US011863278B2

(12) United States Patent
Frenger et al.

(10) Patent No.: US 11,863,278 B2
(45) Date of Patent: Jan. 2, 2024

(54) **APPARATUSES AND METHODS FOR SEQUENTIAL RECEIVE COMBINING**

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

(21) Appl. No.: **17/637,091**

(22) PCT Filed: **Aug. 30, 2019**

(86) PCT No.: **PCT/SE2019/050811**
§ 371 (c)(1),
(2) Date: **Feb. 22, 2022**

(87) PCT Pub. No.: **WO2021/040590**
PCT Pub. Date: **Mar. 4, 2021**

(65) **Prior Publication Data**
US 2022/0286193 A1 Sep. 8, 2022

(51) **Int. Cl.**
H04B 7/08 (2006.01)
H04B 7/022 (2017.01)
H04L 5/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H04B 7/0848*** (2013.01); ***H04B 7/022*** (2013.01); ***H04L 5/0035*** (2013.01); *H04L 5/0016* (2013.01); *H04L 5/0023* (2013.01)

(58) **Field of Classification Search**
CPC H04B 7/0848; H04B 7/022; H04B 7/0452; H04B 7/0857; H04B 7/0854;
(Continued)

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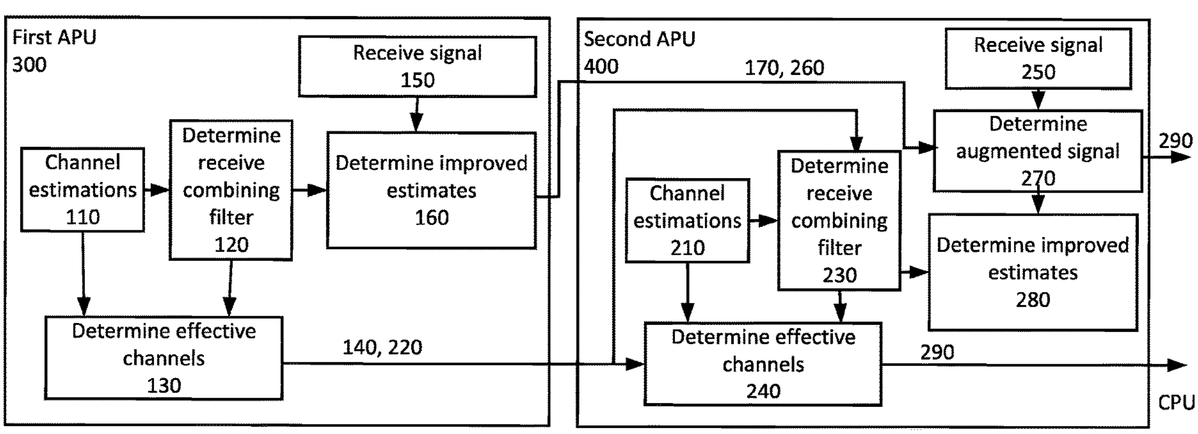
(57) **ABSTRACT**

The present disclosure relates to radio network communication. In one of its aspects, the present disclosure relates to a method, performed by a first APU, for sequential receive combining in a radio stripe system. The system comprises at least two APUs connected in series to a CPU and serves at least two UEs. According to the method, channel estimates for channels to said served UEs are received and based on these, a receive combining filter is determined. The receive combining filter is to be applied to received data signals. Thereafter, based on the obtained channel estimates and the determined receive combining filter, effective channels from said served UEs are determined. These represent the effective channel created after the receive combining filter being applied to each channel for said served UEs. The effective channels are transmitted from said served UEs to at least one subsequent second APU.

17 Claims, 12 Drawing Sheets



(58) **Field of Classification Search**
CPC ... H04B 7/0413; H04L 5/0035; H04L 5/0016; H04L 5/0023; H04J 11/0059; H04W 24/10; Y02D 30/70
See application file for complete search history.

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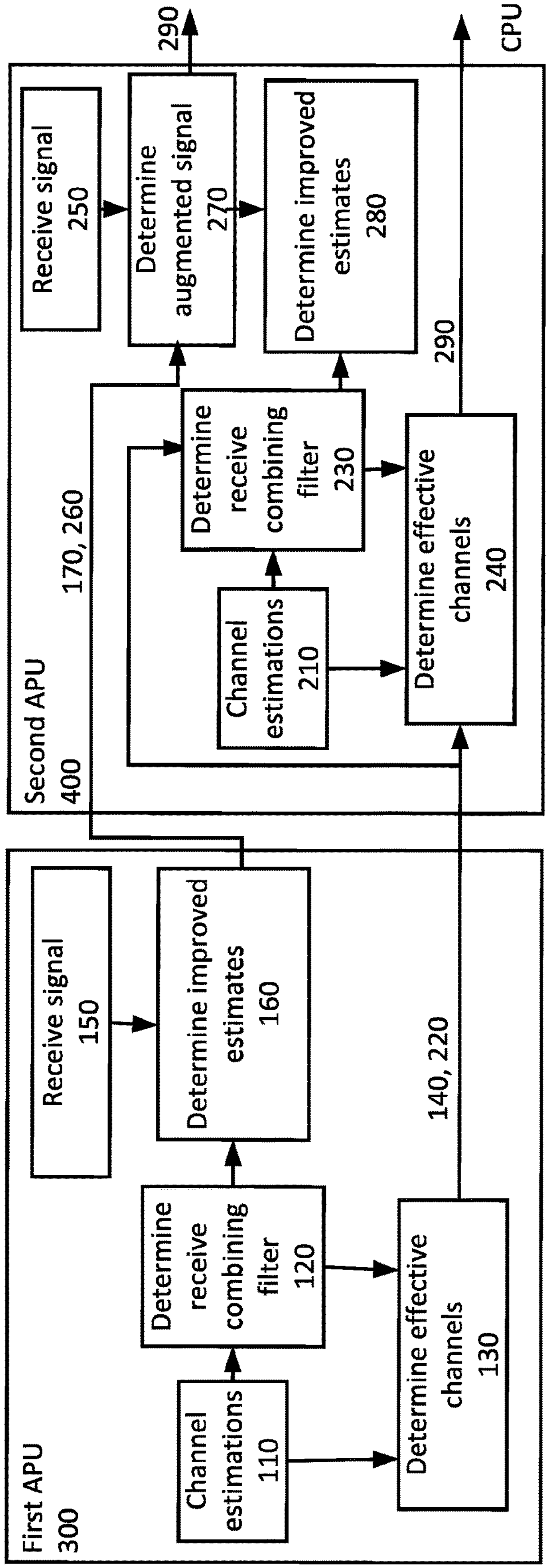
First APU
300
Channel estimations
110
Determine receive combining filter
120
Determine effective channels
130
Receive signal
150
Determine improved estimates
160
140, 220
Second APU
400
170, 260
Channel estimations
210
Determine receive combining filter
230
Determine effective channels
240
Receive signal
250
Determine augmented signal
270
Determine improved estimates
280
290
290
CPU

Fig. 1

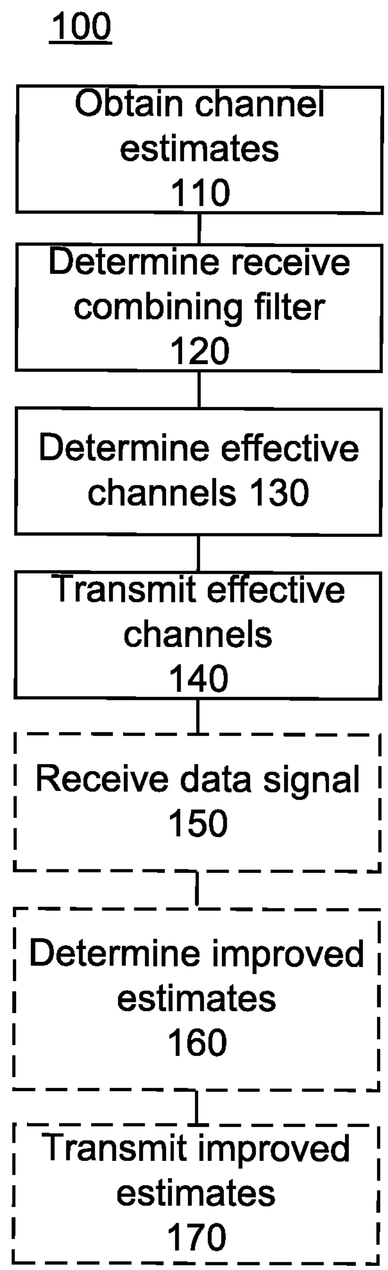
100
Obtain channel estimates 110
Determine receive combining filter 120
Determine effective channels 130
Transmit effective channels 140
Receive data signal 150
Determine improved estimates 160
Transmit improved estimates 170

Fig. 2

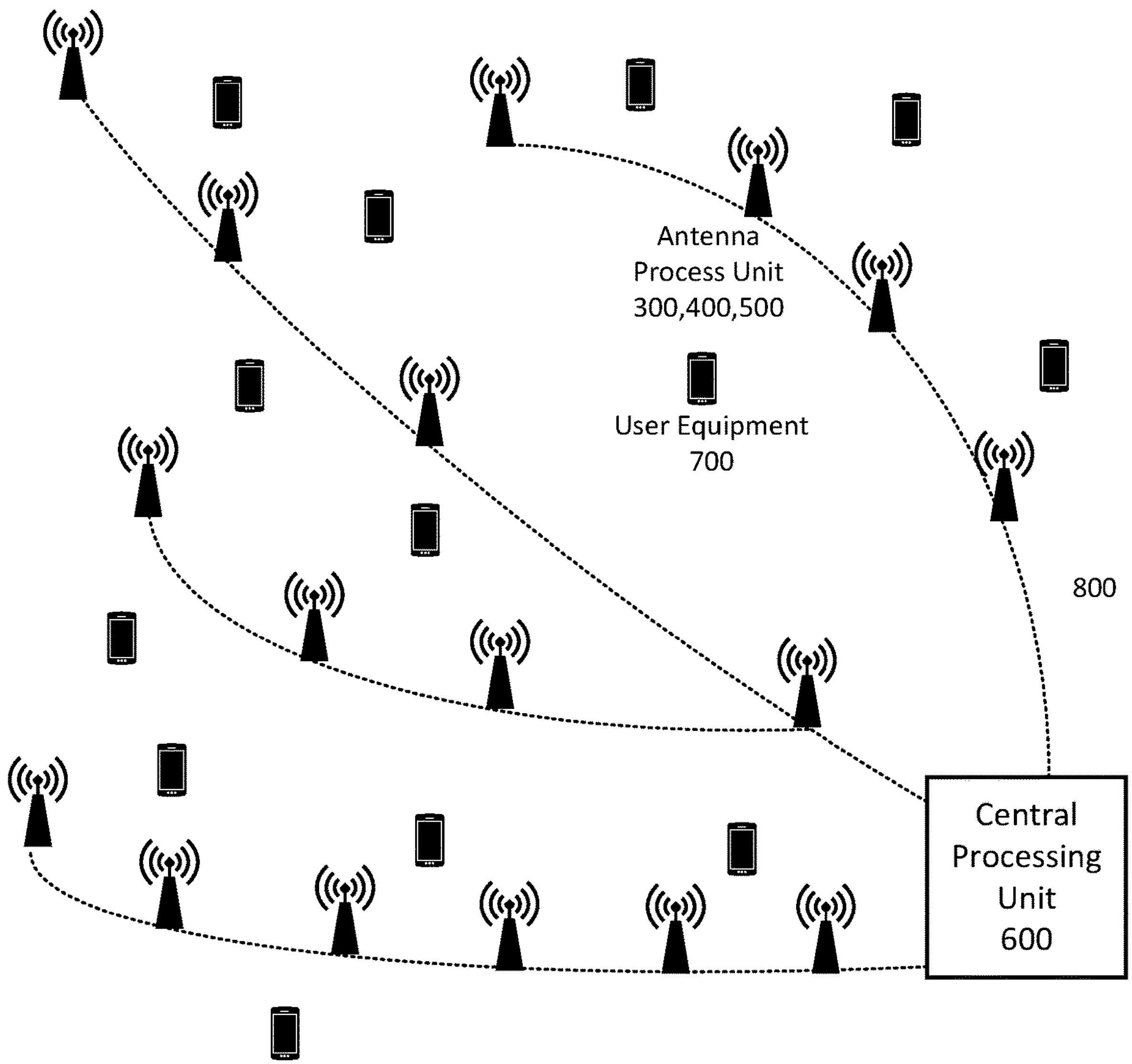
Antenna
Process Unit
300,400,500
User Equipment
700
800
Central
Processing
Unit
600

Fig. 3

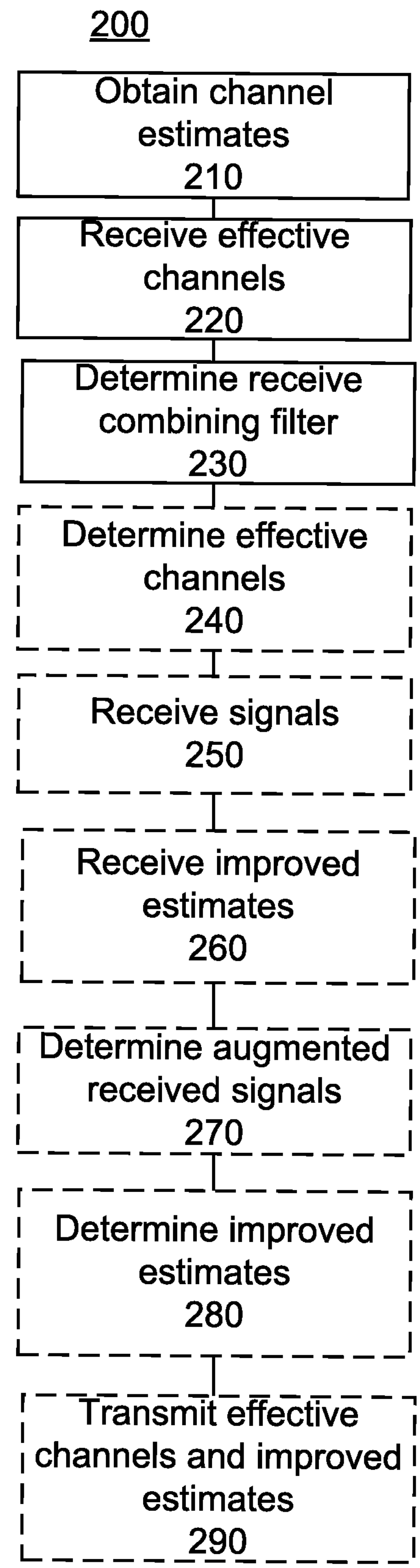
200
Obtain channel estimates 210
Receive effective channels 220
Determine receive combining filter 230
Determine effective channels 240
Receive signals 250
Receive improved estimates 260
Determine augmented received signals 270
Determine improved estimates 280
Transmit effective channels and improved estimates 290

Fig. 4

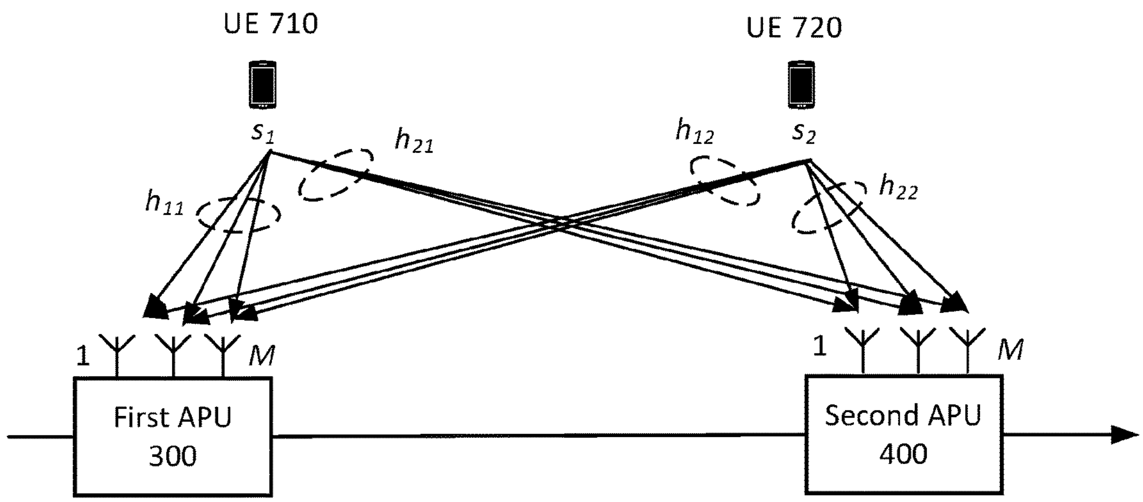

Fig. 5

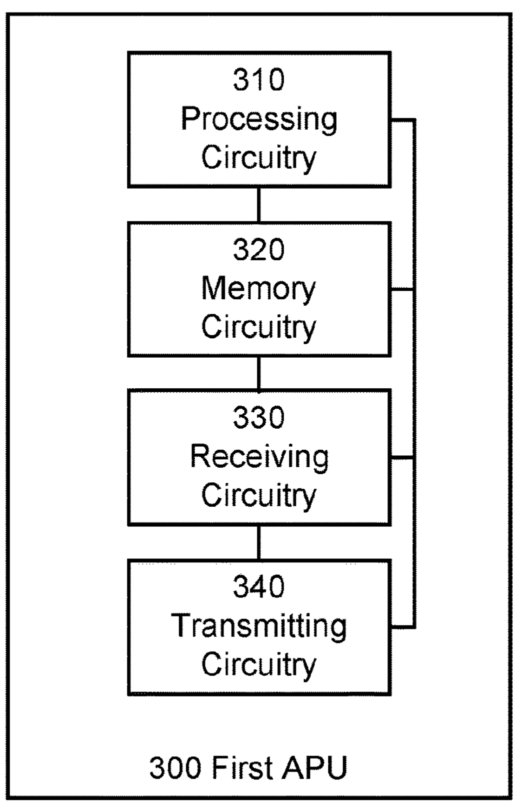

Fig. 6

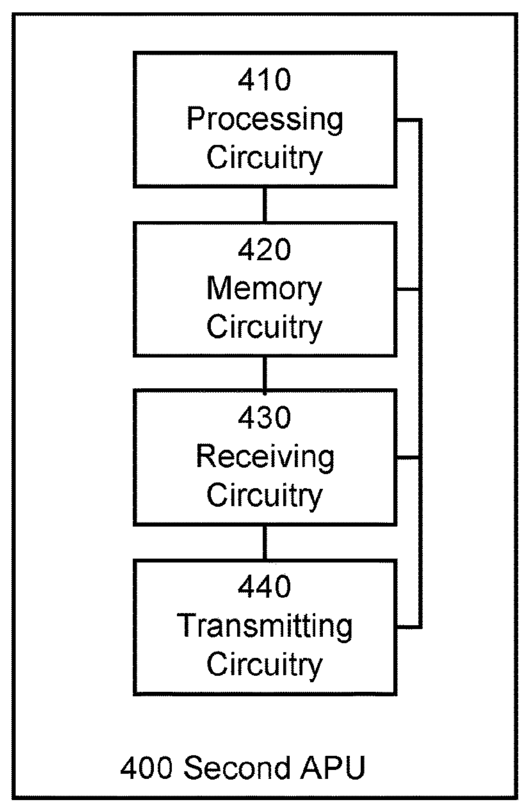

Fig. 7

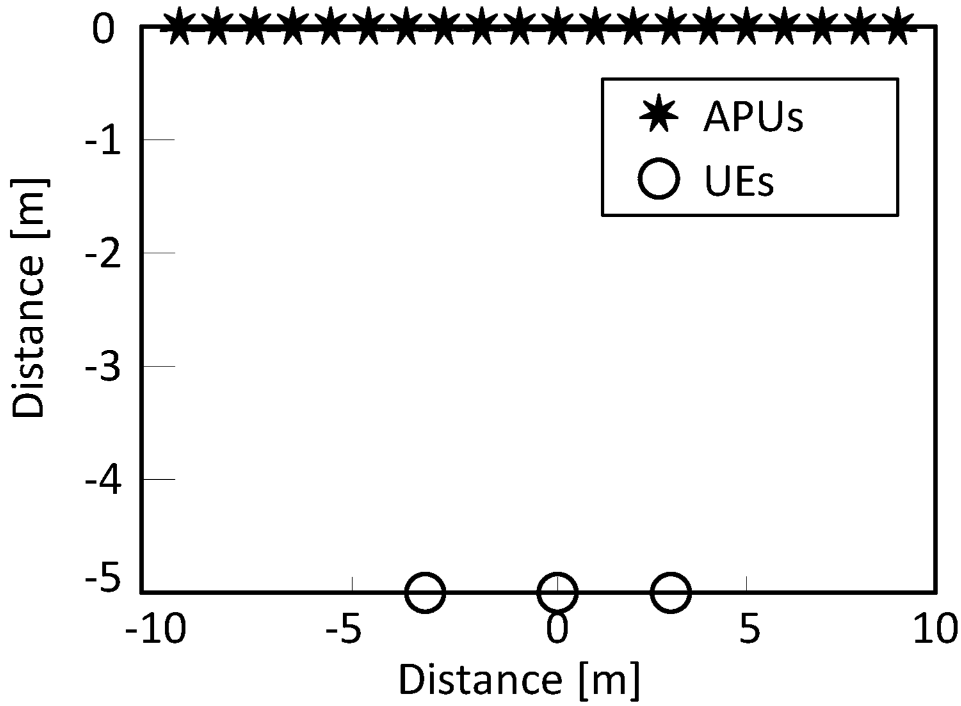
0
-1
-2
-3
-4
-5
Distance [m]
APUs
UEs
-10
-5
0
5
10
Distance [m]

Fig. 8

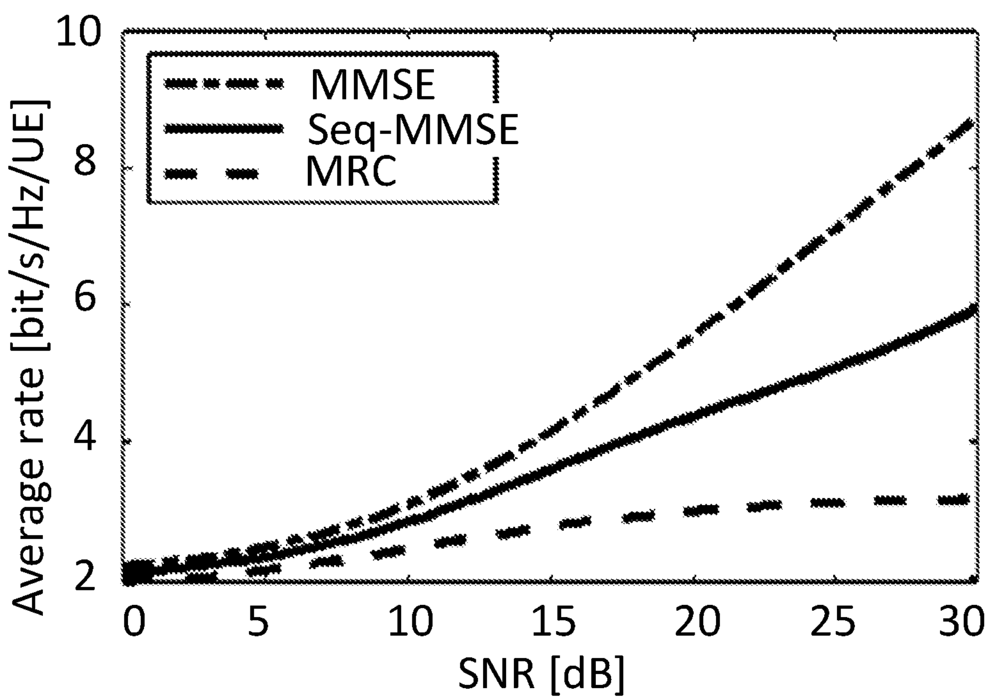
10
8
6
4
2
Average rate [bit/s/Hz/UE]
MMSE
Seq-MMSE
MRC
0
5
10
15
20
25
30
SNR [dB]

Fig. 9

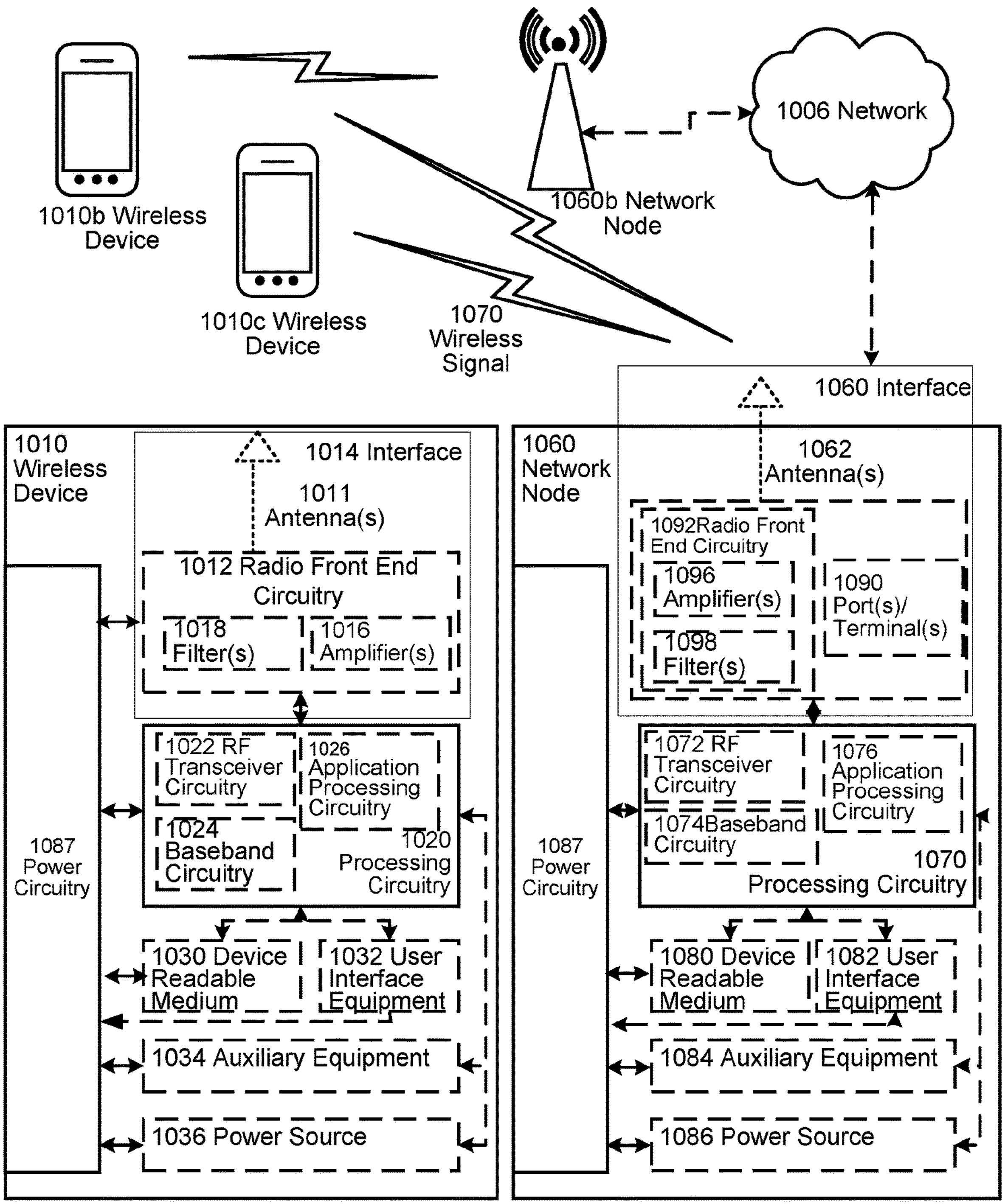
1010b Wireless Device
1010c Wireless Device
1070 Wireless Signal
1060b Network Node
1006 Network
1060 Interface
1010 Wireless Device
1014 Interface
1011 Antenna(s)
1012 Radio Front End Circuitry
1018 Filter(s)
1016 Amplifier(s)
1087 Power Circuitry
1022 RF Transceiver Circuitry
1026 Application Processing Circuitry
1024 Baseband Circuitry
1020 Processing Circuitry
1030 Device Readable Medium
1032 User Interface Equipment
1034 Auxiliary Equipment
1036 Power Source
1060 Network Node
1062 Antenna(s)
1092Radio Front End Circuitry
1096 Amplifier(s)
1098 Filter(s)
1090 Port(s)/ Terminal(s)
1087 Power Circuitry
1072 RF Transceiver Circuitry
1074Baseband Circuitry
1076 Application Processing Circuitry
1070 Processing Circuitry
1080 Device Readable Medium
1082 User Interface Equipment
1084 Auxiliary Equipment
1086 Power Source

Fig. 10

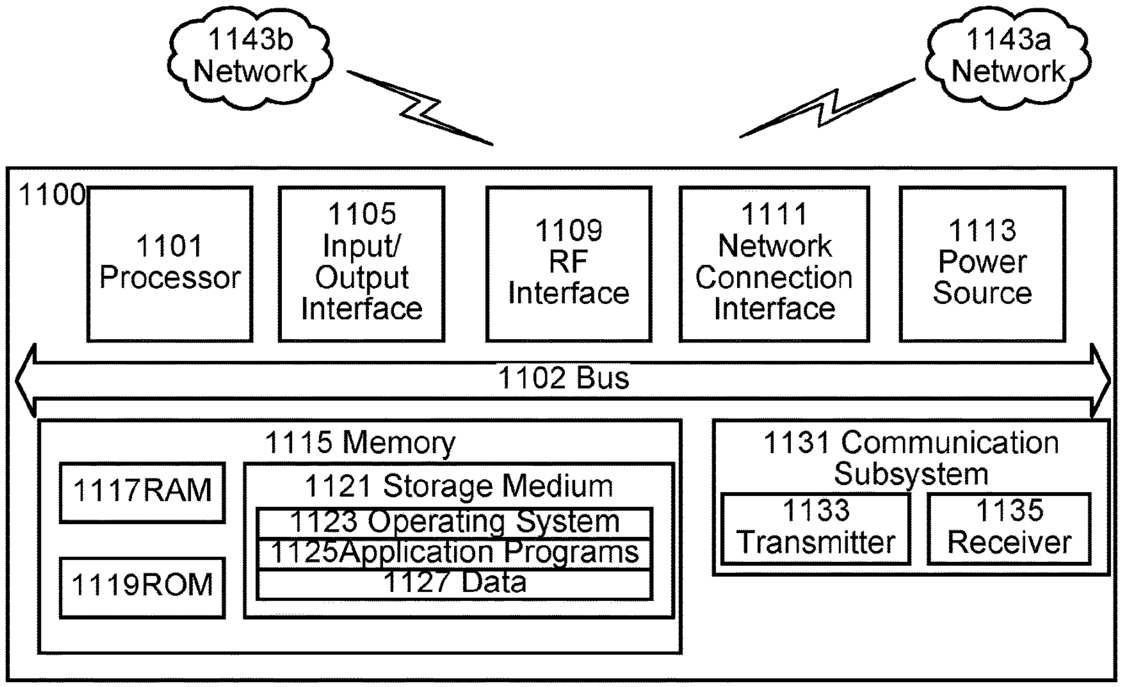
1143b Network
1143a Network
1100
1101 Processor
1105 Input/ Output Interface
1109 RF Interface
1111 Network Connection Interface
1113 Power Source
1102 Bus
1115 Memory
1117RAM
1119ROM
1121 Storage Medium
1123 Operating System
1125Application Programs
1127 Data
1131 Communication Subsystem
1133 Transmitter
1135 Receiver

Fig. 11

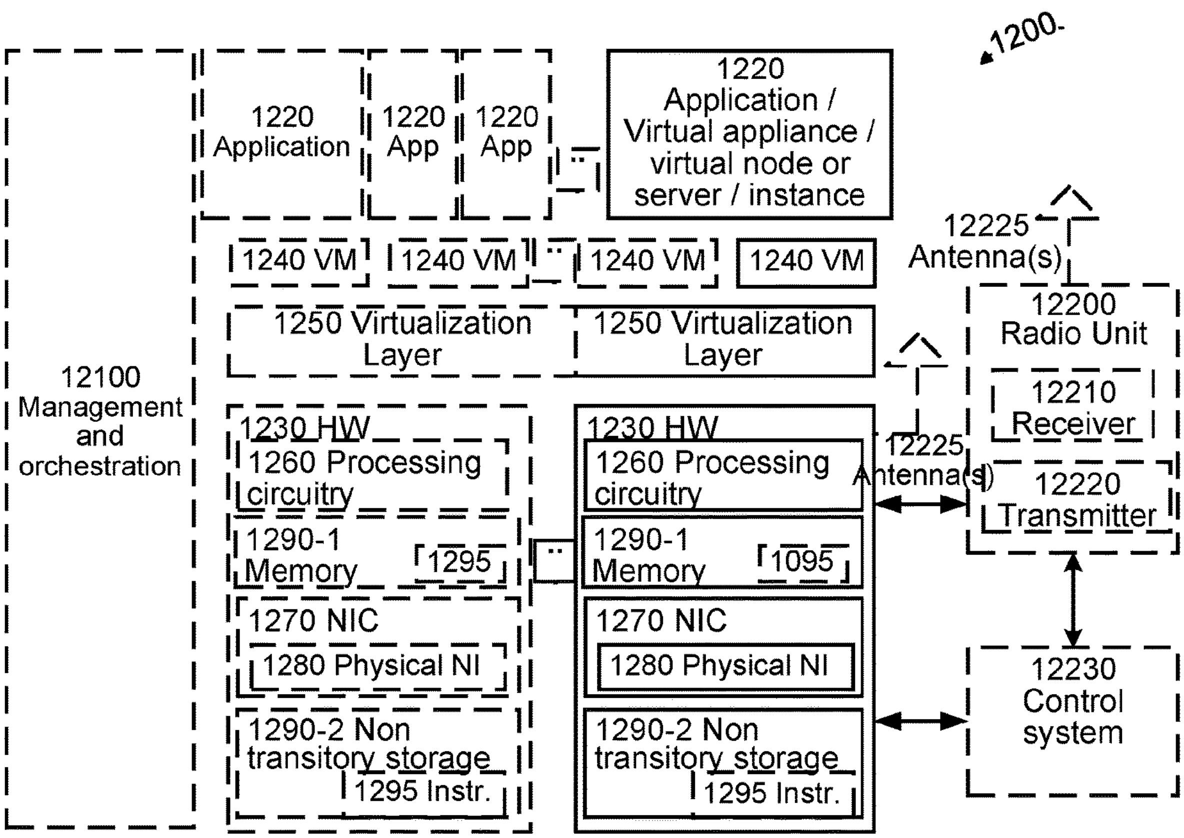
1200
12100 Management and orchestration
1220 Application
1220 App
1220 App
1220 Application / Virtual appliance / virtual node or server / instance
1240 VM
1240 VM
1240 VM
1240 VM
1250 Virtualization Layer
1250 Virtualization Layer
1230 HW
1260 Processing circuitry
1290-1 Memory
1295
1270 NIC
1280 Physical NI
1290-2 Non transitory storage
1295 Instr.
1230 HW
1260 Processing circuitry
1290-1 Memory
1095
1270 NIC
1280 Physical NI
1290-2 Non transitory storage
1295 Instr.
12225 Antenna(s)
12200 Radio Unit
12210 Receiver
12220 Transmitter
12225 Antenna(s)
12230 Control system

Fig. 12

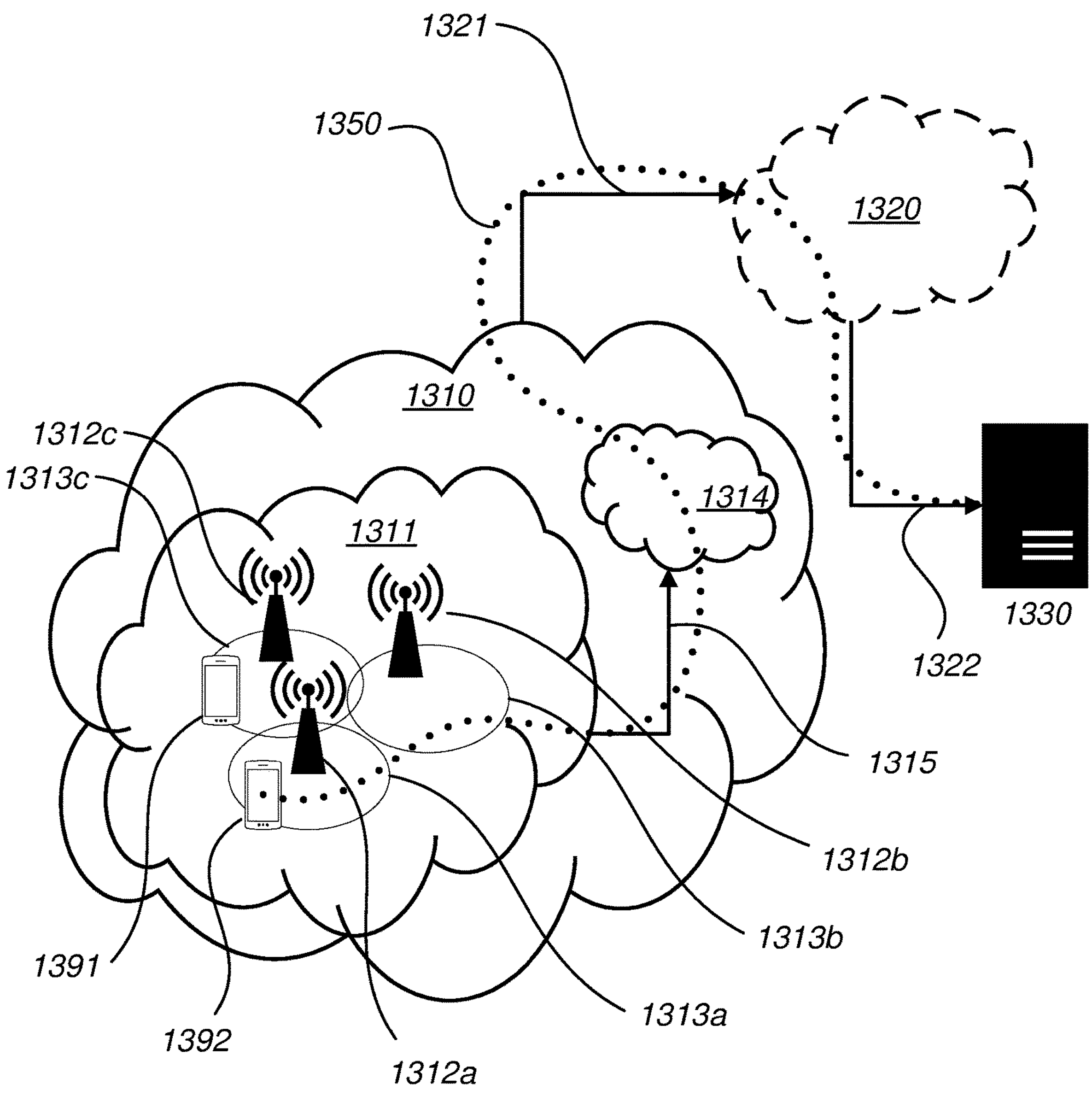
1321
1350
1320
1310
1312c
1313c
1314
1311
1330
1322
1315
1312b
1313b
1391
1392
1313a
1312a

Fig. 13

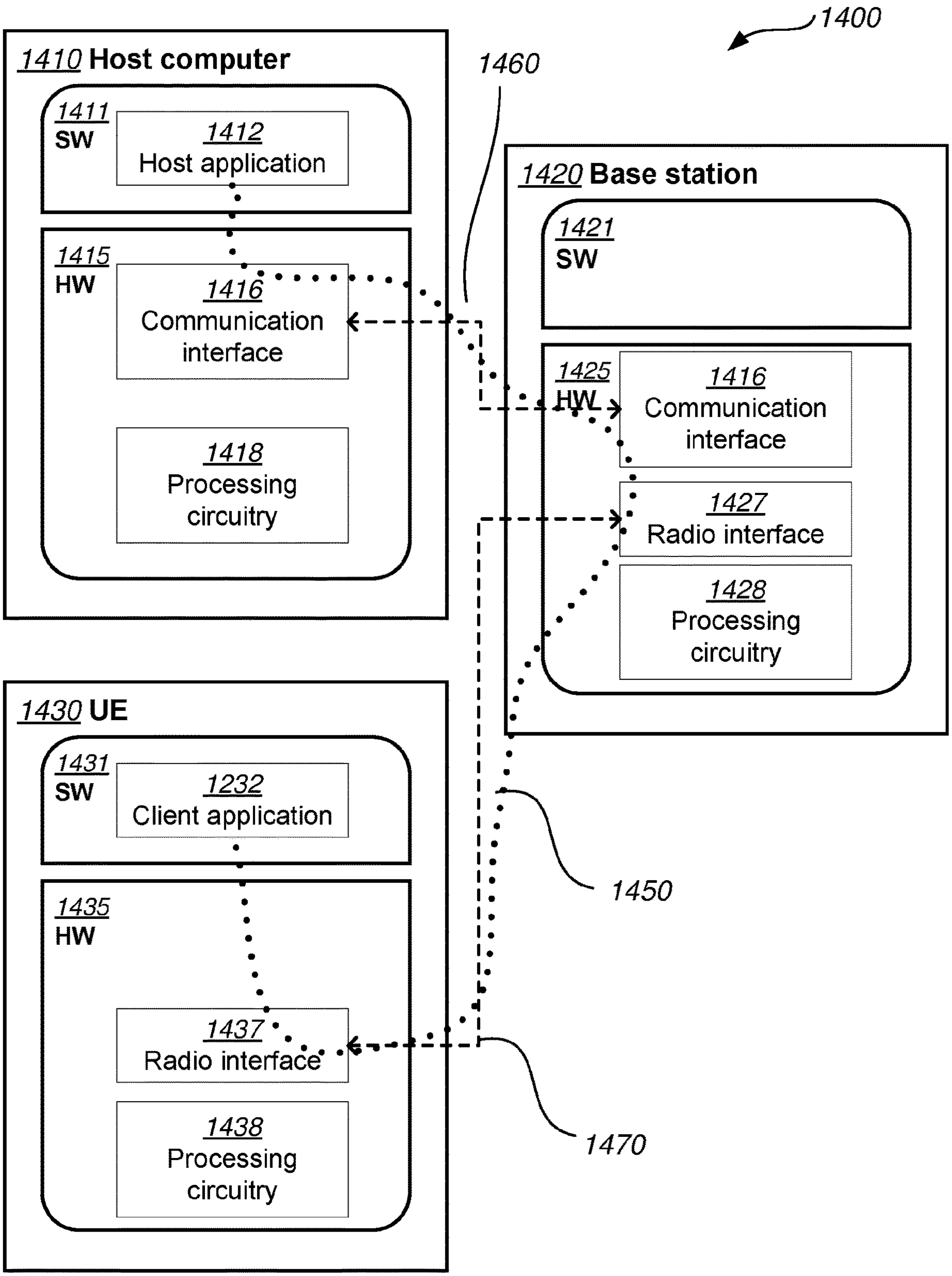
1400
1410 Host computer
1411 SW
1412 Host application
1415 HW
1416 Communication interface
1418 Processing circuitry
1460
1420 Base station
1421 SW
1425 HW
1416 Communication interface
1427 Radio interface
1428 Processing circuitry
1430 UE
1431 SW
1232 Client application
1435 HW
1437 Radio interface
1438 Processing circuitry
1450
1470

Fig. 14

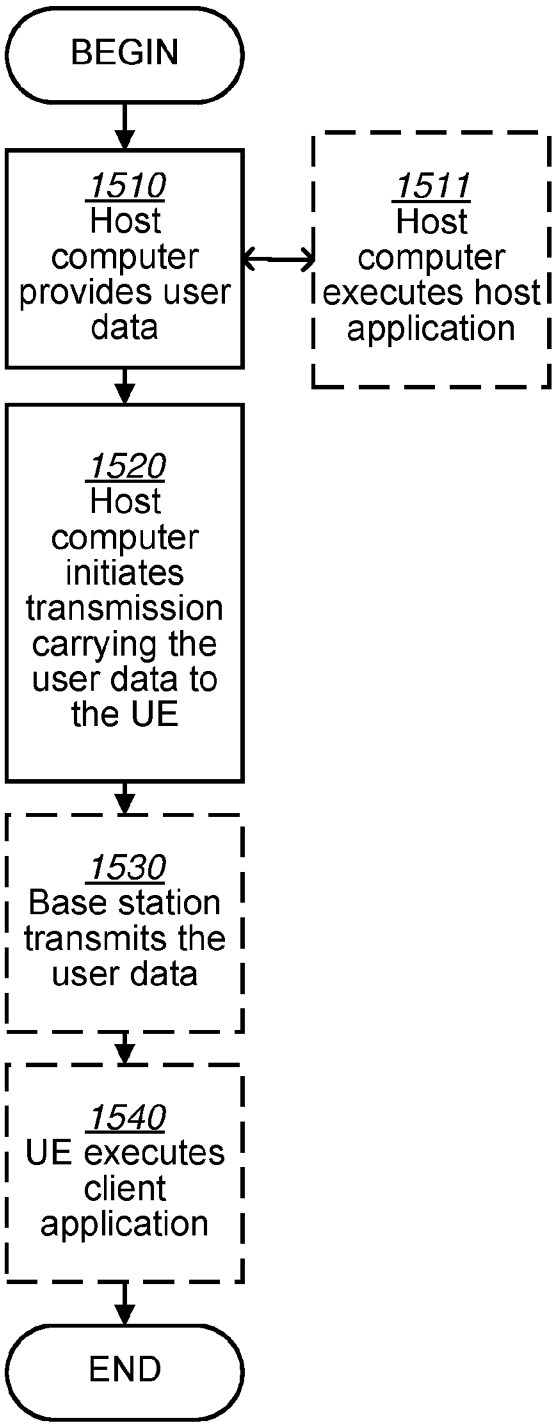
BEGIN
1510
Host computer provides user data
1511
Host computer executes host application
1520
Host computer initiates transmission carrying the user data to the UE
1530
Base station transmits the user data
1540
UE executes client application
END

Fig. 15

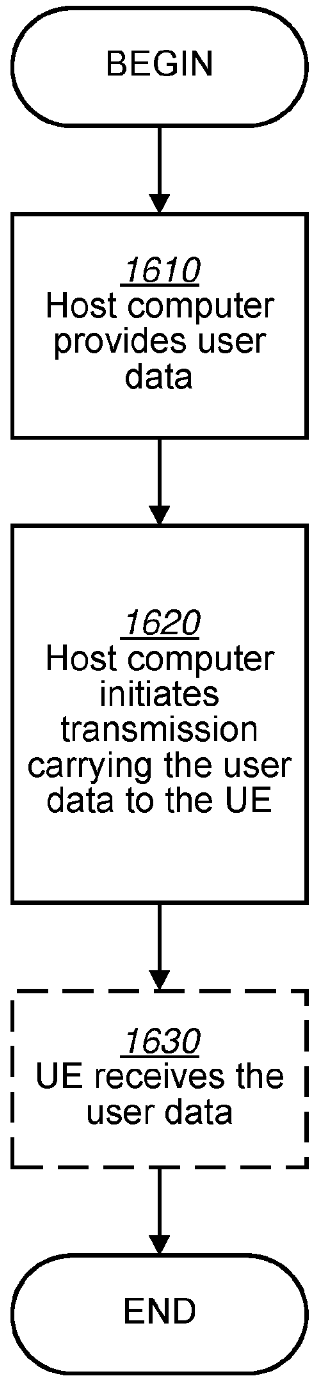
BEGIN
1610
Host computer provides user data
1620
Host computer initiates transmission carrying the user data to the UE
1630
UE receives the user data
END

Fig. 16

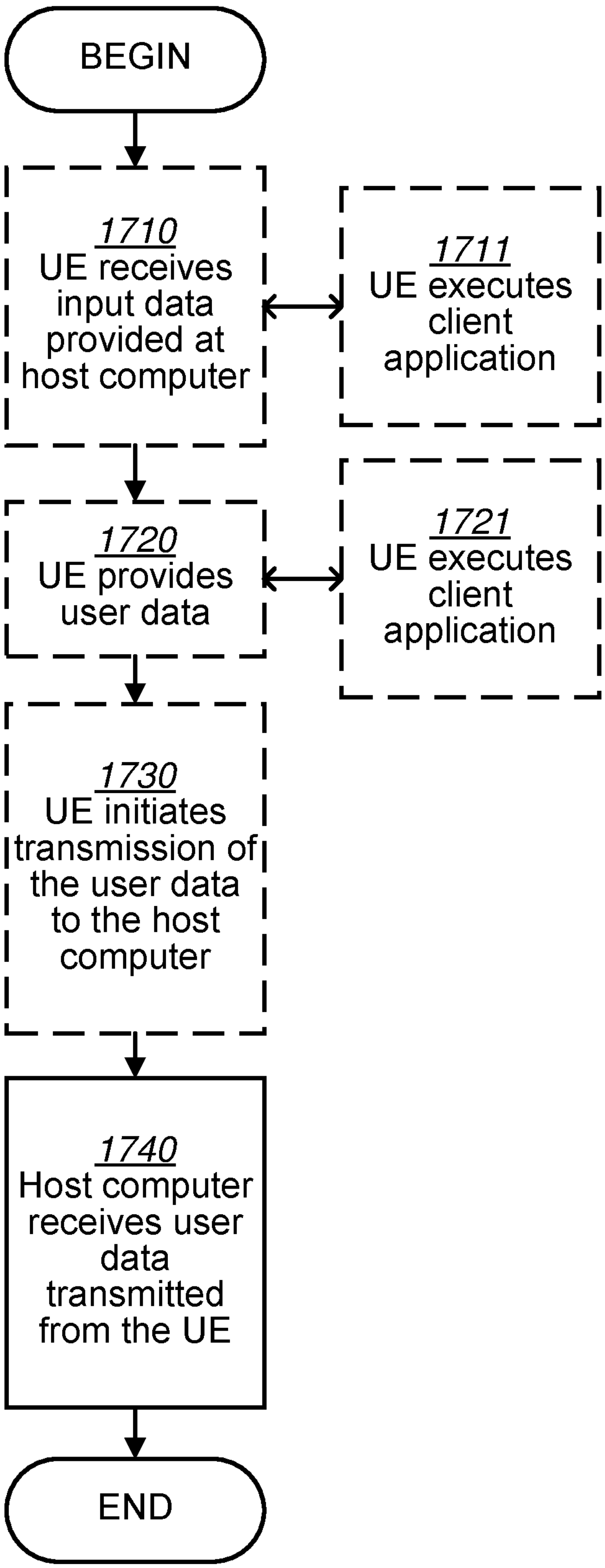
BEGIN
1710
UE receives input data provided at host computer
1711
UE executes client application
1720
UE provides user data
1721
UE executes client application
1730
UE initiates transmission of the user data to the host computer
1740
Host computer receives user data transmitted from the UE
END

Fig. 17

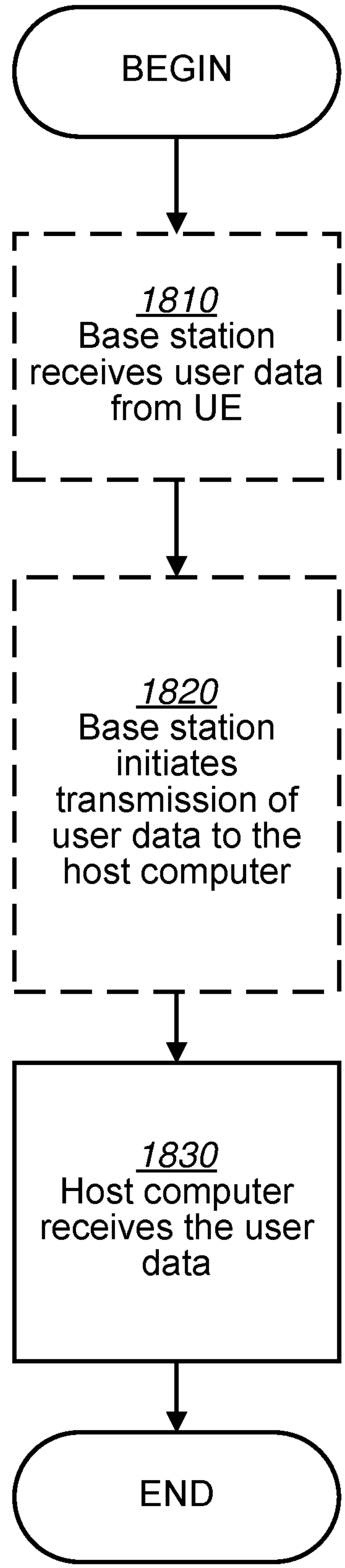
BEGIN
1810
Base station receives user data from UE
1820
Base station initiates transmission of user data to the host computer
1830
Host computer receives the user data
END

Fig. 18

APPARATUSES AND METHODS FOR SEQUENTIAL RECEIVE COMBINING

TECHNICAL FIELD

The present disclosure generally relates to telecommunications. In particular, the various embodiments described in this disclosure relate to apparatuses and methods for sequential receive combining in a radio stripe system.

BACKGROUND

This section is intended to provide a background to the various embodiments of the invention that are described in this disclosure. Therefore, unless otherwise indicated herein, what is described in this section should not be interpreted to be prior art by its mere inclusion in this section.

Traditionally, cellular networks comprise a set of base stations equipped with an array of co-located antenna elements, each forming one or multiple antenna ports. When a User Equipment (UE), or terminal, has data packets to receive in the downlink or transmit in the uplink, it is first associated with one of the base stations and then it is scheduled for transmission on a block of time-frequency resources. In these resource blocks, the serving base station array forms a beam towards the UE, with a spatial signature that is selected based on the spatial position of the UEs and other UEs that are active in the same block. The beam is typically selected to balance between high received signal power at the UE and little interference towards the other UEs that are active in the same block. Each base station and the UEs that it serves constitutes a cell and all desired transmission goes on within the cell. Resource allocation tasks, such as scheduling, power control, and assignment of pilot sequences, are also implemented on a per-cell basis.

An alternative approach to network deployment is to spread out the antennas over the coverage area, using many remote-radio heads, also known as Access Points (APs) or Antenna Processing Units (APUs). Different from traditional cellular networks, where the base stations are surrounded by UEs, the UEs will be surrounded by access point antennas that can all potentially serve them simultaneously. This enables a cell-free network operation where each UE is served by its preferred set of APUs. Large-scale deployment of such networks is known as "Cell-free Massive Multiple-Input Multiple-Output (MIMO)". The physical-layer processing is partially done locally at each APU, using uplink measurements from reference signals (pilots). One way to deploy these networks is to use radio stripes, where multiple APUs are deployed along the same cable and thereby shares the same fronthaul connection. This may lead to less cabling compared to a star-topology where each APU has a dedicated fronthaul connection.

Within the radio stripe, antennas and the associated APUs are serially located inside the same cable, which also provides time and frequency synchronization, data transfer, and power supply via a shared bus. The APU may comprise of antenna elements and circuit-mounted chips (including power amplifiers, phase shifters, filters, modulators, A/D and D/A converters) inside a protective casing of a flexible cable or a stripe. One or more APUs may also be implemented in a non-flexible radio stick that are serially connected to other radio sticks. Each radio stripe or set of radio sticks may then be connected to one or multiple Central Processing Units (CPUs). Since the total number of distributed antennas is assumed to be large, the transmit power of each antenna can be very low, resulting in low heat-dissipation, small volume and weight, and low cost. For example, if the carrier frequency is 5.2 GHz then the antenna size is 2.8-2.9 cm, and for higher carrier frequencies the antenna elements further decrease in size. Thus, the antennas and processing hardware can be easily fitted in a cable/stripe.

SUMMARY

Radio stripe systems may facilitate a flexible and cost efficient implementation of a cell-free Massive Multiple-Input Multiple-Output (MIMO) deployment.

The receive/transmit processing of an antenna in a radio stripe system is performed right next to itself. On the transmitter side, each Antenna Processing Unit (APU) receives multiple streams of input data (e.g. one stream per User Equipment (UE), or terminal, one UE with multiple streams, or some other UE-stream allocation) from the previous APU via the shared bus. In each antenna, the input data streams are scaled with the pre-calculated precoding vector and the sum-signal is transmitted over the radio channel to the receiver(s). By exploiting channel reciprocity, the precoding vector may be a function of the estimated uplink channels. For example, if the conjugate of the estimated uplink channel is used, Maximum Ratio (MR) precoding is obtained. This precoding requires no Channel State Information (CSI) sharing between the antennas.

On the receiver side, the received radio signal is multiplied with the combining vector previously calculated in the uplink pilot phase. The output gives data streams that are then combined with the data streams received from the shared bus and sent again on the shared bus to the next APU.

Joint reception from multiple distributed APUs is mainly beneficial, compared with single-APU reception, if the reception is carried out phase-coherently, so that an array gain is obtained. Methods developed for cell-free massive MIMO and radio stripes may generally be divided into two categories:

- Distributed per-APU processing, also known as "Maximum-Ratio Combining (MRC)" or "matched filtering". This enables a distributed implementation with no sharing of CSI between APUs, but does not support interference suppression where APUs actively and jointly cancel the interference from other uplink transmission on the same radio resources that other APUs have observed, e.g., using zero-forcing. The contributions from the different APUs can be weighted to adapt to the path loss differences, but this does not cancel interference. Interference is a main limiting factor with this type of processing.
- Centralized processing: All APUs may send their received uplink signals over the fronthaul to a CPU that combines the signals coherently, and which in turn can apply more sophisticated signal processing for interference suppression, e.g., Zero-Forcing (ZF) or Minimum Mean Square Error (MMSE) combining. Alternatively, the calculation of receive combining filters to be applied in each APU may be performed in a CPU. This requires that all APUs provide the CPU with CSI information and it also requires feedback of calculated receive combining filters from the CPU to all APUs. The problem is that this requires a huge fronthaul capacity that grows with the number of APUs in the network and with the number of users that these APUs serve.

Both the distributed per-APU processing and the centralized processing methods are methods with drawbacks. The distributed per-APU processing method has low performance, relative to what is obtainable by centralized processing, and the centralized processing method has huge, unscalable fronthaul capacity requirements. Accordingly, there is a need for a scalable solution that enables coherent signal combining and interference suppression in distributed MIMO systems.

It is in view of the above background and other considerations that the various embodiments of the present disclosure have been made.

It is proposed to provide a solution to address this problem, i.e. implementing interference suppression in a sequential manner, by the APUs processing their received signals sequentially during the uplink data transmission.

This general object has been addressed by the appended independent claims. Advantageous embodiments are defined in the appended dependent claims.

According to a first aspect, there is provided a method for sequential receive combining in a radio stripe system. The radio stripe system comprises at least two APUs and a CPU, wherein the at least two APUs are connected in series to the CPU. The radio stripe system serves at least two UEs. The method is performed by a first APU.

The method comprises obtaining channel estimates for channels to said served UEs and determining a receive combining filter based on the obtained channel estimates. The receive combining filter is going to be applied to received data signals. Thereafter, the method comprises determining effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs. The method further comprises transmitting the effective channels from said served UEs to at least one subsequent second APU.

In some embodiments, the method further comprises receiving data signals from said served UEs and determining improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs.

In some embodiments, the method further comprises transmitting the determined improved estimates of the received data signals to at least one subsequent second APU.

In some embodiments, the at least one subsequent second APU (**400**) is located closer to the CPU (**600**) than the first APU (**300**).

In some embodiments, the obtained channel estimates are CSI obtained from reference pilot signals transmitted by said served UEs

In some embodiments, the receive combining filter is generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining.

In some embodiments, each of the at least two APUs in the radio stripe system is equipped with one antenna.

According to a second aspect, there is provided a method for sequential receive combining in a radio stripe system. The radio stripe system comprises at least two APUs and a CPU, wherein the at least two APUs are connected in series from the CPU. The radio stripe system serves at least two UEs. The method is performed by a second APU.

The method comprises obtaining channel estimates for channels to the served UEs and receiving, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU. Thereafter, the method comprises determining a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU. The receive combining filter is going to be applied to received data signals

In some embodiments, the method further comprises determining effective channels from the served UEs based on the obtained channel estimates, the determined receive combining filter and the received effective channels from the at least one preceding first APU. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs.

In some embodiments, the method further comprises receiving data signals from said served UEs and receiving, from the at least one preceding first APU, improved estimates of data signals received by the preceding first APU. Thereafter, the method comprises determining augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU. The method further comprises determining improved estimates of the received data signals by applying the determined receive combining filter to the augmented received data signals from said served UEs.

In some embodiments, the method further comprises transmitting the determined effective channels from said served UEs and the improved estimates of the received data signals to at least one subsequent third APU. The at least one subsequent third APU is located closer to the CPU than the second APU.

In some embodiments, the method further comprises transmitting the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU.

In some embodiments, the at least one preceding first APU is located further away from the CPU than the second APU.

In some embodiments, the obtained channel estimates are CSI obtained from reference pilot signals transmitted by said served UEs.

In some embodiments, the receive combining filter is generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining.

In some embodiments, each of the at least two APUs in the radio stripe system is equipped with one antenna

According to a third aspect, there is provided a first APU configured to perform the method according to the first aspect.

The first APU is configured for receive combining in a radio stripe system. The radio stripe system comprises at least two APUs and a CPU, the at least two APUs being connected in series to the CPU. The radio stripe system serves at least two UEs. The first APU comprises a processing circuitry and a memory circuitry. The memory circuit stores computer program code which, when run in the processing circuitry, causes the first APU to obtain channel estimates for channels to said served UEs and to determine a receive combining filter based on the obtained channel estimates. The receive combining filter is going to be applied to received data signals. The first APU is further caused to determine effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs. The first APU is thereafter caused to transmit the effective channels from said served UEs to at least one subsequent second APU.

In some embodiments, the first APU further comprises a transmitter, or a transmitting circuitry, configured to transmit data to other apparatuses, such as the at least one subsequent second APU. In some embodiments the first APU further comprises a receiver, or a receiving circuitry, configured to receive data from other apparatuses, such the CPU or at least one UE.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the first APU to receive data signals from said served UEs and to determine improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the first APU to transmit the determined improved estimates of the received data signals to at least one subsequent second APU.

In some embodiments, the at least one subsequent second APU is located closer to the CPU than the first APU.

In some embodiments, obtained channel estimates are CSI obtained from reference pilot signals transmitted by said served UEs.

In some embodiments, the receive combining filter is generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining.

In some embodiments, each of the at least two APUs in the radio stripe system is equipped with one antenna

According to a fourth aspect, there is provided a second APU configured to perform the method according to the second aspect.

The second APU is configured for sequential receive combining in a radio stripe system. The radio stripe system comprises at least two APUs and a CPU, wherein the at least two APUs being connected in series to the CPU. The radio stripe system serves at least two UEs. The second APU comprises a processing circuitry and a memory circuitry. The memory circuit stores computer program code which, when run in the processing circuitry, causes the second APU to obtain channel estimates for channels to said served UEs and receive, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU. The second APU is further caused to determine a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU. The receive combining filter is going to be applied to received data signals.

In some embodiments, the second APU further comprises a transmitter, or a transmitting circuitry, configured to transmit data to other apparatuses, such as the at least one subsequent third APU or CPU. In some embodiments the second APU further comprises a receiver, or a receiving circuitry, configured to receive data from other apparatuses, such as the at least one preceding first APU.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the second APU to determine effective channels from said served UEs based on the obtained channel estimates, the determined receive combining filter and the received effective channels from said at least one preceding first APU. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the second APU to receive data signals from said served UEs and to receive, from said at least one preceding first APU, improved estimates of data signals received by the preceding first APU. The second APU is further caused to determine augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU and determine improved estimates of the received data signals by applying the determined receive combining filter to the augmented received data signals from said served UEs.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the second APU to transmit the determined effective channels from said served UEs and the improved estimates of the received data signals to at least one subsequent third APU. The at least one subsequent third APU is located closer to the CPU than the second APU.

In some embodiments, the memory circuitry storing computer program code which, when run in the processing circuitry, further causes the second APU to transmit the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU.

In some embodiments, the at least one preceding first APU is located further away from the CPU than the second APU.

In some embodiments, the obtained channel estimates are CSI obtained from reference pilot signals transmitted by said served UEs.

In some embodiments, the receive combining filter is generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining.

In some embodiments, each of the at least two APUs in the radio stripe system is equipped with one antenna.

According to a fifth aspect, there is provided a computer program, comprising instructions which, when executed on a processing circuitry, cause the processing circuitry to carry out the method according to the first aspect and/or the second aspect.

According to a sixth aspect, there is provided a carrier containing the computer program of the fifth aspect, wherein the carrier is one of an electronic signal, optical signal, radio signal, or computer readable storage medium.

The various proposed embodiments herein provide a solution for enabling coherent signal combining and interference suppression in distributed MIMO systems.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects, features and advantages will be apparent and elucidated from the following description of various embodiments, reference being made to the accompanying drawings, wherein:

FIG. **1** illustrates a message sequence chart of a process for sequential receive combining in a radio stripe system;

FIG. **2** is a flowchart of an example method performed by a first APU;

FIG. **3** shows an example of a radio stripe system;

FIG. **4** is a flowchart of an example method performed by a second APU;

FIG. **5** illustrates an example arrangement comprising two M-antenna APUs and two single-antenna UEs;

FIG. **6** shows an example implementation of a first APU;

FIG. **7** shows an example implementation of a second APU;

FIG. **8** shows one example embodiment of the proposed solution;

FIG. **9** illustrates the achievable rates with the proposed solution compared with two other methods;

FIG. **10** illustrates an example wireless network;

FIG. 11 shows a user equipment according to an embodiment;

FIG. 12 shows a virtualization environment according to an embodiment;

FIG. 13 illustrates an example telecommunication network connected via an intermediate network to a host computer;

FIG. 14 shows a host computer communicating via a base station with a user equipment over a partially wireless connection according to an embodiment;

FIG. 15 shows an example method implemented in a communication system including a host computer, a base station and a user equipment;

FIG. 16 illustrates an example method implemented in a communication system including a host computer, a base station and a user equipment; and

FIGS. 17 and 18 show example methods implemented in a communication system including a host computer, a base station and a user equipment.

DETAILED DESCRIPTION

The present invention will now be described more fully hereinafter. The present invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided by way of example so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those persons skilled in the relevant art. Like reference numbers refer to like elements throughout the description.

In one of its aspects, the disclosure presented herein concerns a method for sequential receive combining in a radio stripe system.

With reference to FIGS. **1** and **2**, a first embodiment will now be described. FIG. **1** illustrates a message sequence chart of a process for sequential receive combining in a radio stripe system. FIG. **2** illustrates a method **100**, performed by a first Antenna Processing Unit (APU), for sequential receive combining in a radio stripe system. The radio stripe system comprises at least two APUs and a Central Processing Unit (CPU). The at least two APUs are connected in series from the CPU. The radio stripe system serves at least two User Equipment (UEs), or terminals. FIG. **3** illustrates an example of such radio stripe system **800**. As seen in FIG. **3**, each radio stripe may comprise multiple APUs, or Access Points (APs), deployed along the same fronthaul connection to a central unit, a cloud-processor, also called the CPU **600**. In some embodiments, the CPU **600** may be called a stripe station or a network node. The radio stripe system **800** may be comprised in a cell-free distributed (massive) Multiple-Input Multiple-Output (MIMO) network.

The method **100** starts at step **110** with the first APU **300** obtaining channel estimates for channels to the served UEs. The obtained channel estimates may be Channel State Information (CSI) obtained from reference pilot signals transmitted by the at least two UEs **700** served by the radio stripe system **800**. Based on the obtained channel estimates, a receive combining filter is determined in step **120**. The receive combining filter is going to be applied to received data signals. The receive combining filter may, for example, be generated by a method selected from the group comprised of: Maximum-Ratio Combining (MRC), Zero-Forcing (ZF) combining and Minimum-Mean Squared Error (MMSE) combining. Alternatively, the receive combining filter may be generated by another method.

Thereafter the method **100** continues at step **130** with determining effective channels from said served UEs **700** based on the obtained channel estimates and the determined receive combining filter. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs **700**.

At step **140**, the determined effective channels are transmitted from said served UEs **700** to at least one subsequent second APU **400**. The at least one subsequent second APU **400** may be located closer to the CPU **600** than the first APU **300**. If it is assumed that the radio stripe system **800** serves K number of UEs **700**, K^2 scalar coefficients will be transmitted to the at least one subsequent second APU **400**. The K^2 scalar coefficients represent the effective K×K channel created after application of the receive combining filter for each of the K served UEs **700**.

In some embodiments, the method **100** may further comprise step **150** of receiving data signals from the served UEs **700** and step **160** of determining improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs **700**. If it is assumed that the radio stripe system **800** serves K UEs **700**, K improved estimates, one per UE, may be determined. Additionally, the method may further comprise step **170** of transmitting the determined improved estimates of the received data signals to at least one subsequent second APU **400**.

The proposed method **100** is a scalable distributed method for coherent signal combining and interference suppression in distributed MIMO systems. The method **100** considers uplink transmission where the served UEs **700** transmit both payload data and reference pilot signals to enable channel estimation. The aim is to decode the signals from at least two served UEs jointly by using the signals from multiple APUs simultaneously to suppress interference and to perform this without gathering all the received signals from data and pilots at one location. The proposed method **100** achieves this by using the sequential topology of the fronthaul in radio stripe systems **800** to implement interference suppression in a sequential manner. The first APU **300** makes a local decision based on its locally received signals and thereafter transmits this information to a second APU **400**. This will enable suppression of interference between the first APU **300** and the second APU **400**. The proposed method **100** is contrary to the existing solutions that are either distributed, but lacks interference suppression capability, or support interference suppression, but require a centralized implementation with heavy fronthaul traffic. The proposed method **100** may greatly increase the system capacity, achievable rates, since cell-free networks typically operate at high Signal-to-Noise-Ratio (SNR) where the system performance is interference limited.

In some embodiments, each of the at least two APUs **300**,**400** in the radio stripe system **800** may be equipped with one antenna. In other embodiments, at least one of the at least two APUs **300**,**400** may have multiple antennas.

According to a second aspect, there is provided a method, performed by a second APU **400**, for sequential receive combining in a radio stripe system **800**.

The method **200** is now going to be described with reference to the FIGS. **1** and **4**. As previously mentioned, FIG. **1** illustrates a message sequence chart of a process for sequential receive combining in a radio stripe system **800**. FIG. **4** illustrates the method **200**, performed by the second APU **400**, for retrieving sequential receive combining in a radio stripe system **800**. The radio stripe system **800** comprises at least two APUs **300**,**400** and a CPU **600**. The at least two APUs **300**,**400** are connected in series from the CPU **600**. The radio stripe system **800** serves at least two UEs **700**. FIG. **3** illustrate an example of such radio stripe system **800**.

The method **200** starts at step **210** with obtaining channel estimates for channels to said served UEs **700**. The obtained channel estimates may be CSI obtained from reference pilot signals transmitted by said served UEs **700**. The proposed method continues with step **220** of receiving, from at least one preceding first APU **300**, effective channels from said served UEs **700** to said preceding first APU **300**. The at least one preceding first APU **300** may located further away from the CPU **600** than the second APU **400**. Thereafter, at step **230**, the proposed method **200** determines a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU **300**. The receive combining filter is going to be applied to received data signals. The receive combining filter may be generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining. Alternatively, the receive combining filter may be generated by some other method.

The proposed method **200** enables the second APU **400** to process its received signals locally and combine them with signals from at least one preceding first APU **300** in a sequential manner. If it is assumed that the second APU **400** comprises M antennas, the second APU **400** may apply a new determined receive combining filter, but the processing will consider an M+1 antenna system. The additional dimension is created based on the input provided by the at least one first preceding APU **300**.

In some embodiments, the method **200** may further comprise the step **240** of determining effective channels from said served UEs **700** based on the obtained channel estimates, the determined receive combining filter and the received effective channels from said at least one preceding first APU **300**. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs. If it is assumed that the radio stripe system serves K UEs, K^2 effective channels representing the effective channel created after the receive combining filter being applied to each channel for said served UEs **700** will be determined.

In some embodiments, the proposed method **200** may further comprise step **250** of receiving data signals from said served UEs **700** and step **260** of receiving, from said at least one preceding first APU **300**, improved estimates of data signals received by the preceding first APU **300**. Thereafter, the method may comprise step **270** of determining augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU **300**. The method **200** thereafter may comprise step **280** of determining improved estimates of the received data signals by applying the determined receive combining filter to the augmented received data signals from said served UEs **700**. If it is assumed that the radio stripe system serves K UEs **700**, K improved estimates, one per UE, may be determined.

According to the proposed method **200**, the second APU **400** will make a local decision based on its locally received signals and fuse it with the information received from the at least one preceding first APU **300**. This will enable suppression of interference between the first APU **300** and the second APU **400**. The proposed method **200** is contrary to existing solutions that are either distributed, but lacks interference suppression capability, or support interference suppression, but require a centralized implementation with heavy fronthaul traffic. The proposed method **200** may greatly increase the system capacity, achievable rates, since cell-free networks typically operate at high Signal-to-Noise-Ratio (SNR) where the system performance is interference limited. A key benefit of the proposed method **200** is that the fronthaul capacity requirement between two APUs **300**,**400** on the same stripe may be the same, irrespective of how many APUs there may be on the stripe, but the APUs **300**,**400** may anyway provide interference suppression.

In some embodiments, the radio stripe system **800** may have a tree structure as illustrated in FIG. **3**, then the second APU **400** may receive effective channels and improved estimates of data signals received from more than one preceding first APU **300**. All these received input, i.e. received effective channels and improved estimates, will then be included in the second APU's **400** processing. If it is assumed that the radio stripe system **800** may serve K UEs, second APU **400** may comprise M antennas and that the second APU **400** may receive input from B number of APUs, the second APU **400** may combine the input with its local information to effectively achieve an M+B antenna system. The second APU **400** may then apply the determined receive combining filter to determine K improved estimates, one per UE. This enables the use of the proposed method **100** with flexible radio stripe systems **800**, which may take several different forms.

In some embodiments, the method **200** may further comprise the step **290** of transmitting the determined effective channels from said served UEs **700** and the improved estimates of the received data signals to at least one subsequent third APU **500**. The at least one subsequent third APU **500** may be located closer to the CPU **600** than the second APU **400**. In another embodiment, the method **200** may further comprise the step of transmitting **290** the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU **600**. This may, for example, happen when no subsequent APU is connected between the second APU and the CPU **600**. The determined effective channels from said served UEs **700** and the improved estimates of the received data signals may then be transmitted to the CPU **600** for final decoding.

It may be appreciated that the number of variables that may be sent from one APU, e.g. the second APU **400**, to another APU, e.g. the third APU **500**, along a radio stripe is the same, irrespective of how many APUs there may be on the radio stripe. If a sequence of data symbols may be received in the same transmission block, they may be combined in the same way. Hence, the K^2 effective desired and interfering scalar channels are identical for all those symbols. Only the K improved estimates may need to be sent once per data symbol. Accordingly, the proposed method **200** provides a scalable solution that may be used in different types of radio stripe systems **800**.

In some embodiments, only a subset of the APUs in the radio stripe system **800** may participate in decoding signal of each UE **700**.

In some embodiments, each of the at least two APUs **300**,**400** in the radio stripe system **800** may be equipped with one antenna. In other embodiments, at least one of the at least two APUs **300**,**400** in the radio stripe system **800** may be equipped with more than one antenna.

The above proposed methods **100**,**200** are now going to be described together with a non-limiting example arrangement. The example arrangement is illustrated in FIG. **5**. The arrangement in FIG. **5** comprises two M-antenna APUs, the first APU **300** and the second APU **400**. The arrangement further comprises two single-antenna UEs, the first UE **710** and the second UE **720**. The first UE **710** transmits the unit-power signal s_1 and the second UE **720** transmits the unit power s_2.

The received signal at the first APU **300** is the M-dimensional vector

$$y_1 = h_{11}s_1 + h_{12}s_2 + n_1$$

where h_{11} is the M-dimensional channel, i.e. channel estimates, from the first UE **710** to the first APU **300** and h_{12} is the M-dimensional channel vector from the second UE **720** to the first APU **300**, while n_1 is the M-dimensional noise vector. As previously described, the first APU **300** may learn the channels h_{11}, h_{12} from uplink pilots that are transmitted from the UEs **710**,**720**. It is here assumed that the first APU **300** may learn these channels without error. The first APU **300** thereafter use this information to determining the M dimensional receive combining filter, or vector, v_{11} for the first UE **710** and v_{12} for the second UE **720**. The first APU **300** applies the receive combining filters to the received signal y_1, wherein improved estimates $\hat{s}_{11}$ and $\hat{s}_{12}$ of the data signals s_1 and s_2 are determined.

$$\hat{s}_{11} = v_{11}^H y_1 = v_{11}^H h_{11} s_1 + v_{11}^H h_{12} s_2 + v_{11}^H n_1 = g_{11}^1 s_1 + g_{12}^1 s_2 + v_{11}^H n_1$$

$$\hat{s}_{12} = v_{12}^H y_1 = v_{12}^H h_{11} s_1 + v_{12}^H h_{12} s_2 = + v_{12}^H n_1 = g_{21}^1 s_1 + g_{22}^1 s_2 + v_{12}^H n_1$$

The notation $g_{ik}^1 = v_{1i}^H h_{1k}$ is introduced for i,k=1, 2. The first APU **300** may thereafter transmit the improved estimates $\hat{s}_{11}$, $\hat{s}_{12}$ of the data signals and the effective channels g_{11}^1, g_{12}^1, g_{21}^1, g_{22}^1 to the second APU **400**.

From the same uplink transmission, the received signal at the second APU **400** is the M-dimensional vector

$$y_2 = h_{21}s_1 + h_{22}s_2 + n_2$$

where h_{21} is the M-dimensional channel from the first UE **710** to the second APU **400** and h_{22} is the M-dimensional channel vector from the second UE **720** to the second APU **400**, while n_2 is the M-dimensional noise vector. In order for the second APU **400** to determine an improved estimate of s_1 it first creates an augmented received signal based on the received data signals and the received improved estimates of the data signals received by the preceding first APU **300**

$$\begin{bmatrix} y_2 \\ \hat{s}_{11} \end{bmatrix} = \begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix} s_1 + \begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix} s_2 + \begin{bmatrix} n_2 \\ v_{11}^H n_1 \end{bmatrix}$$

which is an (M+1)-dimensional vector. The second APU **400** then applies the (M+1)-dimensional receive combining filter v_{21} to determine the improved estimates of the received data signals s_1

$$\hat{s}_{21} = v_{21}^H \begin{bmatrix} y_2 \\ \hat{s}_{11} \end{bmatrix} = v_{21}^H \begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix} s_1 + v_{21}^H \begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix} s_2 + v_{21}^H \begin{bmatrix} n_2 \\ v_{11}^H n_1 \end{bmatrix} = g_{11}^2 s_1 + g_{12}^2 s_2 + v_{21}^H \begin{bmatrix} n_2 \\ v_{11}^H n_1 \end{bmatrix}$$

where notation

$$g_{ik}^2 = v_{2i}^H \begin{bmatrix} h_{2k} \\ g_{1k}^1 \end{bmatrix}$$

is introduced for i,k=1, 2. Similarly, the second APU **400** determines the augmented received signal

$$\begin{bmatrix} y_2 \\ \hat{s}_{12} \end{bmatrix} = \begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix} s_1 + \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix} s_2 + \begin{bmatrix} n_2 \\ v_{12}^H n_1 \end{bmatrix}$$

and then determines an improved estimate of s_2 by applying the (M+1)-dimensional receive combining vector v_{22} to the augmented received signal as

$$\hat{s}_{22} = v_{22}^H \begin{bmatrix} y_2 \\ \hat{s}_{12} \end{bmatrix} = v_{22}^H \begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix} s_1 + v_{22}^H \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix} s_2 + v_{22}^H \begin{bmatrix} n_2 \\ v_{12}^H n_1 \end{bmatrix} = g_{21}^2 s_1 + g_{22}^2 s_2 + v_{22}^H \begin{bmatrix} n_2 \\ v_{12}^H n_1 \end{bmatrix}$$

If the second APU **400** is the "last" APU in the radio stripe system, i.e. there is no other APU between the second APU **400** and the CPU **600**, the second APU **400** transmits the improved estimates $\hat{s}_{21}$,$\hat{s}_{s22}$ of the data signals and the effective channels g_{11}^2, g_{12}^2, g_{21}^2, g_{22}^2 to the CPU **600** for final decoding. If the combining filter has norm one, then the variance of the noise term $v_{12}^H n_1$ is the same as for the entries in the noise vector n_2, and these noise terms are also independent, thus the noise variance needs not to be shared between the at least two APUs **300**,**400**. Hence, $\hat{s}_{21}$,$\hat{s}_{22}$ and g_{11}^2, g_{12}^2, g_{21}^2, g_{22}^2 is all the information that the second APU **400** send to the CPU **600**. Thus, the fronthaul capacity requirement is the same between every pair of APUs, or between the last APU and the CPU **600**, irrespective of how many APUs that may exist along the same fronthaul connection (i.e., the same radio stripe). If there are more than two APUs, APU l for l>2 will operate in the same way as the second APU **400**, but based on the input from the previous APU, i.e. APU l−1.

The proposed methods **100**,**200** are particularly useful when implementing signal combining methods that offer interference suppression. For example, the first APU **300** can use the unit-norm MMSE combining vectors, or filters,

$$v_{11} = \frac{(h_{11}h_{11}^H + h_{12}h_{12}^H + \sigma^2 I_M)^{-1} h_{11}}{\left\|(h_{11}h_{11}^H + h_{12}h_{12}^H + \sigma^2 I_M)^{-1} h_{11}\right\|}$$

$$v_{12} = \frac{(h_{11}h_{11}^H + h_{12}h_{12}^H + \sigma^2 I_M)^{-1} h_{12}}{\left\|(h_{11}h_{11}^H + h_{12}h_{12}^H + \sigma^2 I_M)^{-1} h_{12}\right\|}$$

which maximize the SINRs for the first UE **710** and the second UE **720**, respectively, based on only the received signals at the first APU **300**. In this expression, I_M denotes the identity matrix of size M and σ^2 is the noise variance.

Next, the second APU **400** can select the unit-norm MMSE combining vectors

$$v_{21} = \frac{\left(\begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}\begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}^H + \begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix}\begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix}^H + \sigma^2 I_{M+1}\right)^{-1} \begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}}{\left\|\left(\begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}\begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}^H + \begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix}\begin{bmatrix} h_{22} \\ g_{12}^1 \end{bmatrix}^H + \sigma^2 I_{M+1}\right)^{-1} \begin{bmatrix} h_{21} \\ g_{11}^1 \end{bmatrix}\right\|}$$

$$v_{22} = \frac{\left(\begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix}\begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix}^H + \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}\begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}^H + \sigma^2 I_{M+1}\right)^{-1} \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}}{\left\|\left(\begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix}\begin{bmatrix} h_{21} \\ g_{21}^1 \end{bmatrix}^H + \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}\begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}^H + \sigma^2 I_{M+1}\right)^{-1} \begin{bmatrix} h_{22} \\ g_{22}^1 \end{bmatrix}\right\|}$$

which maximize the SINR for the first UE **710** and the second UE **720**, respectively, based on the available signals at the second APU **400**. Observe that in this example the elementary form is used, where the residual noise term is thermal noise only. In some embodiments, this simplification may be used. In some embodiments, the first APU **300** may also transmit improved estimate of the residual noise term. In some embodiments, the second APU **400** may use a covariance matrix combined with said residual noise term, that is, the last term is a block matrix with one M block and one 1 block.

In an alternative embodiment of the proposed solution, the first APU **300** may determine log-likelihood ratios ("L-values") for each information bit associated with each UE **700** instead of determining effective channels from said served UEs. These determined L-values may then be transmitted to the at least one subsequent second APU **400**. The at least one subsequent APU **400** may then add up its locally obtained log-likelihood ratio values with those obtained from the first APU **300**. This process may continue until the signal reaches the CPU **600**. In some embodiments, each APU may use a threshold to decide if its impact on the log-likelihood is sufficiently large for it to have a non-negligible impact on the final decoding. If not, the APU may forward the log-likelihood ratios without changing them.

According to a third aspect, there is provided a first APU **300** for performing the method **100** according to the first aspect. The first APU **300** may be used in, but are not limited to, a radio stripe system **800** such as illustrated in FIG. **3**.

The first APU **300** is now going to be described with reference to FIG. **6**. The first APU **300** is configured for sequential receive combining in a radio stripe system **800**. The radio stripe system **800** comprises at least two APUs **300**,**400** and a CPU **600**. The at least two APUs **300**,**400** are connected in series to the CPU **600**. The radio stripe system **800** serves at least two UEs **700**. As illustrated in FIG. **6**, the first APU **300** comprises a processing circuitry **310** and a memory circuitry **320**.

Additionally, or alternatively, the first APU **300** may further comprise a transmitter, or a transmitting circuitry **340**, configured to transmit data to other apparatuses, such as the at least one subsequent second APU **400**.

Additionally, or alternatively, the first APU **300** may further comprise a receiver, or a receiving circuitry **330**, configured to receive data from other apparatuses, such as the at least one subsequent second APU **400**.

The memory circuitry **320** stores computer program code which, when run in the processing circuitry **310**, causes the first APU **300** to obtain channel estimates for channels to said served UEs. The obtained channel estimates may be CSI obtained from reference pilot signals transmitted by said served UEs **700**. The first APU **300** is further caused to determine a receive combining filter based on the obtained channel estimates. The receive combining filter is going to be applied to received data signals. The memory circuitry **320** further stores computer program code which, when run in the processing circuitry **310**, causes the first APU **300** to determine effective channels from the served UEs **700** based on the obtained channel estimates and the determined receive combining filter. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs. The first APU **300** is further caused to transmit the effective channels from said served UEs **700** to at least one subsequent second APU **400**. The at least one subsequent second APU **400** may be located closer to the CPU **600** than the first APU **300**.

In some embodiments, the memory circuitry **320** storing computer program code which, when run in the processing circuitry **310**, may further cause the first APU **300** to receive data signals from said served UEs, and to determine improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs **700**.

In some embodiments, the memory circuitry **320** storing computer program code which, when run in the processing circuitry **310**, may further cause the first APU **300** to transmit the determined improved estimates of the received data signals to at least one subsequent second APU **400**.

In some embodiments, the receive combining filter may be generated by a method selected from the group comprised of MRC, ZF combining and MMSE combining.

In some embodiments, each of the at least two APUs **300**, **400** in the radio stripe system may be equipped with one antenna. In other embodiments, at least one of the at least two APUs **300**,**400** may be equipped with more than one antenna.

According to a fourth aspect, there is provided a second APU **400** for implementing the method according to the second aspect.

The second APU **400** is now going to be described with reference to FIG. **7**. The second APU **400** may be used in, but are not limited to, a radio stripe system **800** such as illustrated in FIG. **3**.

The second APU **400** is configured for sequential receive combining in a radio stripe system **800**. The radio stripe system **800** comprises at least two APUs **300**,**400** and a CPU **600**, the at least two APUs **300**,**400** being connected in series to the CPU **600**. The radio stripe system **800** serves at least two UEs **700**. As illustrated in FIG. **7**, the second APU **400** comprises a processor, or a processing circuitry **410**, and a memory, or a memory circuitry **420**.

Additionally, or alternatively, the second APU **400** may further comprise a transmitter, or a transmitting circuitry **440**, configured to transmit data to other apparatuses, such as the at least one preceding first APU **300**.

Additionally, or alternatively, the second APU **400** may further comprise a receiver, or a receiving circuitry **430**, configured to receive data from other apparatuses, such as the at least one preceding first APU **300**.

The memory circuitry **420** storing computer program code which, when run in the processing circuitry **410**, causes the second APU **400** to obtain channel estimates for channels to said served UEs. The obtained channel estimates may be CSI obtained from reference pilot signals transmitted by the served UEs **700**. The second APU **400** is further caused to receive, from at least one preceding first APU **300**, effective channels from said served UEs **700** to said preceding first APU **300**. The at least one preceding first APU **300** may be located further away from the CPU **600** than the second APU **300**. The memory circuitry **420** further stores computer program code which, when run in the processing circuitry **410**, causes the second APU **400** to determine a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU **300**. The receive combining filter is going to be applied to received data signals.

In some embodiments, the memory circuitry **420** storing computer program code which, when run in the processing circuitry **410**, may further cause the second APU **400** to determine effective channels from said served UEs **700** based on the obtained channel estimates, the determined receive combining filter and the received effective channels from said at least one preceding first APU **300**. The effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs.

In some embodiments, the memory circuitry **420** storing computer program code which, when run in the processing circuitry **410**, may further cause the second APU **400** to receive data signals from said served UEs **700** and to receive, from said at least one preceding first APU **300**, improved estimates of data signals received by the preceding first APU **300**. The second APU **400** may further be caused to determine augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU **300**. The second APU **400** may further be caused to determine improved estimates of the received data signals by applying the determined receive combining filter to the augmented received data signals from said served UEs.

In some embodiments, the memory circuitry **420** storing computer program code which, when run in the processing circuitry **410**, may further cause the second APU **400** to transmit the determined effective channels from said served UEs **700** and the improved estimates of the received data signals to at least one subsequent third APU **500**. The at least one subsequent third APU **500** may be located closer to the CPU **600** than the second APU **400**. In other embodiments, the memory circuitry **420** storing computer program code which, when run in the processing circuitry **410**, may further cause the second APU **400** to transmit the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU **600**.

In some embodiments, the receive combining filter is generated by a method selected from the group comprised of: MRC, ZF combining and MMSE combining.

According to a fifth aspect, there is provided a computer program comprising instructions which, when executed on a processing circuitry, cause the processing circuitry to carry out the method according to the first aspect and/or the second aspect.

According to an sixth aspect, there is provided a carrier containing the computer program of the fifth aspect, wherein the carrier is one of an electronic signal, optical signal, radio signal, or computer readable storage medium.

A Numerical Linear Processing Example

In the following, a non-limiting example of the proposed solution will now be described.

A radio stripe with **10** single-antenna equal-spaced APUs may be deployed on a 20-meter-long wall. The CPU may be located at the right end of the stripe such that the fronthaul connection goes from APU**1**-APU**2**-APU**3**- . . . -APU**9**-APU**10**-CPU (the setup may be symmetric, so a mirrored deployment would be equivalent). Three UEs may be located 5 meters from the wall and 3 or 6 meters from each other, as shown in FIG. **8**. The UEs may be transmitting orthogonal pilot sequences, which may enable each APU to estimate its channel to each UE locally, using MMSE estimation. The propagation channels may be computed using free-space line-of-sight propagation modelling at a 3 GHz carrier frequency.

In the following, the proposed solution is compared with two baseline methods during uplink data transmission. These two baseline methods are known in the art and are:

- Distributed MRC, where each APU may process its signal locally and their signals may be accumulated along the radio stripe. The CPU may use the accumulated scalar signals, one per UE, to decode the signals.
- Centralized MMSE combining, where each APU may send its channel estimates and received signals from the data transmission to the CPU, which may perform the decoding using a state-of-the-art MMSE receiver—in a cellular-system fashion.

These baseline methods may be compared with the proposed solution, wherein in this example each APU may use MMSE combining based on its locally available information. The proposed solution is here referred to as “sequential MMSE” or “Seq-MMSE”.

FIG. **9** shows the achievable rates with the proposed solution and the two previously described known methods, as a function of the average Signal-to-Noise-Ratio (SNR) per UE. The performance with the distributed MRC method may saturate at high SNR, due to its lack of interference suppression capabilities. In this short-range scenario, an SNR of 20-30 dB may be achieved even when the transmit power is very low. In contrast, the centralized MMSE method may provide an achievable rate that grows linearly with the SNR in dB-scale, as expected from a method that provides interference suppression and has good CSI. However, its fronthaul requirements are not scalable.

The proposed solution, described herein, may combine the benefits of the two baseline methods. The proposed solution may have a distributed implementation but may also provide achievable rates that grow linearly with the number of antennas. The performance loss compared to centralized MMSE is due to the fact that only two antennas are considered at a time in the interference suppression, as compared to the joint processing of all antennas that is done in the centralized case. This loss will diminish if each APU has multiple antennas as well.

Although the subject matter described herein may be implemented in any appropriate type of system using any suitable components, the embodiments described herein relate to a wireless network, such as the example wireless communication network illustrated in FIG. **10**. For simplicity, the wireless communication network of FIG. **10** only depicts network **1006**, network nodes **1060** and **1060***b*, and Wireless Devices (WDs) **1010**, **1010***b*, and **1010***c*. The wireless communication network may further include any additional elements suitable to support communication between wireless devices or between a wireless device and another communication device, such as a landline telephone. Of the illustrated components, network node **1060** and wireless device (WD) **1010** are depicted with additional detail. The illustrated wireless communication network may provide communication and other types of services to one or more wireless devices to facilitate the wireless devices' access to and/or use of the services provided by the wireless communication network.

The wireless communication network may comprise and/or interface with any type of communication, telecommunication, data, cellular, and/or radio network or other similar type of system. In some embodiments, the wireless communication network may be configured to operate according to specific standards or other types of predefined rules or procedures. Thus, particular embodiments of the wireless communication network may implement communication standards, such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE), and/or other suitable 2G, 3G, 4G, or 5G standards; wireless local area network (WLAN) standards, such as the IEEE 802.11 standards; and/or any other appropriate wireless communication standard, such as the Worldwide Interoperability for Microwave Access (WiMax), Bluetooth, and/or ZigBee standards.

Network **1006** may comprise one or more backhaul networks, core networks, IP networks, public switched telephone networks (PSTNs), packet data networks, optical networks, wide-area networks (WANs), local area networks (LANs), wireless local area networks (WLANs), wired networks, wireless networks, metropolitan area networks, and other networks to enable communication between devices.

Network node **1060** and WD **1010** comprise various components described in more detail below. These components may work together in order to provide network node and/or wireless device functionality, such as providing wireless connections in a wireless network. In different embodiments, the wireless network may comprise any number of wired or wireless networks, network nodes, base stations, controllers, wireless devices, relay stations, and/or any other components that may facilitate or participate in the communication of data and/or signals whether via wired or wireless connections.

As used herein, network node refers to equipment capable, configured, arranged and/or operable to communicate directly or indirectly with a wireless device and/or with other network nodes or equipment in the wireless communication network to enable and/or provide wireless access to the wireless device and/or to perform other functions (e.g., administration) in the wireless communication network. Examples of network nodes include, but are not limited to, access points (APs) (e.g., radio access points), base stations (BSs) (e.g., radio base stations, Node Bs, and evolved Node Bs (eNBs)). Base stations may be categorized based on the amount of coverage they provide (or, stated differently, their transmit power level) and may then also be referred to as femto base stations, pico base stations, micro base stations, or macro base stations. A base station may be a relay node or a relay donor node controlling a relay. A network node may also include one or more (or all) parts of a distributed radio base station such as centralized digital units and/or remote radio units (RRUs), sometimes referred to as Remote Radio Heads (RRHs). Such remote radio units may or may not be integrated with an antenna as an antenna integrated radio. Parts of a distributed radio base station may also be referred to as nodes in a distributed antenna system (DAS). Yet further examples of network nodes include multi-standard radio (MSR) equipment such as MSR BSs, network controllers such as radio network controllers (RNCs) or base station controllers (BSCs), base transceiver stations (BTSs), transmission points, transmission nodes, multi-cell/multicast coordination entities (MCEs), core network nodes (e.g., MSCs, MMEs), O&M nodes, OSS nodes, SON nodes, positioning nodes (e.g., E-SMLCs), and/or MDTs. As another example, network node **1060** may be a virtual network node as described in more detail below. More generally, however, network nodes may represent any suitable device (or group of devices) capable, configured, arranged, and/or operable to enable and/or provide a wireless device with access to the wireless communication network or to provide some service to a wireless device that has accessed the wireless communication network.

In FIG. **10**, Network node **1060** includes processing circuitry **1070**, device readable medium **1080**, interface **1090**, user interface equipment **1082**, auxiliary equipment **1084**, power source **1086**, power circuitry **1087**, and antenna **1062**. Although network node **1060** illustrated in the example wireless communication network of FIG. **10** may represent a device that includes the illustrated combination of hardware components, other embodiments may comprise network nodes with different combinations of components. It is to be understood that a network node may comprise any suitable combination of hardware and/or software needed to perform the tasks, features, functions and methods disclosed herein. Moreover, while the components of network node **1060** are depicted as single boxes located within a larger box, or nested within multiple boxes, in practice, a network node may comprise multiple different physical components that make up a single illustrated component (e.g., device readable medium **1080** may comprise multiple separate hard drives as well as multiple RAM modules).

Similarly, network node **1060** may be composed of multiple physically separate components (e.g., a NodeB component and a RNC component, or a BTS component and a BSC component, etc.), which may each have their own respective components. In certain scenarios in which network node **1060** comprises multiple separate components (e.g., BTS and BSC components), one or more of the separate components may be shared among several network nodes. For example, a single RNC may control multiple NodeBs. In such a scenario, each unique NodeB and RNC pair, may in some instances be considered a single separate network node. In some embodiments, network node **1060** may be configured to support multiple radio access technologies (RATs). In such embodiments, some components may be duplicated (e.g., separate device readable medium **1080** for the different RATs) and some components may be reused (e.g., the same antenna **1062** may be shared by the RATs). Network node **1060** may also include multiple sets of the various illustrated components for different wireless technologies integrated into network node **1060**, such as, for example, GSM, WCDMA, LTE, NR, WiFi, or Bluetooth wireless technologies. These wireless technologies may be integrated into the same or different chip or set of chips and other components within network node **1060**.

Processing circuitry **1070** is configured to perform any determining, calculating, or similar operations (e.g., certain obtaining operations) described herein as being provided by a network node. These operations performed by processing circuitry **1070** may include processing information obtained by processing circuitry **1070** by, for example, converting the obtained information into other information, comparing the obtained information or converted information to information stored in the network node, and/or performing one or more operations based on the obtained information or converted information, and as a result of said processing making a determination.

Processing circuitry **1070** may comprise a combination of one or more of a microprocessor, controller, microcontroller, central processing unit, digital signal processor, application-specific integrated circuit, field programmable gate array, or any other suitable computing device, resource, or combination of hardware, software and/or encoded logic operable to provide, either alone or in conjunction with other network node **1060** components, such as device readable medium **1080**, network node **1060** functionality. For example, processing circuitry **1070** may execute instructions stored in device readable medium **1080** or in memory within processing circuitry **1070**. Such functionality may include providing any of the various wireless features or benefits discussed herein. In some embodiments, processing circuitry **1070** may include a system on a chip (SOC).

In some embodiments, processing circuitry **1070** may include one or more of radio frequency (RF) transceiver circuitry **1072** and baseband processing circuitry **1074**. In some embodiments, radio frequency (RF) transceiver circuitry **1072** and baseband processing circuitry **1074** may be on separate chips (or sets of chips), boards, or units, such as radio units and digital units. In alternative embodiments, part or all of RF transceiver circuitry **1072** and baseband processing circuitry **1074** may be on the same chip or set of chips, boards, or units.

In certain embodiments, some or all of the functionality described herein as being provided by a network node, base station, eNB or other such network device may be provided by processing circuitry **1070** executing instructions stored on device readable medium **1080** or memory within processing circuitry **1070**. In alternative embodiments, some or all of the functionality may be provided by processing circuitry **1070** without executing instructions stored on a separate or discrete device readable medium, such as in a hard-wired manner. In any of those embodiments, whether executing instructions stored on a device readable storage medium or not, processing circuitry **1070** can be configured to perform the described functionality. The benefits provided by such functionality are not limited to processing circuitry **1070** alone or to other components of network node **1060**, but are enjoyed by network node **1060** as a whole, and/or by end users and the wireless network generally.

Device readable medium **1080** may comprise any form of volatile or non-volatile computer readable memory including, without limitation, persistent storage, solid-state memory, remotely mounted memory, magnetic media, optical media, random access memory (RAM), read-only memory (ROM), mass storage media (for example, a hard disk), removable storage media (for example, a flash drive, a Compact Disk (CD) or a Digital Video Disk (DVD)), and/or any other volatile or non-volatile, non-transitory device readable and/or computer-executable memory devices that store information, data, and/or instructions that may be used by processing circuitry **1070**. Device readable medium **1080** may store any suitable instructions, data or information, including a computer program, software, an application including one or more of logic, rules, code, tables, etc. and/or other instructions capable of being executed by processing circuitry **1070** and, utilized by network node **1060**. Device readable medium **1080** may be used to store any calculations made by processing circuitry **1070** and/or any data received via interface **1090**. In some embodiments, processing circuitry **1070** and device readable medium **10100** may be considered to be integrated.

Interface **1090** is used in the wired or wireless communication of signaling and/or data between network node **1060**, network **1006**, and/or WDs **1010**. As illustrated, interface **1090** comprises port(s)/terminal(s) **1094** to send and receive data, for example to and from network **1006** over a wired connection. Interface **1090** also includes radio front end circuitry **1092** that may be coupled to, or in certain embodiments a part of, antenna **1062**. Radio front end circuitry **1092** comprises filters **1098** and amplifiers **1096**. Radio front end circuitry **1092** may be connected to antenna **1062** and processing circuitry **1070**. Radio front end circuitry may be configured to condition signals communicated between antenna **1062** and processing circuitry **1070**. Radio front end circuitry **1092** may receive digital data that is to be sent out to other network nodes or WDs via a wireless connection. Radio front end circuitry **1092** may convert the digital data into a radio signal having the appropriate channel and bandwidth parameters using a combination of filters **1098** and/or amplifiers **1096**. The radio signal may then be transmitted via antenna **1062**. Similarly, when receiving data, antenna **1062** may collect radio signals which are then converted into digital data by radio front end circuitry **1092**. The digital data may be passed to processing circuitry **1070**. In other embodiments, the interface may comprise different components and/or different combinations of components.

In certain alternative embodiments, network node **1060** may not include separate radio front end circuitry **1092**, instead, processing circuitry **1070** may comprise radio front end circuitry and may be connected to antenna **1062** without separate radio front end circuitry **1092**. Similarly, in some embodiments, all or some of RF transceiver circuitry **1072** may be considered a part of interface **1090**. In still other embodiments, interface **1090** may include one or more ports or terminals **1094**, radio front end circuitry **1092**, and RF transceiver circuitry **1072**, as part of a radio unit (not shown), and interface **1090** may communicate with baseband processing circuitry **1074**, which is part of a digital unit (not shown).

Antenna **1062** may include one or more antennas, or antenna arrays, configured to send and/or receive wireless signals. Antenna **1062** may be coupled to radio front end circuitry **1090** and may be any type of antenna capable of transmitting and receiving data and/or signals wirelessly. In some embodiments, antenna **1062** may comprise one or more omni-directional, sector or panel antennas operable to transmit/receive radio signals between, for example, 2 GHz and 66 GHz. An omni-directional antenna may be used to transmit/receive radio signals in any direction, a sector antenna may be used to transmit/receive radio signals from devices within a particular area, and a panel antenna may be a line of sight antenna used to transmit/receive radio signals in a relatively straight line. In some instances, the use of more than one antenna may be referred to as MIMO. In certain embodiments, antenna **1062** may be separate from network node **1060** and may be connectable to network node **1060** through an interface or port.

Antenna **1062**, interface **1090**, and/or processing circuitry **1070** may be configured to perform any receiving operations and/or certain obtaining operations described herein as being performed by a network node. Any information, data and/or signals may be received from a wireless device, another network node and/or any other network equipment. Similarly, antenna **1062**, interface **1090**, and/or processing circuitry **1070** may be configured to perform any transmitting operations described herein as being performed by a network node. Any information, data and/or signals may be transmitted to a wireless device, another network node and/or any other network equipment.

Power circuitry **1087** may comprise, or be coupled to, power management circuitry and is configured to supply the components of network node **1060** with power for performing the functionality described herein. Power circuitry **1087** may receive power from power source **1086**. Power source **1086** and/or power circuitry **1087** may be configured to provide power to the various components of network node **1060** in a form suitable for the respective components (e.g., at a voltage and current level needed for each respective component). Power source **1086** may either be included in, or external to, power circuitry **1087** and/or network node **1060**. For example, network node **1060** may be connectable to an external power source (e.g., an electricity outlet) via an input circuitry or interface such as an electrical cable, whereby the external power source supplies power to power circuitry **1087**. As a further example, power source **1086** may comprise a source of power in the form of a battery or battery pack which is connected to, or integrated in, power circuitry **1087**. The battery may provide backup power should the external power source fail. Other types of power sources, such as photovoltaic devices, may also be used.

Alternative embodiments of network node **1060** may include additional components beyond those shown in FIG. **10** that may be responsible for providing certain aspects of the network node's functionality, including any of the functionality described herein and/or any functionality necessary to support the subject matter described herein. For example, network node **1060** may include user interface equipment to allow input of information into network node **1060** and to allow output of information from network node **1060**. This may allow a user to perform diagnostic, maintenance, repair, and other administrative functions for network node **1060**.

As used herein, wireless device (WD) refers to a device capable, configured, arranged and/or operable to communicate wirelessly with network nodes and/or other wireless devices. Unless otherwise noted, the term WD may be used interchangeably herein with user equipment (UE). Communicating wirelessly may involve transmitting and/or receiving wireless signals using electromagnetic waves, radio waves, infrared waves, and/or other types of signals suitable for conveying information through air. In some embodiments, a WD may be configured to transmit and/or receive information without direct human interaction. For instance, a WD may be designed to transmit information to a network on a predetermined schedule, when triggered by an internal or external event, or in response to requests from the network. Examples of a WD include, but are not limited to, a smart phone, a mobile phone, a cell phone, a voice over IP (VoIP) phone, a wireless local loop phone, a desktop computer, a personal digital assistant (PDA), a wireless cameras, a gaming console or device, a music storage device, a playback appliance, a wearable terminal device, a wireless endpoint, a mobile station, a tablet, a laptop, a laptop-embedded equipment (LEE), a laptop-mounted equipment (LME), a smart device, a wireless customer-premise equipment (CPE), a vehicle-mounted wireless terminal device, etc. A WD may support device-to-device (D2D) communication, for example by implementing a 3GPP standard for sidelink communication, vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-everything (V2X) and may in this case be referred to as a D2D communication device. As yet another specific example, in an Internet of Things (IoT) scenario, a WD may represent a machine or other device that performs monitoring and/or measurements, and transmits the results of such monitoring and/or measurements to another WD and/or a network node. The WD may in this case be a machine-to-machine (M2M) device, which may in a 3GPP context be referred to as an MTC device. As one particular example, the WD may be a UE implementing the 3GPP narrow band internet of things (NB-IoT) standard. Particular examples of such machines or devices are sensors, metering devices such as power meters, industrial machinery, or home or personal appliances (e.g. refrigerators, televisions, etc.) personal wearables (e.g., watches, fitness trackers, etc.). In other scenarios, a WD may represent a vehicle or other equipment that is capable of monitoring and/or reporting on its operational status or other functions associated with its operation. A WD as described above may represent the endpoint of a wireless connection, in which case the device may be referred to as a wireless terminal. Furthermore, a WD as described above may be mobile, in which case it may also be referred to as a mobile device or a mobile terminal.

As illustrated, wireless device **1010** includes antenna **1011**, interface **1014**, processing circuitry **1020**, device readable medium **1030**, user interface equipment **1032**, auxiliary equipment **1034**, power source **1036** and power circuitry **1037**. WD **1010** may include multiple sets of one or more of the illustrated components for different wireless technologies supported by WD **1010**, such as, for example, GSM, WCDMA, LTE, NR, WiFi, WiMAX, or Bluetooth wireless technologies, just to mention a few. These wireless technologies may be integrated into the same or different chips or set of chips as other components within WD **1010**.

Antenna **1011** may include one or more antennas or antenna arrays, configured to send and/or receive wireless signals, and is connected to interface **1014**. In certain alternative embodiments, antenna **1011** may be separate from WD **1010** and be connectable to WD **1010** through an interface or port. Antenna **1011**, interface **1014**, and/or processing circuitry **1020** may be configured to perform any receiving or transmitting operations described herein as being performed by a WD. Any information, data and/or signals may be received from a network node and/or another WD. In some embodiments, radio front end circuitry and/or antenna **1011** may be considered an interface.

As illustrated, interface **1014** comprises radio front end circuitry **1012** and antenna **1011**. Radio front end circuitry **1012** comprise one or more filters **1013** and amplifiers **1016**. Radio front end circuitry **1014** is connected to antenna **1011** and processing circuitry **1020**, and is configured to condition signals communicated between antenna **1011** and processing circuitry **1020**. Radio front end circuitry **1012** may be coupled to or a part of antenna **1011**. In some embodiments, WD **1010** may not include separate radio front end circuitry **1012**; rather, processing circuitry **1020** may comprise radio front end circuitry and may be connected to antenna **1011**. Similarly, in some embodiments, some or all of RF transceiver circuitry **1022** may be considered a part of interface **1014**. Radio front end circuitry **1012** may receive digital data that is to be sent out to other network nodes or WDs via a wireless connection. Radio front end circuitry **1012** may convert the digital data into a radio signal having the appropriate channel and bandwidth parameters using a combination of filters **1013** and/or amplifiers **1016**. The radio signal may then be transmitted via antenna **1011**. Similarly, when receiving data, antenna **1011** may collect radio signals which are then converted into digital data by radio front end circuitry **1012**. The digital data may be passed to processing circuitry **1020**. In other embodiments, the interface may comprise different components and/or different combinations of components.

Processing circuitry **1020** may comprise a combination of one or more of a microprocessor, controller, microcontroller, central processing unit, digital signal processor, application-specific integrated circuit, field programmable gate array, or any other suitable computing device, resource, or combination of hardware, software, and/or encoded logic operable to provide, either alone or in conjunction with other WD **1010** components, such as device readable medium **1030**, WD **1010** functionality. Such functionality may include providing any of the various wireless features or benefits discussed herein. For example, processing circuitry **1020** may execute instructions stored in device readable medium **1030** or in memory within processing circuitry **1020** to provide the functionality disclosed herein.

As illustrated, processing circuitry **1020** includes one or more of RF transceiver circuitry **1022**, baseband processing circuitry **1024**, and application processing circuitry **1026**. In other embodiments, the processing circuitry may comprise different components and/or different combinations of components. In certain embodiments processing circuitry **1020** of WD **1010** may comprise a SOC. In some embodiments, RF transceiver circuitry **1022**, baseband processing circuitry **1024**, and application processing circuitry **1026** may be on separate chips or sets of chips. In alternative embodiments, part or all of baseband processing circuitry **1024** and application processing circuitry **1026** may be combined into one chip or set of chips, and RF transceiver circuitry **1022** may be on a separate chip or set of chips. In still alternative embodiments, part or all of RF transceiver circuitry **1022** and baseband processing circuitry **1024** may be on the same chip or set of chips, and application processing circuitry **1026** may be on a separate chip or set of chips. In yet other alternative embodiments, part or all of RF transceiver circuitry **1022**, baseband processing circuitry **1024**, and application processing circuitry **1026** may be combined in the same chip or set of chips. In some embodiments, RF transceiver circuitry **1022** may be a part of interface **1014**. RF transceiver circuitry **1022** may condition RF signals for processing circuitry **1020**.

In certain embodiments, some or all of the functionality described herein as being performed by a WD may be provided by processing circuitry **1020** executing instructions stored on device readable medium **1030**, which in certain embodiments may be a computer-readable storage medium. In alternative embodiments, some or all of the functionality may be provided by processing circuitry **1020** without executing instructions stored on a separate or discrete device readable storage medium, such as in a hard-wired manner. In any of those particular embodiments, whether executing instructions stored on a device readable storage medium or not, processing circuitry **1020** can be configured to perform the described functionality. The benefits provided by such functionality are not limited to processing circuitry **1020** alone or to other components of WD **1010**, but are enjoyed by WD **1010** as a whole, and/or by end users and the wireless network generally.

Processing circuitry **1020** may be configured to perform any determining, calculating, or similar operations (e.g., certain obtaining operations) described herein as being performed by a WD. These operations, as performed by processing circuitry **1020**, may include processing information obtained by processing circuitry **1020** by, for example, converting the obtained information into other information, comparing the obtained information or converted information to information stored by WD **1010**, and/or performing one or more operations based on the obtained information or converted information, and as a result of said processing making a determination.

Device readable medium **1030** may be operable to store a computer program, software, an application including one or more of logic, rules, code, tables, etc. and/or other instructions capable of being executed by processing circuitry **1020**. Device readable medium **1030** may include computer memory (e.g., Random Access Memory (RAM) or Read Only Memory (ROM)), mass storage media (e.g., a hard disk), removable storage media (e.g., a Compact Disk (CD) or a Digital Video Disk (DVD)), and/or any other volatile or non-volatile, non-transitory device readable and/or computer executable memory devices that store information, data, and/or instructions that may be used by processing circuitry **1020**. In some embodiments, processing circuitry **1020** and device readable medium **1030** may be considered to be integrated.

User interface equipment **1032** may provide components that allow for a human user to interact with WD **1010**. Such interaction may be of many forms, such as visual, audial, tactile, etc. User interface equipment **1032** may be operable to produce output to the user and to allow the user to provide input to WD **1010**. The type of interaction may vary depending on the type of user interface equipment **1032** installed in WD **1010**. For example, if WD **1010** is a smart phone, the interaction may be via a touch screen; if WD **1010** is a smart meter, the interaction may be through a screen that provides usage (e.g., the number of gallons used) or a speaker that provides an audible alert (e.g., if smoke is detected). User interface equipment **1032** may include input interfaces, devices and circuits, and output interfaces, devices and circuits. User interface equipment **1032** is configured to allow input of information into WD **1010**, and is connected to processing circuitry **1020** to allow processing circuitry **1020** to process the input information. User interface equipment **1032** may include, for example, a microphone, a proximity or other sensor, keys/buttons, a touch display, one or more cameras, a USB port, or other input circuitry. User interface equipment **1032** is also configured to allow output of information from WD **1010**, and to allow processing circuitry **1020** to output information from WD **1010**. User interface equipment **1032** may include, for example, a speaker, a display, vibrating circuitry, a USB port, a headphone interface, or other output circuitry. Using one or more input and output interfaces, devices, and circuits, of user interface equipment **1032**, WD **1010** may communicate with end users and/or the wireless network, and allow them to benefit from the functionality described herein.

Auxiliary equipment **1034** is operable to provide more specific functionality which may not be generally performed by WDs. This may comprise specialized sensors for doing measurements for various purposes, interfaces for additional types of communication such as wired communications etc. The inclusion and type of components of auxiliary equipment **1034** may vary depending on the embodiment and/or scenario.

Power source **1036** may, in some embodiments, be in the form of a battery or battery pack. Other types of power sources, such as an external power source (e.g., an electricity outlet), photovoltaic devices or power cells, may also be used. WD **1010** may further comprise power circuitry **1037** for delivering power from power source **1036** to the various parts of WD **1010** which need power from power source **1036** to carry out any functionality described or indicated herein. Power circuitry **1037** may in certain embodiments comprise power management circuitry. Power circuitry **1037** may additionally or alternatively be operable to receive power from an external power source; in which case WD **1010** may be connectable to the external power source (such as an electricity outlet) via input circuitry or an interface such as an electrical power cable. Power circuitry **1037** may also in certain embodiments be operable to deliver power from an external power source to power source **1036**. This may be, for example, for the charging of power source **1036**. Power circuitry **1037** may perform any formatting, converting, or other modification to the power from power source **1036** to make the power suitable for the respective components of WD **1010** to which power is supplied.

FIG. **11** illustrates one embodiment of a UE in accordance with various aspects described herein. As used herein, a user equipment or UE may not necessarily have a user in the sense of a human user who owns and/or operates the relevant device. Instead, a UE may represent a device that is intended for sale to, or operation by, a human user but which may not, or which may not initially, be associated with a specific human user (e.g., a smart sprinkler controller). Alternatively, a UE may represent a device that is not intended for sale to, or operation by, an end user but which may be associated with or operated for the benefit of a user (e.g., a smart power meter). UE **1100** may be any UE identified by the 3rd Generation Partnership Project (3GPP), including a NB-IoT UE, a machine type communication (MTC) UE, and/or an enhanced MTC (eMTC) UE. UE **900**, as illustrated in FIG. **9**, is one example of a WD configured for communication in accordance with one or more communication standards promulgated by the 3rd Generation Partnership Project (3GPP), such as 3GPP's GSM, UMTS, LTE, and/or 5G standards. As mentioned previously, the term WD and UE may be used interchangeable. Accordingly, although FIG. **11** is a UE, the components discussed herein are equally applicable to a WD, and vice-versa.

In FIG. **11**, UE **1100** includes processing circuitry **1101** that is operatively coupled to input/output interface **1105**, radio frequency (RF) interface **1109**, network connection interface **1111**, memory **1115** including random access memory (RAM) **1117**, read-only memory (ROM) **1114**, and storage medium **1121** or the like, communication subsystem **1131**, power source **1133**, and/or any other component, or any combination thereof. Storage medium **1121** includes operating system **1123**, application program **1125**, and data **1127**. In other embodiments, storage medium **1121** may include other similar types of information. Certain UEs may utilize all of the components shown in FIG. **11**, or only a subset of the components. The level of integration between the components may vary from one UE to another UE. Further, certain UEs may contain multiple instances of a component, such as multiple processors, memories, transceivers, transmitters, receivers, etc.

In FIG. **11**, processing circuitry **1101** may be configured to process computer instructions and data. Processing circuitry **1101** may be configured to implement any sequential state machine operative to execute machine instructions stored as machine-readable computer programs in the memory, such as one or more hardware-implemented state machines (e.g., in discrete logic, FPGA, ASIC, etc.); programmable logic together with appropriate firmware; one or more stored program, general-purpose processors, such as a microprocessor or Digital Signal Processor (DSP), together with appropriate software; or any combination of the above. For example, the processing circuitry **1101** may include two central processing units (CPUs). Data may be information in a form suitable for use by a computer.

In the depicted embodiment, input/output interface **1105** may be configured to provide a communication interface to an input device, output device, or input and output device. UE **1100** may be configured to use an output device via input/output interface **1105**. An output device may use the same type of interface port as an input device. For example, a USB port may be used to provide input to and output from UE **1100**. The output device may be a speaker, a sound card, a video card, a display, a monitor, a printer, an actuator, an emitter, a smartcard, another output device, or any combination thereof. UE **1100** may be configured to use an input device via input/output interface **1105** to allow a user to capture information into UE **1100**. The input device may include a touch-sensitive or presence-sensitive display, a camera (e.g., a digital camera, a digital video camera, a web camera, etc.), a microphone, a sensor, a mouse, a trackball, a directional pad, a trackpad, a scroll wheel, a smartcard, and the like. The presence-sensitive display may include a capacitive or resistive touch sensor to sense input from a user. A sensor may be, for instance, an accelerometer, a gyroscope, a tilt sensor, a force sensor, a magnetometer, an optical sensor, a proximity sensor, another like sensor, or any combination thereof. For example, the input device may be an accelerometer, a magnetometer, a digital camera, a microphone, and an optical sensor.

In FIG. **11**, RF interface **1109** may be configured to provide a communication interface to RF components such as a transmitter, a receiver, and an antenna. Network connection interface **1111** may be configured to provide a communication interface to network **1143*a***. Network **1143*a*** may encompass wired and/or wireless networks such as a local-area network (LAN), a wide-area network (WAN), a computer network, a wireless network, a telecommunications network, another like network or any combination thereof. For example, network **1143*a*** may comprise a Wi-Fi network. Network connection interface **1111** may be configured to include a receiver and a transmitter interface used to communicate with one or more other devices over a communication network according to one or more communication protocols, such as Ethernet, TCP/IP, SONET, ATM, or the like. Network connection interface **1111** may implement receiver and transmitter functionality appropriate to the communication network links (e.g., optical, electrical, and the like). The transmitter and receiver functions may share circuit components, software or firmware, or alternatively may be implemented separately.

RAM **1117** may be configured to interface via bus **1102** to processing circuitry **1101** to provide storage or caching of data or computer instructions during the execution of software programs such as the operating system, application programs, and device drivers. ROM **1114** may be configured to provide computer instructions or data to processing circuitry **1101**. For example, ROM **1114** may be configured to store invariant low-level system code or data for basic system functions such as basic input and output (I/O), startup, or reception of keystrokes from a keyboard that are stored in a non-volatile memory. Storage medium **1121** may be configured to include memory such as RAM, ROM, programmable read-only memory (PROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), magnetic disks, optical disks, floppy disks, hard disks, removable cartridges, or flash drives. In one example, storage medium **1121** may be configured to include operating system **1123**, application program **1125** such as a web browser application, a widget or gadget engine or another application, and data file **1127**. Storage medium **1121** may store, for use by UE **1100**, any of a variety of various operating systems or combinations of operating systems.

Storage medium **1121** may be configured to include a number of physical drive units, such as redundant array of independent disks (RAID), floppy disk drive, flash memory, USB flash drive, external hard disk drive, thumb drive, pen drive, key drive, high-density digital versatile disc (HD-DVD) optical disc drive, internal hard disk drive, Blu-Ray optical disc drive, holographic digital data storage (HDDS) optical disc drive, external mini-dual in-line memory module (DIMM), synchronous dynamic random access memory (SDRAM), external micro-DIMM SDRAM, smartcard memory such as a subscriber identity module or a removable user identity (SIM/RUIM) module, other memory, or any combination thereof. Storage medium **1121** may allow UE **1100** to access computer-executable instructions, application programs or the like, stored on transitory or non-transitory memory media, to off-load data, or to upload data. An article of manufacture, such as one utilizing a communication system may be tangibly embodied in storage medium **1121**, which may comprise a device readable medium.

In FIG. **11**, processing circuitry **1101** may be configured to communicate with network **1143*b*** using communication subsystem **1131**. Network **1143*a*** and network **1143*b*** may be the same network or networks or different network or networks. Communication subsystem **1131** may be configured to include one or more transceivers used to communicate with network **1143*b***. For example, communication subsystem **1131** may be configured to include one or more transceivers used to communicate with one or more remote transceivers of another device capable of wireless communication such as another WD, UE, or base station of a radio access network (RAN) according to one or more communication protocols, such as IEEE 802.9, CDMA, WCDMA, GSM, LTE, UTRAN, WiMax, or the like. Each transceiver may include transmitter **1133** and/or receiver **1135** to implement transmitter or receiver functionality, respectively, appropriate to the RAN links (e.g., frequency allocations and the like). Further, transmitter **1133** and receiver **1135** of each transceiver may share circuit components, software or firmware, or alternatively may be implemented separately.

In the illustrated embodiment, the communication functions of communication subsystem **1131** may include data communication, voice communication, multimedia communication, short-range communications such as Bluetooth, near-field communication, location-based communication such as the use of the global positioning system (GPS) to determine a location, another like communication function, or any combination thereof. For example, communication subsystem **1131** may include cellular communication, Wi-Fi communication, Bluetooth communication, and GPS communication. Network **1143***b* may encompass wired and/or wireless networks such as a local-area network (LAN), a wide-area network (WAN), a computer network, a wireless network, a telecommunications network, another like network or any combination thereof. For example, network **1143***b* may be a cellular network, a Wi-Fi network, and/or a near-field network. Power **5** source **1113** may be configured to provide alternating current (AC) or direct current (DC) power to components of UE **1100**.

The features, benefits and/or functions described herein may be implemented in one of the components of UE **1100** or partitioned across multiple components of UE **1100**. Further, the features, benefits, and/or functions described herein may be implemented in any combination of hardware, software or firmware. In one example, communication subsystem **1131** may be configured to include any of the components described herein. Further, processing circuitry **1101** may be configured to communicate with any of such components over bus **1102**. In another example, any of such components may be represented by program instructions stored in memory that when executed by processing circuitry **1101** perform the corresponding functions described herein. In another example, the functionality of any of such components may be partitioned between processing circuitry **1101** and communication subsystem **1131**. In another example, the non-computationally intensive functions of any of such components may be implemented in software or firmware and the computationally intensive functions may be implemented in hardware.

FIG. **12** is a schematic block diagram illustrating a virtualization environment **1200** in which functions implemented by some embodiments may be virtualized. In the present context, virtualizing means creating virtual versions of apparatuses or devices which may include virtualizing hardware platforms, storage devices and networking resources. As used herein, virtualization can be applied to a node (e.g., a virtualized base station or a virtualized radio access node) or to a device (e.g., a UE, a wireless device or any other type of communication device) or components thereof and relates to an implementation in which at least a portion of the functionality is implemented as one or more virtual components (e.g., via one or more applications, components, functions, virtual machines or containers executing on one or more physical processing nodes in one or more networks).

In some embodiments, some or all of the functions described herein may be implemented as virtual components executed by one or more virtual machines implemented in one or more virtual environments **1200** hosted by one or more of hardware nodes **1230**. Further, in embodiments in which the virtual node is not a radio access node or does not require radio connectivity (e.g., a core network node), then the network node may be entirely virtualized.

The functions may be implemented by one or more applications **1220** (which may alternatively be called software instances, virtual appliances, network functions, virtual nodes, virtual network functions, etc.) operative to implement some of the features, functions, and/or benefits of some of the embodiments disclosed herein. Applications **1220** are run in virtualization environment **1200** which provides hardware **1230** comprising processing circuitry **1260** and memory **1290**. Memory **1290** contains instructions **1295** executable by processing circuitry **1260** whereby application **1220** is operative to provide one or more of the features, benefits, and/or functions disclosed herein.

Virtualization environment **1200**, comprises general-purpose or special-purpose network hardware devices **1230** comprising a set of one or more processors or processing circuitry **1260**, which may be commercial off-the-shelf (COTS) processors, dedicated Application Specific Integrated Circuits (ASICs), or any other type of processing circuitry including digital or analogue hardware components or special purpose processors. Each hardware device may comprise memory **1290-1** which may be non-persistent memory for temporarily storing instructions **1295** or software executed by processing circuitry **1260**. Each hardware device may comprise one or more network interface controllers (NICs) **1270**, also known as network interface cards, which include physical network interface **1280**. Each hardware device may also include non-transitory, persistent, machine-readable storage media **1290-2** having stored therein software **1295** and/or instructions executable by processing circuitry **1260**. Software **1295** may include any type of software including software for instantiating one or more virtualization layers **1250** (also referred to as hypervisors), software to execute virtual machines **1240** as well as software allowing it to execute functions, features and/or benefits described in relation with some embodiments described herein.

Virtual machines **1240**, comprise virtual processing, virtual memory, virtual networking or interface and virtual storage, and may be run by a corresponding virtualization layer **1250** or hypervisor. Different embodiments of the instance of virtual appliance **1220** may be implemented on one or more of virtual machines **1240**, and the implementations may be made in different ways.

During operation, processing circuitry **1260** executes software **1295** to instantiate the hypervisor or virtualization layer **1250**, which may sometimes be referred to as a virtual machine monitor (VMM). Virtualization layer **1250** may present a virtual operating platform that appears like networking hardware to virtual machine **1240**.

As shown in FIG. **12**, hardware **1230** may be a standalone network node with generic or specific components. Hardware **1230** may comprise antenna **12225** and may implement some functions via virtualization. Alternatively, hardware **1230** may be part of a larger cluster of hardware (e.g. such as in a data center or customer premise equipment (CPE)) where many hardware nodes work together and are managed via management and orchestration (MANO) **12100**, which, among others, oversees lifecycle management of applications **1220**.

Virtualization of the hardware is in some contexts referred to as network function virtualization (NFV). NFV may be used to consolidate many network equipment types onto industry standard high-volume server hardware, physical switches, and physical storage, which can be located in data centers, and customer premise equipment.

In the context of NFV, virtual machine **1240** may be a software implementation of a physical machine that runs programs as if they were executing on a physical, non-virtualized machine. Each of virtual machines **1240**, and that part of hardware **1230** that executes that virtual machine, be it hardware dedicated to that virtual machine and/or hardware shared by that virtual machine with others of the virtual machines **1240**, forms a separate virtual network elements (VNE).

Still in the context of NFV, Virtual Network Function (VNF) is responsible for handling specific network functions that run in one or more virtual machines **1240** on top of hardware networking infrastructure **1230** and corresponds to application **1220** in FIG. **12**.

In some embodiments, one or more radio units **12200** that each include one or more transmitters **12220** and one or more receivers **12210** may be coupled to one or more antennas **12225**. Radio units **12200** may communicate directly with hardware nodes **1230** via one or more appropriate network interfaces and may be used in combination with the virtual components to provide a virtual node with radio capabilities, such as a radio access node or a base station.

In some embodiments, some signaling can be affected with the use of control system **12230** which may alternatively be used for communication between the hardware nodes **1230** and radio units **12200**.

With reference to FIG. **13**, in accordance with an embodiment, a communication system includes telecommunication network **1310**, such as a 3GPP-type cellular network, which comprises access network **1311**, such as a radio access network, and core network **1314**. Access network **1311** comprises a plurality of base stations **1312***a*, **1312***b*, **1312***c*, such as NBs, eNBs, gNBs or other types of wireless access points, each defining a corresponding coverage area **1313***a*, **1313***b*, **1313***c*. Each base station **1312***a*, **1312***b*, **1312***c* is connectable to core network **1314** over a wired or wireless connection **1315**. A first UE **1391** located in coverage area **1313***c* is configured to wirelessly connect to, or be paged by, the corresponding base station **1312***c*. A second UE **1392** in coverage area **1313***a* is wirelessly connectable to the corresponding base station **1312***a*. While a plurality of UEs **1391**, **1392** are illustrated in this example, the disclosed embodiments are equally applicable to a situation where a sole UE is in the coverage area or where a sole UE is connecting to the corresponding base station **1312**.

Telecommunication network **1310** is itself connected to host computer **1330**, which may be embodied in the hardware and/or software of a standalone server, a cloud-implemented server, a distributed server or as processing resources in a server farm. Host computer **1330** may be under the ownership or control of a service provider, or may be operated by the service provider or on behalf of the service provider. Connections **1316** and **1322** between telecommunication network **1310** and host computer **1330** may extend directly from core network **1314** to host computer **1330** or may go via an optional intermediate network **1320**. Intermediate network **1320** may be one of, or a combination of more than one of, a public, private or hosted network; intermediate network **1320**, if any, may be a backbone network or the Internet; in particular, intermediate network **1320** may comprise two or more sub-networks (not shown).

The communication system of FIG. **13** as a whole enables connectivity between the connected UEs **1391**, **1392** and host computer **1330**. The connectivity may be described as an over-the-top (OTT) connection **1350**. Host computer **1330** and the connected UEs **1391**, **1392** are configured to communicate data and/or signaling via OTT connection **1350**, using access network **1311**, core network **1314**, any intermediate network **1320** and possible further infrastructure (not shown) as intermediaries. OTT connection **1350** may be transparent in the sense that the participating communication devices through which OTT connection **1350** passes are unaware of routing of uplink and downlink communications. For example, base station **1312** may not or need not be informed about the past routing of an incoming downlink communication with data originating from host computer **1330** to be forwarded (e.g., handed over) to a connected UE **1391**. Similarly, base station **1312** need not be aware of the future routing of an outgoing uplink communication originating from the UE **1391** towards the host computer **1330**.

Example implementations, in accordance with an embodiment, of the UE, base station and host computer discussed in the preceding paragraphs will now be described with reference to FIG. **14**. In communication system **1400**, host computer **1410** comprises hardware **1415** including communication interface **1416** configured to set up and maintain a wired or wireless connection with an interface of a different communication device of communication system **1400**. Host computer **1410** further comprises processing circuitry **1418**, which may have storage and/or processing capabilities. In particular, processing circuitry **1418** may comprise one or more programmable processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. Host computer **1410** further comprises software **1411**, which is stored in or accessible by host computer **1410** and executable by processing circuitry **1418**. Software **1411** includes host application **1412**. Host application **1412** may be operable to provide a service to a remote user, such as UE **1430** connecting via OTT connection **1450** terminating at UE **1430** and host computer **1410**. In providing the service to the remote user, host application **1412** may provide user data which is transmitted using OTT connection **1450**.

Communication system **1400** further includes base station **1420** provided in a telecommunication system and comprising hardware **1425** enabling it to communicate with host computer **1410** and with UE **1430**. Hardware **1425** may include communication interface **1426** for setting up and maintaining a wired or wireless connection with an interface of a different communication device of communication system **1400**, as well as radio interface **1427** for setting up and maintaining at least wireless connection **1470** with UE **1430** located in a coverage area (not shown in FIG. **14**) served by base station **1420**. Communication interface **1426** may be configured to facilitate connection **1460** to host computer **1410**. Connection **1460** may be direct, or it may pass through a core network (not shown in FIG. **14**) of the telecommunication system and/or through one or more intermediate networks outside the telecommunication system. In the embodiment shown, hardware **1425** of base station **1420** further includes processing circuitry **1428**, which may comprise one or more programmable processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. Base station **1420** further has software **1421** stored internally or accessible via an external connection.

Communication system **1400** further includes UE **1430** already referred to. Its hardware **1435** may include radio interface **1437** configured to set up and maintain wireless connection **1470** with a base station serving a coverage area in which UE **1430** is currently located. Hardware **1435** of UE **1430** further includes processing circuitry **1438**, which may comprise one or more programmable processors, application-specific integrated circuits, field programmable gate arrays or combinations of these (not shown) adapted to execute instructions. UE **1430** further comprises software **1431**, which is stored in or accessible by UE **1430** and executable by processing circuitry **1438**. Software **1431** includes client application **1432**. Client application **1432** may be operable to provide a service to a human or non-human user via UE **1430**, with the support of host computer **1410**. In host computer **1410**, an executing host application **1412** may communicate with the executing client application **1432** via OTT connection **1450** terminating at UE **1430** and host computer **1410**. In providing the service to the user, client application **1432** may receive request data from host application **1412** and provide user data in response to the request data. OTT connection **1450** may transfer both the request data and the user data. Client application **1432** may interact with the user to generate the user data that it provides.

It is noted that host computer **1410**, base station **1420** and UE **1430** illustrated in FIG. **14** may be similar or identical to host computer **1430**, one of base stations **1312***a*, **1312***b*, **1312***c* and one of UEs **1391**, **1392** of FIG. **13**, respectively. This is to say, the inner workings of these entities may be as shown in FIG. **14** and independently, the surrounding network topology may be that of FIG. **13**.

In FIG. **14**, OTT connection **1450** has been drawn abstractly to illustrate the communication between host computer **1410** and UE **1430** via base station **1420**, without explicit reference to any intermediary devices and the precise routing of messages via these devices. Network infrastructure may determine the routing, which it may be configured to hide from UE **1430** or from the service provider operating host computer **1410**, or both. While OTT connection **1450** is active, the network infrastructure may further take decisions by which it dynamically changes the routing (e.g., on the basis of load balancing consideration or reconfiguration of the network).

Wireless connection **1470** between UE **1430** and base station **1420** is in accordance with the teachings of the embodiments described throughout this disclosure. One or more of the various embodiments improve the performance of OTT services provided to UE **1430** using OTT connection **1450**, in which wireless connection **1470** forms the last segment. More precisely, the teachings of these embodiments may improve the data rate and thereby provide benefits such as better responsiveness.

A measurement procedure may be provided for the purpose of monitoring data rate, latency and other factors on which the one or more embodiments improve. There may further be an optional network functionality for reconfiguring OTT connection **1450** between host computer **1410** and UE **1430**, in response to variations in the measurement results. The measurement procedure and/or the network functionality for reconfiguring OTT connection **1450** may be implemented in software **1411** and hardware **1415** of host computer **1410** or in software **1431** and hardware **1435** of UE **1430**, or both. In embodiments, sensors (not shown) may be deployed in or in association with communication devices through which OTT connection **1450** passes; the sensors may participate in the measurement procedure by supplying values of the monitored quantities exemplified above, or supplying values of other physical quantities from which software **1411**, **1431** may compute or estimate the monitored quantities. The reconfiguring of OTT connection **1450** may include message format, retransmission settings, preferred routing etc.; the reconfiguring need not affect base station **1420**, and it may be unknown or imperceptible to base station **1420**. Such procedures and functionalities may be known and practiced in the art. In certain embodiments, measurements may involve proprietary UE signaling facilitating host computer **1410**'s measurements of throughput, propagation times, latency and the like. The measurements may be implemented in that software **1411** and **1431** causes messages to be transmitted, in particular empty or 'dummy' messages, using OTT connection **1450** while it monitors propagation times, errors etc.

FIG. **15** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **13** and **14**. For simplicity of the present disclosure, only drawing references to FIG. **15** will be included in this section. In step **1510**, the host computer provides user data. In substep **1511** (which may be optional) of step **1510**, the host computer provides the user data by executing a host application. In step **1520**, the host computer initiates a transmission carrying the user data to the UE. In step **1530** (which may be optional), the base station transmits to the UE the user data which was carried in the transmission that the host computer initiated, in accordance with the teachings of the embodiments described throughout this disclosure. In step **1540** (which may also be optional), the UE executes a client application associated with the host application executed by the host computer.

FIG. **16** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **13** and **14**. For simplicity of the present disclosure, only drawing references to FIG. **16** will be included in this section. In step **1610** of the method, the host computer provides user data. In an optional substep (not shown) the host computer provides the user data by executing a host application. In step **1620**, the host computer initiates a transmission carrying the user data to the UE. The transmission may pass via the base station, in accordance with the teachings of the embodiments described throughout this disclosure. In step **1630** (which may be optional), the UE receives the user data carried in the transmission.

FIG. **17** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **13** and **14**. For simplicity of the present disclosure, only drawing references to FIG. **17** will be included in this section. In step **1710** (which may be optional), the UE receives input data provided by the host computer. Additionally or alternatively, in step **1720**, the UE provides user data. In substep **1721** (which may be optional) of step **1720**, the UE provides the user data by executing a client application. In substep **1711** (which may be optional) of step **1710**, the UE executes a client application which provides the user data in reaction to the received input data provided by the host computer. In providing the user data, the executed client application may further consider user input received from the user. Regardless of the specific manner in which the user data was provided, the UE initiates, in substep **1730** (which may be optional), transmission of the user data to the host computer. In step **1740** of the method, the host computer receives the user data transmitted from the UE, in accordance with the teachings of the embodiments described throughout this disclosure.

FIG. **18** is a flowchart illustrating a method implemented in a communication system, in accordance with one embodiment. The communication system includes a host computer, a base station and a UE which may be those described with reference to FIGS. **13** and **14**. For simplicity of the present disclosure, only drawing references to FIG. **18** will be included in this section. In step **1810** (which may be optional), in accordance with the teachings of the embodiments described throughout this disclosure, the base station receives user data from the UE. In step **1820** (which may be optional), the base station initiates transmission of the received user data to the host computer. In step **1830** (which may be optional), the host computer receives the user data carried in the transmission initiated by the base station.

Any appropriate steps, methods, features, functions, or benefits disclosed herein may be performed through one or more functional units or modules of one or more virtual apparatuses. Each virtual apparatus may comprise a number of these functional units. These functional units may be implemented via processing circuitry, which may include one or more microprocessor or microcontrollers, as well as other digital hardware, which may include Digital Signal Processors (DSPs), special-purpose digital logic, and the like. The processing circuitry may be configured to execute program code stored in memory, which may include one or several types of memory such as Read-Only Memory (ROM), Random-Access Memory (RAM), cache memory, flash memory devices, optical storage devices, etc. Program code stored in memory includes program instructions for executing one or more telecommunications and/or data communications protocols as well as instructions for carrying out one or more of the techniques described herein. In some implementations, the processing circuitry may be used to cause the respective functional unit to perform corresponding functions according one or more embodiments of the present disclosure.

The term unit may have conventional meaning in the field of electronics, electrical devices and/or electronic devices and may include, for example, electrical and/or electronic circuitry, devices, modules, processors, memories, logic solid state and/or discrete devices, computer programs or instructions for carrying out respective tasks, procedures, computations, outputs, and/or displaying functions, and so on, as such as those that are described herein.

Numbered Embodiments in Particular Related to FIGS. **10-18**

1. A first APU configured to communicate with a User Equipment (UE), the first APU comprising a radio interface and processing circuitry configured to:
   obtain channel estimates for channels to said served UEs;
   determine a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals;
   determine effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and
   transmit the effective channels from said served UEs to at least one subsequent second APU.
2. The first APU according to embodiment 1, wherein the first APU further is configured to:
   receive data signals from said served UEs; and
   determine improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs.
3. The first APU according to embodiment 2, wherein the first APU further is configured to:
   transmit the determined improved estimates of the received data signals to at least one subsequent second APU.
4. The first APU according to any of embodiments 1 to 3, wherein the at least one subsequent second APU is located closer to the CPU than the first APU.
5. The first BS according to any of embodiments 1 to 4, wherein the obtained channel estimates are Channel State Information, CSI, obtained from reference pilot signals transmitted by said served UEs.
6. The first BS according to any of embodiments 1 to 5, wherein the receive combining filter is generated by a method selected from the group comprised of: Maximum-Ratio Combining, MRC, Zero-Forcing, ZF, combining and Minimum-Mean Squared Error, MMSE, combining.
7. The first BS according to any of embodiments 1 to 6, wherein each of the at least two APUs (**300**, **400**) in the radio stripe system is equipped with one antenna.
8. A communication system including a host computer comprising:
   processing circuitry configured to provide user data; and
   a communication interface configured to forward the user data to a cellular network for transmission to a User Equipment (UE),
   wherein the cellular network comprises a first APU having a radio interface and processing circuitry, the first APU's processing circuitry configured to obtain channel estimates for channels to said served UEs; determine a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals; determine effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and transmit the effective channels from said served UEs to at least one subsequent second APU.
9. The communication system of embodiment 8, further including the first APU.
10. The communication system of embodiment 9, further including the UE, wherein the UE is configured to communicate with the first APU.
11. The communication system of embodiment 10, wherein:
   the processing circuitry of the host computer is configured to execute a host application, thereby providing the user data; and

the UE comprises processing circuitry configured to execute a client application associated with the host application.

12. A method implemented in a first APU, comprising
obtaining channel estimates for channels to said served UEs;
determining a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals;
determining effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and
transmitting the effective channels from said served UEs to at least one subsequent second APU.

13. A method implemented in a communication system including a host computer, a first APU and a User Equipment (UE), the method comprising:
at the host computer, providing user data; and
at the host computer, initiating a transmission carrying the user data to the UE via a cellular network comprising the first APU, wherein the first APU
obtaining channel estimates for channels to said served UEs;
determining a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals;
determining effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and
transmitting the effective channels from said served UEs to at least one subsequent second APU.

14. The method of embodiment 13, further comprising:
at the first APU, transmitting the user data.

15. The method of embodiment 14, wherein the user data is provided at the host computer by executing a host application, the method further comprising:
at the UE, executing a client application associated with the host application.

16. A User Equipment (UE) configured to communicate with a first APU, the UE comprising a radio interface and processing circuitry configured to transmit and receive data to and from the first APU.

17. A communication system including a host computer comprising:
processing circuitry configured to provide user data; and
a communication interface configured to forward user data to a cellular network for transmission to a User Equipment (UE),
wherein the UE comprises a radio interface and processing circuitry, the UE's processing circuitry configured to transmit and receive data to and from a first APU.

18. The communication system of embodiment 16, further including the UE.

19. The communication system of embodiment 17, wherein the cellular network further includes a first APU configured to communicate with the UE.

20. The communication system of embodiment 18 or 19, wherein:
the processing circuitry of the host computer is configured to execute a host application, thereby providing the user data; and
the UE's processing circuitry is configured to execute a client application associated with the host application.

21. A method implemented in a communication system including a host computer, a first APU and a User Equipment (UE), the method comprising:
at the host computer, providing user data; and
at the host computer, initiating a transmission carrying the user data to the UE via a cellular network comprising the first APU, wherein the UE transmits and receives to and from the first APU.

22. The method of embodiment 21, further comprising:
at the UE, receiving the user data from the first APU.

23. A communication system including a host computer comprising:
a communication interface configured to receive user data originating from a transmission from a User Equipment (UE) to a first APU,
wherein the UE comprises a radio interface and processing circuitry, the UE's processing circuitry configured to transmit and receive data to and from the first APU.

24. The communication system of embodiment 23, further including the UE.

25. The communication system of embodiment 24, further including the first APU, wherein the first APU comprises a radio interface configured to communicate with the UE and a communication interface configured to forward to the host computer the user data carried by a transmission from the UE to the first APU.

26. The communication system of embodiment 24 or 25, wherein:
the processing circuitry of the host computer is configured to execute a host application;
and the UE's processing circuitry is configured to execute a client application associated with the host application, thereby providing the user data.

27. The communication system of embodiment 24 or 25, wherein:
the processing circuitry of the host computer is configured to execute a host application, thereby providing request data; and
the UE's processing circuitry is configured to execute a client application associated with the host application, thereby providing the user data in response to the request data.

28. A method implemented in a User Equipment (UE), comprising transmitting and receiving data to and from a first APU.

29. The method of embodiment 28, further comprising:
providing user data; and
forwarding the user data to a host computer via the transmission to the first APU.

30. A method implemented in a communication system including a host computer, a first APU and a User Equipment (UE), the method comprising:
at the host computer, receiving user data transmitted to the first APU from the UE,
wherein the UE transmitting and receiving data to and from the first APU.

31. The method of embodiment 30, further comprising:
at the UE, providing the user data to the first APU.

32. The method of embodiment 31, further comprising:
at the UE, executing a client application, thereby providing the user data to be transmitted; and
at the host computer, executing a host application associated with the client application.
33. The method of embodiment 32, further comprising:
at the UE, executing a client application; and
at the UE, receiving input data to the client application, the input data being provided at the host computer by executing a host application associated with the client application, wherein the user data to be transmitted is provided by the client application in response to the input data.
34. A communication system including a host computer comprising a communication interface configured to receive user data originating from a transmission from a User Equipment (UE) to a first APU, wherein the first APU comprises a radio interface and processing circuitry, the first APU's processing circuitry configured to obtain channel estimates for channels to said served UEs; determine a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals; determine effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and transmitting the effective channels from said served UEs to at least one subsequent second APU.
35. The communication system of embodiment 34, further including the first APU.
36. The communication system of embodiment 35, further including the UE, wherein the UE is configured to communicate with the first APU.
37. The communication system of embodiment 36, wherein:
the processing circuitry of the host computer is configured to execute a host application;
the UE is configured to execute a client application associated with the host application,
thereby providing the user data to be received by the host computer.
38. A method implemented in a communication system including a host computer, a first APU and a User Equipment (UE), the method comprising:
at the host computer, receiving, from the first APU, user data originating from a transmission which the first APU has received from the UE, wherein the UE transmits and receives data to and from the first APU.
39. The method of embodiment 38, further comprising:
at the first APU, receiving the user data from the UE.
40. The method of embodiment 39, further comprising:
at the first APU, initiating a transmission of the received user data to the host computer.
41. A second APU configured to communicate with a User Equipment (UE), the second APU comprising a radio interface and processing circuitry configured to:
obtain channel estimates for channels to said served UEs;
receive, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU; and
determine a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the receive combining filter is going to be applied to received data signals.
42. The second APU according to embodiment 41, wherein the second APU further is configured to:
determine effective channels from said served UEs based on the obtained channel estimates, the determined receive combining filter and the received effective channels from said at least one preceding first APU, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs.
43. The second APU according to embodiment 42, wherein the second APU further is configured to:
receive data signals from said served UEs;
receive, from said at least one preceding first APU, improved estimates of data signals received by the preceding first APU;
determine augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU; and
determine improved estimates of the received data signals by applying the determined receive combining filter to the augmented received data signals from said served UEs.
44. The second APU according to embodiment 43, wherein the second APU further is configured to:
transmit the determined effective channels from said served UEs and the improved estimates of the received data signals to at least one subsequent third APU, wherein the at least one subsequent third APU is located closer to the CPU than the second APU.
45. The second APU according to embodiment 43, wherein the second APU further is configured to:
transmit the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU.
46. The second APU according to any of embodiments 41 to 45, wherein the at least one preceding first APU is located further away from the CPU than the second APU.
47. The second APU according to any of embodiments 41 to 46, wherein the obtained channel estimates are Channel State Information, CSI, obtained from reference pilot signals transmitted by said served UEs.
48. The second APU according to any of embodiments 41 to 47, wherein the receive combining filter is generated by a method selected from the group comprised of: Maximum-Ratio Combining, MRC, Zero-Forcing, ZF, combining and Minimum-Mean Squared Error, MMSE, combining.
49. The second APU according to any of embodiments 41 to 48, wherein each of the at least two APUs (**300**, **400**) in the radio stripe system is equipped with one antenna.
50. A communication system including a host computer comprising:
processing circuitry configured to provide user data; and
a communication interface configured to forward the user data to a cellular network for transmission to a User Equipment (UE), wherein the cellular network comprises a second APU having a radio interface and processing circuitry, the APU's processing circuitry configured to obtain channel estimates for channels to said served UEs; receive, from at least one preceding first APU, effective channels from said served

UEs to said preceding first APU; and determine a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the receive combining filter is going to be applied to received data signals.

51. The communication system of embodiment 50, further including the second APU.

52. The communication system of embodiment 51, further including the UE, wherein the UE is configured to communicate with the second APU.

53. The communication system of embodiment 52, wherein:
the processing circuitry of the host computer is configured to execute a host application, thereby providing the user data; and
the UE comprises processing circuitry configured to execute a client application associated with the host application.

54. A method implemented in a second APU, comprising obtaining channel estimates for channels to said served UEs;
receiving, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU; and
determining a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the receive combining filter is going to be applied to received data signals.

55. A method implemented in a communication system including a host computer, a second APU and a User Equipment (UE), the method comprising:
at the host computer, providing user data; and
at the host computer, initiating a transmission carrying the user data to the UE via a cellular network comprising the second APU, wherein the second APU
obtaining channel estimates for channels to said served UEs;
receiving, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU; and
determining a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the receive combining filter is going to be applied to received data signals.

56. The method of embodiment 54, further comprising:
at the second APU, transmitting the user data.

57. The method of embodiment 55, wherein the user data is provided at the host computer by executing a host application, the method further comprising:
at the UE, executing a client application associated with the host application.

58. A User Equipment (UE) configured to communicate with a second APU, the UE comprising a radio interface and processing circuitry configured to transmit and receive data to and from the second APU.

59. A communication system including a host computer comprising:
processing circuitry configured to provide user data; and
a communication interface configured to forward user data to a cellular network for transmission to a User Equipment (UE),
wherein the UE comprises a radio interface and processing circuitry, the UE's processing circuitry configured to transmit and receive data to and from a second APU.

60. The communication system of embodiment 59, further including the UE.

61. The communication system of embodiment 59, wherein the cellular network further includes a second APU configured to communicate with the UE.

62. The communication system of embodiment 60 or 61, wherein:
the processing circuitry of the host computer is configured to execute a host application, thereby providing the user data; and
the UE's processing circuitry is configured to execute a client application associated with the host application.

63. A method implemented in a communication system including a host computer, a second APU and a User Equipment (UE), the method comprising:
at the host computer, providing user data; and
at the host computer, initiating a transmission carrying the user data to the UE via a cellular network comprising second APU, wherein the UE transmits and receives to and from the second APU.

64. The method of embodiment 63, further comprising:
at the UE, receiving the user data from the second APU.

65. A communication system including a host computer comprising:
a communication interface configured to receive user data originating from a
transmission from a User Equipment (UE) to a second APU,
wherein the UE comprises a radio interface and processing circuitry, the UE's processing circuitry configured to transmit and receive data to and from the second APU.

66. The communication system of embodiment 65, further including the UE.

67. The communication system of embodiment 66, further including the second APU, wherein the second APU comprises a radio interface configured to communicate with the UE and a communication interface configured to forward to the host computer the user data carried by a transmission from the UE to the second APU.

68. The communication system of embodiment 66 or 67, wherein:
the processing circuitry of the host computer is configured to execute a host application;
and the UE's processing circuitry is configured to execute a client application associated with the host application, thereby providing the user data.

69. The communication system of embodiment 66 or 67, wherein:
the processing circuitry of the host computer is configured to execute a host application, thereby providing request data; and
the UE's processing circuitry is configured to execute a client application associated with the host application, thereby providing the user data in response to the request data.

70. A method implemented in a User Equipment (UE), comprising transmitting and receiving data to and from a second APU.

71. The method of embodiment 70, further comprising:
providing user data; and

forwarding the user data to a host computer via the transmission to the second APU.

72. A method implemented in a communication system including a host computer, a second APU and a User Equipment (UE), the method comprising:
at the host computer, receiving user data transmitted to the second APU from the UE, wherein the UE transmitting and receiving data to and from the second APU.

73. The method of embodiment 72, further comprising:
at the UE, providing the user data to the second APU.

74. The method of embodiment 73, further comprising:
at the UE, executing a client application, thereby providing the user data to be transmitted; and
at the host computer, executing a host application associated with the client application.

75. The method of embodiment 74, further comprising:
at the UE, executing a client application; and
at the UE, receiving input data to the client application, the input data being provided at the host computer by executing a host application associated with the client application,
wherein the user data to be transmitted is provided by the client application in response to the input data.

76. A communication system including a host computer comprising a communication interface configured to receive user data originating from a transmission from a User Equipment (UE) to a second APU, wherein the second APU comprises a radio interface and processing circuitry, the second APU's processing circuitry configured to obtain channel estimates for channels to said served UEs; receive, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU; and determine a receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the receive combining filter is going to be applied to received data signals.

77. The communication system of embodiment 76, further including the second APU.

78. The communication system of embodiment 77, further including the UE, wherein the UE is configured to communicate with the second APU.

79. The communication system of embodiment 78, wherein:
the processing circuitry of the host computer is configured to execute a host application;
the UE is configured to execute a client application associated with the host application, thereby providing the user data to be received by the host computer.

80. A method implemented in a communication system including a host computer, a second APU and a User Equipment (UE), the method comprising:
at the host computer, receiving, from the second APU, user data originating from a transmission which the second APU has received from the UE, wherein the UE transmits and receives data to and from the second APU.

81. The method of embodiment 80, further comprising:
at the second APU, receiving the user data from the UE.

82. The method of embodiment 81, further comprising:
at the second APU, initiating a transmission of the received user data to the host computer.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" "comprising," "includes" and/or "including" when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Modifications and other variants of the described embodiments will come to mind to one skilled in the art having benefit of the teachings presented in the foregoing description and associated drawings. Therefore, it is to be understood that the embodiments are not limited to the specific example embodiments described in this disclosure and that modifications and other variants are intended to be included within the scope of this disclosure. Furthermore, although specific terms may be employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation. Therefore, a person skilled in the art would recognize numerous variations to the described embodiments that would still fall within the scope of the appended claims. As used herein, the terms "comprise/comprises" or "include/includes" do not exclude the presence of other elements or steps. Furthermore, although individual features may be included in different claims, these may possibly advantageously be combined, and the inclusion of different claims does not imply that a combination of features is not feasible and/or advantageous. In addition, singular references do not exclude a plurality.

The invention claimed is:

1. A method, performed by a first Antenna Processing Unit (APU) for sequential receive combining in a radio stripe system, wherein the radio stripe system comprises at least two APUs and a Central Processing Unit (CPU) the at least two APUs being connected in series to the CPU, wherein the radio stripe system serves at least two User Equipment (UEs) the method comprising:
obtaining channel estimates for channels to said served UEs;
determining a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals;
determining effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and
transmitting the effective channels from said served UEs to at least one subsequent second APU.

2. The method according to claim **1**, wherein the method further comprises:
receiving data signals from said served UEs; and
determining improved estimates of the received data signals by applying the determined receive combining filter to the received data signals from said served UEs.

3. The method according to claim **2**, wherein the method further comprises:

transmitting the determined improved estimates of the received data signals to at least one subsequent second APU.

4. The method according to claim **1**, wherein the at least one subsequent second APU is located closer to the CPU than the first APU.

5. The method according to claim **1**, wherein the obtained channel estimates are Channel State Information (CSI) obtained from reference pilot signals transmitted by said served UEs.

6. The method according to claim **1**, wherein the receive combining filter is generated by a method selected from the group comprised of: Maximum-Ratio Combining (MRC) Zero-Forcing (ZF) combining and Minimum-Mean Squared Error (MMSE) combining.

7. The method according to claim **1**, wherein each of the at least two APUs in the radio stripe system is equipped with one antenna.

8. A method, performed by a second Antenna Processing Unit (APU) for sequential receive combining in a radio stripe system, wherein the radio stripe system comprises at least two APUs and a Central Processing Unit (CPU) the at least two APUs being connected in series from the CPU, wherein the radio stripe system serves at least two User Equipment (UEs), the method comprising:

obtaining channel estimates for channels to said served UEs;

receiving, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU, the effective channels representing effective channels created after the at least one preceding first APU applies a first receive combining filter to each channel for said served UEs; and

determining a second receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the second receive combining filter is going to be applied to received data signals.

9. The method according to claim **8**, wherein the method further comprises:

determining effective channels from said served UEs based on the obtained channel estimates, the determined second receive combining filter and the received effective channels from said at least one preceding first APU, wherein the effective channels represent the effective channel created after the second receive combining filter being applied to each channel for said served UEs.

10. The method according to claim **9**, wherein the method further comprises:

receiving data signals from said served UEs;

receiving, from said at least one preceding first APU, improved estimates of data signals received by the preceding first APU;

determining augmented received signals based on the received data signals and the received improved estimates of the data signals received by the preceding first APU; and

determining improved estimates of the received data signals by applying the determined second receive combining filter to the augmented received data signals from said served UEs.

11. The method according to claim **10**, wherein the method further comprises:

transmitting the determined effective channels from said served UEs and the improved estimates of the received data signals to at least one subsequent third APU, wherein the at least one subsequent third APU is located closer to the CPU than the second APU.

12. The method according to claim **10**, wherein the method further comprises:

transmitting the determined effective channels from said served UEs and the improved estimates of the received data signals to the CPU.

13. The method according to claim **8**, wherein the at least one preceding first APU is located further away from the CPU than the second APU.

14. The method according to claim **8**, wherein the obtained channel estimates are Channel State Information (CSI) obtained from reference pilot signals transmitted by said served UEs.

15. The method according to claim **8**, wherein the second receive combining filter is generated by a method selected from the group comprised of: Maximum-Ratio Combining (MRC) Zero-Forcing (ZF) combining and Minimum-Mean Squared Error (MMSE) combining.

16. A first Antenna Processing Unit (APU) for sequential receive combining in a radio stripe system, wherein the radio stripe system comprises at least two APUs and a Central Processing Unit (CPU), the at least two APUs being connected in series to the CPU, wherein the radio stripe system serves at least two User Equipment (UEs), the first APU comprising:

a processing circuitry; and

a memory circuitry storing computer program code which, when run in the processing circuitry, causes the first APU to:

obtain channel estimates for channels to said served UEs;

determine a receive combining filter based on the obtained channel estimates, wherein the receive combining filter is going to be applied to received data signals;

determine effective channels from said served UEs based on the obtained channel estimates and the determined receive combining filter, wherein the effective channels represent the effective channel created after the receive combining filter being applied to each channel for said served UEs; and

transmit the effective channels from said served UEs to at least one subsequent second APU.

17. A second Antenna Processing Unit (APU) for sequential receive combining in a radio stripe system, wherein the radio stripe system comprises at least two APUs and a Central Processing Unit (CPU), the at least two APUs being connected in series to the CPU, wherein the radio stripe system serves at least two User Equipment (UEs), the second APU comprising:

a processing circuitry; and

a memory circuitry storing computer program code which, when run in the processing circuitry, causes the second APU to:

obtain channel estimates for channels to said served UEs;

receive, from at least one preceding first APU, effective channels from said served UEs to said preceding first APU, the effective channels representing effective channels created after the at least one preceding first APU applies a first receive combining filter to each channel for said served UEs; and

determine a second receive combining filter based on the obtained channel estimates and the received effective channels from said at least one preceding first APU, wherein the second receive combining filter is going to be applied to received data signals.

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