US 20250266864A1

(19) **United States**

(12) **Patent Application Publication**

**FERRANTE et al.**

(10) **Pub. No.: US 2025/0266864 A1**

(43) **Pub. Date: Aug. 21, 2025**

(54) **CONFIGURING A RECONFIGURABLE INTELLIGENT SURFACE (RIS)**

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(21) Appl. No.: **18/706,168**

(22) PCT Filed: **Nov. 1, 2021**

(86) PCT No.: **PCT/SE2021/051090**

§ 371 (c)(1),
(2) Date: **Apr. 30, 2024**

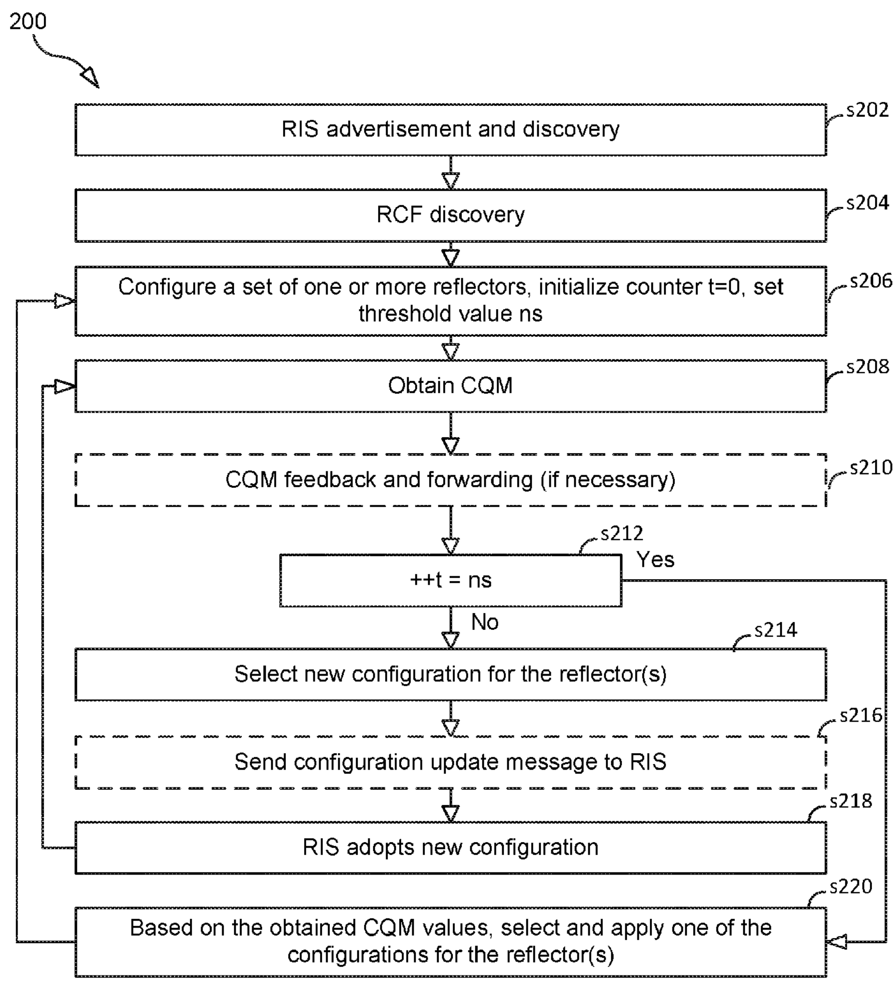
**Publication Classification**

(51) **Int. Cl.**
***H04B 7/04*** (2017.01)
***H04B 17/309*** (2015.01)

(52) **U.S. Cl.**
CPC ....... ***H04B 7/04013*** (2023.05); ***H04B 17/309*** (2015.01)

(57) **ABSTRACT**

A method (**1100**) for configuring a RIS (**106**), wherein the RIS comprises a plurality of configurable reflectors (**120**). The method includes obtaining (s**1102**) a first set of CQM values (e.g., SNR, RSRP, etc.), wherein the first set of COM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration. The method also includes, based on the obtained first set of CQM values, selecting (s**1104**) a reflector configuration. The method further includes configuring (s**1106**) at least the first particular configurable reflector based on the selected reflector configuration. In one embodiments, the method is performed by the RIS and the step of obtaining the CQM values comprises obtaining the CQM values from a network node. In another embodiment, the method is performed by a network node (**102**, **104**, **190**) and the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.



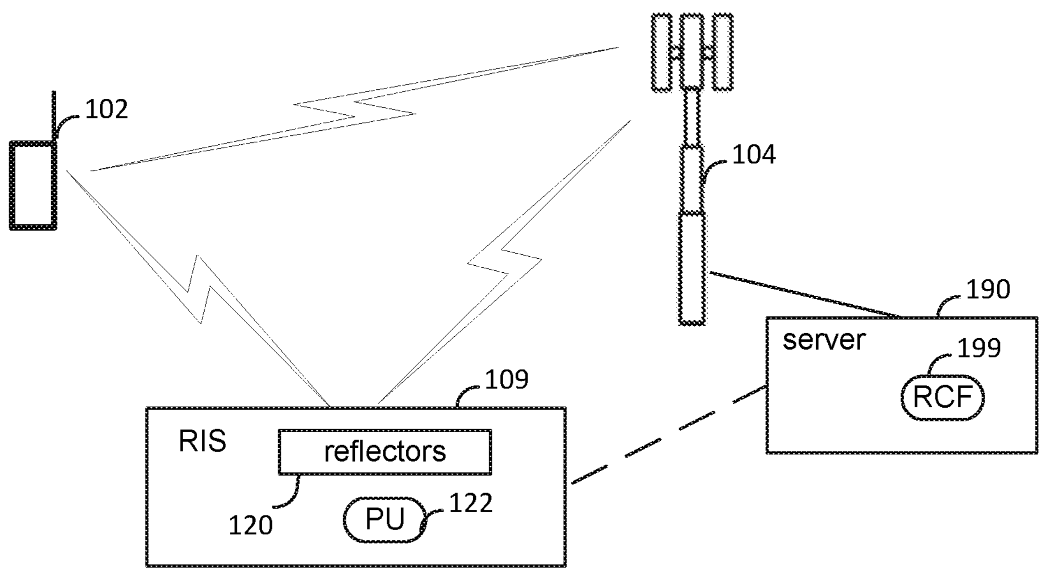



FIG. 1

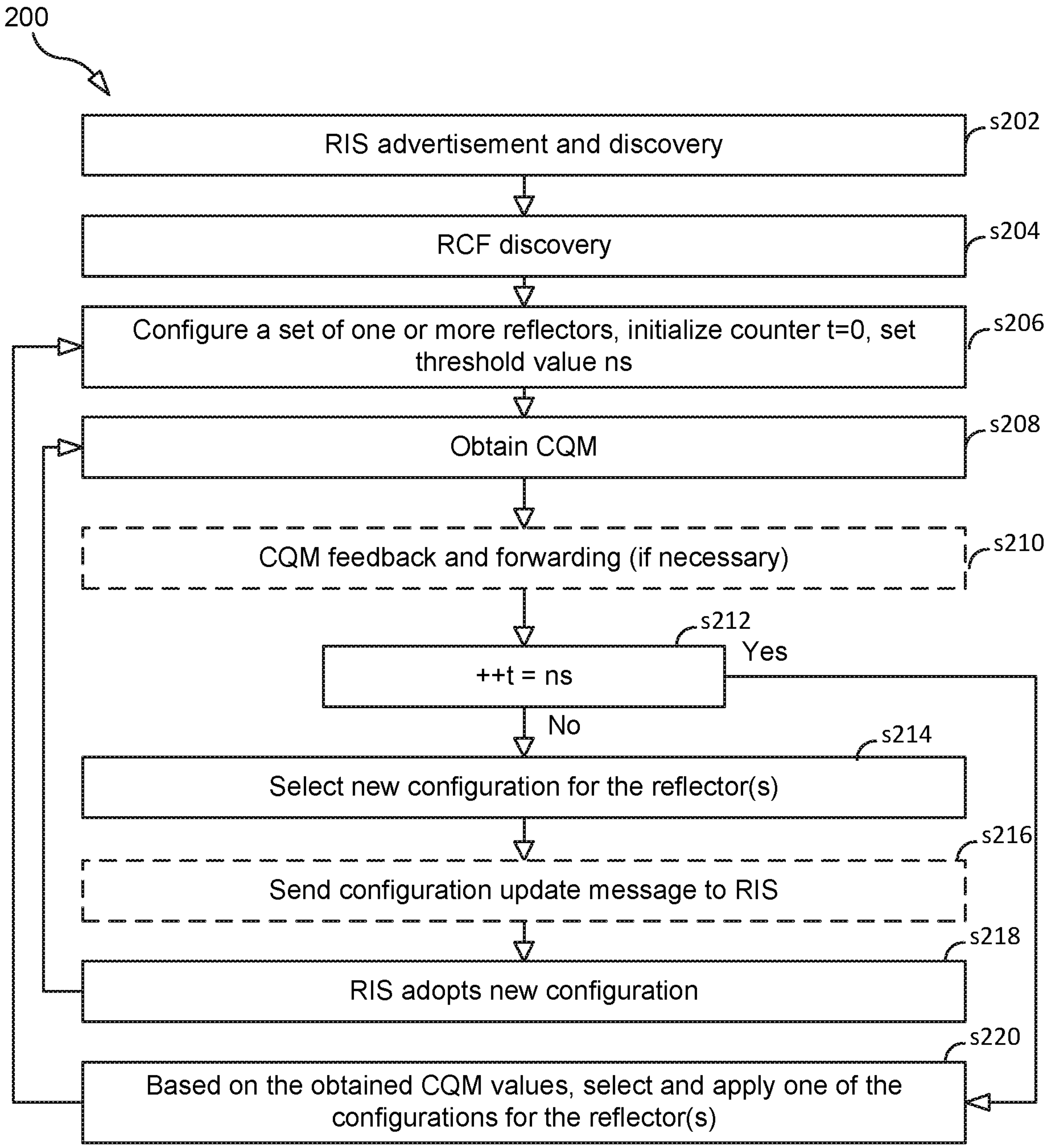

200
RIS advertisement and discovery
s202
RCF discovery
s204
Configure a set of one or more reflectors, initialize counter t=0, set threshold value ns
s206
Obtain CQM
s208
CQM feedback and forwarding (if necessary)
s210
++t = ns
s212
Yes
No
Select new configuration for the reflector(s)
s214
Send configuration update message to RIS
s216
RIS adopts new configuration
s218
Based on the obtained CQM values, select and apply one of the configurations for the reflector(s)
s220

FIG. 2

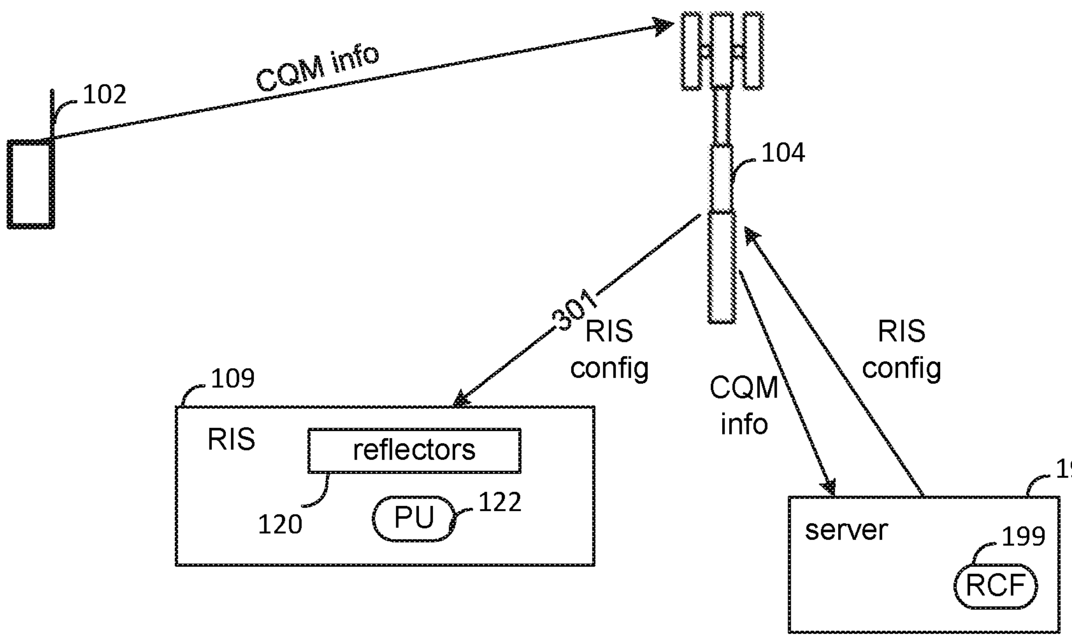

CQM info
102
104
301
RIS
config
CQM
info
RIS
config
109
RIS
reflectors
120
PU
122
190
server
199
RCF

FIG. 3

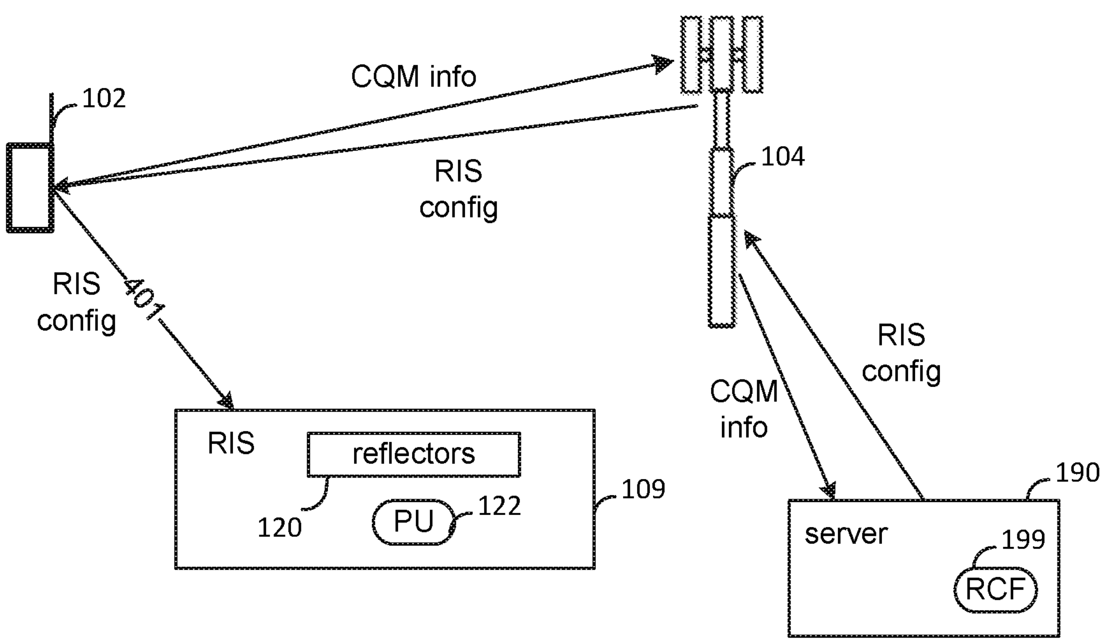

CQM info
102
RIS
config
104
RIS
config
401
RIS
config
CQM
info
RIS
reflectors
109
120
PU
122
190
server
199
RCF

FIG. 4

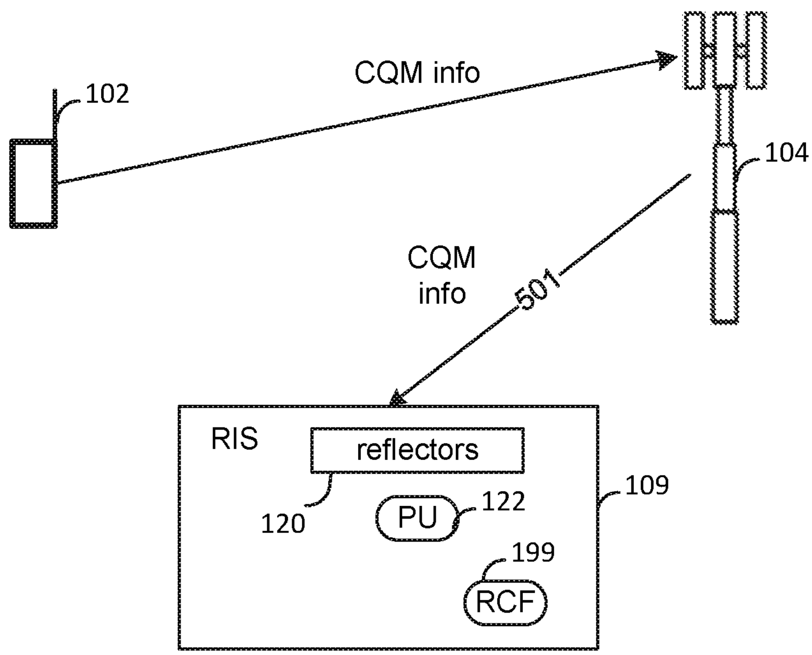

CQM info
102
104
CQM
info
501
RIS
reflectors
120
PU
122
109
199
RCF

FIG. 5

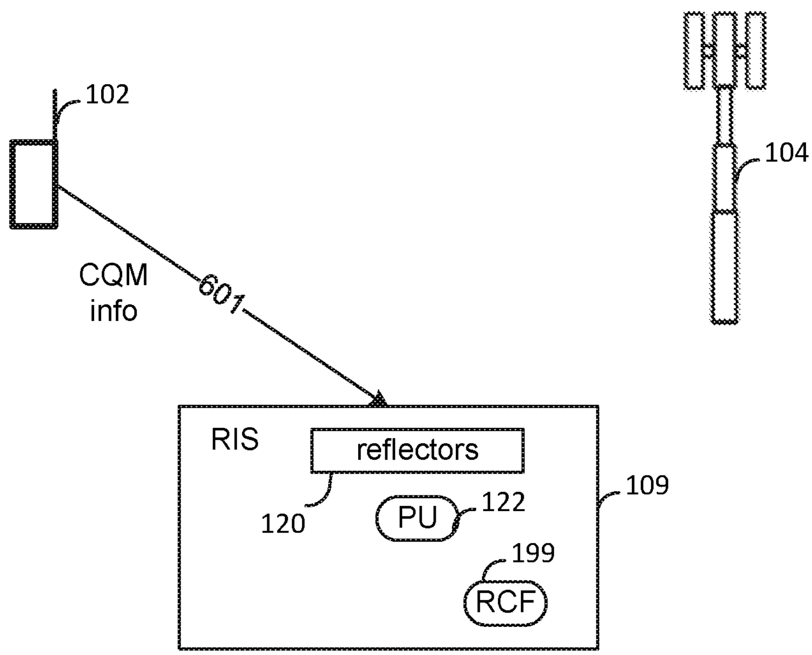



FIG. 6

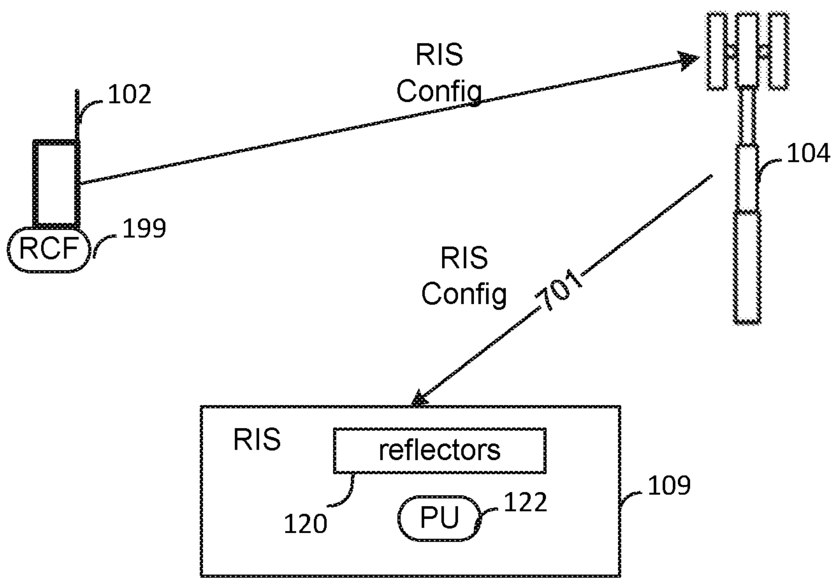

RIS
Config
102
104
RCF
199
RIS
Config
701
RIS
reflectors
120
PU
122
109

FIG. 7

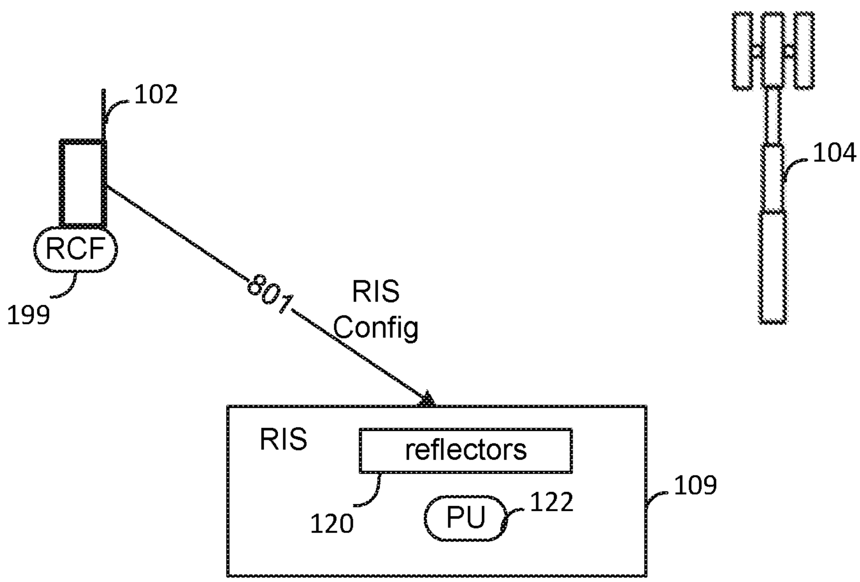



FIG. 8

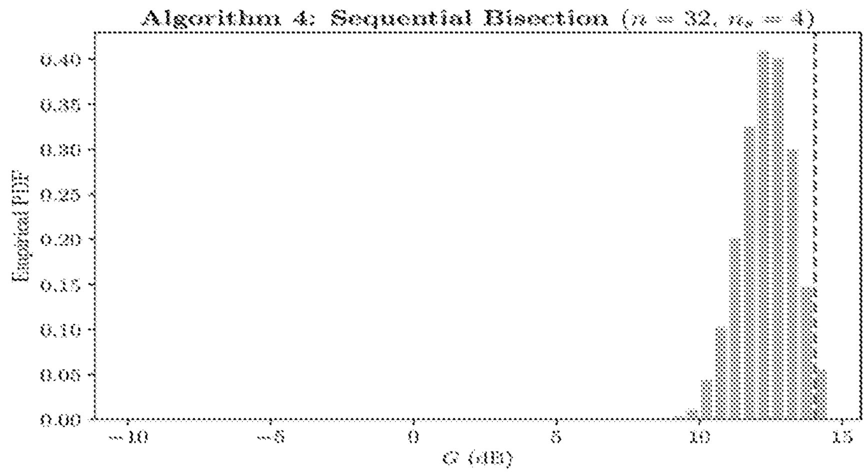



FIG. 9A

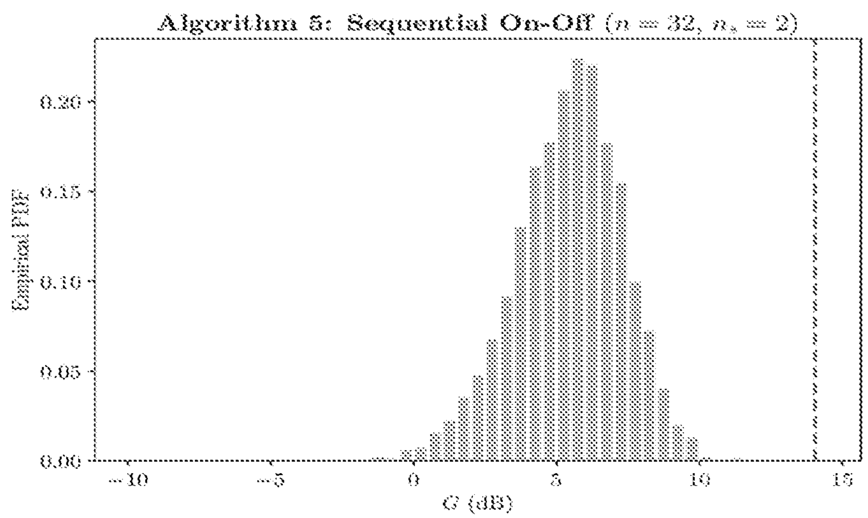



FIG. 9B

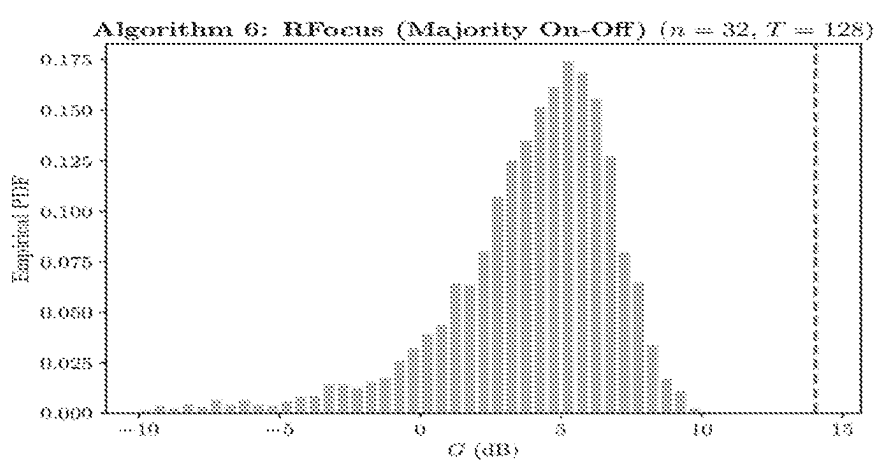



FIG. 9C

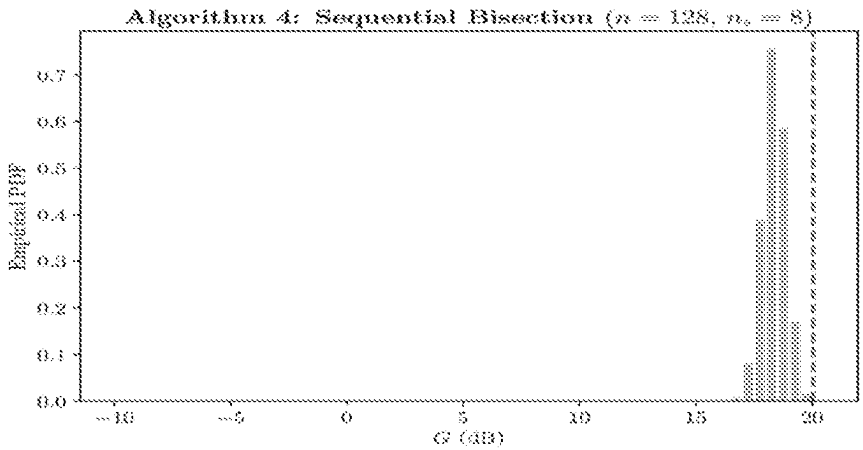



FIG. 10A

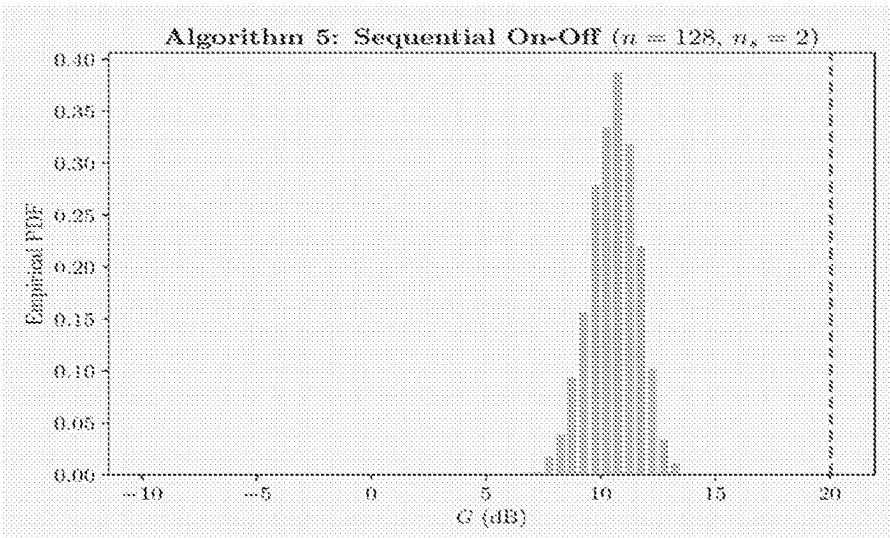



FIG. 10B

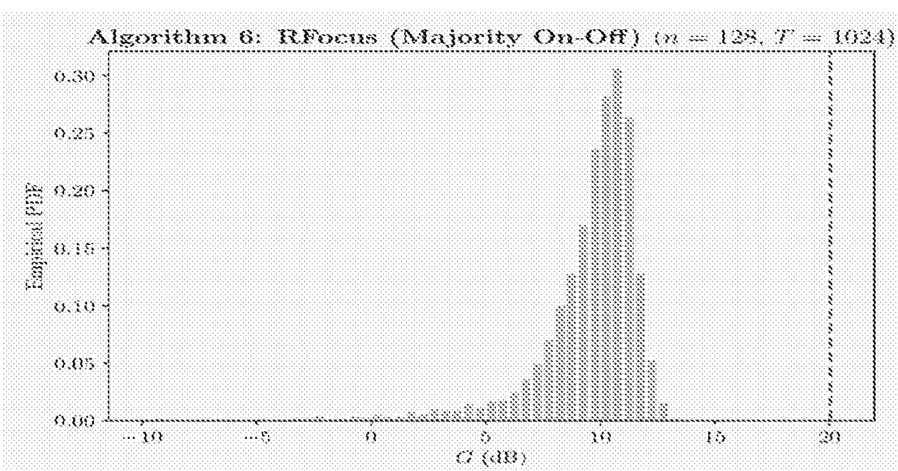



FIG. 10C

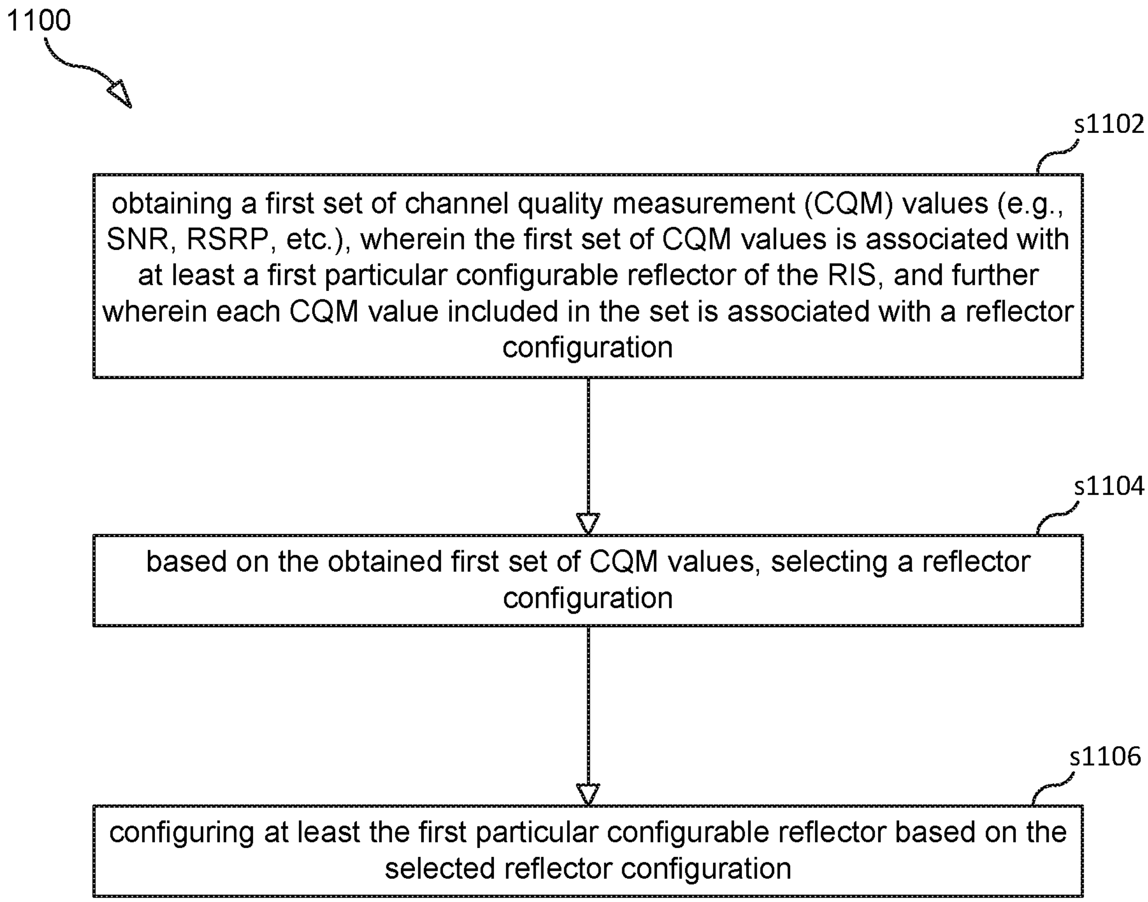

1100
s1102
obtaining a first set of channel quality measurement (CQM) values (e.g., SNR, RSRP, etc.), wherein the first set of CQM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration
s1104
based on the obtained first set of CQM values, selecting a reflector configuration
s1106
configuring at least the first particular configurable reflector based on the selected reflector configuration

FIG. 11

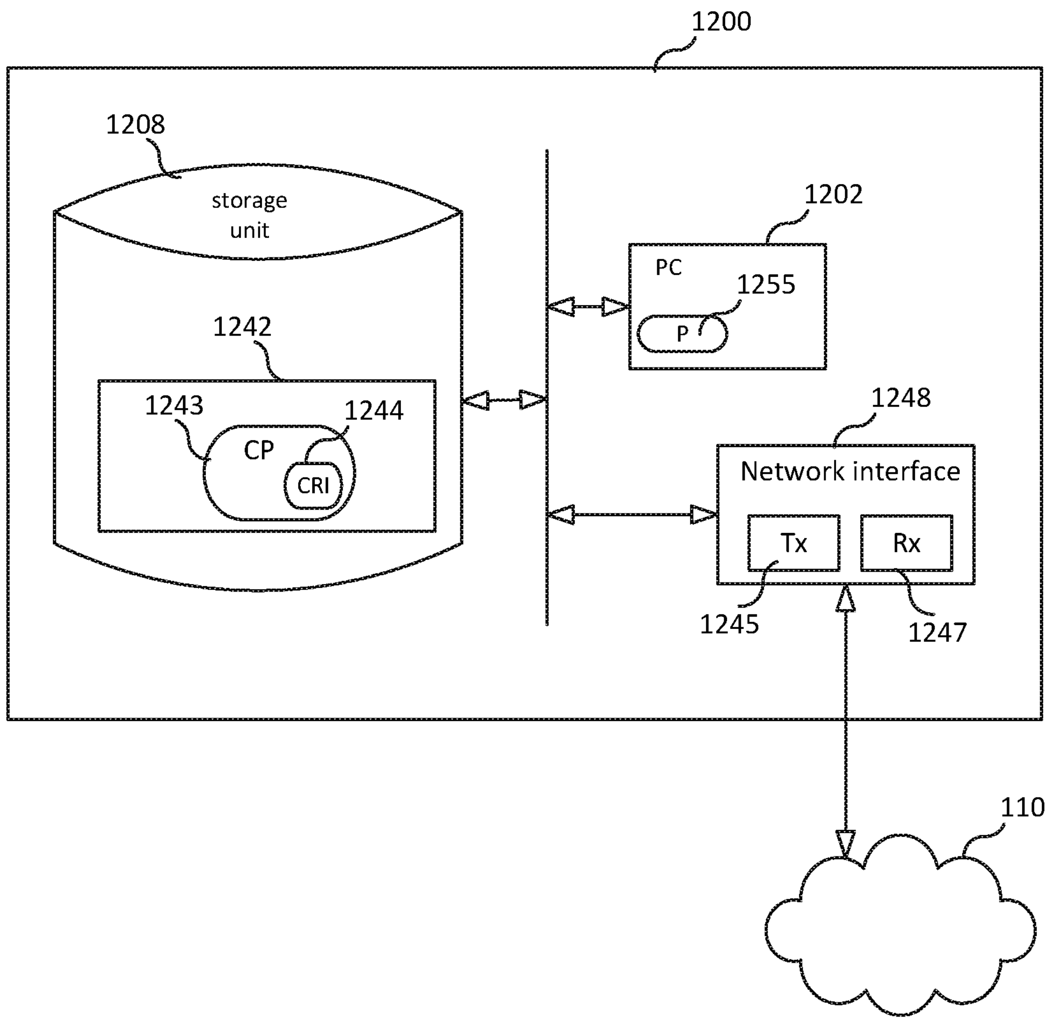

1200
1208
storage unit
1242
1243
1244
CP
CRI
1202
PC
1255
P
1248
Network interface
Tx
Rx
1245
1247
110

FIG. 12

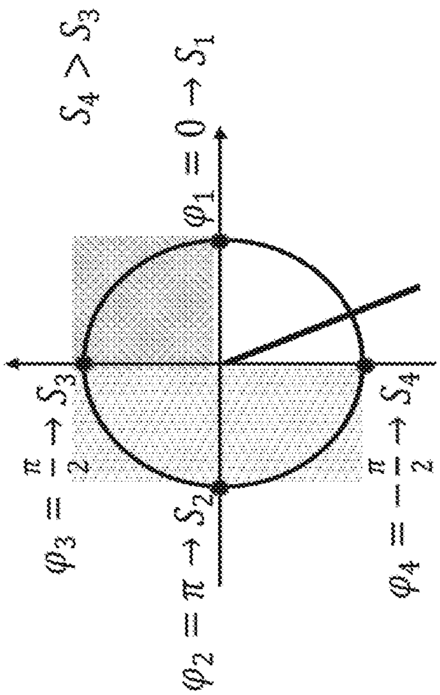



FIG. 13B

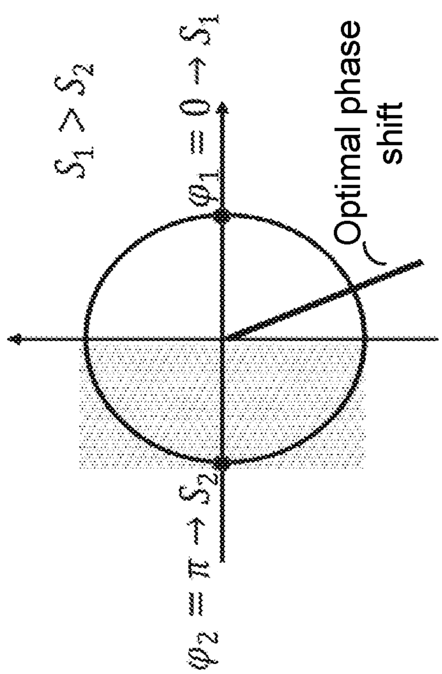



FIG. 13A

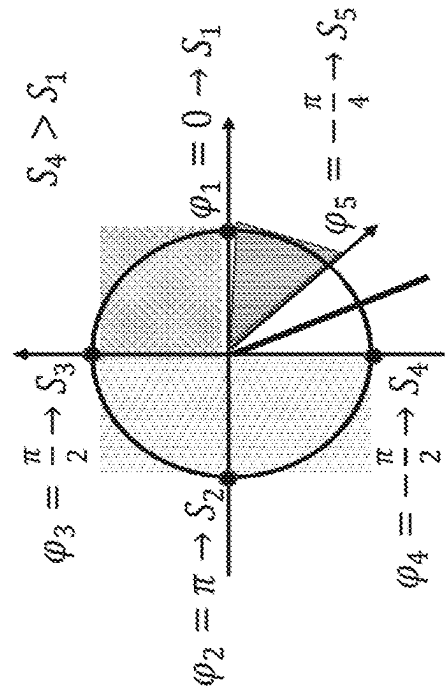



FIG. 13C

# CONFIGURING A RECONFIGURABLE INTELLIGENT SURFACE (RIS)

## TECHNICAL FIELD

**[0001]** Disclosed are embodiments related to reconfigurable intelligent surfaces (RISs).

## BACKGROUND

**[0002]** Reconfigurable intelligent surfaces (RISs) are regarded as a promising emerging hardware technology to improve the spectrum and energy efficiency of wireless networks by reconfiguring the propagation environment of electromagnetic waves.

**[0003]** A RIS generally comprises an array of low-cost and low-complexity signal reflectors. The reflectors are passive. That is, a transmitted signal impinging on the RIS is neither amplified nor processed. The reflectors are also configurable (i.e., programmable). That is, the phases of the reflectors can be adjusted in real-time so that an impinging signal can be re-phased by adjusting the phases of the reflectors. This re-phasing is done to efficiently re-direct the impinging signal towards an in-range receiver (e.g., a user equipment (UE)). (See e.g., M. Di Renzo et al., 2020 (reference [1])).

**[0004]** In many cases, the programmability is achieved by equipping the RIS with a network interface and a processing unit (e.g., microcontroller, microprocessor, etc.). The network interface enables the establishment of a control link between the RIS and a network node (e.g., access point, UE, etc.) through which the RIS can receive feedback, for example, in terms of Signal-to-Noise Ratio or Signal-to-Interference-plus-Noise-Ratio (the acronym SNR is used broadly to encompass either ratio) and/or instructions (e.g., how to adjust the phases of reflectors). In some configurations, the processing unit allows the RIS to execute pre-computed instructions (microcontroller), while in other configurations the processing unit computes-and-executes instructions based on the received feedbacks.

**[0005]** RIS deployment aims to increase coverage (e.g., in terms of SNR) at network edge and in poor coverage areas (e.g., indoor environments) and to improve end-user performance (e.g., data rate). RIS deployment is more scalable than massive Multiple-Input-Multiple-Output (MIMO) deployment and heterogeneous network (macro cells and small cells) deployment in terms of complexity, interference management, power consumption, and costs. Use cases include RIS deployment for smart cities (e.g., on the external façade of buildings) and smart indoor environments (e.g., in private homes and large indoor open spaces such as malls and airports).

**[0006]** Theoretical studies assuming complete knowledge of channel coefficients and thus optimal re-phasing of reflectors show a significant potential improvement in terms of SNR in a simple scenario with one user. It has been shown that the maximum achievable SNR gain is equal to the number of reflectors squared. Moreover, as the number of reflectors becomes large, the scaling of the SNR gain does not depend on the re-phasing granularity, and the use of discrete rather than continuous phase shifts only incur a fixed loss independent of the number of reflectors (see, e.g., Q. Wu and R. Zhang, 2020 (reference [2])).

**[0007]** Algorithms to configure a RIS have been proposed. One such algorithm is referred to as "RFocus" (see V. Arun 2019 (reference [3])). RFocus performs the RIS configuration based on SNR feedbacks. Results confirm that SNR gains are attainable using the RFocus algorithm (see reference [3]). The algorithm allows for activating a subset of reflectors to improve the SNR at the receiver end. It performs several iterations to search for the subset of reflectors to activate. It has been shown that power can be focused on a point in space by such a simple on-off strategy.

## SUMMARY

**[0008]** Certain challenges presently exist. For example, there have been few studies with respect to how best configure a RIS and, consequently, there are no specific protocols detailing the procedure that should be followed to configure a RIS. Moreover, most theoretical studies do not delve into a key detail that is necessary for configuring the RIS, namely, how to acquire the knowledge of the channel coefficient phases.

**[0009]** All the RIS configuration algorithms that assume an active channel training phase with cooperation or coordination between the RIS and another end of the communication blur the difference between a RIS and an access point or relay. Some of the existing literature refers to control links that are used to send over full knowledge of channel state information, i.e., the instantaneous channel coefficients to and from the RIS.

**[0010]** Some algorithms attempt to estimate channels using a subset of reflectors with the goal of using the channel estimate on the entire RIS, but these algorithms have limited applicability in practice. This approach is useful only in limited cases, i.e., those cases where the scattering environment is not rich, and the channel is not Rayleigh fading. However, it is in the Rayleigh fading scenario that focusing the wave, rather that only reflecting it, is possible. All existing deep learning algorithms trying to interpolate channel coefficients among different reflectors by only knowing the coefficients for a subset of reflectors cannot theoretically work in the Rayleigh fading scenario because channel coefficients are independent (if reflectors are spaced half-wavelength or more). That makes sense only if reflectors are placed at a distance shorter than half-wavelength, but in that case also the focusing capability and SNR gain are deteriorated.

**[0011]** With respect to the RFocus algorithm mentioned above, this algorithm is limited in at least three respects. First, the algorithm itself is heuristic and is unlikely to achieve the theoretical optimum performance. Second, the algorithm is based on only switching on and off reflectors rather than changing phases. In other words, it works on amplitudes rather than phases. Each reflector either absorbs power or reflect it according to Snell's law. Third, to configure the RIS, a first phase is performed where several random phases and the corresponding SNR feedbacks are collected. During this phase, the performance of the RIS is equivalent to a random algorithm.

**[0012]** Accordingly, there is provided a method for configuring a RIS, wherein the RIS comprises a plurality of configurable reflectors. In one embodiment, the method includes obtaining a first set of channel quality measure (CQM) values (e.g., SNR, RSRP, etc.), wherein the first set of CQM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration. The method also includes, based on the obtained first set of CQM values, selecting a reflector configuration. The method further includes configuring at least the first particular configurable reflector based on the selected reflector configuration. In one embodiment, the method is performed by the RIS and the step of obtaining the CQM values comprises obtaining the CQM values from a network node. In another embodiment, the method is performed by a network node and the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.

**[0013]** There is also provided a computer program comprising instructions which when executed by processing circuitry of a network node causes the network node to perform any of the methods disclosed herein. In one embodiment, there is provided a carrier containing the computer program wherein the carrier is one of an electronic signal, an optical signal, a radio signal, and a computer readable storage medium.

**[0014]** There is also provided a network node that is configured to perform the methods disclosed herein. In some embodiments, the network node comprises a storage unit and processing circuitry coupled to the storage unit, wherein the network node is configured to perform the methods disclosed herein.

**[0015]** An advantage of the embodiments disclosed herein is that they enable configuration of an RIS based on channel quality measurements (CQMs) (e.g., SNR, reference signal received power (RSRP)) feedbacks only. Such kind of feedback provides a small amount of information that an algorithm should receive to be able to configure the RIS, and thus the protocol disclosed herein is based on the simplest possible signaling. Also, the embodiments are shown to work on more general channel models than the Rayleigh fading one presented typically in the literature. Moreover, the embodiments account for the possibility of not only amplitude-only configuration (RIS without the capability of adjusting phases but only turning on and off reflectors) but also configuring phases.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0016]** The accompanying drawings, which are incorporated herein and form part of the specification, illustrate various embodiments.

**[0017]** FIG. **1** illustrates a communication system according to an embodiment.

**[0018]** FIG. **2** is a flowchart illustrating a process according to some embodiments.

**[0019]** FIG. **3** illustrates a communication system according to an embodiment.

**[0020]** FIG. **4** illustrates a communication system according to an embodiment.

**[0021]** FIG. **5** illustrates a communication system according to an embodiment.

**[0022]** FIG. **6** illustrates a communication system according to an embodiment.

**[0023]** FIG. **7** illustrates a communication system according to an embodiment.

**[0024]** FIG. **8** illustrates a communication system according to an embodiment.

**[0025]** FIGS. **9**A-**9**C illustrate a first set of simulation results.

**[0026]** FIGS. **10**A-**10**C illustrate a second set of simulation results.

**[0027]** FIG. **11** is a flowchart illustrating a process according to some embodiments.

**[0028]** FIG. **12** is a block diagram of a network node according to some embodiments.

**[0029]** FIGS. **13**A, **13**B, and **13**C together illustrate a bisection method for determining an optimal phase shift according to some embodiments.

## DETAILED DESCRIPTION

**[0030]** FIG. **1** illustrates a communication system **100** according to an embodiment. Communication system includes: an access point (AP) **104** (e.g., a radio access network (RAN) node a cellular network (e.g., a base station) or other access point), a user equipment (UE) **102**, and a RIS **106**, which comprises a set of reflectors **120** and a processing unit **122**. As used herein a "UE" is any device (e.g., mobile phone, router, sensor, appliance, vehicle) capable of wireless communication with access point **104**. As shown in FIG. **1**, a signal transmitted by access point **104** impinges on RIS **106** and RIS **106** is configured to reflect the impinging signal toward UE **102**. As also shown in FIG. **1**, communication system may include a computer **190** (a.k.a., "server") that executes a RIS control function (RCF) **199** that implements a method for configuring RIS **106**. That is, RCF **199** is configured to select the configuration(s) for configuring one or more reflectors of RIS **106**.

**[0031]** Presented below is a mathematical model that is a generalization of the ones available in the literature. The model assumes that RIS **106** is equipped with a set of N reflectors, and both UE **102** and AP **104** are equipped with a single antenna.

**[0032]** In the most general scenario, there is a channel between RIS and user (denoted $h_{RU}$), a channel between access point and RIS (denoted $h_{AR}$), and a channel between access point and user (denoted $h_{AU}$). All of them may be in part line of sight, and thus Rician distributed. However, such a general model introduces many parameters, and some of them do not change qualitatively the behavior of the channel. The literature focuses on the absence of $h_{AU}$ and Rayleigh combined channel $h_{AR}$ $h_{RU}$. To extend the literature, $h_{AU}$ is assumed to be line of sight.

**[0033]** The one in the literature (absent direct path) is the most challenging scenario, where the significant pathloss required for the model to hold demands the use of a RIS; if there was already a line-of-sight (LOS) component due to a wave reflected by a normal (non-intelligent, non-programmable) surface, the higher SNR would not demand the addition of the RIS in the propagation environment.

**[0034]** All channels are quasi-static, which means that they are unknown but fixed. Mathematically, $h_{AU}$ is a complex scalar, and both $h_{AR}$ and $h_{RU}$ are complex Gaussian vectors (Rayleigh fading). From the phase shift point of view, it wouldn't make any difference if either $h_{AR}$ or $h_{RU}$ were line of sight and the other Rayleigh (although it would make a small quantitative difference with respect to the amplitude distribution, which we may regard as a detail since also Rayleigh fading is an approximation of reality).

**[0035]** To make notation simpler, let $h_d = h_{AU}$, $h_1 = h_{AR}$, and $h_2 = h_{RU}$. If a complex symbol x is transmitted on a resource element, then the received signal y is thus given by:

$$y = \left[ \sqrt{\kappa}\, h_d + \sqrt{1-\kappa} \sum_{i=1}^{n} h_{1i} h_{2i} a_i e^{i\varphi_i} \right] x + z$$

where the parameter $\kappa \in [0, 1]$ determines the relative power coming from the line-of-sight (LOS) path. Here, the amplitudes $(a_i)_{i=1}^n$ and phases $(\varphi_i)_{i=1}^n$ are chosen by the RIS. Notice that all other channels are complex, and thus the phases $(\varphi_i)_{i=1}^n$ are added to the phases of channel branches $(h_{1i}h_{2i})_{i=1}^n$. In the expression above, the variance of x accounts for the received power (=transmitted power–path-loss) and the variance of the noise z and all channel coefficients can be set to unity.

**[0036]** The maximum SNR (divided by the variance of x) in the absence of direct path ($\kappa$=0) is $n^2$, or 20 $\log_{10}$ n in dB. As mentioned above, a few algorithms to configure a RIS have been proposed in the literature in an attempt to reach such gain. The literature is mostly focused on the scenario with no direct path.

## Brief Summary of Various Embodiments

**[0037]** Described herein are different architectures to enable coordination among UE **102**, AP **104**, RIS **106**, and RCF **199** to configure the RIS. Also described are methods performed by RCF **199** for selecting a RIS configuration. The selection, in one embodiment, is based solely on channel quality measurements (CQMs) (e.g., SNR measurements). FIG. **1** shows RCF **199** being executed server **190** (e.g., a server in the "cloud"), but in other embodiments, RCF **199** can be executed by another network node, such as AP **104**, UE **102**, or the RIS **106** itself. In one embodiment, RIS **106** is configured to advertise its features and capabilities.

**[0038]** Several different architectures are proposed. The architectures differentiate in terms of the network node that executes RCF **199**. In this respect, cloud-based, AP-based, RIS-based, and UE-based architectures are proposed. The architectures also differentiate in terms of the network node that establishes the control link towards RIS **106**.

**[0039]** Several methods performed by RCF **199** to configure RIS **106** are proposed. Two classes of methods are described, which are referred to as "sequential' and "simultaneous." Methods in the sequential class work by adjusting the reflectors of RIS **106** one at a time. Methods in the simultaneous class work by jointly adjusting all reflectors of RIS **106**.

## Details of Various Embodiments

**[0040]** Described below are ways to configure RIS **106** so as to improve performance (e.g., increase the SNR) of the combined direct (AP-UE) and reflected (AP-RIS-UE) channels. FIG. **2** is a flowchart illustrating a process **200**, according to one embodiment, to execute the configuration of RIS **106**. The steps of process **200** are described below.

**[0041]** S202. RIS advertisement and discovery: RIS **106** transmits periodically a beacon signal (e.g., over the low-power IoT communication link) to advertise itself and its capabilities; and AP **104** or UE **102** receive the beacon, thereby discovering the RIS. The beacon may include information indicating capabilities of RIS **160**

**[0042]** S204. RCF discovery: The network node that receives the beacon initiates a signaling exchange to determine where RCF **199** is executed—in the network (AP **104** or server **190**), in UE **102**, or in RIS **106**.

**[0043]** S206. In this step RCF **199** selects a set of one or more reflectors and selects a configuration for the reflector (s). And in this step a counter variable (t) may be set equal to 0 and a quantization variable ($n_s$) for the reflector(s) is set (e.g., $n_s$=8). If RIS **106** does not execute RCF **199**, then RCF **199** communicates the selected configuration so that it can be received and implemented by RIS **106**.

**[0044]** S208: Obtain CQM: UE **102** obtains a CQM (e.g., UE **102** measures the SNR).

**[0045]** S210. COM feedback and forwarding (if necessary): If RCF **199** is executed in UE **102**, proceed to step s**212**, otherwise UE **102** transmits CQM to AP **104** or to RIS **106**. If RCF **199** is executed in server **190**, UE transmits CQM to AP **104** which then forwards the CQM to server **190**.

**[0046]** S212. In this step, t is incremented by one and the new t value is compared to $n_s$. If the new t value is equal to $n_s$, then process **200** skips to step s**220**, otherwise, process **200** proceeds to step s**214**.

**[0047]** S214. In this step RCF **199** uses one of the below described methods to select a configuration for the set of reflectors. For example, RFC **199** may randomly select a configuration (e.g., phase shift) or RFC **199** may select a configuration from a list of configurations or RFC may use a bisection method to select a configuration.

**[0048]** S216. Send configuration update message to RIS **106** (if necessary): If RCF **199** is not executed by RIS **106**, the configuration (e.g., phase shift information) is feed back to RIS **106**. Otherwise, proceed to step s**218**.

**[0049]** S218. RIS **106** adopts the new configuration. After step s**218** is performed, process **200** returns to step s**208**.

**[0050]** S220. In this step, RCF **199** uses all of the CQM values that have been obtained to select a configuration for the reflectors and applies the reflected configuration. That is, for example, each CQM value is associated with a configuration, and RCF **199** determines the best CQM value (e.g., the highest CQM value or the lowest CQM value) and then selects the configuration with which the best CQM value is associated. This selected configuration is then applied by RIS **106** (the selected configuration needs to be communicated to RIS **106** if RIS **106** does not execute RCF **199**).

**[0051]** After step s**220** is performed the process may back to step s**206** where RCF **199** selects a new set of one or more reflectors, or the process may end (e.g., the process may end once all reflectors of RIS **106** have been configured).

**[0052]** Using process **200**, at least a subset of the reflectors of RIS **106** can be configured so as to improve the performance of communication system **100** (i.e., improve the combined direct (AP-UE) and reflected (AP-RIS-UE) channels).

## Details on the Signaling Phase for Architecture Selection

**[0053]** In one embodiment, a lightweight discovery-and-configuration procedure is implemented so that the involved system entities can preliminarily coordinate and select one of the architectures described above. The procedure is carried out on the control link, assuming that this link is always active between RIS **106** and at least one of the other network nodes (AP **104** and/or UE **102**). The following operations and signaling are performed:

**[0054]** 1. RIS advertisement: RIS **106** advertises its presence along with its features and capabilities via beacon packets on the control link, e.g., an Internet-of-Things (IoT) broadcast link. In particular, RIS **106** informs if it is ready to be used, how many reflectors it has, and if its processing unit is equipped with a microprocessor along with a microcontroller so that Architectures **2***a* and **2***b* (described below) may be considered as available options.

**[0055]** 2. RIS discovery: Either AP **104** or UE **102** receives the beacon, decodes it, and initiates the RCF selection phase.

**[0056]** 3. RCF selection: Once RIS **106** is discovered, access point and UE **102** coordinate by adopting an ACK/NACK message exchange on the architecture to be used (e.g., the device has to communicate if it is able to compute the phase shifts so that Architectures **3***a* and **3***b* may be considered as available options, while AP **104** can communicate its preferences on the architectures to be used). This can be done on the control link but also on the main data/signaling link if one entity (e.g., UE **102**) is not equipped with the control link. Finally, RIS **106** is informed on the agreed architecture via a control link.

## Details on the Control Link

**[0057]** In all the proposed architectures, a control link is needed for communicating with RIS **106**. It can be observed that such a link is needed for sending a small number of bits to RIS **106** so to transmit either SNR feedbacks (up to tens of kbps) or configuration information (e.g., phase shifts) (up to hundreds of kbps). While also considering the need for maintaining satisfactory energy efficiency at RIS **106** end, a Low-Power Wide-Area Network (LPWAN) technology could be directly employed for the control link establishment. Among others, cellular-based IoT (CIoT) technologies, such as Narrowband IoT (NB-IoT), can be envisioned for this task.

## Details on the Architectures

**[0058]** Six different architectures for augmenting a communication link with a RIS are described below.

### Architecture 1*a*: Network-Based RIS Configuration and Network-Based RIS Control

**[0059]** Architecture **1***a* is illustrated in FIG. **3**. In this architecture, RCF **199** is executed by server **190**, which may be a cloud server or edge-cloud server. In addition, a control link **301** is established between AP **104** and RIS **106** so that AP **104** can forward the selected RIS configuration (e.g., computed phase shifts) to RIS **106**. Finally, processing unit **122** RIS **106** is equipped with a microcontroller for executing the received configuration. The following operations and signaling are performed:

**[0060]** 1. COM (e.g., SNR) feedback: For each data signal transmitted by AP **104** to UE **102**, UE **102** receives the data signal, evaluates a CQM (e.g., SNR), and then sends to AP **104** CQM feedback information specifying the evaluated CQM.

**[0061]** 2. CQM forwarding: AP **104** forwards the CQM feedback information server **190**.

**[0062]** 3. RCF execution: Server **190** executes RCF **199**, which is configured to select an RIS configuration to be applied by RIS **106** reflectors during the next packet transmission.

**[0063]** 4. Configuration update message: AP **104** receives the new RIS configuration (e.g., phase shifts) from server **190** and in turn communicates it to RIS **106** via the control link **301**.

**[0064]** 5. Configuration update: Upon receiving the RIS configuration from AP **104**, RIS **106** configures at least one reflector to apply the new configuration via the processing unit **122**.

### Architecture 1*b*: Network-Based RIS Configuration and User-Based RIS Control

**[0065]** Like Architecture **1***a*, Architecture **1***b*, which is illustrated in FIG. **4**, also exploits server **190** for evaluating the configuration of RIS **106** reflectors. However, in this embodiment, a control link **401** is established between UE **102** and RIS **106** so that the former can forward the RIS configuration to the latter, after receiving them from AP **104**. The following operations and signaling are performed:

**[0066]** 1. COM feedback: As Architecture **1***a*.

**[0067]** 2. CQM forwarding: As Architecture **1***a*.

**[0068]** 3. Algorithm execution: As Architecture **1***a*.

**[0069]** 4. Configuration update message: AP **104** receives the new RIS configuration from server **190** and in turn communicates them to UE **102** adopting the same feedback-based communication protocol used for CQM feedback. Then, UE **102** communicates the RIS configuration to RIS **106** via the control link **401**.

**[0070]** 5. Configuration update: As Architecture **1***a*.

### Architecture 2*a*: RIS-Based RIS Configuration and Network-Based RIS Control

**[0071]** In Architecture **2***a*, which is illustrated in FIG. **5**, processing unit **122** of RIS comprises a microcontroller and a microprocessor for executing RFC **199** (e.g., evaluating the configuration of RIS **106** reflectors). In addition, a control link **501** is established between AP **104** and RIS **106** so that the former can forward the CQM feedbacks to the latter, after receiving them from UE **102**. Finally, the on-RIS microcontroller executes the configuration evaluated by the microprocessor. The following operations and signaling are performed:

**[0072]** 1. CQM feedback: As Architecture **1***a*.

**[0073]** 2. CQM forwarding: AP **104** forwards CQM feedbacks to RIS **106** via the control link **501**.

**[0074]** 3. RCF execution: The on-RIS microprocessor executes RCF **199** which performs a method for selecting the RIS configuration (e.g., evaluating the phase shifts to be applied by RIS **106** reflectors) during the next packet transmission.

**[0075]** 4. Configuration update message: The microprocessor forwards the computed RIS configuration to the microcontroller.

**[0076]** 5. Configuration update: The microcontroller instructs the reflectors to apply the new RIS configuration.

### Architecture 2*b*: RIS-Based RIS Configuration and User-Based RIS Control

**[0077]** Like Architecture **2***a*, Architecture **2***b*, which is shown in FIG. **6**, exploits an on-RIS microprocessor for evaluating the configuration of RIS **106** reflectors. However, a control link **601** is this case established between UE **102**

and RIS **106** so that the former can forward the CQM feedbacks to the latter. The following operations and signaling are performed:

**[0078]** 1. CQM feedback: UE **102** evaluates the CQM on each data packet received by the network access point and sends it to RIS **106** via the control link.

**[0079]** 2. Algorithm execution: As Architecture **2**_a_.

**[0080]** 3. Configuration update message: As Architecture **2**_a_.

**[0081]** 4. Configuration update: As Architecture **2**_a_.

Architecture **3**_a_: User-Based RIS Configuration and Network-Based RIS Control

**[0082]** In Architecture **3**_a_, which is illustrated in FIG. **7**, RCF **199** is executed by UE **102**. In addition, a control link **701** is established between AP **104** and RIS **106** so that the former can forward the RIS configuration to the latter, after receiving them from UE **102**. Finally, RIS **106** is equipped with a microcontroller for executing the received RIS configuration. Note that, compared to the previous architectures, in this and following case, there is no need for CQM feedback and/or forwarding steps, since UE **102** computes the CQM values and uses them for the local execution of the configuration algorithm. Therefore, the following operations and signaling are performed:

**[0083]** 1. COM and Algorithm execution: UE **102** evaluates the CQM on each data signal received from AP **104** and uses them for executing one of the proposed methods for evaluating the configuration (e.g., phase shifts) to be applied by RIS **106** reflectors during the next packet transmission.

**[0084]** 2. Configuration update message: UE **102** communicates the configuration to AP **104** adopting a feedback-based communication protocol. Then, AP **104** communicates the RIS configuration to RIS **106** via the control link **701**.

**[0085]** 3. Configuration update: As Architecture **1**_a_.

Architecture **3**_b_: User-Based RIS Configuration and User-Based RIS Control

**[0086]** Like in architecture **3**_a_, in Architecture **3**_b_, which is shown in FIG. **8**, UE **102** executes RCF **199** for evaluating the configuration of RIS **106** reflectors. However, a control link **801** is this case established between UE **102** and RIS **106** so that the former can forward the configuration information to the latter. The following operations and signaling are performed:

**[0087]** 1. COM and Algorithm execution: As Architecture **3**_a_.

**[0088]** 2. Configuration update message: UE **102** communicates the configuration information to RIS **106** via the control link **801**.

**[0089]** 3. Configuration update: As Architecture **1**_a_.

Architectural Trade-Offs

**[0090]** The proposed architectures differently leverage the existing tradeoff between communication, computational capabilities, and energy consumption across the involved system entities, and particularly at RIS **106**.

**[0091]** On the one hand, Architectures **1**_a_, **1**_b_, **3**_a_, and **3**_b_ require RIS **106** to be equipped with a microcontroller, thus minimizing RIS computational power and energy consumption. However, these architectures require increased communication capabilities due to the need for transmitting the selected configuration information towards RIS **106** in a timely manner. Architecture **3**_b_ results in the lowest communication requirement compared to Architectures **1**_a_, **1**_b_, and **3**_a_, since the entity executing RCF **199** (i.e., UE **102**) does not need to feedback CQM values towards to the network (as in Architectures **1**_a_ and **1**_b_) and is also part of the control link towards RIS **106**, thus making it possible to transmit the configuration information directly to RIS **106** (differently from Architecture **3**_a_, where the configuration first transmitted to AP **104** and then to RIS **106**). Architecture **3**_b_, however, leads to increased energy consumption at UE **102** due to the local execution of the configuration algorithm (RCF **199**).

**[0092]** On the other hand, in Architectures **2**_a_ and **2**_b_, RIS **106** locally executes the configuration algorithm through a microprocessor. This maximizes RIS computational power and energy consumption while minimizing the need for communication, since CQM feedbacks are transmitted to RIS **106** via the control link but the configuration information is readily available to the microcontroller after being computed by the on-RIS microprocessor. Architecture **2**_b_ results in a single-hop CQM feedback (from UE **102** to RIS), but the need for establishing the control link also incurs in addition power consumption at the user end compared to Architecture **2**_a_.

**[0093]** In all the proposed architectures, the selection of the configuration is executed by via one of the proposed methods, described in the following.

**[0094]** Details on Methods performed by RCS **199** for selecting a reflector configuration (e.g., phase shift):

**[0095]** The methods are categorized in terms of their action on reflectors. They act on reflectors in a sequential or simultaneous manner, and by adjusting their phases or amplitudes.

**[0096]** Referring to RFocus, RFocus is a simultaneous on-off algorithm. It acts at the same time on all reflectors and tries to select the best subset of reflectors to be on. When a reflector is on, it reflects the impinging wave. If it is turned off, then it absorbs the impinging wave. Intuitively, there should be a subset of reflectors turned off if their phases cannot be changed, as is the case of RFocus, since the reflected wave can interfere destructively at the receiver. The exact procedure followed by RFocus is explained in reference [3]. At a high level, the algorithm performs a certain number of iterations during each of which some reflectors are turned on or off, and the new configuration is kept according to a majority rule.

**[0097]** In sequential algorithms, there is an implicit order of reflectors that needs to be chosen beforehand. Given the channel model that we are using such an order is irrelevant, namely reflectors can be chosen at random. However, in practice, there may be cases where a particular order is preferable to the random one.

**[0098]** Simultaneous vs sequential algorithms differ as follows:

**[0099]** Simultaneous: at each iteration of the algorithm, all reflectors are adjusted at the same time.

**[0100]** Sequential: At the beginning of the configuration phase, only one reflector is activated, and all others absorb the impinging wave. After the configuration of the reflector is completed, a second reflector is configured while the phase of the first one remains fixed, and so on. Thus, during the configuration of reflector m, there are $m-1$ reflectors that are active and whose phases are kept fixed, and n-m reflectors that are inactive and absorb the impinging wave.

Method **1**: Simultaneous Random Baseline (Random Phases)

**[0101]** In the Simultaneous Random Baseline method, all reflectors are always on. For a predetermined number of iterations, phases of all reflectors are randomly and independently chosen. A feedback is received at each iteration, and the configuration with the best feedback is kept track of.

Method **2**: Sequential Random Phases

**[0102]** In the Sequential Random Phases method, during the configuration of a reflector, a number of random phases are tried (equal to the number of iterations that can be spent to configure one reflector, that is the total number of iterations allowed for configuration divided by the number of reflectors). The best phase is then kept.

Method **3**: Sequential List Phase Discovery

**[0103]** In the Sequential List Phase Discovery method, during the configuration of a reflector, a list of phases is attempted. The list is predetermined and arbitrary. To be concrete, consider a regular phase discovery where a length-m list is given by $\{0, 2\pi/m, 2*2\pi/m, \ldots, (m-1)*2\pi/m\}$. An early-stop strategy can be implemented as follows. As soon as the second difference, i.e., the discrete version of the second derivative of the SNR feedback is negative, which requires $m \geq 3$, the algorithm is stopped, and the next reflector, if any remain, is configured.

Method **4**: Sequential Bisection Phase Discovery

**[0104]** In the Sequential Bisection Phase Discovery method, the method proceeds sequentially as in the previous method, but now there is no predetermined list. Instead, a prefixed number of iterations is performed on the configuration of each reflector to determine (e.g., estimate) the optimal phase shift for the reflector. The method identifies a phase interval in which the optimal phase shift for the reflector can be found, and the reflector is re-phased by considering the mid-point of such an interval. To identify the interval, a "bisection" method is applied. The bisection method according to one embodiment is illustrated in FIGS. **13**A, **13**B, and **13**C and includes the following steps.

**[0105]** Step **1**: The phase shift for the reflector under consideration is set to 0 (i.e., $\varphi_1=0$) and then an SNR feedback value $S_1$ is received (see FIG. **13**A).

**[0106]** Step **2**: The phase shift for the reflector is set to $\pi$ (i.e., $\varphi_2=\pi$). The SNR feedback value received is $S_2$ (see FIG. **13**A). Based on $S_1$ and $S_2$, we reject a half plane. Because in this example, $S_1>S_2$, the left-half plane is rejected (i.e., the angles outside $[-\pi/2, \pi/2)$. Had $S_1$ not been greater than $S_2$, then the right half-plane (i.e., angles in $[-\pi/2, \pi/2]$) would have been rejected.

**[0107]** Step **3**: The phase shift for the reflector is set to $\pi/2$ (i.e., $\varphi_3=\pi/2$) and then the feedback SNR values received is $S_3$ (see FIG. **13**B).

**[0108]** Step **4**: The phase shift for the reflector is set to $-\pi/2$ (i.e., $\varphi_4=-\pi/2$) and then the SNR feedback value received is $S_4$. Based on $S_3$ and $S_4$, we reject a quarter plane. If $S_4>S_3$, we reject the upper quarter-plane, i.e., angles in $[0, \pi/2]$. Otherwise, we reject the lower quarter-plane, i.e., angles in $[-\pi/2, 0]$. In FIG. **13**B, the upper quarter-plane is rejected because $S_4>S_3$.

**[0109]** From this step on, the algorithm proceeds iteratively. The algorithm has already discovered a quarter plane where the correct angle lies. Therefore, we specify the below step as "step k" where k=5, 6, . . . up to a predetermined limit.

**[0110]** Step k: Define the best extreme angle as the angle between the two current extreme angles at which feedback is maximum. For example, in FIG. **13**B, the two extreme angles are $\varphi_4=-\pi/2$ and $\varphi_1=0$, therefore the best extreme angle is $\varphi_4=-\pi/2$ because $S_4>S_1$. Compute the angle that lies in the middle of the two extreme angles referred to as the mid-angle. For example, in FIG. **13**C the mid-angle is $\varphi_5=-\pi/4$. Accept the part of plane between the mid-angle and the best extreme angle. The two extreme angles become, therefore, the mid-angle and the best extreme angle. In FIG. **13**C, we accept the part of plane between $\varphi_5$ and $\varphi_4$ because $S_4>S_1$. In another example, it could have happened that $S_4<S_1$, in which case we would have accepted the part of plane between $\varphi_5$ and $\varphi_1$. Finally, unless step k is the last step, receive feedback $S_k$, which will be used at the next step. If this is the last step, consider the mid-angle between the two new extreme angles, and report that angle as the output of the method. Any other angle in the interval would perform similarly. For example, if k=5 was the last step, the output of the method would be $\varphi_6=-3\pi/8$. Any other angle between $\varphi_4$ and $\varphi_5$ would perform similarly.

Method **5**: Sequential On-Off Discovery

**[0111]** In the Sequential On-Off Discovery method, the method proceeds sequentially as in the previous algorithm but now there is no re-phasing. Reflectors can only be activated, in which case they reflect the impinging wave, or deactivated, in which case they absorb the impinging wave. For each reflector, both configurations are tested, and the best one is kept.

**[0112]** Variations of the above embodiments:

**[0113]** In one embodiment, a subset of reflectors is configured with higher quantization than the remaining (e.g., for a subset of reflectors $n_s=8$, whereas for the remaining reflectors $n_s=4$). In another embodiment, each reflector is independently assigned a quantization value.

**[0114]** In another embodiment, a multi-stage algorithm is applied where at each stage the increment in the feedback metric before and after configuration is taken track of, and each stage focuses more resources (e.g., iterations) towards those reflectors that already showed the largest (or the lowest) increment in previous stages, thereby increasing inequality (or equality) of the configuration accuracy across reflectors.

**[0115]** In another embodiment, subsets of reflectors are configured (per iteration or step of the algorithm) instead of one at a time, up to the extreme case where all reflectors are configured simultaneously, possibly repeatedly.

**[0116]** There are simultaneous counterparts to some of the above sequential algorithms that are not describe here for brevity. They can be considered variations of the sequential algorithms.

## Performance Evaluation

**[0117]** The maximum SNR (divided by the variance of x) in the presence of a direct path is given by:

$$S_{max} = \kappa + (1-\kappa)\left(n + n(n-1)\pi/4\right) + 2\sqrt{\kappa(1-\kappa)}\,n\pi/4.$$

**[0118]** The terms including π/4 are due to Rayleigh fading; if the amplitudes were exactly unit-norm rather than Rayleigh distributed with unit second moment, those π/4 would be equal to 1, and the expression would simplify slightly. The important fact is that when κ≠1 the scaling of $S_{max}$ is with $n^2$, as reported in the literature.

**[0119]** If RIS **106** is not configured, then $S_{nc}=\kappa+(1-\kappa)n$. In this case, the scaling of SNR is with n rather than $n^2$.

**[0120]** In some of the literature, the SNR gain is also reported to scale with $n^2$ but we should clarify what such a gain is referring to. The SNR gain reported in the literature refers to the difference in SNR (dB) between the case of configured RIS and the absence of RIS or equivalently a RIS with one element only. Notice that the number of channel branches differs in the two cases.

**[0121]** Therefore, we call SNR gain the gain in SNR that we get by configuring RIS **106**. That is, the difference in SNR (dB) between the configured and un-configured RIS.

$$G(\kappa) := \frac{S_{max}}{S_{nc}}$$

or in dB

$$10\log_{10} G(\kappa) := 10\log_{10} S_{max} - 10\log_{10} S_{nc}.$$

**[0122]** Therefore, G~n for n large (for κ≠1) because $S_{max}\sim n^2$ but $S_{nc}\sim n$.

## Simulation Results

**[0123]** We present below simulation results showing the gain G in SNR achieved with the different algorithms detailed above. In the present setting, the SNR gain translates into a throughput gain via the expression $R=\log_2(1+\text{SNR})$.

**[0124]** Simulation results were obtained. The simulations began with the case of no direct path with relatively few reflectors and relatively short configuration time measured in terms of number of feedbacks received. Then we investigated the case with 4× more reflectors and proportional larger configuration time. Finally, we repeated the last investigation in the presence of a direct path.

**[0125]** In all cases, our proposed sequential bisection algorithm approaches the theoretical maximum. RFocus was shown to perform worse. Among the proposed algorithms, the sequential on-off algorithm is shown to perform similarly to RFocus but without the long left-tail of the latter. Moreover, the benefit of sequential algorithms is that the evolution of the gain is monotonic while RFocus is designed to collect the feedbacks of random choices and process them, but in so doing the evolution of the gain is equal to the simultaneous random algorithm up to the very last step, at which RFocus processes the data differently than just picking the best outcome.

**[0126]** From the simulation results, we concluded that: gain G increases as number of reflectors increases and RIS **106** is well-configured; the sequential bisection method approaches the theoretical maximum gain; the sequential on-off algorithm performs similarly to RFocus but without the left-tail gains (losses); in the presence of a direct path that does not bring the majority of the power received by the user, a configured RIS still offers a significant SNR gain; we do not report the case where the direct path brings the vast majority of the power since in that case the maximum theoretical gain is very limited and not representative of the expected use case of a RIS deployment; the quantization of re-phasing is not a major limiting factor for achieving nearly-optimal gains; and configuring well (high accuracy, high quantization) a subset of reflectors rather than configuring at best all reflectors is beneficial (thereby opening the possibility of an algorithm where a subset of reflectors is well-configured while the remaining is coarsely configured).

**[0127]** FIGS. **9**A-**9**C show simulation results for the Sequential Bisection Phase Discovery, Sequential On-Off Discovery, and RFocus methods, respectively where the RIS has 32 reflectors and the quantization ($n_s$) is 4 for Sequential Bisection Phase Discovery (i.e., the total number of simulated configurations per reflector) and $n_s$ is 2 for Sequential On-Off Discovery. For RFocus, the total number of iterations (T) is equal to 128. Each of FIGS. **9**A-**9**C shows the distribution of gains at the end of configuration for the given method. Randomness is due to different channel realizations. The vertical dashed line corresponds to the maximum theoretical gain averaged over channel realizations.

**[0128]** FIGS. **10**A-**10**C show simulation results for the Sequential Bisection Phase Discovery, Sequential On-Off Discovery, and RFocus methods, respectively where the RIS has 1024 reflectors and the quantization was 8 for Sequential Bisection Phase Discovery and 2 for Sequential On-Off Discovery. Each of FIGS. **10**A-**10**C shows the distribution of gains at the end of configuration for the given method. Randomness is due to different channel realizations. The vertical dashed line corresponds to the maximum theoretical gain averaged over channel realizations.

**[0129]** FIG. **11** is a flowchart illustrating a process **1100**, according to an embodiment, that is performed by a network node (server **190**, AP **104**, UE **102**, RIS **106**) for configuring RIS **106**. Process **1100** may begin in step s**1102**.

**[0130]** Step s**1102** comprises obtaining a first set of channel quality measurement (CQM) values (e.g., SNR, RSRP, etc.), wherein the first set of CQM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration.

**[0131]** Step s**1104** comprises, based on the obtained first set of CQM values, selecting a reflector configuration.

**[0132]** Step s**1106** comprises configuring at least the first particular configurable reflector based on the selected reflector configuration. In one embodiment, the method is performed by the RIS and the step of obtaining the CQM values comprises obtaining the CQM values from a network node. In another embodiment, the method is performed by a network node (e.g. UE **102**, AP **104**, server **190**) and the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration. The control message for the RIS may be transmitted directly to the RIS or indirectly to the RIS (e.g., AP **104** may transmit the control message to UE **102** which then relays the control message to RIS **106**).

**[0133]** In some embodiments, obtaining the first set of CQM values comprises: configuring the first particular configurable reflector in accordance with a first reflector configuration; after configuring the first particular configurable reflector in accordance with the first reflector configuration, obtaining a first CQM value (CQM**1**) associated with the first reflector configuration; configuring the first particular configurable reflector in accordance with a second reflector configuration; and after configuring the first particular configurable reflector in accordance with the second reflector configuration, obtaining a second CQM value (CQM**2**) associated with the second reflector configuration.

**[0134]** In some embodiments, selecting a reflector configuration based on the obtained first set of CQM values comprises: determining the best CQM value from among the CQM values included in the first set of CQM values; and selecting the reflector configuration associated with the best CQM value. In some embodiments, selecting a reflector configuration based on the obtained first set of CQM values comprises: comparing the first CQM value with the second CQM value; and selecting the first or second reflector configuration based on the comparison. In some embodiments, selecting the first or second reflector configuration based on the comparison comprises: selecting the first reflector configuration if the first CQM value is greater than the second CQM value; selecting the second reflector configuration if the first CQM value is less than the second CQM value; or selecting either the first or the second reflector configuration if the first CQM value is equal to the second CQM value.

**[0135]** In some embodiments, the first reflector configuration specifies a first phase shift, configuring the first particular configurable reflector in accordance with the first reflector configuration comprises configuring the first particular configurable reflector to produce the first phase shift, the second reflector configuration specifies a second phase shift, and configuring the first particular configurable reflector in accordance with the second reflector configuration comprises configuring the first particular configurable reflector to produce the second phase shift.

**[0136]** In some embodiments, the first phase shift is X radians, and the second phase shift is $(X+\pi)$ or $(X-\pi)$ radians.

**[0137]** In some embodiments, obtaining the first set of CQM values further comprises: configuring the first particular configurable reflector in accordance with a third reflector configuration; after configuring the first particular configurable reflector in accordance with the third reflector configuration, obtaining a third CQM value (CQM**3**) associated with the third reflector configuration; configuring the first particular configurable reflector in accordance with a fourth reflector configuration; and after configuring the first particular configurable reflector in accordance with the fourth reflector configuration, obtaining a fourth CQM value (CQM**4**) associated with the fourth reflector configuration, wherein the third reflector configuration specifies a third phase shift, configuring the first particular configurable reflector in accordance with the third reflector configuration comprises configuring the first particular configurable reflector to produce the third phase shift, the fourth reflector configuration specifies a fourth phase shift, and configuring the first particular configurable reflector in accordance with the fourth reflector configuration comprises configuring the first particular configurable reflector to produce the fourth phase shift, the third phase shift, φ**3**, is $(X+\pi/2)$ or $(X-\pi/2)$ radians, and the fourth phase shift, φ**4**, is (φ**3**+π) or (φ**3**−π).

**[0138]** In some embodiments, obtaining the first set of CQM values further comprises: selecting a fifth phase shift, φ**5**, based on the obtained CQM values, wherein φ**5**=(φ**1**−π/4) if (CQM**1**>CQM**2** && CQM**4**>CQM **3**), φ**5**=(φ**1**+π/4) if (CQM**1**>CQM**2** && CQM**3**>CQM **4**), φ**5**=(φ**2**+π/4) if (CQM**2**>CQM**1** && CQM**4**>CQM **3**), or φ**5**=(φ**2**−π/4) if (CQM**2**>CQM**1** && CQM**3**>CQM **4**); and configuring the first particular configurable reflector to produce the fifth phase shift, and after configuring the first particular configurable reflector to produce the fifth phase shift, obtaining a fifth CQM value, CQM**5**, associated with the fifth phase shift.

**[0139]** In some embodiments, obtaining the first set of CQM values further comprises selecting a sixth phase shift, φ**6**, based on the obtained CQM values, wherein φ**6**=(φ**5**−π/8), or φ**6**=(φ**5**+π/8)); configuring the first particular configurable reflector to produce the sixth phase shift, and, after configuring the first particular configurable reflector to produce the sixth phase shift, obtaining a sixth CQM value, CQM**6**, associated with the sixth phase shift.

**[0140]** In some embodiments, CQM**1**>CQM**2**, CQM**4**>CQM**3**, CQM**4**>CQM**1**, and selecting the reflector configuration comprises one of: selecting φ**4** if CQM**4**>CQM**5** and CQM**4**>CQM**6**; selecting φ**5** if CQM**5**>CQM**4** and CQM**5**>CQM**6**; or selecting φ**6** if CQM**6**>CQM**4** and CQM**6**>CQM**5**.

**[0141]** In some embodiments, the first reflector configuration specifies an off state, configuring the first particular configurable reflector in accordance with the first reflector configuration comprises placing the first particular configurable reflector in the off state, the second reflector configuration specifies an on state, and configuring the first particular configurable reflector in accordance with the second reflector configuration comprises placing the first particular configurable reflector in the on state.

**[0142]** In some embodiments, the method is performed by RIS **106**, and the step of obtaining the CQM values comprises obtaining the CQM values from a network node (e.g., from UE **102** or AP **104** or server **190**).

**[0143]** In some embodiments, the method is performed by a network node (e.g., UE **102** or AP **104** or sever **190**), and the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.

**[0144]** In some embodiments, the network node is UE **102**, and the step of transmitting the control message for the RIS comprises: i) the UE transmitting the control message to the RIS or ii) the UE transmitting the control message to another network node capable of communicating with the RIS.

**[0145]** In some embodiments, the network node is an AP **104**, and the step of transmitting the control message for the RIS comprises: i) the AP **104** transmitting the control message directly to the RIS or ii) AP **104** transmitting the control message to another network node (e.g., UE **102**) capable of communicating with the RIS.

**[0146]** In some embodiments, the network node is server **190**, and the step of transmitting the control message for the RIS

RIS comprises: i) the server transmitting the control message directly to the RIS or ii) the server transmitting the control message to another network node capable of communicating with the RIS.

**[0147]** In some embodiments, obtaining the first set of CQM values further comprises: configuring the first particular configurable reflector in accordance with a third reflector configuration; and after configuring the first particular configurable reflector in accordance with the third reflector configuration, obtaining a third CQM value associated with the third reflector configuration. In some embodiments, the third reflector configuration specifies a phase shift; and configuring the first particular configurable reflector in accordance with the third reflector configuration comprises configuring the first particular configurable reflector to produce the phase shift.

**[0148]** FIG. **12** is a block diagram of network node **1200**, according to some embodiments, that can implement any one or more of the network nodes described herein. That is, network node **1200** can perform the above described methods. As shown in FIG. **12**, network node **1200** may comprise: processing circuitry (PC) **1202**, which may include one or more processors (P) **1255** (e.g., a general purpose microprocessor and/or one or more other processors, such as an application specific integrated circuit (ASIC), field-programmable gate arrays (FPGAs), and the like), which processors may be co-located in a single housing or in a single data center or may be geographically distributed (i.e., network node **1200** may be a distributed computing apparatus); at least one network interface **1248** comprising a transmitter (Tx) **1245** and a receiver (Rx) **1247** for enabling network node **1200** to transmit data to and receive data from other nodes connected to a network **110** (e.g., an Internet Protocol (IP) network) to which network interface **1248** is connected (directly or indirectly) (e.g., network interface **1248** may be wirelessly connected to the network **110**, in which case network interface **1248** is connected to an antenna arrangement); and a storage unit (a.k.a., "data storage system") **1208**, which may include one or more non-volatile storage devices and/or one or more volatile storage devices. In embodiments where PC **1202** includes a programmable processor, a computer readable medium (CRM) **1242** may be provided. CRM **1242** stores a computer program (CP) **1243** comprising computer readable instructions (CRI) **1244**. CRM **1242** may be a non-transitory computer readable medium, such as, magnetic media (e.g., a hard disk), optical media, memory devices (e.g., random access memory, flash memory), and the like. In some embodiments, the CRI **1244** of computer program **1243** is configured such that when executed by PC **1202**, the CRI causes network node **1200** to perform steps described herein (e.g., steps described herein with reference to the flow charts). In other embodiments, network node **1200** may be configured to perform steps described herein without the need for code. That is, for example, PC **1202** may consist merely of one or more ASICs. Hence, the features of the embodiments described herein may be implemented in hardware and/or software.

**[0149]** While various embodiments are described herein, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of this disclosure should not be limited by any of the above-described exemplary embodiments. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the disclosure unless otherwise indicated herein or otherwise clearly contradicted by context.

**[0150]** Additionally, while the processes described above and illustrated in the drawings are shown as a sequence of steps, this was done solely for the sake of illustration. Accordingly, it is contemplated that some steps may be added, some steps may be omitted, the order of the steps may be re-arranged, and some steps may be performed in parallel.

## REFERENCES

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**1**. A method for configuring a reconfigurable intelligent surface, RIS, wherein the RIS comprises a plurality of configurable reflectors, the method comprising:

obtaining a first set of channel quality measurement, CQM, values, wherein the first set of COM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration;

based on the obtained first set of CQM values, selecting a reflector configuration; and

configuring at least the first particular configurable reflector based on the selected reflector configuration, wherein

a) the method is performed by the RIS and the step of obtaining the CQM values comprises obtaining the CQM values from a network node, or

b) the method is performed by a network node and the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.

**2**. The method of claim **1**, wherein obtaining the first set of CQM values comprises:

configuring the first particular configurable reflector in accordance with a first reflector configuration;

after configuring the first particular configurable reflector in accordance with the first reflector configuration, obtaining a first CQM value, CQM**1**, associated with the first reflector configuration;

configuring the first particular configurable reflector in accordance with a second reflector configuration; and

after configuring the first particular configurable reflector in accordance with the second reflector configuration, obtaining a second CQM value, CQM**2**, associated with the second reflector configuration.

**3**. The method of claim **2**, wherein selecting a reflector configuration based on the obtained first set of CQM values comprises:

determining the best CQM value from among the CQM values included in the first set of CQM values; and

selecting the reflector configuration associated with the best CQM value.

**4**. The method of claim **2**, wherein selecting a reflector configuration based on the obtained first set of CQM values comprises:

comparing the first CQM value with the second COM value; and

selecting the first or second reflector configuration based on the comparison.

**5**. The method of claim **4**, wherein selecting the first or second reflector configuration based on the comparison comprises:

selecting the first reflector configuration if the first CQM value is greater than the second CQM value;

selecting the second reflector configuration if the first CQM value is less than the second CQM value; or

selecting either the first or the second reflector configuration if the first CQM value is equal to the second CQM value.

**6**. The method of claim **2**, wherein

the first reflector configuration specifies a first phase shift,

configuring the first particular configurable reflector in accordance with the first reflector configuration comprises configuring the first particular configurable reflector to produce the first phase shift,

the second reflector configuration specifies a second phase shift, and

configuring the first particular configurable reflector in accordance with the second reflector configuration comprises configuring the first particular configurable reflector to produce the second phase shift.

**7**. The method of claim **6**, wherein

the first phase shift, $\varphi\mathbf{1}$, is X radians, and

the second phase shift, $\varphi\mathbf{2}$, is $(X+\pi)$ or $(X-\pi)$ radians.

**8**. The method of claim **2**, wherein

the first reflector configuration specifies an off state,

configuring the first particular configurable reflector in accordance with the first reflector configuration comprises placing the first particular configurable reflector in the off state,

the second reflector configuration specifies an on state, and

configuring the first particular configurable reflector in accordance with the second reflector configuration comprises placing the first particular configurable reflector in the on state.

**9**. The method of claim **1**, wherein

the method is performed by the RIS, and

the step of obtaining the CQM values comprises obtaining the CQM values from a network node.

**10**. The method of claim **9**, wherein the network node is:

a user equipment,

an access point, or

a server.

**11**. The method of claim **1**, wherein

the method is performed by a network node, and

the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.

**12**. The method of claim **11**, wherein

the network node is a user equipment, UE, and

the step of transmitting the control message for the RIS comprises: i) the UE transmitting the control message to the RIS or ii) the UE transmitting the control message to another network node capable of communicating with the RIS.

**13**. The method of claim **11**, wherein

the network node is an access point, AP, and

the step of transmitting the control message for the RIS comprises: i) the AP transmitting the control message directly to the RIS or ii) the AP transmitting the control message to another network node capable of communicating with the RIS.

**14**. The method of claim **11**, wherein

the network node is a cloud server, and

the step of transmitting the control message for the RIS comprises: i) the cloud server transmitting the control message directly to the RIS or ii) the cloud server transmitting the control message to another network node capable of communicating with the RIS.

**15**. The method of claim **8**, wherein obtaining the first set of COM values further comprises:

configuring the first particular configurable reflector in accordance with a third reflector configuration; and

after configuring the first particular configurable reflector in accordance with the third reflector configuration, obtaining a third CQM value associated with the third reflector configuration.

**16**. The method of claim **15**, wherein

the third reflector configuration specifies a phase shift; and

configuring the first particular configurable reflector in accordance with the third reflector configuration comprises configuring the first particular configurable reflector to produce the phase shift.

**17**. (canceled)

**18**. (canceled)

**19**. (canceled)

**20**. (canceled)

**21**. A non-transitory computer readable storage medium storing instructions which when executed by processing circuitry of a network node causes the network node to perform the method of claim **1**.

**22**. (canceled)

**23**. A first network node for configuring a reconfigurable intelligent surface, RIS, wherein the RIS comprises a plurality of configurable reflectors, the first network node comprising:

a storage unit; and

processing circuitry coupled to the storage unit, wherein the network node is configured to:

obtain a first set of channel quality measurement, COM, values, wherein the first set of CQM values is associated with at least a first particular configurable reflector of the RIS, and further wherein each CQM value included in the set is associated with a reflector configuration;

based on the obtained first set of CQM values, select a reflector configuration; and

configure at least the first particular configurable reflector based on the selected reflector configuration, wherein

a) the first network node is the RIS and the step of obtaining the CQM values comprises obtaining the COM values from a second network node, or

b) the step of configuring the first particular configurable reflector comprises transmitting a control message for the RIS, wherein the control message indicates the reflector configuration.

**24**. (canceled)

**25**. (canceled)

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