS CONFIGURATION TRANSMITTED TO NODES
202
AT DEFINED TRIGGER EVENT NODES SAMPLE SIGNALS FROM NON-NETWORK ENVIRONMENT
204
NODES TRANSMIT MEASUREMENT REPORTS
206
LOCATION OF EXTERNAL INTERFERENCE SOURCE ESTIMATED FROM MEASUREMENT REPORT CONTENT USING FIRST PARTICLE FILTER PROCESS
208
EXTERNAL INTERFERENCE SOURCE IS CHARACTERISED (PARAMETERISED) USING ESTIMATED LOCATION AND RECEIVED SIGNAL STRENGTH USING SECOND PARTICLE FILTER PROCESS
210
WIRELESS NETWORK CONTROLLER CALCULATES NODE CONFIGURATIONS TO MITIGATE INTERFERENCE FROM THIS SOURCE AND TRANSMITS THESE TO THE NODES
212

FIG. 18

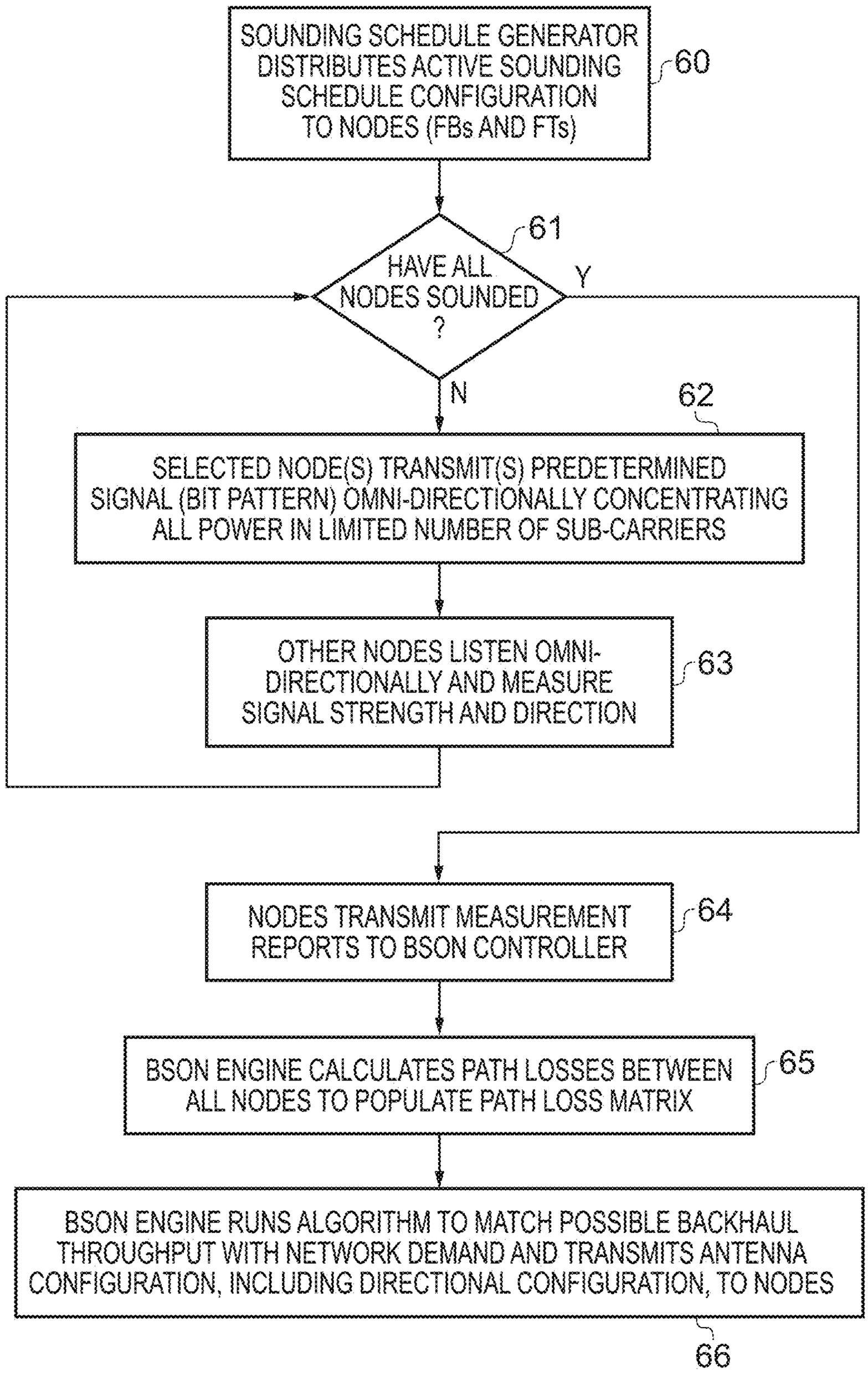

SOUNDING SCHEDULE GENERATOR DISTRIBUTES ACTIVE SOUNDING SCHEDULE CONFIGURATION TO NODES (FBs AND FTs)
60
HAVE ALL NODES SOUNDED ?
61
Y
N
SELECTED NODE(S) TRANSMIT(S) PREDETERMINED SIGNAL (BIT PATTERN) OMNI-DIRECTIONALLY CONCENTRATING ALL POWER IN LIMITED NUMBER OF SUB-CARRIERS
62
OTHER NODES LISTEN OMNI-DIRECTIONALLY AND MEASURE SIGNAL STRENGTH AND DIRECTION
63
NODES TRANSMIT MEASUREMENT REPORTS TO BSON CONTROLLER
64
BSON ENGINE CALCULATES PATH LOSSES BETWEEN ALL NODES TO POPULATE PATH LOSS MATRIX
65
BSON ENGINE RUNS ALGORITHM TO MATCH POSSIBLE BACKHAUL THROUGHPUT WITH NETWORK DEMAND AND TRANSMITS ANTENNA CONFIGURATION, INCLUDING DIRECTIONAL CONFIGURATION, TO NODES
66

FIG. 19

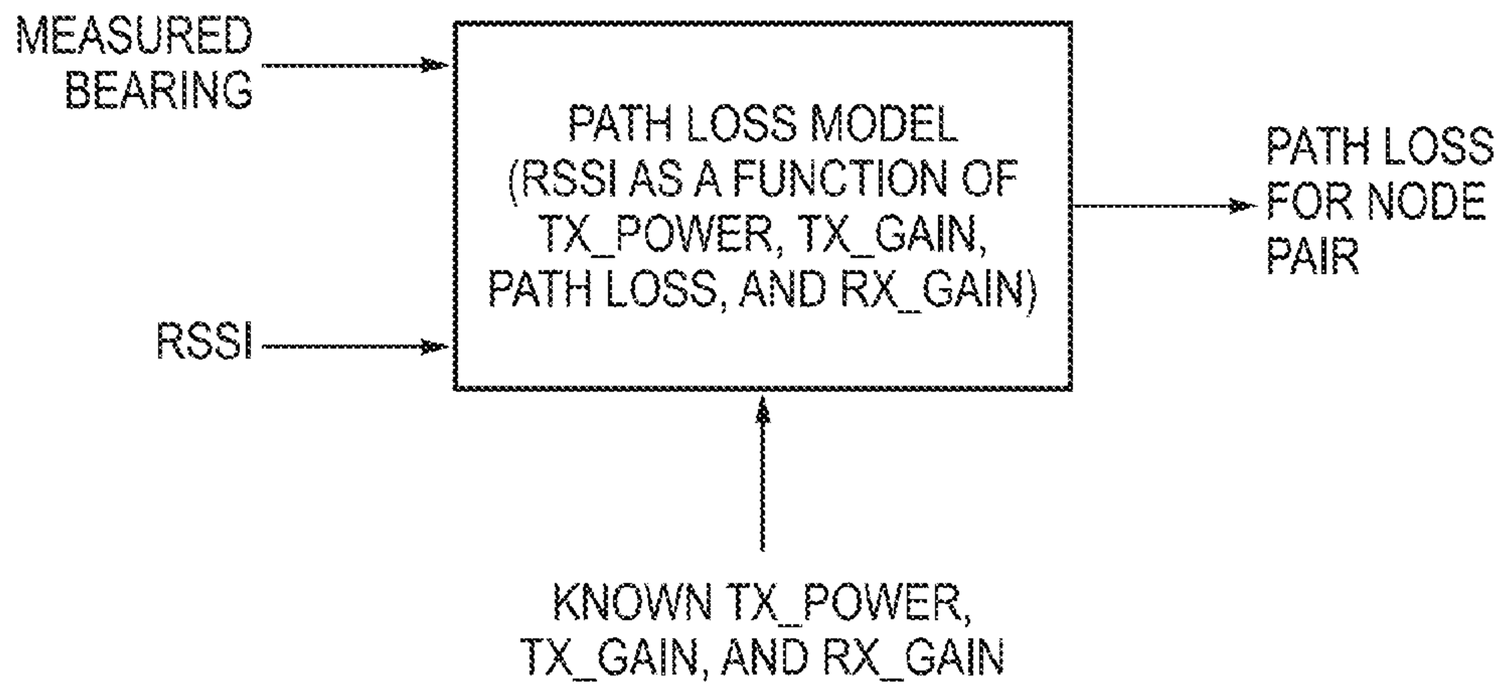

MEASURED BEARING
RSSI
PATH LOSS MODEL (RSSI AS A FUNCTION OF TX_POWER, TX_GAIN, PATH LOSS, AND RX_GAIN)
PATH LOSS FOR NODE PAIR
KNOWN TX_POWER, TX_GAIN, AND RX_GAIN

FIG. 20

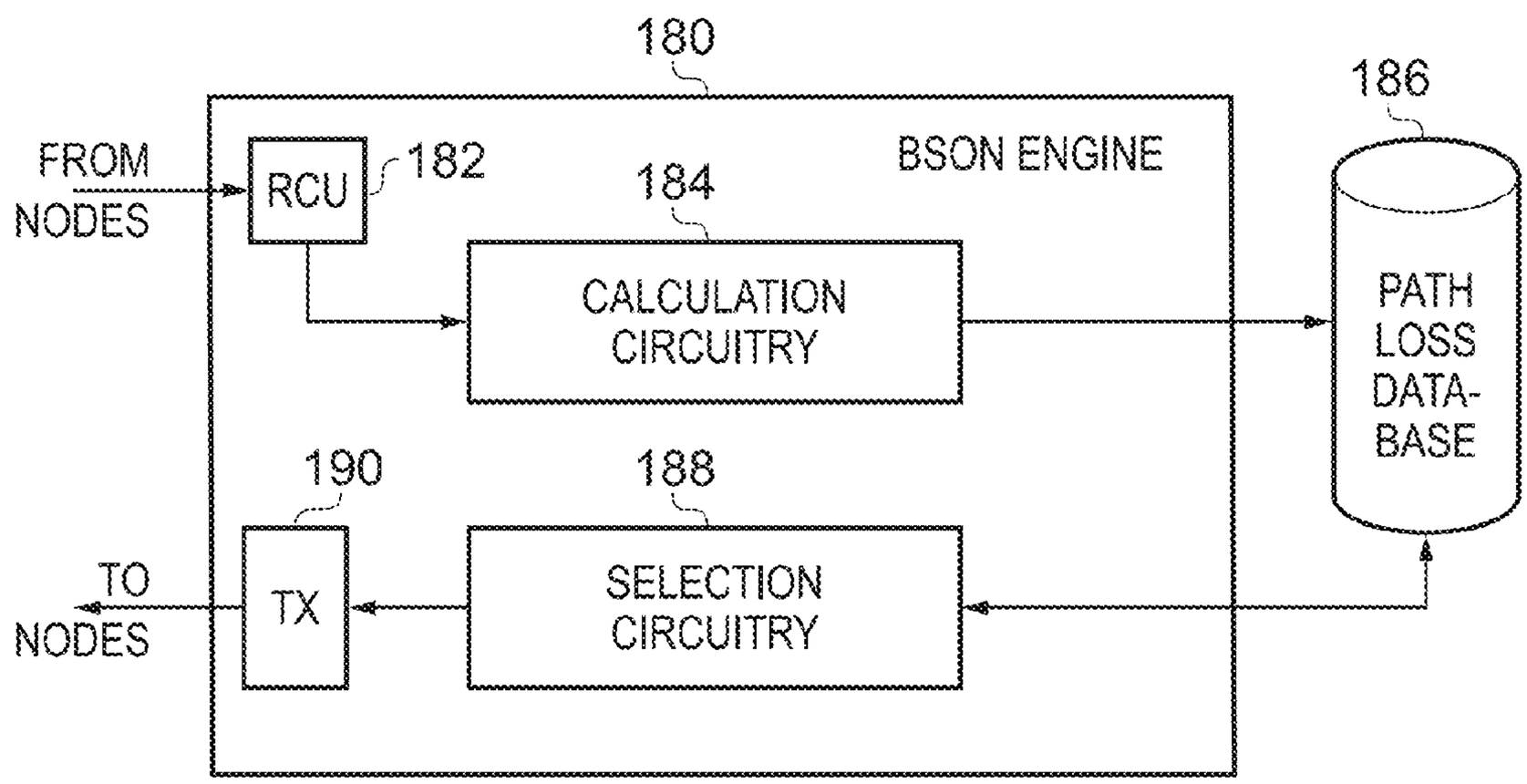

180
186
FROM NODES
RCU
182
184
BSON ENGINE
CALCULATION CIRCUITRY
PATH LOSS DATA-BASE
190
188
TO NODES
TX
SELECTION CIRCUITRY

FIG. 21

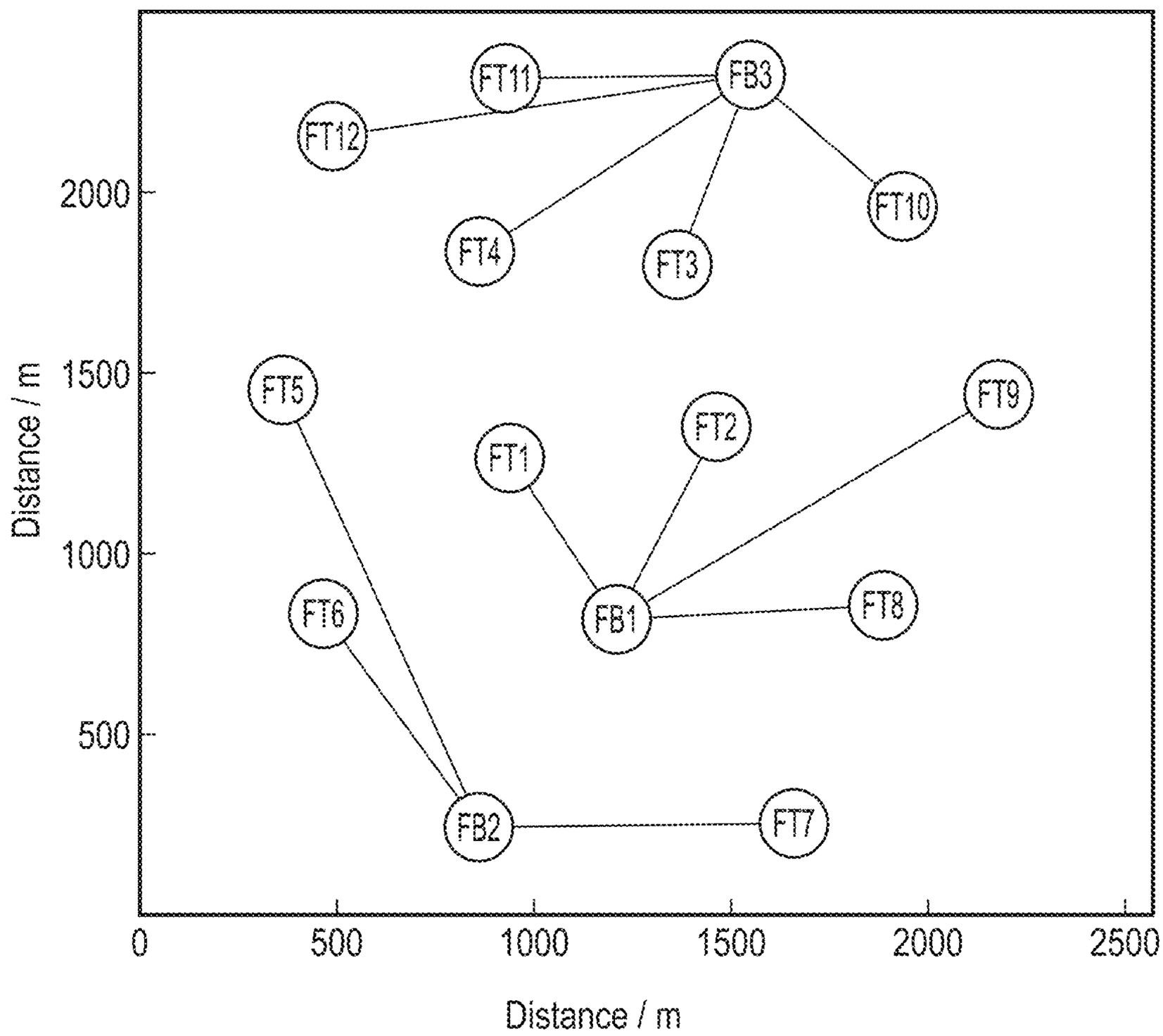

FT11
FB3
FT12
FT10
FT4
FT3
FT5
FT9
FT2
FT1
FT6
FB1
FT8
FB2
FT7
2000
1500
1000
500
Distance / m
0
500
1000
1500
2000
2500
Distance / m

FIG. 22

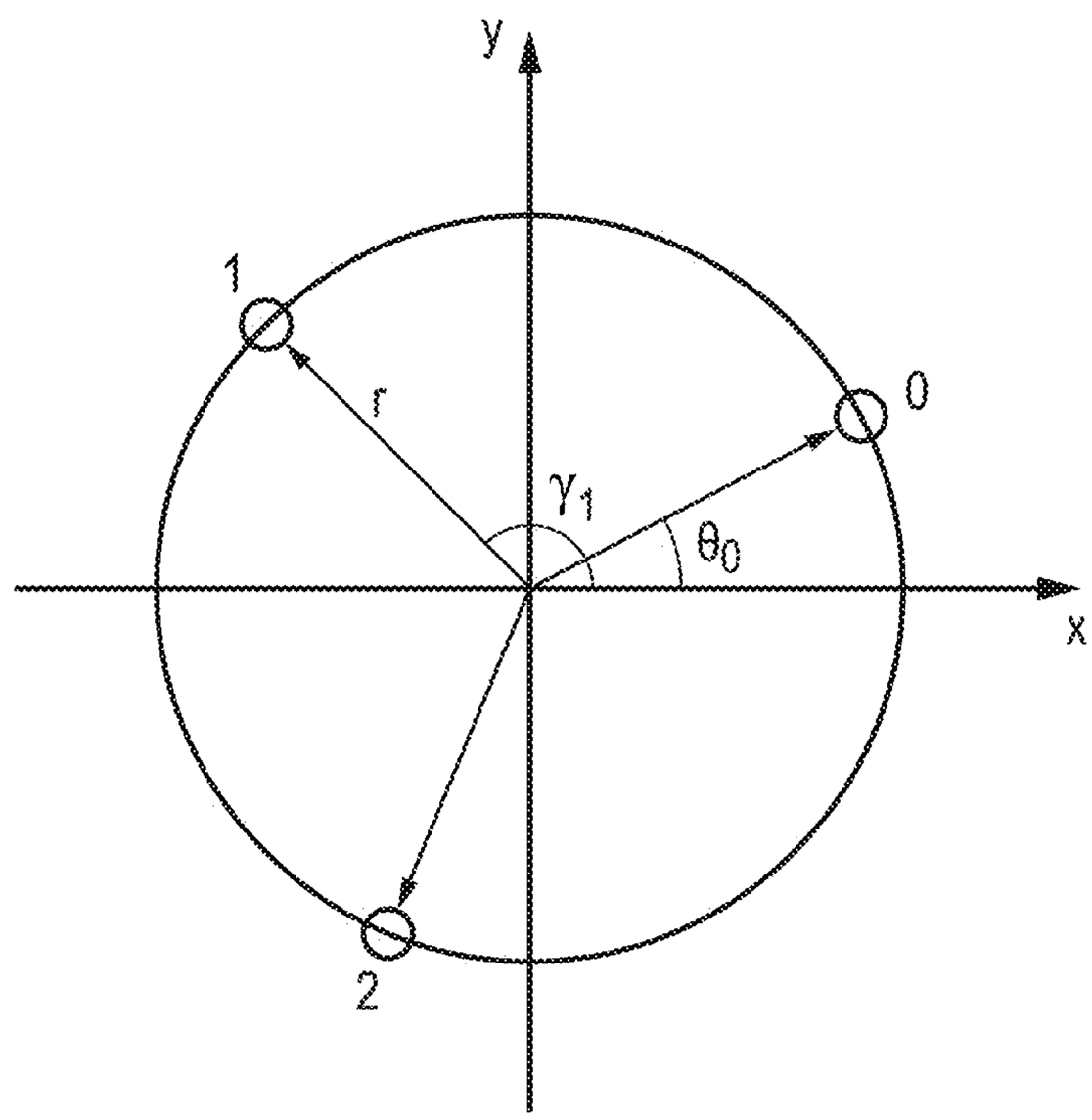


FIG. 23

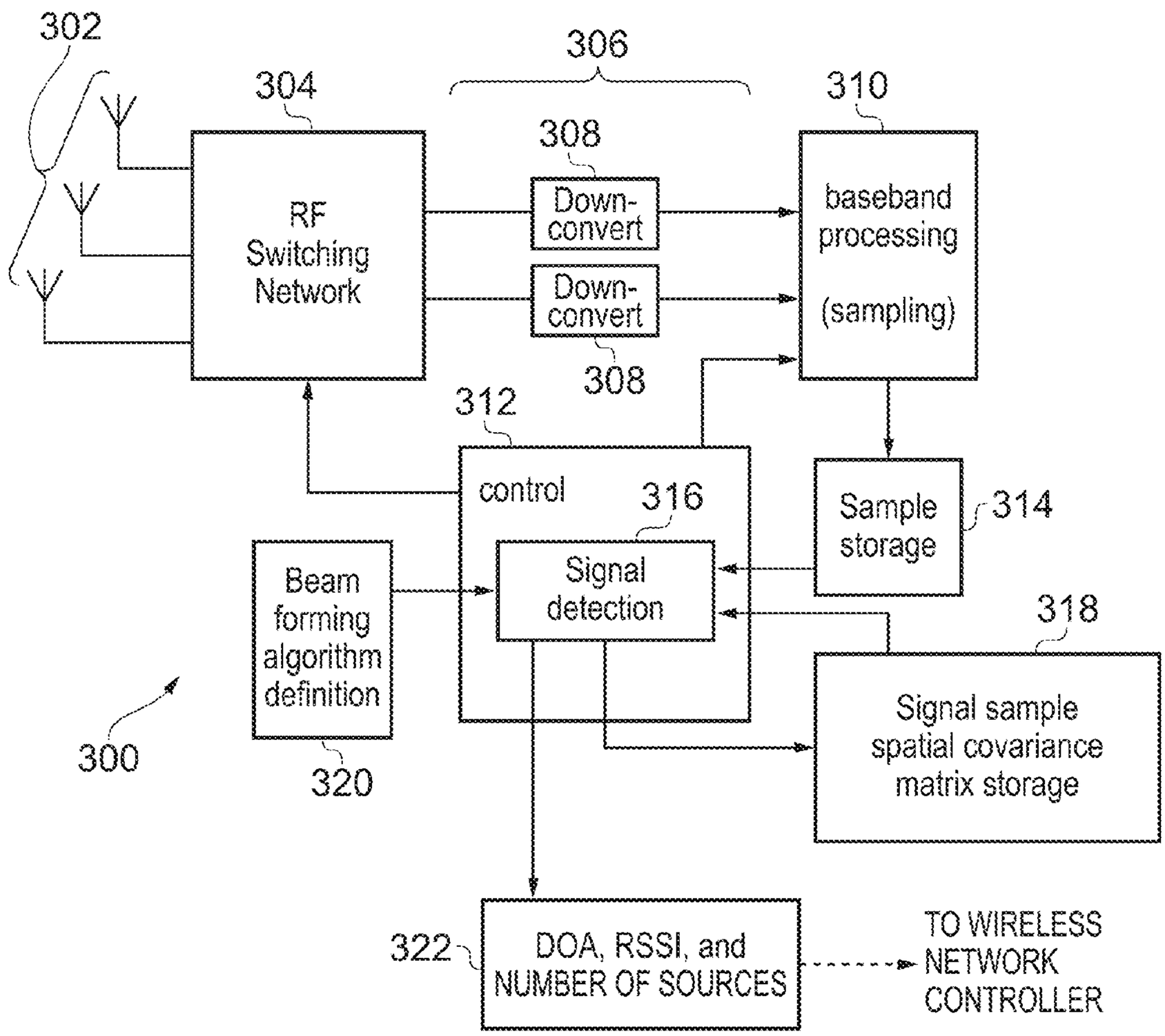

302
304
306
308
310
RF Switching Network
Down-convert
Down-convert
baseband processing
(sampling)
308
312
control
316
Sample storage
314
Beam forming algorithm definition
Signal detection
318
Signal sample spatial covariance matrix storage
300
320
322
DOA, RSSI, and NUMBER OF SOURCES
TO WIRELESS NETWORK CONTROLLER

FIG. 24

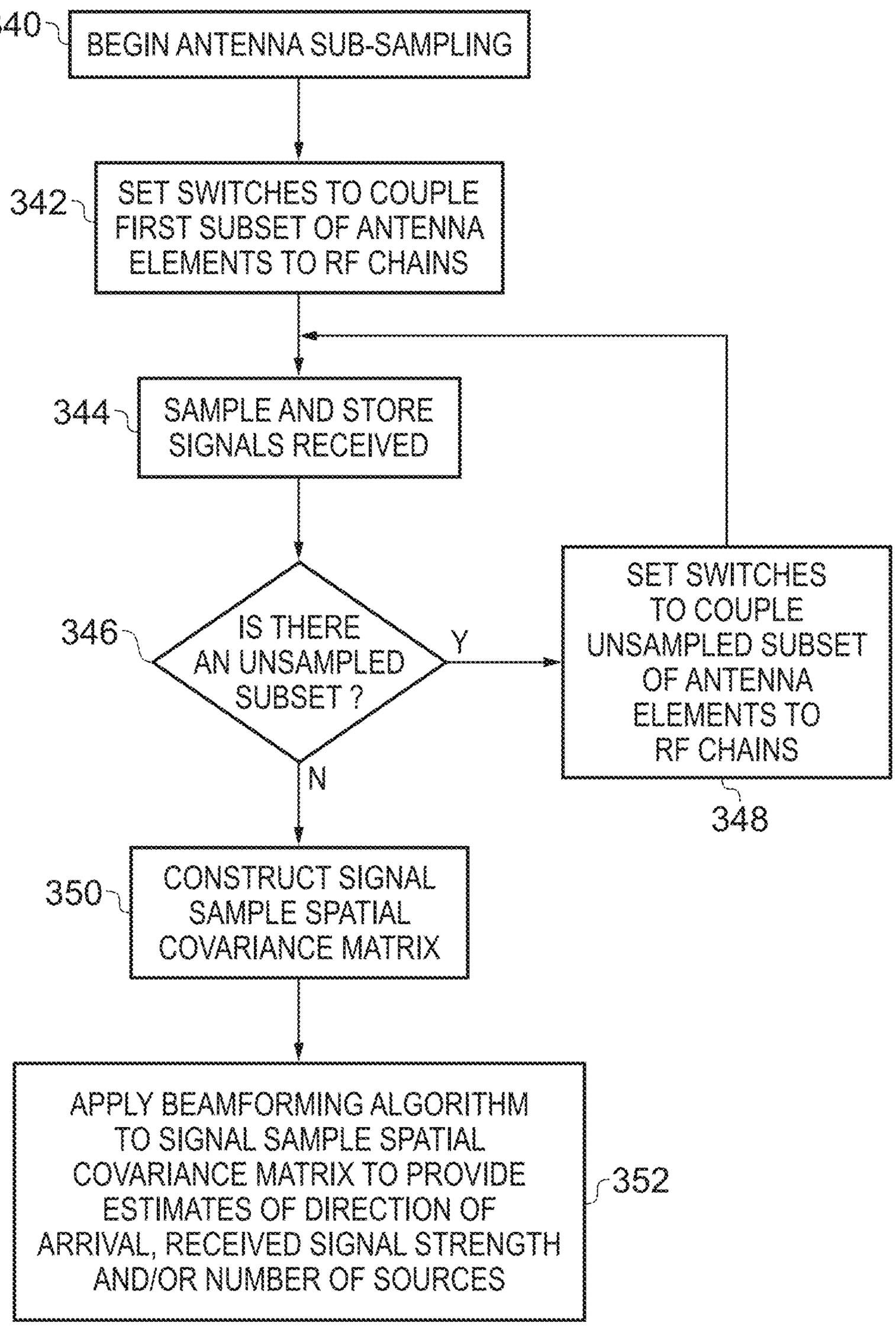

340
BEGIN ANTENNA SUB-SAMPLING
342
SET SWITCHES TO COUPLE FIRST SUBSET OF ANTENNA ELEMENTS TO RF CHAINS
344
SAMPLE AND STORE SIGNALS RECEIVED
346
IS THERE AN UNSAMPLED SUBSET ?
Y
N
SET SWITCHES TO COUPLE UNSAMPLED SUBSET OF ANTENNA ELEMENTS TO RF CHAINS
348
350
CONSTRUCT SIGNAL SAMPLE SPATIAL COVARIANCE MATRIX
APPLY BEAMFORMING ALGORITHM TO SIGNAL SAMPLE SPATIAL COVARIANCE MATRIX TO PROVIDE ESTIMATES OF DIRECTION OF ARRIVAL, RECEIVED SIGNAL STRENGTH AND/OR NUMBER OF SOURCES
352

FIG. 25

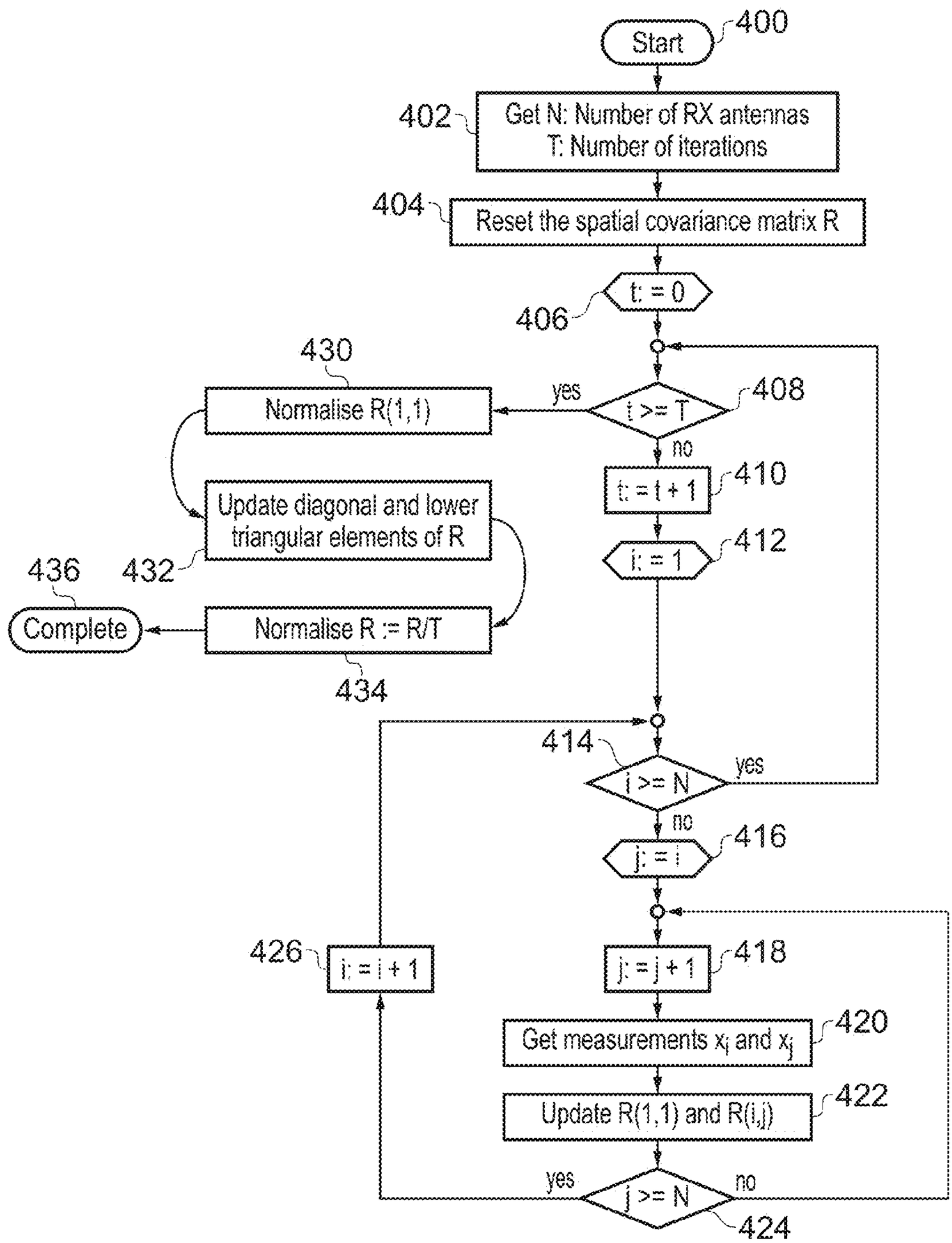

Start
400
Get N: Number of RX antennas
T: Number of iterations
402
Reset the spatial covariance matrix R
404
t: = 0
406
t >= T
408
yes
no
Normalise R(1,1)
430
t: = t + 1
410
Update diagonal and lower triangular elements of R
432
i: = 1
412
436
Complete
Normalise R := R/T
434
414
i >= N
yes
no
j: = i
416
426
i: = i + 1
j: = j + 1
418
Get measurements x_i and x_j
420
Update R(1,1) and R(i,j)
422
yes
j >= N
no
424

FIG. 26

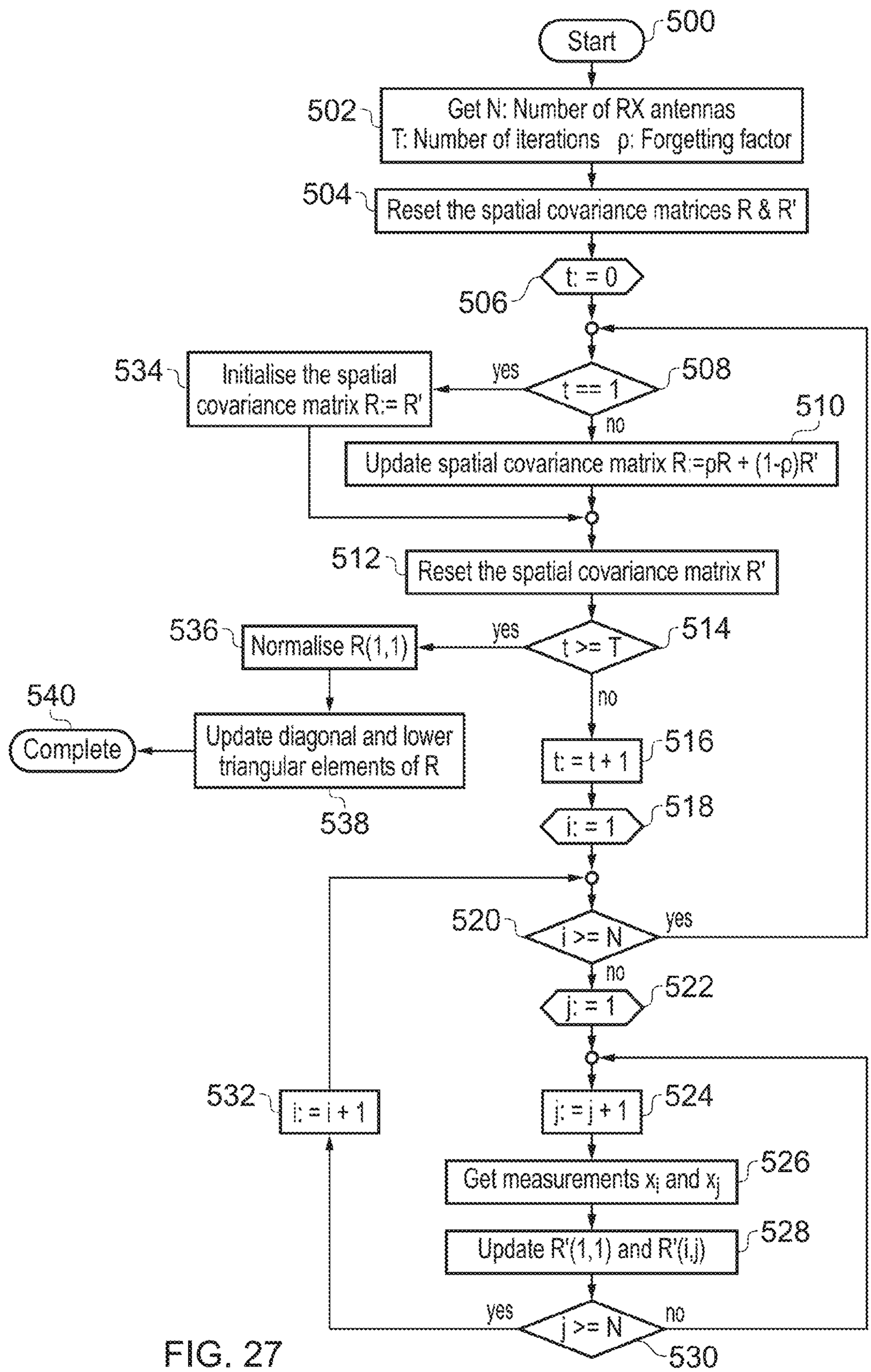
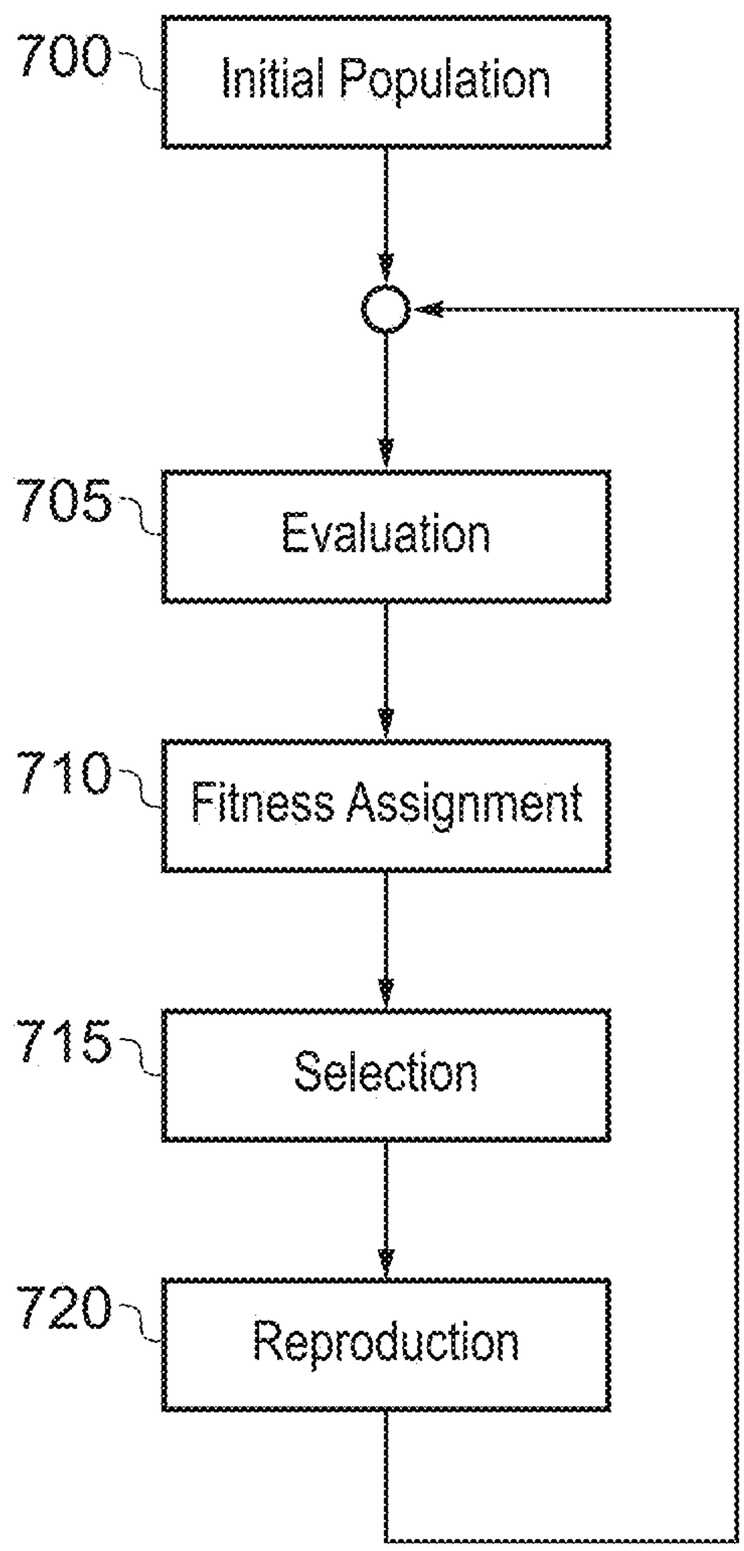

Start
500
502
Get N: Number of RX antennas
T: Number of iterations ρ: Forgetting factor
504
Reset the spatial covariance matrices R & R'
t: = 0
506
534
Initialise the spatial covariance matrix R:= R'
yes
t == 1
508
no
510
Update spatial covariance matrix R:=ρR + (1-ρ)R'
512
Reset the spatial covariance matrix R'
536
Normalise R(1,1)
yes
t >= T
514
no
540
Complete
Update diagonal and lower triangular elements of R
538
t: = t + 1
516
i: = 1
518
520
i >= N
yes
no
j: = 1
522
532
i: = i + 1
j: = j + 1
524
Get measurements x_i and x_j
526
Update R'(1,1) and R'(i,j)
528
yes
j >= N
no
530

FIG. 27



Steps in an evolutionary algorithm

FIG. 28

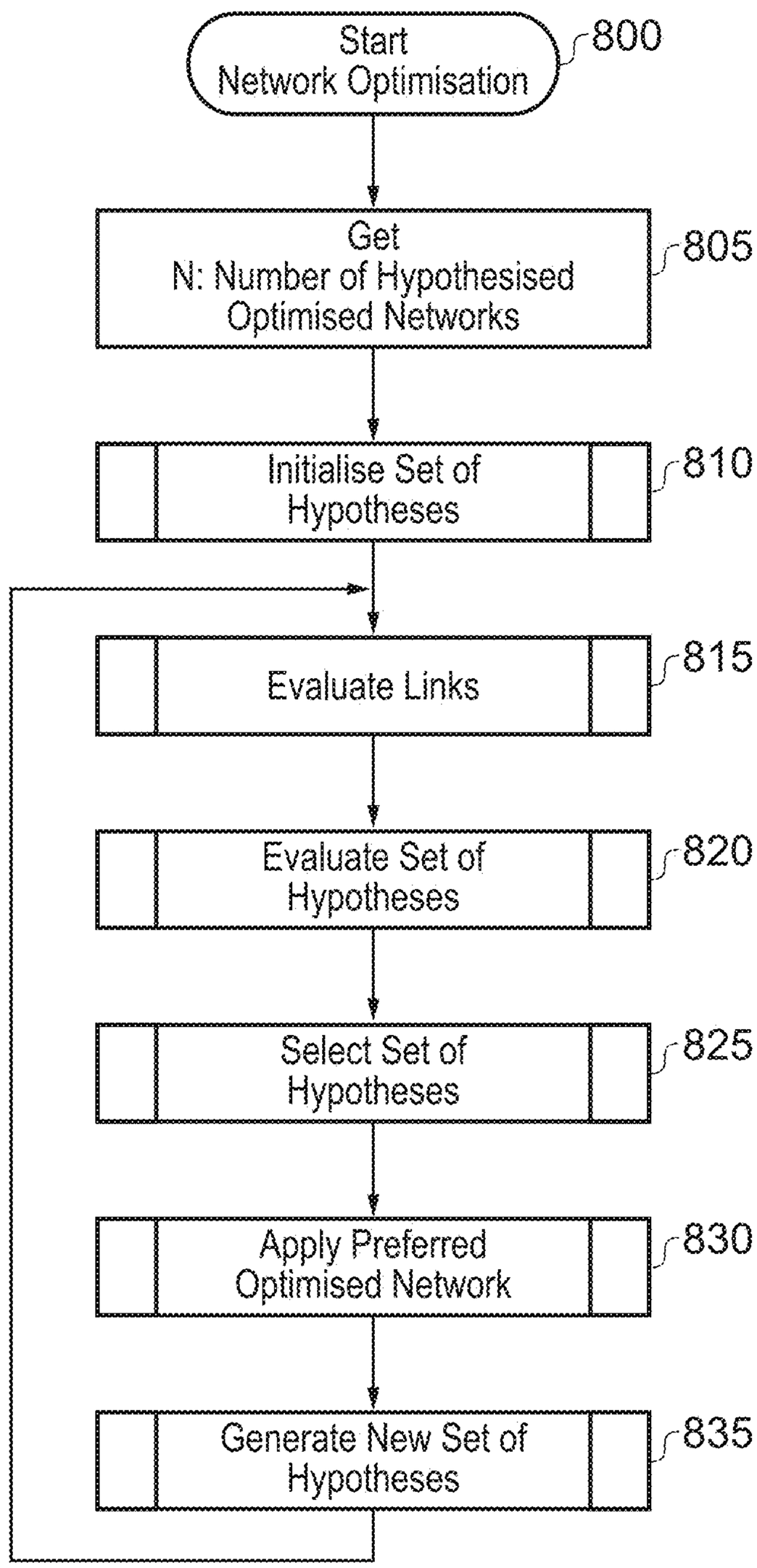

Start
Network Optimisation
800
Get
N: Number of Hypothesised
Optimised Networks
805
Initialise Set of
Hypotheses
810
Evaluate Links
815
Evaluate Set of
Hypotheses
820
Select Set of
Hypotheses
825
Apply Preferred
Optimised Network
830
Generate New Set of
Hypotheses
835

FIG. 29

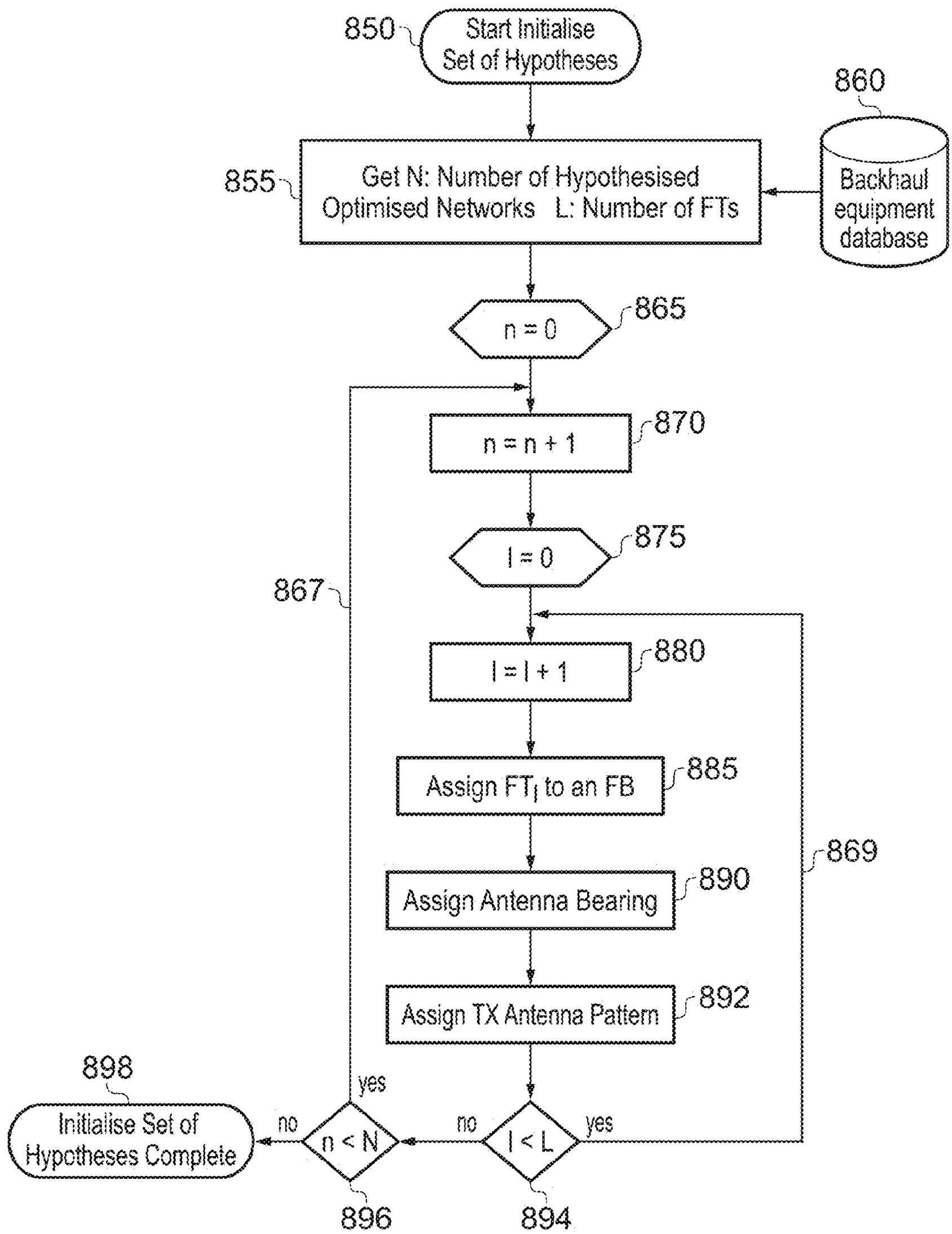

850
Start Initialise Set of Hypotheses
860
Backhaul equipment database
855
Get N: Number of Hypothesised Optimised Networks L: Number of FTs
n = 0
865
n = n + 1
870
l = 0
875
867
l = l + 1
880
Assign FTl to an FB
885
869
Assign Antenna Bearing
890
Assign TX Antenna Pattern
892
898
Initialise Set of Hypotheses Complete
no
n < N
yes
no
l < L
yes
896
894

FIG. 30

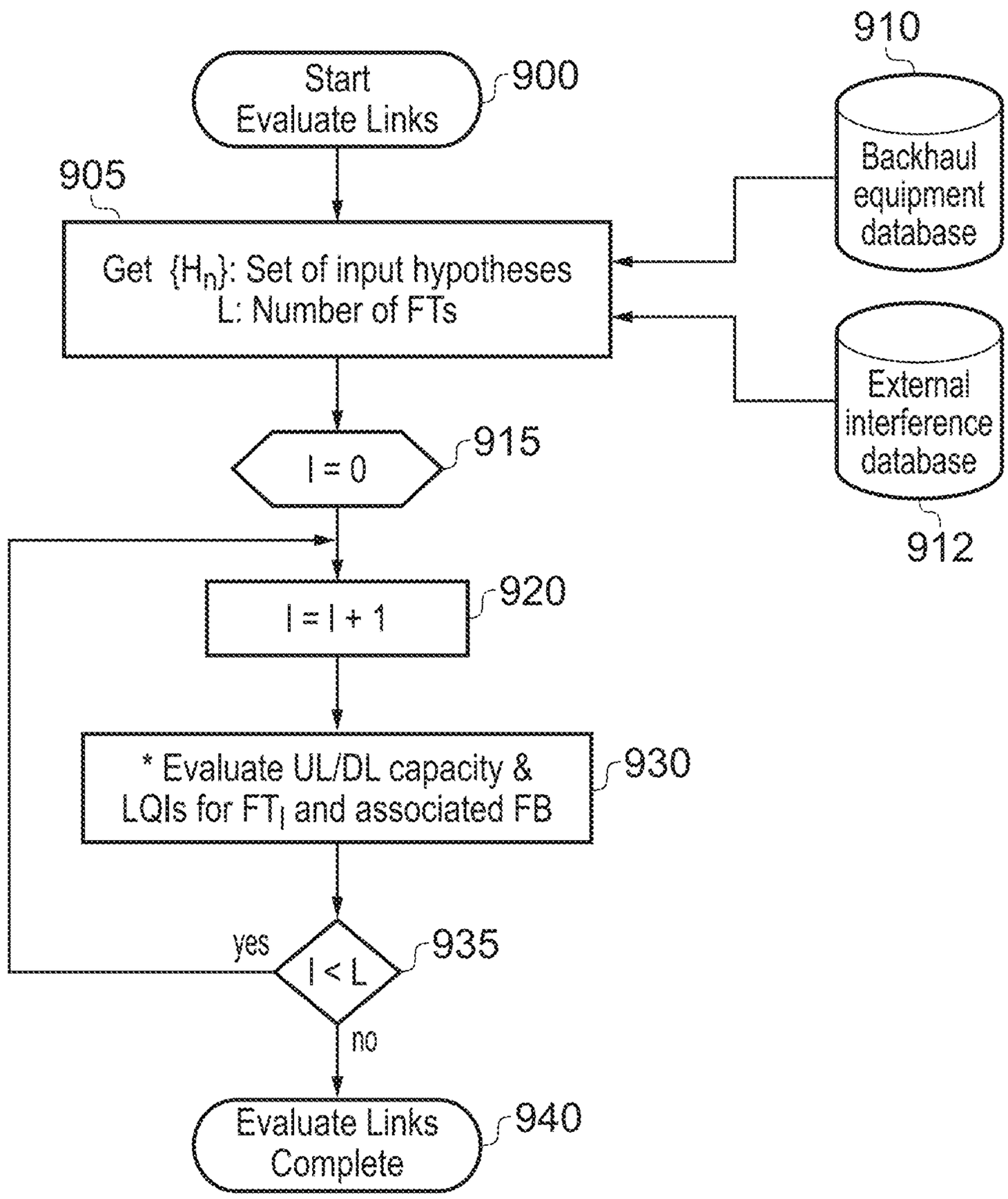

Start
Evaluate Links
900
910
Backhaul
equipment
database
905
Get {H_n}: Set of input hypotheses
L: Number of FTs
External
interference
database
912
l = 0
915
l = l + 1
920
* Evaluate UL/DL capacity &
LQIs for FT_l and associated FB
930
yes
l < L
935
no
Evaluate Links
Complete
940

FIG. 31

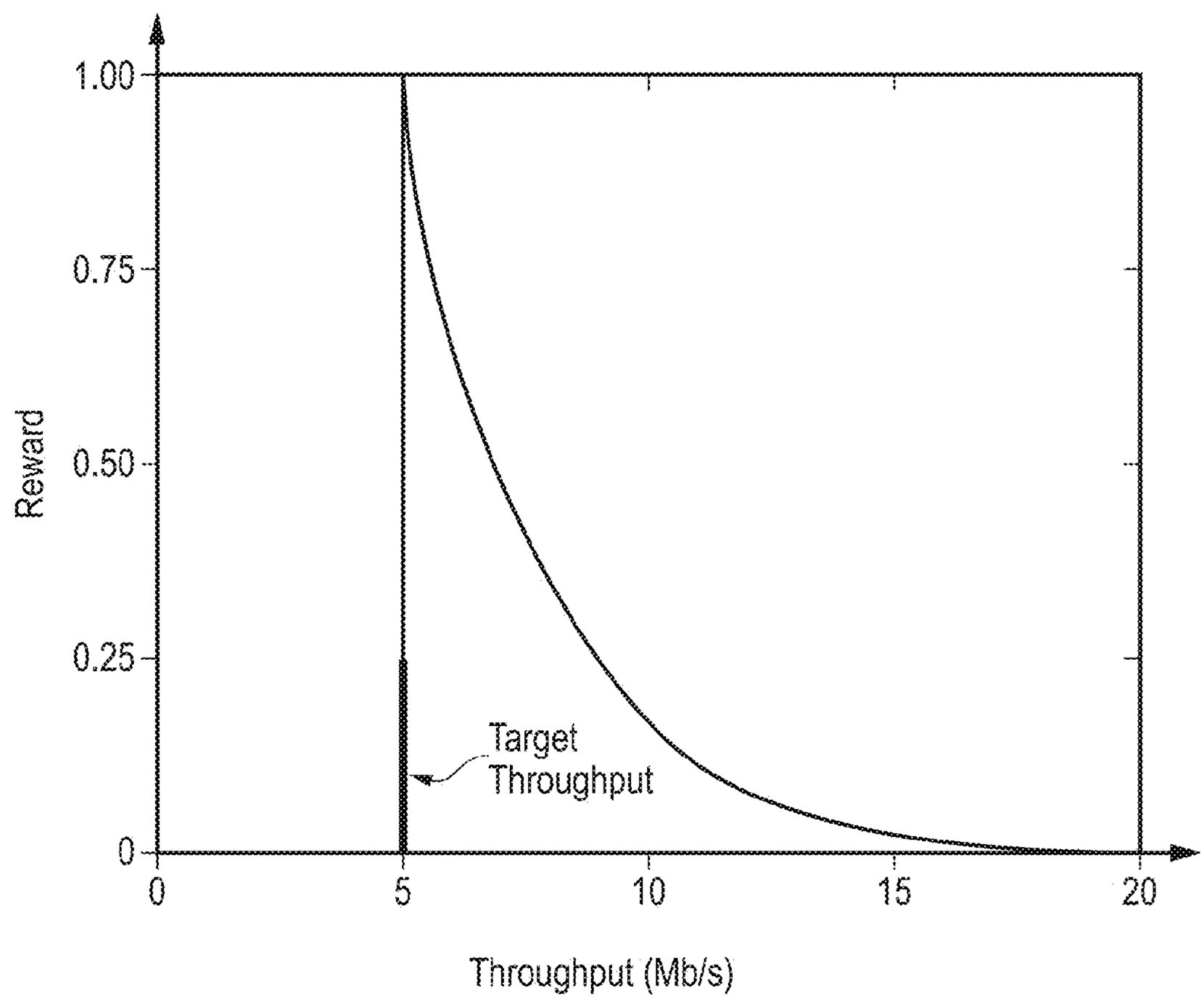

1.00
0.75
0.50
0.25
0
Reward
Target
Throughput
0
5
10
15
20
Throughput (Mb/s)

FIG. 32

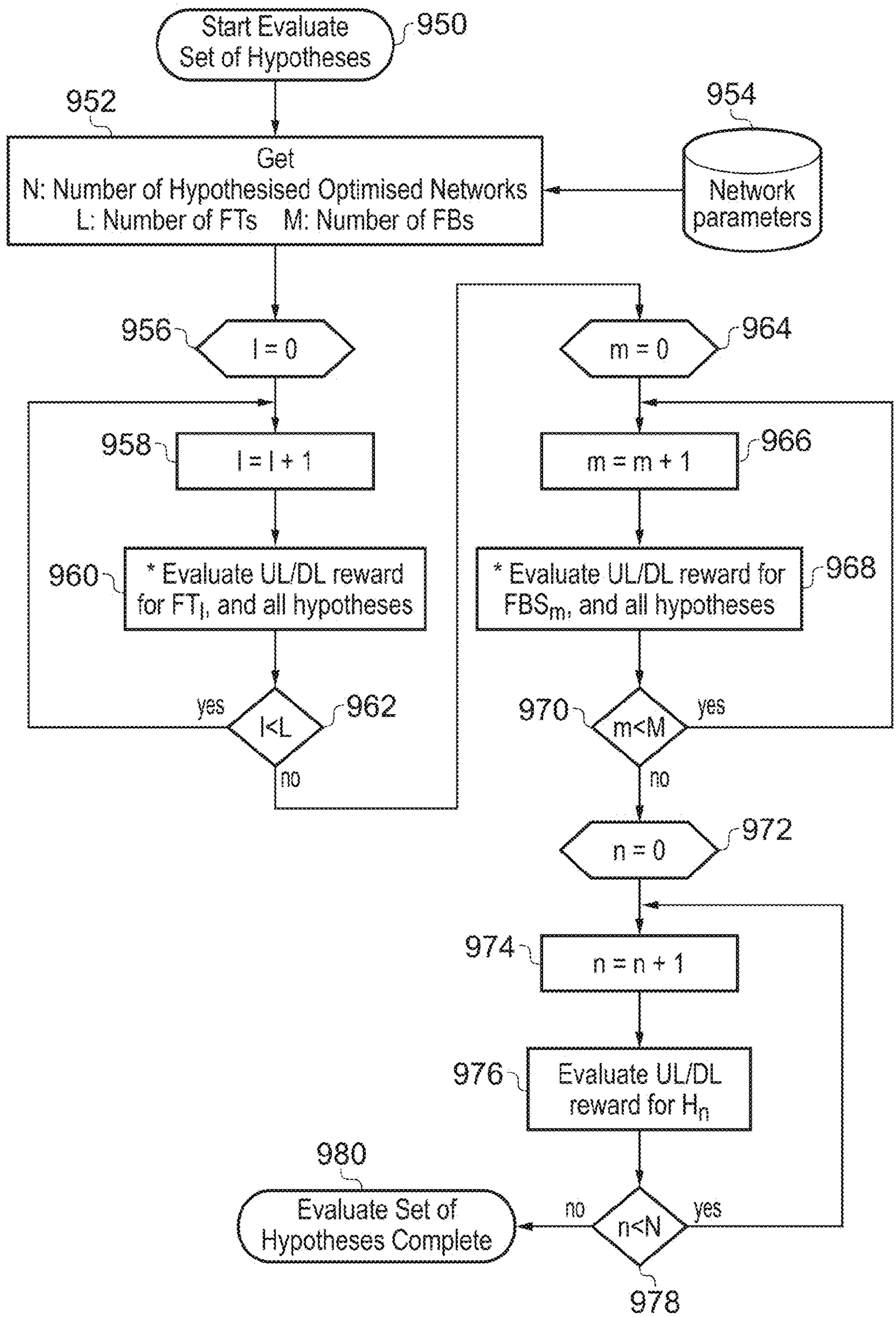

Start Evaluate Set of Hypotheses
950
952
Get
N: Number of Hypothesised Optimised Networks
L: Number of FTs M: Number of FBs
954
Network parameters
956
l = 0
958
l = l + 1
960
* Evaluate UL/DL reward for FTl, and all hypotheses
yes
l<L
962
no
964
m = 0
966
m = m + 1
968
* Evaluate UL/DL reward for FBSm, and all hypotheses
970
m<M
yes
no
972
n = 0
974
n = n + 1
976
Evaluate UL/DL reward for Hn
980
Evaluate Set of Hypotheses Complete
no
n<N
yes
978

FIG. 33

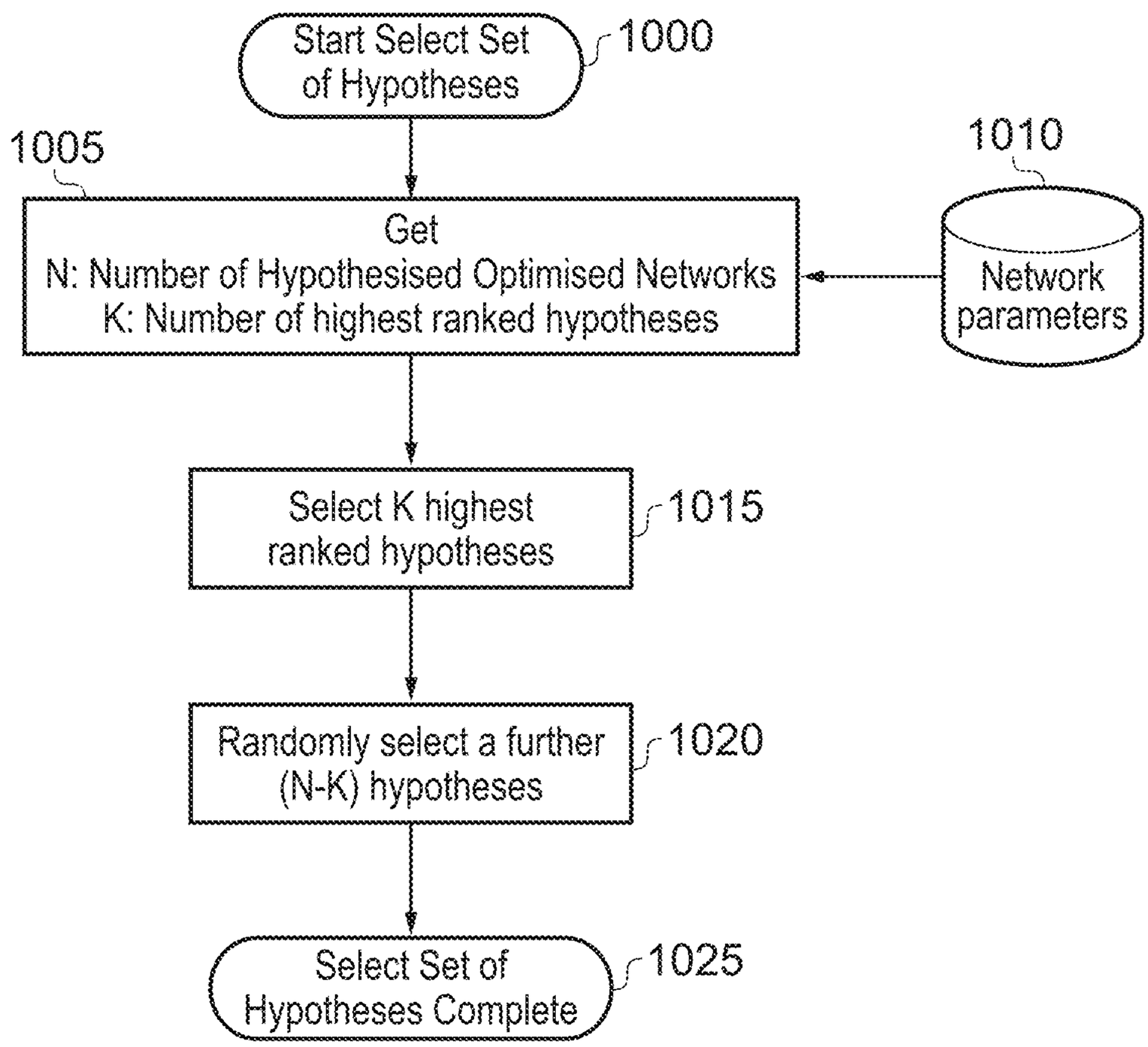

Start Select Set of Hypotheses
1000
1005
Get
N: Number of Hypothesised Optimised Networks
K: Number of highest ranked hypotheses
1010
Network parameters
Select K highest ranked hypotheses
1015
Randomly select a further (N-K) hypotheses
1020
Select Set of Hypotheses Complete
1025

FIG. 34

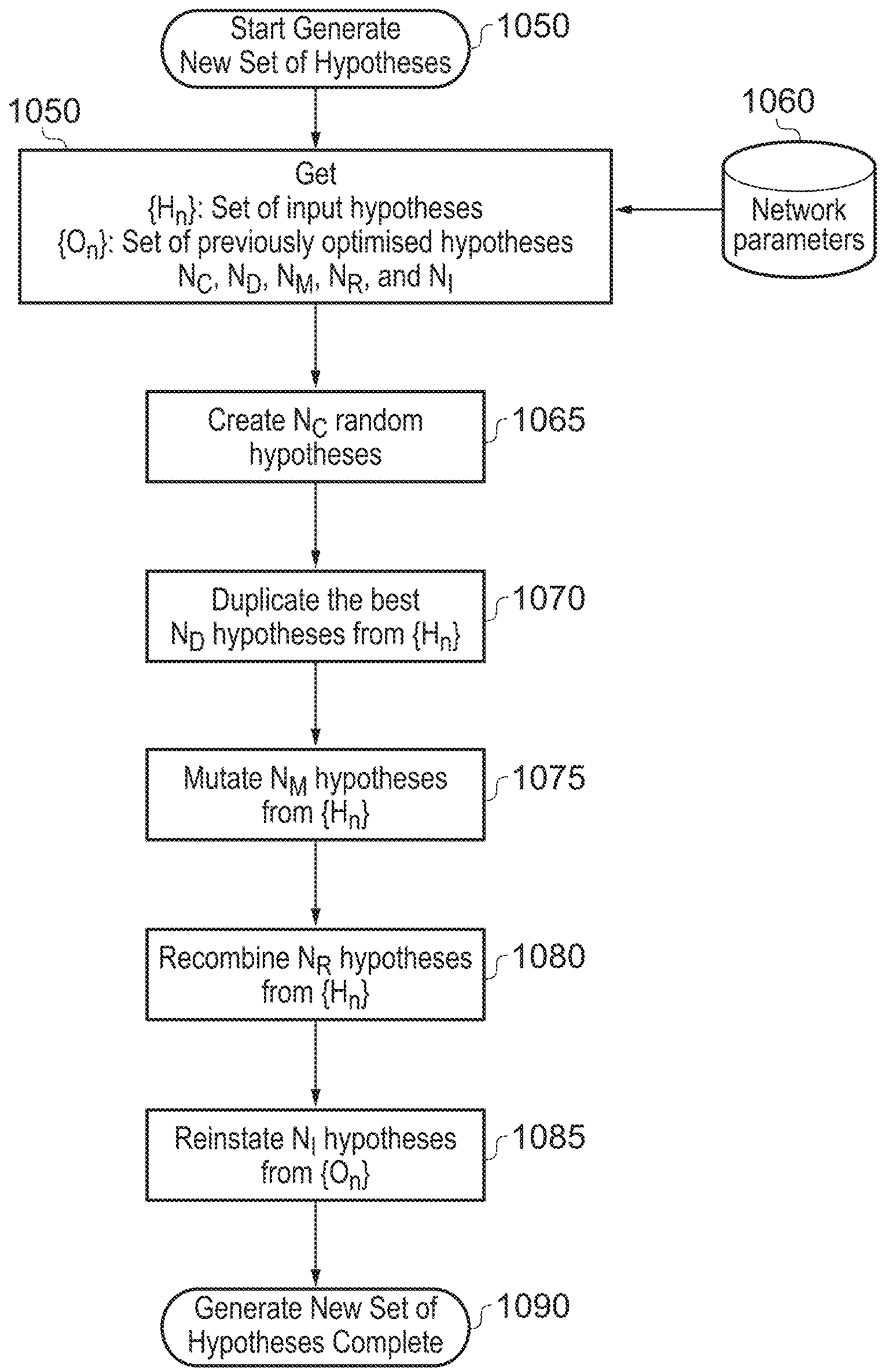

Start Generate New Set of Hypotheses
1050
1050
Get
{Hn}: Set of input hypotheses
{On}: Set of previously optimised hypotheses
NC, ND, NM, NR, and NI
1060
Network parameters
Create NC random hypotheses
1065
Duplicate the best ND hypotheses from {Hn}
1070
Mutate NM hypotheses from {Hn}
1075
Recombine NR hypotheses from {Hn}
1080
Reinstate NI hypotheses from {On}
1085
Generate New Set of Hypotheses Complete
1090

FIG. 35

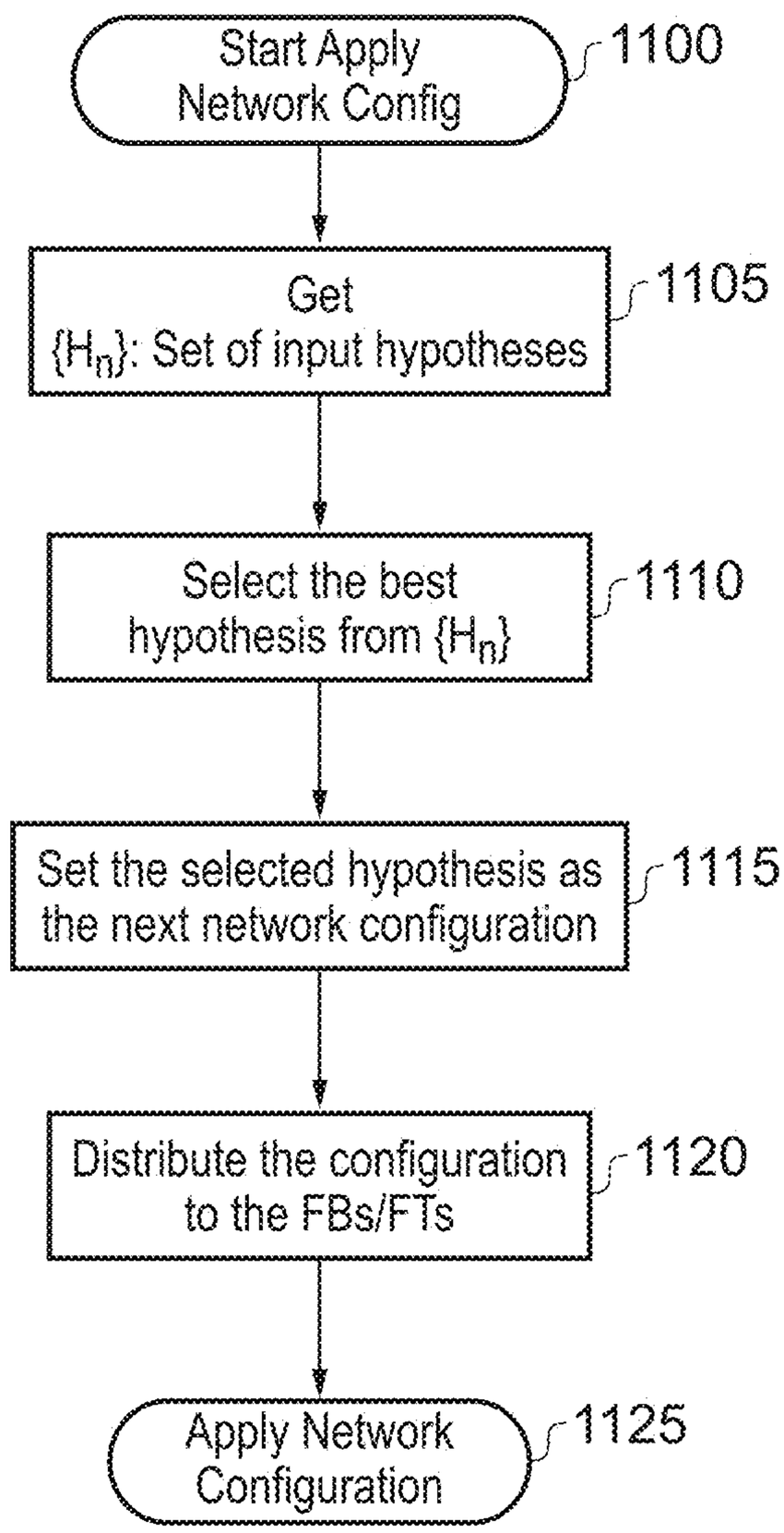

Start Apply Network Config
1100
Get {H_n}: Set of input hypotheses
1105
Select the best hypothesis from {H_n}
1110
Set the selected hypothesis as the next network configuration
1115
Distribute the configuration to the FBs/FTs
1120
Apply Network Configuration
1125

FIG. 36

WIRELESS NETWORK CONFIGURATION USING PATH LOSS DETERMINATION BETWEEN NODES

CROSS-REFERENCE TO OTHER APPLICATIONS

This application claims priority under 35 U.S.C. 119(b) to UK Application No. 1511200.6, filed 25 Jun. 2015 and entitled "STEERABLE ANTENNA SYSTEM", and to UK Application No. 1519273.5, filed 30 Oct. 2015 and entitled "WIRELESS NETWORK CONFIGURATION USING PATH LOSS DETERMINATION BETWEEN NODES". Both applications are incorporated by reference herein.

TECHNICAL FIELD

The present disclosure relates to a wireless network. More particularly it relates to path losses encountered between nodes in a wireless network.

BACKGROUND

A wireless network may be provided to serve a range of different functions, but one use of a wireless network is to perform backhaul in a communications network where user equipment devices (e.g. mobile telephones) communicate with nodes of the wireless network and the wireless network then enables these nodes to communicate with other nodes of the wireless network, which then connect (typically in a wired manner) to a physical communications infrastructure and then on to a wired communications network such as the internet. There are a number of different use cases and different types of backhaul technologies available to mobile network operators, but in this context there are a number of reasons why it would be desirable to provide terminal nodes of a wireless backhaul network (also referred to herein as feeder terminals) which only communicate with user equipment within a relatively small cell. Small cell deployment can be useful to provide the enhanced quality of service demanded by the ever increasing number of mobile data consumers. Small cells have a number of advantages such as: they allow capacity hot-spots to be targeted to ease congestion, they are appropriate for deploying in a dense outdoor urban environment, for example on street furniture, they can be deployed in specific known "not-spots" where macrocell coverage is poor or within indoor not-spots which experience steady daily traffic with occasional significant peaks, such as dense urban indoor environments like stadiums, shopping malls, and so on. Further, small cells may also be appropriate for mobile deployment, such as in trains, or other moving transport.

In the wireless backhaul use case discussed above, a feeder terminal (FT), i.e. the backhaul node nearest to an access point (AP), which may for example be an eNodeB (eNB) in the context of LTE, may typically be mounted on street furniture or a building façade perhaps 3-6 meters above street level. Conversely, a feeder base (FB), i.e. the backhaul node nearest to the core network, utilises the same infrastructure as the access macro network.

In view of the above usage context, it is inevitable that some degree of outage will occur when the backhaul connectivity is unavailable. Outage may for example occur when there is equipment failure, or a persistent or temporary physical obstruction such as heavy rain or vehicles in the line of sight of the backhaul link. Although the use of small cells may enable the target availability of the connectivity to be relaxed, it would advantageous if the nodes of the wireless network were able to reconfigure themselves to provide different communications paths when such outage does occur. Moreover, given the greater number of FTs which need to be deployed when smaller cells are used, in order to facilitate fast, large scale deployment with little engineering required at a new installation site, the ability for the nodes (both FTs and FBs) to self-organise and self-configure is very desirable.

In the context of wireless networks, a further consideration which may need to be allowed for is the carrier frequency in which the wireless network operates, both in terms of the corresponding propagation which the carrier frequency allows, but also in terms of the regulatory licencing regimes which apply to a given carrier frequency. Whilst it would be advantageous to provide a wireless network which operates in a license-exempt frequency band, due to its free availability, the lack of official regulation in such an unlicensed band means that the wireless network must be able to cope with co-channel and adjacent channel interference from unsolicited and uncoordinated wireless sources and furthermore despite any initial well planned deployment, if the wireless network is to be durable (in time) it must be able to adapt rapidly to static or dynamic, fixed or mobile radio traffic from other sources. One possible approach to the provision of a wireless backhaul network in such an environment would be the use of a contention-based protocol such as IEEE802.11 (WiFi), but then care must be exercised to ensure that the access does not interfere with the backhaul by separating the two air interfaces into separate bands, yet nonetheless other mobile devices or operators may still use the same spectrum causing significant interference. Although the widespread availability of WiFi may represent a cheaper approach, WiFi cannot quickly address rapid spatial and temporal interference pattern variations, making it in practice less suitable for the stringent requirements of real time backhaul services. Moreover the use of WiFi can be expected to require careful engineering and to be used in narrow point-to-point modes, which limits its deployment possibilities.

SUMMARY

In example embodiments a method is provided of network configuration selection in a wireless network comprising a plurality of nodes, the method comprising the steps of: configuring a subset of nodes of the plurality of nodes to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an antenna array of that node; receiving measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength; determining a path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and selecting a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

The present techniques recognise that the performance of a wireless network can strongly depend on the particular configuration adopted for the network in terms of the transmitter node receiver node pairs which are used for communicating data through the network. Moreover, it is recognised that even when the nodes of the network are individually well known, for example in terms of their

location, their beam patterns, their orientation, their transmission power, and so on, when deployed in a real and complex environment such as a busy urban situation using the above described unlicensed frequency bands, it is insufficient when seeking to select a wireless network configuration to rely on known individual characteristics of the nodes, and an improved network configuration may be achieved by assessing the ability of transmitter node receiver node pairs to communicate. In particular, the present techniques recognise that a critical parameter in such assessment is the path loss between the transmitter node and any receiver nodes. Accordingly the present techniques provide a method which enables a set of path losses to be determined for the nodes of the wireless network, such that these may be taken into account when selecting a wireless network configuration. The method begins by configuring a subset of nodes of the plurality of nodes in the wireless network to participate in a sounding process. It should be noted here that in this context the term "subset" should be understood in its mathematical sense, i.e. this could be all nodes of the wireless network, but in may also be a strict subset (i.e. less than of all nodes of network, for example only those in a given geographical area). This subset of the nodes then participates in the sounding process in order to allow the determination of this set of path losses. The sounding process is also referred to herein as an "active" sounding process, since at each step of the sounding a selected node of the subset omni-directionally transmits a predetermined signal—to be contrasted with a "passive" sounding process in which all participating nodes of the wireless network may simultaneously listen, with the aim of identifying an external interference source.

Control over the sounding process is typically maintained by a wireless network controller, which forms a centralised device within the wireless network, although other configurations are also contemplated here, such as one of the nodes of the wireless network also being responsible for the configuration of the wireless network or the function of the wireless network controller being physically distributed across several network components e.g. feeder base stations.

The other nodes of the subset of nodes sample the predetermined signal which the sounding node is (omni-directionally) transmitting, and this sampling is taken from the signal received by an antenna array of that receiving node. To support this omni-directional transmission and reception, the nodes participating in the transmission or reception of sounding signals employ an omni-directional antenna provided to support this function. The participating nodes each transmit their own measurement reports based on their own sampled signals, in particular communicating a signal source angle and a received signal strength to the recipient of the measurement report. The set of path losses is determined using this information and covers multiple transmitter node receiver node pairs. On the basis of this calculated set of path losses a configuration for the network can be selected, in which the current "in-situ" possible data throughput for each transmitter node receiver node pair (which for each possible node-node link in the network is dependent on the path loss calculated for that node-node link) is taken into account. Selection of this network configuration may for example be performed using an evolutionary algorithm. Each node (antenna) of the subset of nodes comprises a directional antenna (i.e. distinct from the omni-directional antenna used in the sounding process) and the network configuration includes a directional configuration for the directional antenna of each node of the subset, wherein the directional antenna is used for data transmission. Accordingly, antenna nodes of the network can advantageously fully determine their ability to communicate data with other antenna nodes of the network, and then on the basis of the selected direction of a selected partner node (with which the node should communicate), having regard to (own) co-channel interference, strong communication in this direction (for the transmission of data) is then enabled by appropriate directional configuration of a directional antenna.

The sounding process may be organised in a variety of ways, but in some embodiments the sounding process is a multiple step sounding process, wherein at each step of the multiple step sounding process only one node of the subset of nodes transmits the predetermined signal. Ensuring that only one node of the subset of nodes transmits the predetermined signal at a time (at a given step), supports a "clean" sounding environment, in which it can be guaranteed that when the predetermined signal as received it can only have one (known) source.

This one-at-a-time sounding arrangement is however not essential, as long as the source of a given predetermined signal can be identified in some other way, and thus in some embodiments in the sounding process the predetermined signal transmitted by each node of the subset of nodes is unique to that node and the subset of nodes transmit their unique predetermined signals concurrently.

The directional configuration which is applied to the antenna nodes of the network on the basis of the determined set of path losses may take a variety of forms in that the "directionality" may in principle be achieved in a number of ways. For example the directional configuration may be electronic or physical or both. In some embodiments in which the directional antenna is configured to be rotationally positioned, the directional configuration comprises a rotational position for the directional antenna. Such a directional antenna can thus be physically rotated, and the degree of physical rotation may then be determined in order to support the selected network configuration.

In some embodiments the method further comprises selecting at least one transmitter node receiver node pair to use in data transmission in dependence on the set of path losses. The transmitter node receiver node pairs used may therefore in some cases remain the same, for example with only the directional configuration of one or more antenna nodes being adjusted, but in other cases the transmitter node receiver node pairings may also be varied, if this is determined to result in an improved network configuration.

As mentioned above the directional configuration may take a variety of forms. In some embodiments the directional configuration comprises a beam pattern for the directional antenna. This beam pattern may be implemented by a number of known techniques.

In some embodiments the method further comprises calculating a predicted received signal strength at a receiver node when using a first beam pattern for the directional antenna of a transmitter node and a second beam pattern for the directional antenna of the receiver node, and selecting the directional configuration for the directional antenna of each node of the subset of nodes to use in data transmission is performed in further dependence the predicted received signal strength. Thus, typically, the directional configuration the directional antenna of each node will be selected in order to improve (where possible) the predicted received signal strength at each node, and the data throughput from the transmitter node to the receiver node is similarly improved (where possible).

The estimated path loss may be determined for all possible combinations of pairs of nodes, and thus in some embodiments generating the set of path losses generates an estimated path loss between all pairs of nodes in the subset of nodes.

In some embodiments determining the path loss is performed in dependence on a transmission power and antenna gain of the transmitting node and a reception antenna gain of the receiving node. Each path loss can thus be more accurately determined.

The particular manner in which the sounding process is arranged to occur may take a variety of forms, in particular in that the sounding process may be initiated in a number of different ways. However in some embodiments configuring the subset of nodes to simultaneously participate in the sounding process comprises defining a trigger type for initiation of the sounding process. The requirements of the wireless network may determine different trigger types which are appropriate for initiating the sounding process, but may comprise the arrival of a predetermined start time such that the nodes will coordinate to participate in the sounding process for example at an appropriate expected low data throughput time during the day.

In example embodiments an apparatus is provided for configuration selection in a wireless network comprising a plurality of nodes, the apparatus comprising: transmission circuitry to transmit a sounding configuration to a subset of nodes of the plurality of nodes to cause the subset to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node; reception circuitry to receive measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength; calculation circuitry to calculate a path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and selection circuitry to select a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

In example embodiments an apparatus is provided for configuration selection in a wireless network comprising a plurality of nodes, the apparatus comprising: means for transmitting a sounding configuration to a subset of nodes of the plurality of nodes to cause the subset to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node; means for receiving measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength; means for calculating a path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and means for selecting a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

BRIEF DESCRIPTION OF THE DRAWINGS

The present techniques will be described further, by way of example only, with reference to embodiments thereof as illustrated in the accompanying drawings, in which:

FIG. **1** schematically illustrates a communications network providing connectivity for end user equipment which employs a wireless backhaul network in which antenna apparatuses may be deployed to provide backhaul nodes;

FIG. **2** schematically illustrates an apparatus for controlling a wireless network, referred to in this embodiment as a backhaul self-organising network controller;

FIG. **3** schematically illustrates an antenna apparatus which is subject to configuration by a controller such as that shown in FIG. **2** in one embodiment;

FIG. **4** schematically illustrates the control electronics of an antenna apparatus such as that shown in FIG. **3** in one embodiment;

FIG. **5** shows a subset of the beam patterns which are available to an antenna apparatus in one embodiment;

FIG. **6** schematically illustrates one embodiment of control circuitry and signal processing circuitry which are connected to the antenna arrays of a node, both within the antenna apparatus itself and in other network components to which it is connected;

FIG. **7** schematically illustrates the interaction of a feeder terminal and a feeder base station with a network controller in one embodiment;

FIG. **8** schematically illustrates an uncoordinated (external) interference source and a set of nodes of a wireless network in its vicinity;

FIG. **9** shows an example set of signals sampled by three nodes in a wireless network, from which time-difference-of-arrival measurements are made in one embodiment;

FIG. **10** shows a sequence of steps which are taken when using a Particle Filter algorithm in one example embodiment;

FIG. **11** schematically illustrates the use of a first particle filter algorithm to estimate the location of an external interference source and the use of a second particle filter algorithm to estimate, on the basis of the output of the first particle filter algorithm and a received signal strength indication, up to four characterising parameters of the external interference source;

FIG. **12** illustrates the initial location and configurations of an external interference source and seven nodes of a wireless network in a simulation;

FIG. **13** shows a simulation of the initial locations of a set of particles used in a particle filter algorithm for locating the external interference source shown in FIG. **12**;

FIG. **14** shows the set of particles of FIG. **13** after simulating the usage of seven items of angle of arrival (bearing) information and two items of time difference of arrival in a particle filter algorithm;

FIG. **15** shows the initial set of set of particles parameterised by beam width, antenna bearing, source power and front-to-back-transmission ratio in the simulation of FIGS. **12-14**;

FIG. **16** shows the set of particles of FIG. **13** after a first iteration of a particle filter algorithm;

FIG. **17** shows the set of particles of FIG. **13** after ten iterations of the particle filter algorithm;

FIG. **18** shows a sequence of steps carried out in the method of one embodiment when performing passive sounding to assess the environment;

FIG. **19** shows a sequence of steps which are carried out in one embodiment when performing active sounding to assess the path loss between nodes;

FIG. **20** schematically illustrates the calculation of a path loss for a node pair using a path loss model;

FIG. **21** schematically illustrates some components of a wireless network controller in one embodiment;

FIG. **22** shows an example set of selected node pairs for data transmission in a wireless network, selected on the basis of a set of path losses calculated for all node pairs;

FIG. **23** schematically illustrates the geometry of a uniform circular array in one embodiment;

FIG. **24** schematically illustrates some components of an antenna apparatus in one embodiment;

FIG. **25** shows a sequence of steps which are taken in operating an antenna apparatus in one example embodiment in order to perform signal detection process;

FIG. **26** shows a sequence of steps which are taken in the method of one embodiment to generate a signal sample spatial covariance matrix;

FIG. **27** shows a sequence of steps which are taken in the method of one embodiment to generate a signal sample spatial covariance matrix;

FIG. **28** is a flow diagram illustrating the basic steps of an evolutionary algorithm;

FIG. **29** is a flow diagram illustrating how an evolutionary algorithm is used in one embodiment to determine a revised network configuration;

FIG. **30** is a flow diagram illustrating the process performed at step **810** of FIG. **29** in accordance with one embodiment;

FIG. **31** is a flow diagram illustrating the process performed at step **815** of FIG. **29** in accordance with one embodiment;

FIG. **32** shows an example reward function for evaluating a hypothesis in one embodiment;

FIG. **33** is a flow diagram illustrating the process performed at step **820** of FIG. **29** in accordance with one embodiment;

FIG. **34** is a flow diagram illustrating the process performed at step **825** of FIG. **29** in accordance with one embodiment;

FIG. **35** is a flow diagram illustrating the process performed at step **835** of FIG. **29** in accordance with one embodiment; and

FIG. **36** is a flow diagram illustrating the process performed at step **830** of FIG. **29** in accordance with one embodiment.

DESCRIPTION OF EMBODIMENTS

Some particular embodiments are now described with reference to the figures. FIG. **1** schematically illustrates a multi-component network which provides connectivity for user equipment (UE) to a communications network such as the internet. The items of user equipment **10-15** of this example communicate wirelessly with LTE base stations—enhanced node B's (eNBs). Note that the LTE air interface represented in FIG. **1** is only an example and the present techniques are equally applicable to other suitable non-LTE air interfaces. Also, whilst for simplicity each access base station is shown as communicating with a single item of end user equipment, it will be appreciated that in practice such access base stations form point-to-multipoint devices enabling a plurality of items of end-user equipment to communicate with an individual access base station. These eNB access stations then either have a direct wired connection (via IP protocol) with the communications infrastructure **20** in the case of **21** and **22**, or are connected to an associated feeder terminal (FT) in the case of eNBs **23-26**. Each FT is in wireless communication with a feeder base (FB), shown as **31** and **32** in this figure. These FBs are then provided with a wired connection (via IP protocol) to the communications infrastructure **20**. However, it should be noted that the FBs can also be coupled to the communications infrastructure via a further level of wireless backhaul network.

Also shown in FIG. **1** is a backhaul self-organising network (BSON) server (controller) **33**, which is shown to be in communication via the dashed line labelled "backhaul control" with the FTs and FBs of the wireless backhaul network. It should be appreciated that this connection shown is logical and in fact will typically be provided via the wired connection to the communications infrastructure and the wired and/or wireless connection discussed above leading to these FBs and FTs. The communications infrastructure **20** is connected to a communications network (e.g. the internet) via the evolved packet core (EPC) **34**. In the particular example of the wireless backhaul network shown in FIG. **1**, the nodes (FBs and FTs) are intended to support the provision of relatively small cells, to be easily and rapidly deployable, to operate well in an unlicensed region frequency band, such that they must be able to cope with co-channel and adjacent channel interference from unsolicited and uncoordinated wireless sources and furthermore be adaptable when the conditions in which they are operating change.

FIG. **2** schematically illustrates a wireless network controller **35** (also referred to here as a backhaul self-organising network (BSON) controller in one embodiment). The wireless network controller **35** is shown in FIG. **2** as being communication with a "backhaul network", which in the present context will be understood to comprise at least one feeder base and a feeder terminal forming nodes of the wireless network. It will be understood however, for example with reference to FIG. **1**, that the BSON controller **35** will typically be in communication with (and in control of) more feeder bases and feeder terminals than this, and references to just one node pair like this, where made, are merely to illustrate a principle. Conversely, note that in a full wireless network more than one wireless network controller may be provided, with a group of feeder bases and figure terminals, for example grouped together by geographical location, under the control of a given single wireless network controller. The wireless network controller **35** in FIG. **2** comprises circuitry which provides a backhaul SON (self-organising network) engine **37**, which forms the main processing component of the wireless network controller and is where the various calculations described herein are performed. It should be noted that there is no need for the BSON engine **37** to be exclusively located within a dedicated physical device, and the data processing capability which this BSON engine **37** provides may in fact be distributed between multiple physical devices which may be somewhat remote from each other and indeed this capability could be distributed across suitable nodes of the wireless network, for example such as some or all of the feeder base stations.

The wireless network controller shown further comprises a backhaul equipment database **39**, a backhaul network configuration database **41**, a path loss data base **43**, and an external interference database **45**. The backhaul equipment database **39** is used by the wireless network controller to store information relating to the geographical location of each of the antenna apparatuses (nodes) under its control, as well as their particular individual capabilities. This information for a given antenna apparatus is populated in the database when that antenna apparatus is first deployed. The backhaul network configuration database **41** stores configuration information for the antenna apparatuses, such as antenna beam pattern information, antenna bearing infor-

mation, transmission power information, time-frequency resource allocation information, and traffic demand information. The external interference database **45** is used by the BSON engine **37** to store characterisations of external interference sources which it has detected and characterised, for example in terms of geographical location, antenna beam pattern, antenna bearing, transmission power (e.g. equivalent isotropic radiated power—EIRP), time-frequency resource allocation and other time characteristics (such as an observed time pattern of an external interference source—continuous, intermittent, only between certain hours, etc.). Associated with the BSON engine **37** is the sounding schedule generation circuitry, which generates sounding schedules which are distributed to the relevant nodes of the wireless network, and may include an active sounding schedule, according to which a node transmits a known sounding signal whilst another node listen for that signal to thus determine characteristics such as the path loss between those two nodes. Node-to-node path losses can be stored in the backhaul network configuration database **41**. The sounding schedules may also include a passive sounding schedule, namely one which is used to listen for external interference source(s). As described elsewhere herein, implementation of either a passive or an active sounding schedule comprises a measurement (sounding) report being transmitted from a wireless network node, which in the example of FIG. **2** is received by the backhaul SON engine **37**. The result of an external interference source characterisation is stored in the external interference database **45**. FIG. **2** also shows circuitry providing an element management system (EMS) **49** and EMS server circuitry **51**. These are generally provided to support the management of one or more types of element of the wireless network on the network element-management layer (NEL) of the Telecommunications Management Network (TMN) model, with which one of ordinary skill in the art will be familiar and further description is not provided here. These EMS components **49** and **51** also populate top-level data into the respective databases at initialisation.

The ability of the wireless network controller to adapt and improve the configuration of the wireless network is enhanced, the greater the configurability of the nodes of the wireless network. FIG. **3** schematically illustrates the components of an antenna apparatus **70** which is provided as a node of the wireless network in one example, which has a high degree of configurability. A protective radome cover of the antenna apparatus has been removed, merely to assist the description of its covered components. In this embodiment, the directional antenna **71** can be seen to comprise 25 antenna array components (darker squares) arranged in a 5×5 grid. RF and base band electronics (i.e. essentially the RF chains) and other control circuitry **72** are provided behind the main directional antenna assembly. These are not directly visible in the illustration of FIG. **3** due to the casing. The antenna **70** further comprises a rear-firing antenna **73** which is orientated in the opposite direction to the front firing main antenna **71**. Although not visible in FIG. **3**, the rear firing antenna **73** comprises a single column of antenna array elements forming a single antenna array component, which is physically very similar to a single column within the 5×5 array of antenna array elements of the front antenna **71**. A circular (omnidirectional) antenna **74** is mounted on top of the front-firing main antenna **71** and is configured as a triple-monopole antenna which is used, as described herein, on the one hand when assessing the environment in which the antenna **70** finds itself, i.e. when detecting external interference sources, and on the other hand when participating in an active sounding schedule to support the determination, in coordination with other antennas in the network, of a full set of path losses. A further GPS antenna **75** is also provided in the antenna apparatus **70**, which is used for node location, orientation and precise time synchronisation. A motorised steering mechanism **76** enables the antenna apparatus to be orientated in any direction in azimuth, and a gigabit Ethernet network interface **77** is provided to connect the antenna further. The fins **78** are for heat dissipation. Note also that the RF/base band electronics and control circuitry **72** mounted behind the front firing main antenna **71** are also connected to the circular antenna **74** and the rear firing antenna **73**, as will be discussed in more detail below.

FIG. **4** schematically illustrates some components of an antenna apparatus **80**, such as the antenna apparatus **70** of FIG. **3**. As illustrated in the figure the antenna apparatus **80** can be seen to comprise a directional antenna **82**, a rear directional antenna **84**, and a uniform circular antenna array **86**. The individual antenna components of these three different types of antenna are connected to RF chains which are shown in FIG. **4** as forming part of the control circuitry **88**. The control circuitry **88** comprises control device **90** which, in particular, configures the components of the RF chains, controls the operation of two signal processing devices **92** and **94**, and controls the operation of the motor control device **96**. The motor control device **96** controls the motor **98** which can cause the rotatable part of the antenna apparatus to be rotatably positioned with respect to a fixed non-rotatable part of the antenna apparatus by which the antenna apparatus is fixed with respect to its physical location.

Considering first the configuration of the three antennas of the antenna apparatus, the control circuitry **90** determines the settings of the set of switches **100**, the gain circuitry **104**, and the phase circuitry **108** in the RF chains for the uniform circular antenna array **86**. Similarly the control circuitry **90** determines the settings of the set of switches **102**, the gain circuitry **106**, and the phase circuitry **110** in the RF chains of the directional antenna **82** and rear directional antenna **84**. Although not explicitly shown in the illustration of FIG. **4**, at least some of the components of the RF chains for the antennas may also be shared, for example amongst the phase circuitry **108** and **110**. Phase shifters can be costly and large, and such sharing therefore enables the antenna apparatus to be provided in a cost-effective and physically compact manner.

Thus, when the antenna apparatus is either (active sounding) transmitting/listening for a known sounding signal, or (passive sounding) listening for an external interference source, by means of the uniform circular antenna array **86** and the RF chains **100**, **104**, **108**, the signal processing circuitry **92** (comprising a transceiver) processes the signals in order to determine signal strength information and direction information for the signals received. The signal strength information and direction information determined by processing the signals can then be stored in the control device **90**, for example so that this information can be gathered into a single bundled transmission—a measurement report—to a wireless network controller during an expected non-busy period for the network, such as at 3 am. However, under control of the control circuitry **90**, the signal processing device **92** is also able to directly communicate this signal strength information and direction information to the wireless network controller, essentially as soon as it has been determined.

In accordance with the present techniques, the antenna apparatus is instructed to participate in either the active

sounding process or the external interference sampling (passive) process, the control over this being provided by the wireless network controller, as is also described above with reference to FIG. **2** and below with reference to FIG. **6**. When the antenna apparatus participates in one version of the external interference sampling process, only its uniform circular antenna array is active (in reception mode), so that the antenna apparatus can gather information relating to other sources of wireless signals in its environment. Similarly, when the antenna apparatus participates in one version of the active sounding process, only its uniform circular antenna array is active (in transmission/reception mode as appropriate), to allow an omni-directional transmission and reception of the sounding signal.

Once the wireless network controller has determined a set of path losses or characterised the external interference source, and has determined that some adaptation of the configuration of at least one antenna apparatus would improve the performance of the wireless network, a new configuration is transmitted to the control circuitry **90**. This new configuration can adapt any configurable aspect of the antenna apparatus **80**, for example an azimuthal position for the antenna apparatus, which is then implemented by the motor control circuitry **96** controlling the motor **98**. Moreover, as well as the azimuthal position determined for the antenna apparatus, a beam pattern configuration for use during data communication for the antenna apparatus can also be determined and the control circuitry **90** can then configure any of the directional antenna **82**, the rear directional antenna **84** and the uniform circular antenna array **86** in order to implement that beam pattern configuration, by appropriate setting of the switches **100**, **102**, the gain circuitry **104**, **106** and the phase circuitry **108**, **110**. At least some of the switches **100**, **102**, the gain circuitry **104**, **106** and the phase circuitry **108**, **110** may be shared between the antenna (front, rear and circular) components, enabling a reduced size of RF electronics and cost thereof, in particular when phase shifting circuitry is shared, such that not only is an antenna apparatus which is cheaper is provided, but also one in which the readout electronics can be easily comprised within the portion of the antenna which rotates, and thus in close proximity to the antenna array components, thus improving signal fidelity, yet also allowing the rotation of the directional antennas.

FIG. **5** shows a subset of the beam patterns which can be generated by an antenna array configured such as is illustrated in FIGS. **3** and **4**, showing the useful range of beam patterns available. In FIG. **6** the following classes of beam patterns can be identified:•Narrow beams with a single main lobe and of various beam widths, where side lobes are significantly reduced relative to the main lobe;

- Electronically steered beams that combine signals at RF, enabling antenna directivity to the left or right of the bore sight of the array;
- Beams with grating lobes, where the array pattern has equally strong peaks in multiple directions and deep nulls with significant attenuation (gain <1) in other directions;
- A bowtie configuration;
- Three 'beacon' omni-directional patterns.

Combined with the above discussed rotating mechanism, the antenna apparatus thus provided, using a fixed set of beam patterns, improves over traditional uniform linear arrays, by being able to maintain a peak gain in any direction. For uniform linear arrays, it is known that the array gain decreases as the angle from the bore sight increases. In addition, the antenna apparatus provided is economically more attractive than more complex circular arrays. For example, ten complete transceiver chains with an aperture of 6.08λ, would generate an antenna pattern with 25° beam width. Embodiments of the antenna apparatus described herein have an aperture which is 4λ and use only two transceiver chains (note that the RF chains shown in FIG. **5** can be shared to reduce down to two connections in the receiver direction and two connections in the transmitter direction) and the narrowest beam that can be generated is 15°. Overall therefore the antenna apparatus provided by the present techniques enables the maximum gain to be orientated in any direction in 360°, whilst improving diversity reception and conversely interference nulling from any direction using a rich set of multiple transmitter and receiver beams.

FIG. **6** schematically illustrates the connections of the antenna arrays (front, rear and circular) **110** in one embodiment. The antenna arrays **110** are controlled by some of the other components shown in FIG. **6**. A backhaul self-organising network (BSON) client **112** (software running in the same housing the antenna apparatus) provides node configuration including antenna beam width and direction, and transmit power and a nulling trigger to an antenna controller **114**. This BSON client communicates with an external BSON server (not shown in this figure). However, additionally the antenna controller **114** may autonomously select the receiver pattern which maximises throughput based on carrier to interface and noise ratio (CINR) measurements. The antenna controller **114** controls the antenna arrays by passing configuration information for the transmit mode, the transmit power and the receiver pattern to the front end circuitry **116**. The front end control circuitry **116** converts these into the required switch control signals, gain control signals and phase shift control signals which are passed to the RF front end module **118**. The RF front end module **118** represents the components of FIG. **6** in which the components other than the antenna array components in FIG. **4** are to be found. The antenna controller **114** also indicates an antenna direction to the antenna motor control circuitry **120**, which controls the motor **122** in order to orientate the antenna arrays **110** in azimuth. A modem data path is provided comprising the MAC **124**, the PHY **126** and the RF transceiver **128**, which then couples to the RF front end module **118** in order to provide this with the RF signals which the RF chains modify before passing them to the antenna arrays **110**. In other words, data packets are sent between the MAC **124** and the PHY **126**, digital IQ samples are passed between the PHY **126** and the RF transceiver **128**, and RF signals are exchanged between the RF transceiver **128** and the RF front end module **118**. The BSON client **112** (BSON controller) also generates sounding schedules to be implemented by the antenna apparatus which are received by the MAC **124**. The MAC **124**, like the BSON client **112** communicates with a Layer 2 bridge **129** which is coupled to the network interface.

FIG. **7** schematically illustrates some components and processing stages related to the sounding process. This sounding process may be the external interference sampling process in one example and may be the active (path-loss assessing) sounding process in another example. It should be appreciated that in the passive sounding case (external interference measurement) the characteristics of the interference sources (for example beamwidth and direction) are measured, whereas in the active sounding case angle-of-arrival (AOA) and a received signal strength indication (RSSI) are measured for the network's own nodes which participate in the active sounding process. A network con-

troller **130**, a feeder base station **132** and a feeder terminal **134** are shown. The network controller **130** comprises sounding manager **138** and a report collection unit **140**, which form part of a backhaul SON engine **136**. When a sounding process (either an external interference sampling process or an active sounding process) is to be carried out, the network controller **130** transmits a sounding report (SR) control message detailing the parameters of the sounding process to the feeder base station **132**. The SR control message of this example comprises at least some of:

Sounding type: active or passive;

Node ID: a list of the nodes (FTs and FBs) that shall carry out the sounding/interference measurements;

Measurement type: Received signal power, angle of arrival, time domain samples;

Trigger type: Periodic or event based;

Report interval: Length of time of reporting when the trigger type is periodic;

Number of reports: number of measurement reports to be generated during the reporting interval; and

Event trigger type: Throughput range, SNR range.

The portion of the feeder base station **132** which receives this SR control message then communicates it further to the feeder terminal **134**, as well as to the portion of the feeder base station **132** itself which administers its part of the sounding process. The box **142** in FIG. **7** then illustrates the processing steps by which the sounding process is carried out and the resulting sounding reports are returned to the network controller **130**. For an external interference sampling process the SR control message defines the conditions (event trigger type) which must be met for the external interference sampling process to be carried out. This trigger may be purely time based in that the external interference sampling process is carried out at a specific time following receipt of the SR control message, or is carried out at a specific time intervals following receipt of the SR control message, and so on. However the trigger may also be event related, such that the external interference sampling process is carried out when a defined event occurs in at least one of the feeder terminal **130** and the feeder base station **132**. Such trigger events may for example to be defined as when the data throughput of the feeder terminal or feeder base station departs from a predetermined range, in particular when the data throughput falls below a predetermined threshold. Alternatively or in addition a trigger event may be defined as when the signal-to-noise ratio for the feeder terminal or feeder base station departs from a predetermined range, in particular when the signal-to-noise ratio falls below a predetermined threshold. Where a time varying external interference source causes a reduction in wireless network performance because of the effect it is now having on the data throughput or signal-to-noise ratio of a feeder terminal feeder base station, the wireless network can adapt its configuration in response by first performing the external interference sampling process to assess or reassess relevant characteristics of the external interference source.

Conversely, in the case of an active sounding process event based triggers (e.g. triggered by recording lower than anticipated SNR values) cannot be used. The active sounding requires a known sounding signal to be transmitted from a cooperating source and hence both transmission and reception are coordinated by the BSON.

A sounding report (SR measurement) is then transmitted from the feeder terminal **134** to the feeder base station **132**, and from the portion of the feeder base station **132** which administers its part of the sounding process to the portion of the feeder base station **132** which handles data processing, storage and transmission. The SR measurement reports are then logged (**146**) within the feeder base station **132** and then some local processing of the data (**148**) may also be carried out. For example, the feeder base station may carry out time-difference-of-arrival measurements by computing the cross-correlation between signals received from two backhaul nodes. However it should be noted that it is not necessary for the feeder base station to perform the computation of cross-correlations between the signals in order to calculate at least one time-difference-of-arrival, and this data processing may be left to the backhaul SON engine **136**, although it is recognised that doing this will almost inevitably increase the size of the SR file transfer. The decision as to where this processing should occur can therefore made on the one hand in dependence on where the required processing capability is available and on the other hand in dependence on whether the size of the SR file is a significant factor in maintaining good wireless network performance.

For the external interference sampling process with multiple uncoordinated nodes, the circuitry of the base station which supports this "locally process data" step **148** may also include successive interference cancellation (SIC) circuitry to enhance the quality of the signal of the weakest interferer by subtracting the signal from the strongest interferer.

Following the logging and local processing, and when the sounding report (SR file) is ready (**150**), the feeder base station **132** indicates to the report collection unit **140** that a sounding report is ready for transmission. The sounding report is then transferred to the report collection **140** such that the backhaul SON engine **136** can then process this sounding report, most likely with further sounding reports from other feeder terminals or feeder base stations. It should be noted that typically, although an active sounding process or external interference sampling processes may be carried out at various times and indeed may be carried out repeatedly throughout a 24-hour period, transmission of one or more sounding reports to the backhaul SON engine and reconfiguration of the wireless network may be restricted to a particular short period, for example around 3 am, when data transmission usage of the wireless network is expected to be low and therefore minimally disrupted.

Returning to a consideration of the two part process of characterising an external interference source, namely firstly by estimating a location of the external interference source using at least one received measurement report and then by using the estimated location of the external interference source and the received signal strength to calculate at least one of: a source power; a beam width; an antenna bearing; and a front-to-back transmission ratio, FIG. **8** shows an example situation in which three feeder bases (FBs) and twelve feeder terminals (FTs) encounter an external interference source X. In the example of FIG. **8**, the feeder bases and feeder terminals are at distances from the external interference source X which range from approximately 100 m to approximately 1 km. The circles which surround the FBs and FTs indicate that for the external interference sampling of this example, the FBs and FTs are configured to use their circular (omnidirectional) antennas having circular beam patterns, whilst the beam pattern of the external interference source X is notably asymmetric (a fact which of course cannot be known within the wireless network before the external interference sampling, location estimation and characterisation has been carried out). It will therefore be clear that node X can be thought of as an uncoordinated interferer (i.e. not belonging to the wireless network) and is utilising a narrow beam shape to communicate with another uncoordinated interfering node (not shown in the figure).

FIG. **9** shows an example of time-domain signal samples made at three nodes (FT**1**, FT**6** and FB**2**) in a wireless network, and the manner in which time-difference-of-arrival information is derived therefrom. Where the time-domain signal samples made by different nodes are to be expected to be correlated, but with a time offset, a given signal sample which can be identified across the three different nodes can be used to determine the required time-difference-of-arrival information. A cross-correlation process between two sets of time-domain samples identifies the required time differences. For the identified sample S, the time differences Δt_{1-2}, Δt_{1-6}, and Δt_{6-2}, i.e. between FT**1** and FB**2**, between FT**1** and FT**6**, and between FT**6** and FB**2** are shown. In the example of FIG. **9**, an approximately 10 m resolution from the resulting time differences is achieved.

Some specific details of the how sources are parameterised in a backhaul SON engine in one example embodiment in order either: to estimate the location of an external interference source on the basis of interference measurement reports and further to characterise the interference source; or to calculate path losses between participant sources using active sounding process, are now described.

Path Loss

For a number of WINNER2 path loss models, the path loss PL (measured in dB) is assumed to be a function of the distance d (measured in meters) and the frequency f (measured in MHz) and parameterised by the constants p_a, p_b, p_c, such that:

$$PL(d,f;p_a,p_b,p_c)=p_a \log_{10}(d)+p_b+p_c \log_{10}(f/5000)$$

where, for example:

for free space: $p_a=20$, $p_b=46.4$, $p_c=20$;

and for the "b5a" urban feeder line-of-sight (LOS) rooftop model: $p_a=23.5$, $p_b=42.5$, $p_c=20$

Shadow fading may also be included, for non-line-of-sight (NLOS) links, modelled as a log normal fading. For example in the "c2b" urban macro path loss model the standard deviation of shadow fading is 4 dB.

Antenna Pattern

The antenna pattern (in the passive sounding case) in dB, at an angle θ is given by

$$AP(\theta;\theta_0,\overline{\theta}_0,b_0) = -\min\left(12\left(\frac{\angle e^{j(\theta-\theta_0)}}{\overline{\theta}_0}\right)^2, b_0\right)$$

where ∠r, denotes the angle of the complex number r. θ_0 is the antenna bearing, $\overline{\theta}_0$ is the antenna 3 dB beamwidth and b_0 is the front-to-back ratio. The angles are in radians and the front-to-back ratio is in dB.

In the active sounding case the process is carried out by the beacon (omnidirectional) antennas and the antenna patterns (both transmission and reception antenna gains) are assumed to be 0 dB in all directions.

EIRP

For the passive sounding case, the equivalent isotropic radiated power (EIRP) is equal to the peak power in the direction of the maximum antenna gain, denoted by e_0.

For the active sounding case, given the above-mentioned assumed 0 dB gain, the EIRP is taken to be equal to the peak power P, which is assumed to be known, or indeed explicitly communicated by the BSON.

RSSI

A received signal strength indicator RSSI or more simply r represents the received power at sensor m in the log domain, and for the passive sounding case is given by the sum of the transmitted power, the antenna gain at the transmitter, the path loss and the antenna gain of the receiver:

$$RSSI=TX\text{power}+TX\text{antennaGain}-PL+RX\text{antennaGain}$$

where TX and RX refer to transmission and reception respectively.

For the active sounding case the RSSI is simply (in the log domain) equal to TXpower−PathLoss.

TDOA

In the example of passive sounding (external interference measuring) and concerning time difference of arrival, let $q_0(t)$ denote the transmitted interference signal located at x_0, y_0, for t=0, 1, . . . , T−1. The received signal at sensor (node) n located at x_n,y_n is given by

$$q_n(t)=a_n q_0(t-\tau_n)+w_n$$

where w_n denotes the Additive White Gaussian noise (AWGN) term and a_n denotes the signal attenuation and includes the effects of TX power, the TX antenna gain, the radio propagation losses and the RX antenna gain. τ_n denotes the propagation delay from sensor 0 to sensor n. If c is the speed of light, then the distance between sensors m and 0 is given by

$$c\tau_n=\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}$$

In one example of the gathering of the time-domain samples described above, in accordance with the configuration defined in the SR control message, more than one FT transmits the RX samples to their connected FBs, where pairwise cross-correlations take place to compute Time Difference of Arrival (TDOA) measurements. The cross-correlation between signals $q_m(t)$ and $q_n(t)$, corresponding to sensors m and n, respectively, is given by

$$c_{m,n}(\tau) = \sum_{t=-T+1}^{T-1} q_m^*(t)q_n(t+\tau)$$

The estimate of the time difference of arrival $\Delta\tau_{m,n}(=\tau_m-\tau_n)$ is derived by seeking to find the peak of cross-correlation function. Specifically,

$$\Delta\tau_{m,n} = T - \arg\max_{\tau}|c_{m,n}(\tau)|$$

Finally the TDOA estimate is a function of the sensor locations, given by

$$\Delta\tau_{m,n}=c^{-1}\sqrt{(x_m-x_0)^2+(y_m-y_0)^2}-c^{-1}\sqrt{(x_n-x_0)^2+(y_n-y_0)^2}+\nu_\tau$$

where ν_τ is a non-Gaussian observation error term.

Bearing

The bearing, or angle of arrival (AOA) of sensor 0 at sensor m is given by

$$\theta_m = a\tan\left(\frac{y_0-y_m}{x_0-x_m}\right)+\nu_\theta$$

where ν_θ is a non-Gaussian observation error term.

Turning now to the evaluation of estimates of some of these quantities, a particle filter is a powerful tool for computing optimal estimates for non-linear and non-Gauss-

ian optimisation problems. A sampling importance resampling particle filter algorithm is shown in FIG. **10**, with reference to the example of characterising external interference sources. The algorithm begins at the start step **152** and a number of definitions are made at step **154**, such as the number of observations to be made, T, a definition of the search space, X, and the number of particles, N, to be used in the algorithm. It should be noted that the number of particles chosen may vary significantly depending on the problem to be solved, for example in the present context an example number of particles used for the source location estimation without time distance of arrival (TDOA) information is approximately 50, whilst an example number of particles used when including time difference of arrival information is approximately 500. In general the number of particles used will typically depend on the number of measurements being used. For example it has been found in simulation studies of the present techniques that satisfactory results are achieved when 500 particles are used for 2 TDOA measurements, and with 100 particles or less when three or more TDOA measurements are used. An iteration parameter, t, is set to 0 at step **156**.

The core steps of the algorithm are now described:

A. (step **158**) Initialise Particles:

a. For n=1, . . . , N, sample $s^{(n)}[0]\sim f(s[0])$, where f[0]) is the prior probability distribution function of the state x at time t=0

B. Get a new measurement:

a. (step **160**) Increment time index: t:=t+1

b. (step **162**) Get new observation: z_t

C. (box **164**) Importance Sampling

a. (step **166**) Generate Particles: for n=1, . . . , N, sample $s^{(n)}[t]\sim f(s[t]|s^{(n)}[t-1])$

b. (step **168**) Compute Weights: for n=1, . . . , N, sample $w^{(n)}[t]\sim f(z[t]|s^{(n)}[t])$

c. (step **170**) Normalise Weights: $c=\Sigma_{n=1}^{N} w^{(n)}[t]$, $w^{(n)}[t]:=c^{-1}w^{(n)}[t]$

D. (step **172**) Resampling

a. Resample with replacement N particles according to weights $w_t^{(n)}$

E. Termination Steps

a. (step **174**) If t<T then go to step **160**

b. (step **176**) Compute Estimates:

i. Conditional Mean $(\mu=E\{s[T]\}):\hat{s}[T]=N^{-1}\Sigma_{n=1}^{N} s^{(n)}[T]$

ii. Covariance Matrix $(P=E\{[T]-\mu)(s[T]-\mu)^H\}:\hat{P}_T=N^{-1}\Sigma_{n=1}^{N}(s^{(n)}[T]-\hat{s}[T])(s^{(n)}[T]-\hat{s}[T])^H$

iii. Algorithm complete (step **178**).

Note firstly that the aim of the resampling step is to replicate particles with high weights and ignore particles with low weights. Note also that s [t] denotes the state at time instant t. In context of the external interference measurement process (passive sounding) s[t] comprises six variables,

$$s[t]=\begin{bmatrix} x_0[t] \\ y_0[t] \\ \theta_0[t] \\ \overline{\theta}_0[t] \\ e_0[t] \\ b_0[t] \end{bmatrix}$$

where $x_0[t]$, $y_0[t]$, $\theta_0[t]$, $\overline{\theta}_0[t]$, $e_0[t]$, and $b_0[t]$ denote the location of the unknown source in x, in y, the bearing, the beamwidth, the EIRP and front-to-back ratio, respectively, at time index t. The time evolution of the state is modelled as a random walk, that is

$$s[t+1]=s[t]+A[t]v[t]$$

where the process noise $v[t]\sim N(0_{6\times1},I_{6\times6})$ are independent and identically distributed AWGN terms, with zero mean and variance given by the 6×6 identity matrix. The matrix A is given by

$$A[t]=\begin{bmatrix} \sigma_x[t] & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_y[t] & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_\theta[t] & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_{\overline{\theta}}[t] & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_e[t] & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_b[t] \end{bmatrix}$$

where for example $\sigma_x[t]$ denotes the standard deviation of the position noise process at t. While here the model has been generalised to include time varying aspects of the interferer, in practice the interferer state may remain static during the entire measurement process.

Note also that z[t] is the measurement vector at t. In the present context the measurement may include the bearing $z_{\theta_m}[t]$ and RSSI measurements $z_{r_m}[t]$ at sensor m, or time difference of arrival $z_{\tau_{m,n}}[t]$ measured at m and n.

$$z_{\theta_m}[t]=a\tan\left(\frac{y_0[t]-y_m}{x_0[t]-x_m}\right)+v_\theta[t]$$

$$z_{r_m}[t]=e_0[t]-\min\left(12\left(\frac{\angle e^{j(\theta_m-\theta_0)}}{\overline{\theta}_0}\right)^2, b_0\right)-\frac{p_a}{2}\log_{10}((x_m-x_0[t])^2+(y_m-y_0[t])^2)-p_b-p_c\log_{10}(f/5000)+v_r[t]$$

$$z_{\tau_{m,n}}[t]=c^{-1}\sqrt{(x_m-x_0[t])^2+(y_m-y_0[t])^2}-c^{-1}\sqrt{(x_n-x_0[t])^2+(y_n-y_0[t])^2}+v_\tau[t]$$

where θ_m in $z_{r_m}[t]$ denotes the angle of departure (AOD) from node **0** to node m, i.e.

$$\theta_m=\text{atan}\left(\frac{y_m-y_0[t]}{x_m-x_{0[t]}}\right).$$

FIG. **11** schematically illustrates the use of a two stage particle filter state estimator. As shown a first stage particle filter **180** is utilised to extract an external interference source's x, y co-ordinates from bearing and time difference of arrival measurements. The RSSI measurements together with the x, y external interference source location estimates are input to the second stage particle filter **182** that computes (listed from top to bottom) the EIRP, the bearing, the 3 dB beamwidth, and the front-to-back ratio of the source. A notable feature of this arrangement is the replacement of a 6 dimensional search space into two smaller sub-problems. In the first sub-problem location estimates $(\hat{x}_0,\hat{y}_0)$ are computed. The location estimates are used in the direction of departure and path loss terms of the RSSI measurement instead of the unknown source location (x_0, y_0). Thus the RSSI measurement is approximated by

$$z_{\hat{r}_m} = e_0[t] - \min\left(12\left(\frac{\angle e^{j(\hat{\theta}_m-\theta_0)}}{\overline{\theta}_0}\right)^2, b_0\right) - \frac{p_a}{2}\log_{10}\left((x_m-\hat{x}_0[t])^2+(y_m-\hat{y}_0[t])^2\right) - p_b - p_c\log_{10}(f/5000) + v_{\hat{r}}[t]$$

$$\text{where } \hat{\theta}_m = \operatorname{atan}\left(\frac{y_m-\hat{y}_0[t]}{x_m-x_0[t]}\right)$$

A simulation of the observation and characterisation of an external interference source X is now illustrated in FIGS. **12-17**. FIG. **12** shows the interference source X, which has been set up with a bearing of −45 degrees, a 70 degree 3 dB beamwidth, an EIRP of 30 dB, and a front-to-back ratio of 20. Seven nodes of the wireless network (**1-7**) configured in omnidirectional reception mode are also shown. FIG. **13** shows the x, y locations of the set of initial particles in the first stage particle filter used for estimation of the interference source location. FIG. **14** shows the particles after using seven angle of arrival and two TDOA estimates. The interfering node (source) is located at (0,−250). Using these seven AOA and two TDOA estimates the location particle filter (after 10 iterations, i.e. T=8 referring to FIG. **10**) computes the average interferer location as (−3.6, −256.2). FIG. **15** shows distributions of the bearing, beamwidth, EIRP, and front-to-back ratio for a the initial set of particles in the second stage particle filter, FIG. **16** shows the distributions at the first iteration, and FIG. **17** shows them at ten iterations. The resulting estimated parameters are:

Bearing: −45.196 degrees

Beamwidth: 72.066 degrees

EIRP: 29.724 dBm

F2B ratio: 19.714 dB

FIG. **18** shows a sequence of steps which are taken in the method of one example embodiment when employing a passive (external interference sampling) process. At step **200** the wireless network controller (BSON engine) generates the required configuration for an external interference sampling process, in particular defining the nodes which should participate in that process. Then at step **202** this process configuration is transmitted to those nodes. At step **204**, when the trigger event defined by the wireless network controller for the external interference sampling process to take place (e.g. a predetermined time) the nodes sample signals from non-network environment components and at step **206** transmit measurement reports based on the signal samples to the wireless network controller (possibly via one or more intermediate components such as a feeder base station as described above). Then at step **208** the wireless network controller estimates the location of the external interference source using the content of the measurement reports by means of a first particle filter process as described above. Then at step **210** the external interference sources characterised (parameterised) by the wireless network controller using the estimated location and the received signal strength (forming part of the measurement reports) this is done, as described above, using a second particle filter process. Thus, having parameterised the external interference source the wireless network controller calculates node configurations to mitigate the interference being caused from this source and transmits these configurations to the relevant nodes in the wireless network at step **212**. The network configuration which mitigates the interference may be determined by the wireless network controller using an evolutionary algorithm as is described below with reference to FIGS. **28** to **36**.

Returning now to a consideration of an active sounding process, as mentioned above the path loss is simply given by: TXpower-RSSI. Formally, the received RSSI is given by:

$$z_{r_m}[t] = P - \left(\frac{p_a}{2}\log_{10}((x_m-x_0[t])^2+(y_m-y_0[t])^2) + p_b + p_c\log_{10}(f/5000)\right) + v_r[t]$$

The second term above is the WINNER2 PL model, parameterised by p_a, p_b and p_c. The parameters are given for an assumed path loss model, or may be estimated using a particle filter. Note that (x_0,y_0) is the coordinates of the active sounding source. Again, it may be assumed that this location is known (i.e. can be specified by the BSON, which stores this information in the backhaul equipment database), or it may be chosen to estimate the location using the same technique as in the passive sounding case.

In context of the active sounding process, s[t] comprises five variables:

$$s[t] = \begin{bmatrix} x_0[t] \\ y_0[t] \\ p_a[t] \\ p_b[t] \\ p_c[t] \end{bmatrix}$$

where $x_0[t]$, $y_0[t]$, $p_a[t]$, $p_b[t]$, and $p_c[t]$ denote the location of the sounding source signal in x and y, and the three path loss parameters, respectively, at time index t. The time evolution of the state is modelled as a random walk, that is:

$$s[t+1]=s[t]+A[t]v[t]$$

where the process noise $v[t]\sim N(0_{5\times1},I_{5\times5})$ are independent and identically distributed AWGN terms, with zero mean and variance given by the 5×5 identity matrix. The matrix A is given by:

$$A[t] = \begin{bmatrix} \sigma_x[t] & 0 & 0 & 0 & 0 \\ 0 & \sigma_y[t] & 0 & 0 & 0 \\ 0 & 0 & \sigma_a[t] & 0 & 0 \\ 0 & 0 & 0 & \sigma_b[t] & 0 \\ 0 & 0 & 0 & 0 & \sigma_c[t] \end{bmatrix}$$

where for example $\sigma_x[t]$ denotes the standard deviation of the position noise process at t. It should be appreciated that whilst here the model has been generalised to include time varying aspects of the sounding source location and the model parameters, in practice these quantities may remain static during the entire measurement process. Nevertheless, incorporating a time varying element into the process permits the use of the static Particle Filter algorithm as described in F. Gustafsson, and F. Gunnarsson, "Positioning using time-difference of arrival measurements", IEEE International Conference on Acoustics, Speech, and Signal Processing, 2003 (Proceedings, ICASSP '03).

Note also that z[t] is the measurement vector at t. In the present (active sounding) context the measurement may include the bearing $z_{\theta_m}[t]$ and RSSI measurements $z_{r_m}[t]$ at sensor m, or time difference of arrival $z_{\tau_{m,n}}[t]$ measured atm and n:

$$z_{\theta_m}[t] = \operatorname{atan}\left(\frac{y_0[t] - y_m}{x_0[t] - x_m}\right) + v_\theta[t]$$

$$z_{r_m}[t] = P - \left(\frac{p_a[t]}{2}\log_{10}((x_m - x_0[t])^2 + (y_m - y_0[t])^2) + p_b[t] + p_c[t]\log_{10}(f/5000)\right) + v_r[t]$$

$$z_{\tau_{m,n}}[t] = c^{-1}\sqrt{(x_m - x_0[t])^2 + (y_m - y_0[t])^2} - c^{-1}\sqrt{(x_n - x_0[t])^2 + (y_n - y_0[t])^2} + v_\tau[t]$$

Evaluation of the path loss model parameters may be performed by various algorithms. A first example algorithm is a single stage filter, which jointly estimates source location and path loss model parameters. A second example algorithm is a two stage filter. The first stage can be by-passed if the sounding (transmitting) node coordinates are known. Recall that they may be communicated to the receiver by the BSON. If the sounding locations are not known, then the first stage particle filter is utilised to extract the sounding source's x, y coordinates from bearing and time difference of arrival measurements. The RSSI measurements, together with the x, y sounding node location estimates, are input to the second stage particle filter that computes the WINNER2 path loss model parameters. A notable feature of this arrangement is the replacement of a 5-dimensional search space into two smaller sub-problems. In the first sub-problem location estimates ($\hat{x}_0$, $\hat{y}_0$) are computed. The location estimates are used in the path loss terms of the RSSI measurements instead of the unknown sounding location (x_0, y_0). Thus the RSSI measurement is approximated by

$$z_{\hat{r}_m}[t] = P - \left(\frac{\hat{p}_a}{2}\log_{10}\left((x_m - \hat{x}_0)^2 + (y_m - \hat{y}_0)^2\right) + \hat{p}_b + \hat{p}_c\log_{10}(f/5000)\right) + v_{\hat{r}}[t]$$

Importantly, as a by-product of either of the example first or second algorithms, the path loss between source node **0** and destination (receiver) node m is derived as follows:

$$PL_{0,m} = \frac{\hat{p}_a}{2}\log_{10}\left((x_m - \hat{x}_0)^2 + (y_m - \hat{y}_0)^2\right) + \hat{p}_b + \hat{p}_c\log_{10}(f/5000)$$

Despite the detailed mathematical background set out above, it should be appreciated that the essence of the active sounding process is to compute the node-to-node path losses, which may be simply derived by subtracting the RSSI from the transmission power. The two particle filter algorithms described are useful, but non-essential tools. Nevertheless, this usefulness is realised in two ways. Firstly, they may be used to verify the node locations. Secondly, and in practice more importantly, they help to determine whether there is a Line of Sight (LOS) link between two nodes and if not, to measure the deviation from the free space path loss model where p_a=20, p_b=46.4, p_c=20. A network configuration may then be determined by the BSON engine by running an algorithm to match possible backhaul throughput (which for each possible node-node link in the network is dependent on the path loss calculated for that node-node link) with the current network demand. An example evolutionary algorithm which may be used in this way is described below with reference to FIGS. **28** to **36**.

FIG. **19** shows a sequence of steps which are taken when using an active sounding schedule to determine a set of path losses for the network and on that basis to configure to the antennas of the nodes in the network. The method begins at step **60**, where the sounding schedule generator **47** (see FIG. **2**) of the wireless network controller distributes an active sounding schedule configuration to the nodes (both feeder base stations and feeder terminals) of the wireless network. The nodes of the wireless network then cooperate to participate in the sounding schedule, and at step **61** it is determined if all nodes of the network have actively sounded. Of course at the first iteration this cannot be the case, and the flow proceeds to step **62**. Here one or more selected nodes then transmits a predetermined signal (bit pattern) omni-directionally (using its omnidirectional (beacon) antenna). It should be noted that in some configurations only one node will transmit at any given time, but the predetermined signal, in particular the selection of subcarrier or subcarriers used for its transmission by each node, can be chosen such that more than one node can transmit at a time. The concentration of a transmitting node's transmission power into a specific, limited number of subcarriers, means that it is possible to allow simultaneous sounding from more than one node to take place, without significant interference between those transmitting nodes occurring. Step **63** shows all other nodes in the wireless network which are not transmitting at this iteration listening omni-directionally and measuring signal strength and direction. The flow then returns to step **61** for one or more further nodes to carry out their sounding, this iterative process around steps **61**, **62** and **63** continuing until all nodes have sounded. The flow then proceeds to step **64** where the nodes of the wireless network which have participated in this active sounding procedure then transmits their measurement reports to the wireless network (BSON) controller. At step **65**, the BSON engine within the wireless network controller and then calculates a set of path losses between all nodes which have participated in the active sounding procedure in order to populate a 2-D path loss matrix. Finally, at step **66**, the BSON engine then runs an algorithm to match possible backhaul throughput (which for each possible node-node link in the network is dependent on the path loss calculated for that node-node link) with the current network demand. This algorithm can vary model parameters including, for each node, the antenna pattern, the antenna direction, and the antenna transmission power, as well as the choice of node-node pairing for data transmission. An optimised (or at least improved, where possible) network topology including antenna configurations for each node, is then communicated to all relevant nodes in the network.

FIG. **20** schematically illustrates the use of a path loss model, as outlined above, to determine a path loss for a given node-node pair. The RSSI measurement made by the receiving node for the transmitting node, together with the measured bearing of the signal received by the receiving node from the transmitting node, are input into a the log-domain RSSI equation given above, i.e.:

$$RSSI = TX\text{power} + TX\text{antennaGain} - PL + RX\text{antennaGain}$$

where the path loss PL is the only unknown in the case of an active sounding transmission from the transmitting node to the receiving node.

FIG. **21** schematically illustrates some components of a BSON engine **180** in one embodiment. Measurement reports are received by a report collection unit (RCU) **182** and

passed to calculation circuitry **184** which, in the manner described above, determines a set of path losses for each node-node pair which participated in the active sounding process, and this set is stored in the path loss database **186**. Selection circuitry **188**, on the basis of the set of path losses stored in the path loss database **186**, then determines a revised configurations for the network, both in terms of the selected node-node pairs for the data transmission, and the individual antenna configurations of each node. These revised configurations are then passed to the transmission circuitry **190** which communicates these to the nodes of the network.

FIG. **22** shows an example set of three feeder base stations and twelve feeder terminals which have participated in an active sounding process under the control of a wireless network controller, and following a determination of the path losses for each node-node pair, each feeder terminal has been paired with one of the three feeder base stations, as shown by the links in the figure.

FIG. **23** schematically illustrates the geometry of a uniform circular array (UCA), i.e. beacon antenna, such as that shown as item **74** in FIG. **3** or item **86** FIG. **4**. The schematic representation shows the three (omnidirectional) antenna elements **0-2** set out on a circle of radius r. The orientation of this array of antenna elements, e.g. the angular offset θ_0 of the first element of the array relative to East shown, is known for example from deployment of this antenna apparatus. This permits angle of arrival estimates to be measured in global (absolute) coordinates, and angle γ_1 shows the (global coordinate) angle of antenna element **1** relative to East. This beacon antenna is used on the one hand for locating other nodes (antennas) belonging to the same (intra-system) network and to characterise the transmission paths from those other nodes to this antenna (in particular in terms of the path loss encountered). On the other hand this beacon antenna is also used to characterise the interference generated by inter-system nodes, i.e. coming from external sources.

FIG. **24** schematically illustrates some components of an antenna apparatus **300** in one embodiment. Nevertheless only those components of particular relevance to a discussion of sub-sampling the array of antenna elements are shown in the figure and other components of the antenna apparatus can be inferred from the other figures herein. The set of antenna elements **302** shown corresponds to the omnidirectional antenna elements of a beacon antenna of this antenna apparatus. Accordingly, these antenna elements **302** correspond to the beacon antenna **74** of FIG. **3** and the uniform circular antenna array **86** of FIG. **4**. However, by comparison to FIG. **4** a notable feature of the arrangement shown in FIG. **24** is that fewer RF chains than antenna elements are provided. Specifically, in the example embodiment shown in FIG. **24**, three antenna elements, but only two RF chains are present. This enables the antenna apparatus to be more cheaply and compactly provided, but a mechanism must then also be provided in order to appropriately connect the antenna elements. This mechanism is provided by the RF switching network **304** which couples the antenna elements **302** to the RF chains **306**. The RF chains **306** each comprise respective down-conversion circuitry **308**. Comparing to FIG. **4**, the down conversion circuitry **308** comprises elements such as the gain circuitry **104** and the phase circuitry **108**. Signals received by the antenna elements **302** and down-converted by the RF chains **306** are processed by the baseband processing circuitry (sampling circuitry) **310**. Which of the antenna elements **302** are connected to the RF chains **306** is determined by the control circuitry **312**. The control circuitry **203** replaces the control circuitry **90** of FIG. **4**. Most importantly in the present context, the control circuitry **312** and administers an iterative process by which pairs of the antenna elements **302** are coupled to the two RF chains in order to sample the signals received. It should be noted that this may be part of a passive sounding procedure to assess external interference sources or may equally be part of an active sounding procedure to assess the influence of the environment in which this antenna apparatus and at least one other antenna apparatus are deployed on the ability of this antenna apparatus to receive data transmissions from that at least one other antenna apparatus. Both are referred to here as a "signal detection process". As a brief aside with regard to the type of sounding, note that there is no need to populate all subcarriers for active sounding, whilst this is needed for passive sounding, since there is no a priori knowledge of how what form of signal the external interference source will represent. Also, note that in principle active sounding can happen in parallel with data transmission, but is limited by the number of RF chains and by the allocation of OFDM frames. Whilst it would be desirable to continually maximise data transmission and reception, it is necessary to allocate one OFDM signal/subcarrier for this active sounding, which necessarily reduces the data throughput budget. Active sounding may therefore be scheduled for a period in the day when data transmission rates are likely to be low.

In performing such assessments the control circuitry **312** controls the antenna apparatus **300** such that the Direction of Arrival (DOA) (or Angle of Arrival (AoA)) and the Received Signal Strength Indicator (RSSI) of the co-channel signals impinging onto the antenna apparatus are estimated. Simultaneous sampling of more than one (in this example embodiment, two out of three of the) antenna elements facilitates the DOA measurements. The antenna apparatus **300** further comprises signal sample storage **314**, into which the sampling circuitry **310** stores samples taken at each iteration of the signal detection process. Moreover, several iterations of the signal detection process may by run, each providing a "snapshot" of the signals sampled by all antenna elements, and stored in the sampling circuitry **310** before these samples are processed to generate a signal sample spatial covariance matrix. These signal samples are retrieved by the signal detection circuitry **316** which forms part of the control circuitry **312** and which, as will be described in more detail below, iteratively generates a signal sample spatial covariance matrix derived from the signal samples taken in the signal detection process and stored in the sample storage **314**. The signal sample spatial covariance matrix storage **318** is provided for the storage and updating of this signal sample spatial covariance matrix. It should be appreciated that sample storage **314** and signal sample spatial covariance matrix storage **318** may for example be provided by a single memory device, to which the control circuitry **312** has access. Generating the signal sample spatial covariance matrix may be done afresh at each rerun of the signal detection process, or, depending on the control circuitry settings, may instead comprise retrieving a previously generated signal sample spatial covariance matrix from the signal sample spatial covariance matrix storage **318** and updating it with the measurements made at this run of the signal detection process. Once a complete signal sample special covariance matrix has been generated, the signal detection circuitry **316** makes use of a beamforming algorithm (which in this example is stored within the antenna apparatus as a beamforming algorithm definition **320**, which itself may also be stored within the above-mentioned single memory) in order to generate specific parameterisations of the signal sources observed. In this example these are a DOA estimate, an RSSI estimate, and an indication (discrete estimate) of the number of sources, shown as item **322** in FIG. **24**. These estimates may remain locally stored for a

while, but will ultimately typically be communicated further to a wireless network controller, which receives such estimates from a number of antenna apparatuses in the wireless network, and which will then seek to improve the wireless network configuration in the light of these interference estimates where possible.

FIG. **25** shows a sequence of steps which are taken in operating an antenna apparatus in one example embodiment in order to perform the signal detection process. Reference is made to the example components of FIG. **24**. The flow begins at step **342** and proceeds to step **340**, where the control circuitry **312** sets the switches of the RF switching network **304** in order to couple a first subset of the antenna elements to the RF chains **306**. Then at step **344** the control circuitry **312** controls the sampling circuitry **310** to sample the signals received by this subset of the antenna elements and to store the results in the sample storage **314**. It is then determined at step **346** if there is a further subset (permutation of pairs) of the antenna elements which has not yet been sampled. When this is the case the flow proceeds to step **348**, where the control circuitry **312** controls the RF switching network **304** to couple an identified unsampled subset of the antenna elements to the RF chains **306**. The flow then returns to step **344**. Once all such subsets (pair permutations) of the antenna elements have been sampled in this way then from step **346** the flow proceeds to step **350** where the signal detection circuitry **316** of the control circuitry **312** constructs a signal sample spatial covariance matrix using the samples stored in the sample storage **314**. More detail of this construction is given below. It should be noted that, for clarity, only the sampling of one "snapshot", and the subsequent construction of a signal sample spatial covariance matrix, is shown in FIG. **25**, but as mentioned, several snapshots may be taken and stored before the signal sample spatial covariance matrix is generated from the combination of those snapshots, and for this purpose a decision point (if further snapshots are required) and return path from the "No" exit of step **346** can be added to lead back to step **340**. Finally the flow then proceeds to step **352**, where the signal detection circuitry **316** applies the beamforming algorithm to the signal sample spatial covariance matrix to provide estimates of the direction of arrival, the received signal strength and/or the number of sources of the signals observed.

Some more detailed description of a (signal sample) spatial covariance matrix and a beamforming algorithm is now provided, in the context of the example antenna apparatus shown in FIG. **24**, i.e. which has three antenna elements and thus the spatial covariance matrix is a 3×3 matrix in this example. The spatial covariance matrix R is not known in advanced and needs to be estimated from the received data. The sampled spatial covariance matrix $\hat{R}$ using T snapshots is given by

$$\hat{R} = \frac{1}{T}\sum_{t=1}^{T} x(t)x^H(t)$$

The eigendecomposition of the 3×3 spatial covariance matrix R can be written as

$$R=E_s\Lambda_s E_s^H+E_n\Lambda_n E_n^H$$

where Λ_s and Λ_n are diagonal matrices corresponding to the eigenvalues of the signal and the noise subspaces, respectively, whereas the columns of the matrices E_s and E_n comprise the eigenvectors of the signal and the noise subspaces of R, respectively. E_s and E_n are orthogonal, i.e. g $E_s^H E_n=0$ and $E_n^H E_s=0$. In this example, the DOA and signal power estimation is performed by using the Multiple Signal Classification (MUSIC) beamforming algorithm as described in R. Schmidt, "Multiple emitter location and signal parameter estimation," IEEE Transactions on Antennas and Propagation, vol. 34, no. 3, pp. 276-280, 1986. MUSIC is a subspace method that can provide asymptotically unbiased estimates of the number of incident wavefronts (i.e. sources) present, the directions of arrival (DOA), and the strengths and cross correlations among the incident waveforms. The MUSIC spectrum is given by

$$P_{MU}(\phi) = \frac{1}{a^H(\phi)E_nE_n^H a(\phi)}$$

where a(φ) is the steering vector (or spatial signature) of the array element corresponding to angle φ. Note that the peaks of $P_{MU}(\varphi)$ indicate a possible signal source. For an UCA the spatial signature is given by

$$a(\phi) = \begin{bmatrix} e^{j\frac{2\pi r}{\lambda}\cos(\phi-\gamma_0)} \\ e^{j\frac{2\pi r}{\lambda}\cos(\phi-\gamma_1)} \\ \vdots \\ e^{j\frac{2\pi r}{\lambda}\cos(\phi-\gamma_{N-1})} \end{bmatrix}$$

where λ denotes the wavelength of the radiated signal. N(=3 in this example) denotes the number of elements in the array. a(φ) here implies that the antenna elements are omni-directional with unit gain. If the first element is located at an angle θ_0 relative to the positive x-axis, the angular displacement γ_n of the nth element is given by

$$\gamma_n = \theta_0 + 2\pi\frac{n}{N}$$

$$\text{for } n = 0, 1, \ldots, N-1.$$

Now let K denote the number of impinging signals on the array at angles $\varphi_1, \varphi_2, \ldots, \varphi_K$. The signal received by the array at time instant t is given by

$$y(t) = \sum_{k=1}^{K} a(\phi_k)s_k(t) + n(t) = As(t) + n(t)$$

where $s(t)=[s_1(t), s_2(t), \ldots, s_K(t)]^T$, $s_k(t)$ is the signal from the kth source, n(t) is the independent and identically distributed (i.i.d.), zero mean, Additive White Gaussian Noise (AWGN) term with covariance $\sigma^2 I$, and $A=[a(\varphi_1), a(\varphi_2), \ldots, a(\varphi_K)]$ is the observation matrix. The spatial covariance matrix is given by

$$R=E\{y(t)y^H(t)\}=APA^H+\sigma^2 I$$

where the diagonal matrix P denotes the average received signal power as measured at a single antenna element. Taking into account the activity factor, the transmission (TX) power, the path loss and the processing gain, the received power matrix P is given by:

$$P=\begin{bmatrix} p_1g_1 & 0 & \dots & 0 \\ 0 & p_2g_2 & 0 & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & p_Kg_K \end{bmatrix}$$

FIG. **26** shows a sequence of steps which are taken in the method of one embodiment to generate the signal sample spatial covariance matrix. The flow begins at step **400** and proceeds to step **402** where the number of (RX) antenna elements is set as a variable N and the required number of iterations of the signal detection process is set as variable T. Then at step **404** the spatial covariance matrix R is reset. At step **406** an iteration variable t is set to zero. Then at step **408** it is determined if t is equal to or exceeds T (and of course at the first iteration it will not). The flow then proceeds to step **410** where t is incremented and at the following step **412** an antenna element loop iteration variable i is set to zero. At step **414** it is determined if i is greater than or equal to N. This not being the case the flow proceeds to step **416** where a further antenna element loop iteration variable j is set to the value of i. Then, at step **418**, j is incremented, such that now i and j represent the indices of two antenna elements which have not yet been paired for signal sample gathering. At step **420** measurements for antenna elements x, and x_j are made, and at step **422** the spatial covariance matrix elements R(1,1) and R(i,j) are updated. More detail of this updating is given below. Then at step **424** it is determined if j is greater than or equal to N, and whilst this is not the case the flow iterates through steps **418**, **420** and **422** again. Once j reaches N, i.e. antenna element i has been paired with all other antenna elements of higher index, then the flow proceeds to step **426** where i is incremented and then to step **414** to determine once more if i has reached N. Once this is the case the flow returns to step **408**. Further iterations of the signal detection process, iteratively taking measurements from all antenna element pairs, are then carried out until t becomes equal to or exceeds T and the flow branches to step **430**. There the value accumulated in the matrix element R(1,1) is normalised on the basis of the number of antenna elements (N) and at step **432** the diagonal and lower triangle elements of matrix R are updated (more detail below). At step **434** all elements of the matrix normalised on the basis of the number of iterations (T) of the signal detection process carried out. The procedure is complete at step **436**. It will be appreciated from a consideration of FIG. **26** that a "batch" process is therefore described in this example embodiment in which T iterations of the signal detection process are carried out and one resulting spatial covariance matrix is generated.

Referring back to the "Update R(1,1) & R(i,j)" step **422** of FIG. **26**, this comprises the following accumulations:

$$R(1,1):=R(1,1)+x_ix_i^*+x_jx_j^*$$

$$R(i,j):=R(i,j)+x_ix_j^*$$

It should therefore be noted that the matrix element R(1,1) (essentially a power measurement) is updated with zero lag autocorrelation measurements from all antenna elements (i.e. not just from antenna element **1**) being added to the existing value of that element, whilst matrix element R(i,j) is updated with zero lag cross-correlation measurements (from antenna element pair (i,j) being added to the existing value of that element.

The "Normalise R(1,1) step **430** of FIG. **26** comprises the following calculation:

$$R(1,1):=\frac{R(1,1)}{N(N-1)}$$

Note that R(1,1) is therefore normalised by a value which is double the number of antenna element pair combinations (N(N−1)/2), since at each accumulation step for R(1,1) both the $x_ix_i^*$ and the $x_jx_j^*$ terms are added, and double the power is thus accumulated. The "Update diagonal and lower triangular elements of R" step **432** of FIG. **26** comprises the following allocations:

$$R(n,n):=R(1,1),\text{for } n=2:N$$

$$R(n,m):=R^*(m,n),\text{for } n=2:N, m=1:n-1$$

Thus the now-normalised power value for antenna element **1** is reproduced for the other antenna elements, and cross-correlation values in the upper triangle of the matrix are conjugated and index-swopped to populate the lower triangle of the matrix.

FIG. **27** shows a variant on the method shown in FIG. **26**, in which a modified sequence of steps are taken in the method of one embodiment to generate the (signal sample) spatial covariance matrix, where the accumulation of R further makes use of a time-evolution factor ρ (also referred to as a "forgetting factor"), such that respective weightings may be applied to the current sample matrix R' and the previously accumulated sample matrix R as follows:

$$R:=\rho R+(1-\rho)R'$$

Note that the respective weightings applied to the current measurements and the previous measurements thus sum to one, and the ρ may be freely set in the range (0,1) in dependence on the desired influence that the current measurements and the previous measurements should have on the resulting matrix. For example, for parametrising the results of an active sounding procedure, ρ may be chosen to be close to 0, thus permitting rapid adaptation of R since the sounding signal is known. On the other hand, for parametrising the results of a passive sounding procedure ρ may be set to a value close to 1 (typically ρ=0.95) to permit long term averaging and at the same time allow R to adapt to time varying signals.

The flow of FIG. **27** begins at step **500** and proceeds to step **502** where the number of (RX) antenna elements is set as a variable N, the required number of iterations of the signal detection process is set as variable T, and the "forgetting factor" ρ is set. Then at step **404** the spatial covariance matrices R and R' are reset. At step **506** an iteration variable t is set to zero. Then at step **508** it is determined if t is equal to one (and of course at the first iteration it will not). The flow then proceeds to step **510**, where the spatial covariance matrix R is updated as a linear combination of R and R', using the "forgetting factor" ρ as a weighting for R and (1−ρ) as a weighting for R'. The matrix R' is then reset at step **512**. Then at step **514** it is determined if t is equal to or exceeds T (and of course at the first iteration it will not). The flow then proceeds to step **516** where t is incremented and at the following step **518** an antenna element loop iteration variable i is set to zero. At step **520** it is determined if i is greater than or equal to N. This not being the case the flow proceeds to step **522** where a further antenna element loop iteration variable j is set to the value of i. Then, at step **524**, j is incremented, such that now i and j represent the indices of two antenna elements which have not yet been paired for signal sample gathering. At step **526** measurements for antenna elements x_i and x_j are made, and at step

528 the spatial covariance matrix R' is updated, for elements R'(1,1) and R('i,j). This is as described above. Then at step 530 it is determined if j is greater than or equal to N, and whilst this is not the case the flow iterates through steps 524, 526, and 528 again. Once j reaches N, i.e. antenna element i has been paired with all other antenna elements of higher index, then the flow proceeds to step 532 where i is incremented and then to step 520 to determine once more if i has reached N. Once this is the case the flow returns to step 508. On returning to this step for the first time, t will indeed be equal to one, and the flow branches for this iteration to step 534, where the spatial covariance matrix R is initialised using the values of the spatial covariance matrix R' which have just been calculated at the very first iteration. The flow then proceeds to step 512, and spatial covariance matrix R' is reset.

Further iterations of the signal detection process, iteratively taking measurements from all antenna element pairs, are then carried out until t becomes equal to or exceeds T and the flow branches to step 536. There the value accumulated in the matrix element R(1,1) is normalised and at step 538 the diagonal and lower triangle elements of matrix R are updated (as described above). The procedure is complete at step 540. It will be appreciated from a consideration of FIG. 27 that an "adaptive" process is therefore described in this example embodiment in which T iterations of the signal measuring process are carried out, allowing the resulting spatial covariance matrix to evolve over each iteration.

Whatever the source of the revised parameterisation of the environment, the optimisation of the network is then performed in one example embodiment by the BSON controller using an Evolutionary Algorithm (EA), as for example described in the articles T. Back, "Evolutionary Algorithms in Theory and Practice: Evolution Strategies, Evolutionary Programming, Genetic Algorithms", Oxford University, 1996, T. Bäck, U. Hammel, and H. P. Schwefel, "Evolutionary computation: comments on the history and current state", *IEEE Transactions on Evolutionary Computation*, vol. 1, pp. 3-17, April 1997. Online available at citeseerx.ist.psu(dot)edu/viewdoc/summary?doi=10.1.1.6.5943, and Weise T., "Global Optimization Algorithms, Theory and Application", it-weise.de/projects/book(dot)pdf.

EAs are generic, population based, metaheuristic optimisation algorithms, largely inspired by biological mechanisms, such as mutation, crossover (reproduction) and selection (see page 95 of the above-mentioned "Global Optimization Algorithms, Theory and Application" document). The basic cycle of EAs is illustrated in FIG. 28 and it comprises five blocks (as discussed on page 96 of the above-mentioned "Global Optimization Algorithms, Theory and Application" document):

Initial Population (step 700)
Evaluation (step 705)
Fitness Assignment (step 710)
Selection (step 715)
Reproduction (step 720)

The reader is referred to the document "Global Optimization Algorithms, Theory and Application" for a general discussion on the functionalities of the above mentioned blocks. The following discussion will describe how the basic evolutionary algorithm approach illustrated in FIG. 28 is adapted to enable its use in the current situation to provide rapid updates of the network based on changing conditions. However, in general terms, the initial population stage 700 involves creating a set of individual entries, each individual entry in this case being an hypothesised optimised network. During the evaluation stage 705, each of the individuals in the population are evaluated, and hence in the current context the channel capacity for every feeder link in the network is computed for each hypothesised optimised network. Then, during fitness assignment step 710, for each link the channel capacity is converted to throughput. This throughput is compared against the target throughput and an associated reward is allocated to each link. A reward can then be calculated for each hypothesised optimised network.

The selection stage then involves applying a process to select the individuals (i.e. the hypothesised optimised networks) with high rewards more often than those with low rewards so that the individual entries with low fitness values will eventually be discarded and those with high values will enter the mating pool then used for the reproduction stage 720. At the reproduction stage, pairs in the mating pool are selected and for each pair offspring are created by combining or modifying the attributes of their parents. This results in a revised set of hypothesised optimised networks which can then be subjected to another iteration of the evolutionary algorithm.

FIG. 29 is a flow diagram illustrating the steps performed to compute and apply an optimised network configuration. At step 800, the process is started, whereafter at step 805 a variable N is set equal to the number of hypothesised optimised networks that are to be considered by the evolutionary algorithm. Thereafter, at step 810, a set of hypotheses are initialised. This process will be described in more detail later with reference to FIG. 30. Thereafter, a process of evaluating the various links between feeder terminals and feeder base stations is performed at step 815, this process being described later with reference to FIG. 31. Then, at step 820, the current set of hypotheses are evaluated based on the output of the link evaluation process, in order to associate a reward with each hypothesis in the set. This process will be described in more detail later with reference to FIG. 33. Thereafter, a selection process is performed at step 825 to select a modified set of hypotheses, this process being described in more detail later with reference to FIG. 34.

Then, at step 830, a process is performed to determine and apply a preferred optimised network configuration based on the modified set of hypotheses determined at step 825. For a system including a BSON, this process will be described in more detail later with reference to FIG. 36. It should be noted that whilst in FIG. 29 step 830 is shown as being performed on each iteration of the evolutionary algorithm, it does not need to be performed on each iteration, and instead can be performed merely as and when a predetermined trigger condition occurs. This trigger condition may be completion of the current iteration of the evolutionary algorithm, or may instead be a less frequently occurring trigger condition, such as an update to a certain traffic report, the receipt of updated sounding data, etc.

At step 835, a reproduction process is performed in order to produce a replacement set of hypotheses, after which the process returns to step 815. The process at step 835 will be discussed in more detail later with reference to FIG. 35.

A more detailed discussion of the steps 810 to 835 of FIG. 29 will now be provided with reference to the further flow diagrams.

Initialise Hypotheses

In this stage, multiple optimised network hypotheses are generated. Each hypothesis corresponds to a candidate optimised network. In one embodiment, an entry in the hypothesis consists of an uplink (UL) or downlink (DL) transmission and:

1. Feeder Base (FB) and a Feeder Terminal (FT) association.

2. Antenna Bearing (AB), specifying the azimuth orientation of the main directional antenna.
3. Transmit Antenna Pattern (TX AP), instructing the beam pattern to be used during transmission.
4. Relative Throughput Weight Coefficient (W), defining the relative throughput between the FTs connected to the same FB.
5. Link Quality Indicator (LQI); a measure of the quality of the data stream.

With reference to FIG. **22**, an example hypothesis is given in Table 1 below. For clarity of discussion, first consider the third row in Table 1. In this example, FB_1 is linked to FT_2 in the DL transmitting at a bearing of 45 degrees. In addition, antenna pattern **1** and a relative throughput weight of 2 are specified. The LQI of 10 is also derived. To further clarify the significance of W, and based on Table 1, the DL throughput from FB_1 to FT_2 should be twice as high as the throughput to FT_1 and FT_8. The weights W are specified using the traffic demand information stored in the backhaul network configuration database **41** of FIG. **2**. In the absence of traffic demand, the Ws are set to unity.

TABLE 1

Example hypothesised optimised network.

FB	FT	UL/DL	AB	TX AP	W	LQI
1	1	DL	145	1	1	8
1	2	DL	45	1	2	7
1	8	DL	45	1	1	10
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
3	3	DL	−135	1	1	9
3	4	DL	−135	1	1	7
1	1	UL	−45	3	2	8
1	2	UL	−120	3	1	10
1	8	UL	−180	3	1	7
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
3	3	UL	60	3	1	8
3	4	UL	45	3	2	9

FIG. **30** illustrates the steps for generating multiple optimised network hypotheses. Following start of the process at step **850** the number of FTs (L) is obtained at step **855** from the backhaul equipment database **860**. In FIG. **30**, two iterations take place—the outer loop **867** generates N hypotheses, whereas the inner loop **869** will, for each hypothesis H_n, assign an FT to a FB and assign an antenna bearing and a TX antenna pattern. Notice that the derivation of the LQIs has been omitted here. Their entries in the hypotheses are left empty, to be computed during the evaluation phase of the algorithm. In addition, the entries of the Ws have also been omitted here. Their entries are computed based on the FB to FT associations and the traffic demand. The entries are recomputed if there is a change in the FB-FT association or a change in the traffic demand.

Accordingly, considering FIG. **30** in more detail, a variable n is set equal to 0 at step **865**, and it then incremented at step **870**. Thereafter, a variable I is set equal to 0 at step **875**, and then incremented at step **880**. At step **885**, feeder terminal I for hypothesised optimised network n is assigned to a FB. The association may be random, or based on distance. Thereafter, at step **890**, an antenna bearing is assigned for feeder terminal I of the hypothesised optimised network n. The bearing is set equal to the direction towards the associated FB, or may be random. At step **892** an antenna pattern is assigned for feeder terminal I of hypothesised optimised network n. Recall that the backhaul equipment database **860** stores the geolocation of FT and FB nodes, and thus deriving the FT-FB relative bearing is straightforward. For example, the FB antenna bearing may point generally in the direction of its associated FTs using a wide (sector covering) antenna pattern, or alternatively, FB antenna bearing and antenna pattern may be assigned randomly.

At step **894**, it is determined whether I is less than L, where (as discussed earlier) L denotes the number of feeder terminals. If it does, then the inner loop is repeated, beginning at step **880**. However, if at step **894** it is determined that I is not less than L, then the process proceeds to step **896**, where it is determined whether n is less than N (as discussed earlier N being the number of hypothesised optimised networks to be used by the evolutionary algorithm). If it is, then the outer loop is reiterated by returning to step **870**. If it is not, then this indicates that all of the hypothesised optimised networks have been produced, and accordingly the process proceeds to step **898** where the initialisation of the set of hypotheses is considered to be completed. Note that the antenna bearings and beam patterns for the FBs can for example be assigned randomly at step **898**.

Evaluate Links

In accordance with step **815** of FIG. **29**, every FT/FB link within each hypothesis is evaluated. This phase is highly parallelised and may be implemented in a distributed fashion. During this phase, while considering the co-channel interference, the channel capacity for every link in the network is computed. The co-channel interference may originate from nodes in the wireless network itself (reuse one is the preferred multiple access technique), or originate from uncoordinated unsolicited nodes. The capacity is measured in bits per second per Hz and takes into account all implementation losses. The implementation losses are calculated at the FTs and communicated at the associated FBs and forwarded to the backhaul equipment database.

FIG. **31** illustrates the steps for evaluating the links, i.e. corresponding to step **815** of FIG. **29**. In summary, for each FT, the UL and DL capacities are evaluated. Parallelisation is indicated by the asterisk in the figure. Considering FIG. **31** in more detail, at step **900**, the process starts, whereafter at step **905** the set of input hypotheses and the number of feeder terminals in the system are obtained from the network parameters of backhaul equipment database **910**. Thereafter, at step **915**, a variable I is set equal to 0, and is then incremented at step **920**. At step **930**, the uplink and downlink capacities and LQIs are evaluated for feeder terminal I, again across all hypotheses. This process can be highly parallelised, given the separate nature of the individual hypotheses. During step **930**, the computed LQIs take into account the unsolicited and uncoordinated transmissions characterised by the external interference database of **912**. At step **935** it is determined whether the variable I is less than the total number of FTs, and if so the process loops back to step **920**. However, when it is determined at step **935** that the variable I is no longer less than the number of FTs, and accordingly all FTs have been analysed, then the process proceeds to step **940**, where the evaluate links process is considered complete.

Evaluate Hypotheses

Here each hypothesis H_n is awarded a score r_n. As a rule, the higher the score the better the hypothesis. For each link, the channel capacity per link is converted to throughput (bits per second). The throughput per link is checked against the target throughput. A reward is then allocated to each link. The reward, which is a positive value, is a function of the

offered throughput and the desired throughput. An example reward function is given in FIG. **32**. In FIG. **32**, no reward is allocated if the offered traffic in a link is less than the desired throughput. A maximum reward is allocated to a link if the target is met. A diminishing reward is applied if the offered traffic far exceeds the target throughput. Throughput targets are time and location dependent, that is, a certain link may demand different amounts of traffic depending on the time of day. Furthermore, it may also be expected that business districts will be heavily loaded during the day and lightly loaded during the night or during public holidays; the reverse may be true in suburban areas.

For each hypothesis, the vector of (total) rewards is mapped to a single scalar that determines the overall fitness value of the hypothesis. There are a number of mapping functions, for example:

Mean (arithmetic or harmonic): this yield an average fitness value;

x^{th} percentile: (for example the 5th percentile) that ensures (100-x) percent of links have the same or better fitness value;

min: returns the fitness value of the worst link.

FIG. **33** is a flow diagram illustrating how the above evaluation process is performed in one embodiment. At step **950**, the evaluation process begins, whereafter at step **952** the number of hypothesised optimised networks, the number of FTs and the number of FBs are obtained from the network parameters database **954**.

At step **956**, the variable I is set equal to 0, whereafter at step **958** I is incremented. Then, at step **960** the uplink and downlink reward for feeder terminal I is evaluated across all hypotheses. This process is performed in parallel, due to the discrete nature of the different hypotheses. Thereafter, at step **962**, it is determined whether the variable I is less than the number of FTs, and if so the process returns to step **958**. However, when it is determined at step **962** that the variable I is no longer less than the number of FTs, then at this point the uplink and downlink rewards for all feeder terminals across all hypotheses is complete, and the process proceeds to step **964**. Steps **964**, **966**, **968** and **970** perform the same process as steps **956**, **958**, **960**, **962**, but in respect of each FB rather than each FT. Again, step **968** can be performed in parallel for all hypotheses. Once it is determined at step **970** that all FBs have been considered, then the process proceeds to step **972**.

At step **972** a variable n is set equal to 0 and then at step **974** *n* is incremented. Thereafter, at step **976** the various uplink and downlink rewards for hypothesis n are evaluated in order to produce a reward value for the hypothesis. At step **978**, it is determined whether all hypotheses have been considered, and if not the process returns to step **974**. However, once it is determined at step **978** that all hypotheses have been considered, then the process proceeds to step **980** where the evaluation process is considered complete.

Select Hypothesis

The selection performed at step **825** of FIG. **29** is done in a random fashion, selecting the hypotheses with high rewards more often. As a consequence, hypotheses with low rewards will eventually be discarded and those with high values will proceed to the next stage. If N denotes the number of (input) hypotheses that enter the selection process, then N will also be the number of (output) hypotheses that will be generated by the selection process. It should be clear that some output hypotheses will be in duplicate.

FIG. **34** illustrates the steps performed in one embodiment in order to select a modified set of hypotheses. At step **1000**, the process begins, whereafter at step **1005** the number of hypothesised optimised networks N is obtained, and then the number of highest ranked hypotheses K is determined with reference to the results of the evaluation process described with reference to FIG. **33**, this information being stored as network parameters **1010**. At step **1015**, the K highest ranked hypotheses are selected, whereafter at step **1020** a further N-K hypotheses are selected randomly. Thereafter, at step **1025**, the selection process is considered complete, and the resultant modified set of hypotheses are output. In practice, the value K is typically equal to one or two. The selection of the K highest ranked hypotheses guarantees the survival of the best solution.

Generate a New Set of Hypotheses

After the modified set of hypotheses has been produced by step **825** of FIG. **29**, a replacement set of hypotheses is created by the reproduction step **835** of FIG. **29**. If N denotes the number of (input) hypotheses that enter this process, then N will also be the number of new (output) hypotheses that will be generated. This phase contains the following four operations, described for example in the publication Weise T., "Global Optimization Algorithms, Theory and Application", available at it-weise.de/projects/book(dot)pdf.

Creation: One or more hypotheses are generated with random attributes.

Duplication: One or more input hypotheses with the highest score are copied without any modifications.

Mutation: A minor attribute of an input hypothesis is randomly modified to generate a new hypothesis. The selected input hypotheses for this stage are selected in a random fashion.

Recombination (or Crossover): Attributes from pairs of input hypotheses are randomly swapped to create pairs of new hypotheses. The selected input hypotheses for this stage are selected by random.

In one embodiment, a fifth new operation is also added:

Reincarnation: Reinstate one or more optimised networks (stored in a database). For example, reinstate an optimised network that was applied 24 h and/or 7 days ago. The assumption here is that traffic demand is cyclostationary.

Let N_C, N_D, N_M, N_R, and N_I, denote the number of creations, duplications, mutations, recombinations and reincarnations, respectively. It will be clear that $N=N_C+N_D+N_M+N_R\ N_I$. In one example embodiment, N_C is typically set to 1; random starting points are generally a good idea to avoid local minima during optimisation. N_D is typically set to 2 ensuring the survival of the fittest. The number of recombination N_R is by design an even number and usually does not exceed the number of mutations N_M. During a mutation or a recombination one or more attributes of the hypotheses are modified. This is carried out by modifying or appending one of the following:

1. FT to FB association;
2. Antenna bearing;
3. TX antenna pattern.

FIG. **35** illustrates the steps for generating a new set of hypotheses. At step **1050**, the generation step begins, whereafter at step **1055** the set of input hypotheses are obtained from the network parameters **1060** along with a set of previously optimised hypotheses, for example hypotheses that are considered to provide particularly good solutions having regard to a particular time of day, day of the week, etc. The variables N_C, N_D, N_M, N_R, and N_I are also obtained, these values typically having been set in advance. Thereafter, at step **1065**, N_C random hypotheses are created, and at step **1070** the best N_D hypotheses from the set of input hypotheses are duplicated. At step **1075**, N_M hypotheses

from the set of input hypotheses are mutated, with the hypotheses selected for this process typically being random. At step **1080**, N_R hypotheses from the set of input hypotheses are subjected to the recombination process. Again, the hypotheses chosen for this process are typically random, other than the requirement for an even number of hypotheses to be chosen. At step **1085**, N_I hypotheses are reinstated from the set of previously optimised hypotheses, whereafter the generation process is considered complete at step **1090**.

It will be appreciated that the various parameters N_C, N_D, N_M, N_R, and N_I can be varied if desired. For example, whilst at some times of the day it may be appropriate to reinstate a hypothesis from a set of previously optimised hypotheses at step **1085**, there may be other times of day when this is not appropriate, and accordingly it would be appropriate to set the variable N_I to 0 and to adjust the other variables accordingly.

Apply Preferred Optimised Network

This procedure (step **830** of FIG. **29**) is responsible for selecting the optimised network and disseminating the information to the various nodes of the network. Specifically, the BSON searches through the current set of hypotheses and selects the one yielding the highest score. The selected hypothesis will thus be the next optimised network to be applied to the network. The BSON is also responsible for communicating the optimised network to the FBs and FTs. In order to minimise the amount of information sent to each node in the network, the BSON will communicate portions of the optimised network pertinent to each FB and associated FTs.

FIG. **36** is a flow diagram illustrating the above process. At step **1100**, the process starts, whereafter at step **1105** the set of input hypotheses is obtained. At step **1110**, the best hypothesis from the set, based on its current reward value, is selected, and then at step **1115** the selected hypothesis is set as the next optimised network. Thereafter, at step **1120**, the optimised network is distributed to the FBs and FTs, whereafter the process is considered completed at step **1125**.

By way of brief overall summary a method and corresponding apparatus are provided for network configuration selection in a wireless network comprising a plurality of nodes. A subset of nodes of the plurality of nodes are configured to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node. Measurement reports are received from the subset of nodes, each measurement report comprising a signal source angle and a received signal strength. A path loss is determined in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs. Then a directional configuration is selected for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

In the present application, the words "configured to . . . " are used to mean that an element of an apparatus has a configuration able to carry out the defined operation. In this context, a "configuration" means an arrangement or manner of interconnection of hardware or software. For example, the apparatus may have dedicated hardware which provides the defined operation, or a processor or other processing device may be programmed to perform the function. "Configured to" does not imply that the apparatus element needs to be changed in any way in order to provide the defined operation.

Although illustrative embodiments have been described in detail herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to those precise embodiments, and that various changes, additions and modifications can be effected therein by one skilled in the art without departing from the scope and spirit of the invention as defined by the appended claims. For example, various combinations of the features of the dependent claims could be made with the features of the independent claims without departing from the scope of the present invention.

The invention claimed is:

1. A method of network configuration selection in a wireless network comprising a plurality of nodes, the method comprising the steps of:

configuring a subset of nodes of the plurality of nodes to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node;

receiving measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength;

determining a path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and selecting a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

2. The method as claimed in claim **1**, wherein the sounding process is a multiple step sounding process, wherein at each step of the multiple step sounding process only one node of the subset of nodes transmits the predetermined signal.

3. The method as claimed in claim **1**, wherein in the sounding process the predetermined signal transmitted by each node of the subset of nodes is unique to that node and the subset of nodes transmit their unique predetermined signals concurrently.

4. The method as claimed in claim **1**, wherein the directional antenna is configured to be rotationally positioned, and the directional configuration comprises a rotational position for the directional antenna.

5. The method as claimed in claim **1**, further comprising selecting at least one transmitter node receiver node pair to use in data transmission in dependence on the set of path losses.

6. The method as claimed in claim **1**, wherein the directional configuration comprises a beam pattern for the directional antenna.

7. The method as claimed in claim **1**, further comprising calculating a predicted received signal strength at a receiver node when using a first beam pattern for the directional antenna of a transmitter node and a second beam pattern for the directional antenna of the receiver node,

and selecting the directional configuration for the directional antenna of each node of the subset of nodes to use in data transmission is performed in further dependence the predicted received signal strength.

8. The method as claimed in claim **1**, wherein generating the set of path losses generates an estimated path loss between all pairs of nodes in the subset of nodes.

9. The method as claimed in claim **1**, wherein determining the path loss is performed in dependence on a transmission

power and antenna gain of the transmitting node and a reception antenna gain of the receiving node.

10. The method as claimed in claim **1**, wherein configuring the subset of nodes to simultaneously participate in the sounding process comprises defining a trigger type for initiation of the sounding process.

11. The method as claimed in claim **10**, wherein the trigger type is arrival of a predetermined start time.

12. Apparatus for configuration selection in a wireless network comprising a plurality of nodes, the apparatus comprising:

transmission circuitry to transmit a sounding configuration to a subset of nodes of the plurality of nodes to cause the subset to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omnidirectional antenna array of that node; reception circuitry to receive measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength;

calculation circuitry to calculate an path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and

selection circuitry to select a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

13. Apparatus for configuration selection in a wireless network comprising a plurality of nodes, the apparatus comprising:

sounding schedule generation circuitry arranged to transmit a sounding configuration to a subset of nodes of the plurality of nodes to cause the subset to simultaneously participate in a sounding process, in which a node of the subset omni-directionally transmits a predetermined signal and in which other nodes of the subset of nodes sample the predetermined signal as received by an omni-directional antenna array of that node;

backhaul self-organising network engine circuitry arranged to receive measurement reports from the subset of nodes, wherein each measurement report comprises a signal source angle and a received signal strength;

the backhaul self-organising network engine circuitry further arranged to calculate a path loss in dependence on each measurement report to generate a set of path losses covering a plurality of transmitter node receiver node pairs; and

the backhaul self-organising network engine circuitry further arranged to select; a directional configuration for a directional antenna of each node of the subset of nodes to use in data transmission in dependence on the set of path losses.

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