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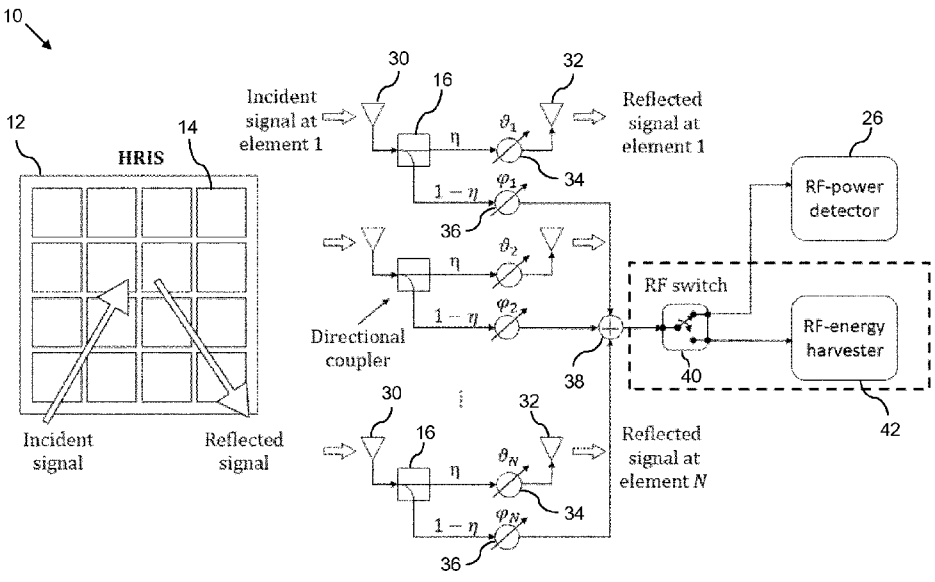


Fig. 2

(57) Abstract: The invention provides a reflective device (10) as well as a method of operating a reflective device (10) comprising an array of reflective elements (14), each reflective element (14) being under control of a control element (28). According to an embodiment, the method comprises dividing, for each of the reflective elements (14), an incident RF signal into at least a first portion and at least a second portion; providing the first portion of the RF signal as reflection signal of the respective reflective element (14); and selectively setting either a first operational state, in which the second portion of the RF signal is provided as probing signal for performing an analysis of the incident RF signal, or a second operational state, in which the second portion of the RF signal is fed into an energy harvester (42) configured to collect the RF-energy of the RF signal.

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ENERGY SELF-SUFFICIENT AUTONOMOUS RECONFIGURABLE INTELLIGENT SURFACES, RIS, AND METHOD FOR OPERATING THE SAME

The present invention relates to a reflective device comprising an array of reflective elements as well as to a method for operating such reflective device.

Reflective intelligent surfaces (RISs) are a groundbreaking technology that has the capability of controlling how signal waves propagate. In particular, they can be dynamically configured to modulate their reflection properties to steer and focus the reflected signal towards the intended directions and improve the overall propagation conditions. For example, they can be used to create high-gain reflected paths able to overcome propagation impairments like attenuating objects, e.g. walls and buildings, to reach users in shadowed communication areas. The ability of controlling the propagation properties provided by RISs brings the feature of programmability in the radio environment, which has been always considered as an adversary black box, making it de-facto a new variable to be optimized for improved communication performances.

To properly optimize the RIS configuration in a base station (BS)/user equipments (UEs) setting, the BS-RIS and the RIS-UEs channels must be known. Therefore, it is required to execute a channel estimation procedure before optimizing the RIS configuration. Due to the absence of signal processing capabilities at the RIS, channel estimation is typically performed on the cascaded end-to-end BS-RIS-UEs channel, i.e., the BS-RIS and RIS-UEs channels are obtained indirectly via complex channel estimation techniques leveraging on channel measurements at the BS and/or at the UEs. Such techniques require control on the RIS configuration, e.g. by setting predefined RIS configurations and measuring their effect on the cascaded channel. Moreover, they imply the availability of an ad-hoc control channel between the BS and the RIS allowing them to coordinate their operations during channel estimation.

Recently, a Hybrid RIS (HRIS) hardware architecture has been proposed. HRISs can absorb a portion of the impinging signal, thus enabling some processing. On

top of the HRIS hardware architecture and its signal processing ability, the channel estimation of the RIS-BS and RIS-UEs channel can be done locally at the RIS (as described, e.g., in I. Alamzadeh, G.C. Alexandropoulos, N. Shlezinger *et al.,* "A reconfigurable intelligent surface with integrated sensing capability," *Sci Rep* **11**, 20737 (2021). doi: 10.1038/s41598-021-99722-x), and be used to autonomously configure the surface without involving an ad-hoc control channel between the RIS and the BS (for reference, see A. Albanese, F. Devoti, V. Sciancalepore, M. Di Renzo and X. Costa-Pérez, "MARISA: A Self-configuring Metasurfaces Absorption and Reflection Solution Towards 6G," *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*, 2022, pp. 250-259, doi: 10.1109/INFOCOM48880.2022.9796976). The self-configuring feature enables a seamless integration of the RIS devices into existing networks and standards, making their deployment agile.

The HRIS hardware, due to its quasi-passive behaviour, is in general characterized by a very limited operational power consumption. Hence, compact batteries may be sufficient to power HRISs for a reasonably long period of time, which depends on the overall battery capacity and power consumption of the device. Nonetheless, in order to keep the device operational, the use of batteries requires unavoidable periodic maintenance to substitute or recharge them when out of charge. Alternatively, HRISs could be supplied with an external power source, e.g. power plug, which however would limit their deployment agility and flexibility.

It is therefore an object of the present invention to improve and further develop a reflective device of the initially described type and a method for operating the same in such a way that the deployment agility and flexibility is improved.

In accordance with the invention, the aforementioned object is accomplished by a method of operating a reflective device comprising an array of reflective elements, each reflective element being under control of a control element, wherein the method comprises: dividing, for each of the reflective elements, an incident RF signal into at least a first portion and at least a second portion; providing the first portion of the RF signal as reflection signal of the respective reflective element; and selectively setting either a first operational state, in which the second portion of the

RF signal is provided as probing signal for performing an analysis of the incident RF signal, or a second operational state, in which the second portion of the RF signal is fed into an energy harvester configured to collect the RF-energy of the RF signal.

Furthermore, the aforementioned object is accomplished by a reflective device comprising: a control element; an energy harvester configured to collect the RF-energy of a received RF signal; an array of reflective elements, wherein each reflective element is under control of the control element and comprises means for dividing an incident RF signal into at least a first portion and at least a second portion and for providing the first portion of the RF signal as reflection signal of the respective reflective element; and a switching mechanism configured to allow to selectively set either a first operational state, in which the second portion of the RF signal is provided as probing signal for performing an analysis of the incident RF signal, or a second operational state, in which the second portion of the RF signal is fed into the energy harvester.

Embodiments of the present disclosure provide an energy harvesting solution for hybrid and self-configuring RISs, which elides the need for external power sources to run the RIS hardware. In an embodiment, the RIS exploits the local CSI already available for the self-configuration of its reflection properties for maximizing the energy absorbed from the active devices and harvest it to power the active components of the hardware without requiring external power sources. It is worth mentioning that the proposed solution to the power supply by means of an energy harvesting technique, when integrated in the self-configuring HRIS, leads to a fully-autonomous RISs, i.e. self-sufficient from the energetic point of view and self-configuring.

According to an embodiment, the reflective device is based on a hardware architecture including an RF switch, a power harvester and two independent phase shifter banks for – independent – absorption and reflection optimization, which is providing the HRIS with efficient harvesting capabilities, thereby removing the need for external power sources. The harvesting process may be optimized according to the channel conditions estimated during a self-configuration phase, which may exploit the absorbed power of incoming signals not only for communication but also

for harvesting. As such, the proposed solution enables advanced energy harvesting at the RIS (without disrupting the service) to effectively gather energy from communicating devices and operate the RIS hardware.

According to an embodiment, for providing the reflective device with energy harvesting capabilities, the method of operating the reflective device may include one or more of the following steps:

1) Partially absorb the RF signal incident on the reflective device for a probing phase in a HRIS.
2) Perform channel estimation based on the output of the probing phase
3) Optimize the harvesting process based on the estimated channel
4) Convert the absorbed RF signal into useful energy
5) Implement a closed loop control that monitors the state of charge of a battery and prevents from power loss.

According to an embodiment, the RF-energy collected by the energy harvester may be converted into useful energy to operate the reflective device. In other words, the energy harvester may convert the absorbed RF power to electrical power, which can then be used to operate the reflective device, possibly without the need for an external power supply. For instance, the energy harvester may be configured to extract energy from the EM fields of the RF signal in the form of DC voltage by means of a rectifier or a voltage multiplier that boosts the output DC by stacking multiple rectifiers.

According to an embodiment, the converted energy, i.e. the electrical power, may be provided for direct use by the reflective device. Alternatively or additionally, the converted energy may be stored in an energy storage system of the reflective device, e.g. a rechargeable battery, for later use.

According to an embodiment, the second portions of the RF signal from all reflective elements of the reflective device may be summed up by means of one or more RF combiners. Preferably, the RF combiners are placed upstream the switching mechanism such that only the resulting signal is fed into the switching mechanism.

According to an embodiment, the switching mechanism may include an RF switch configured to selectively steer the summed up RF signal either to an RF-power detector configured to obtain a power profile of the signal or to the energy harvester. Specifically, considering a reflective device, e.g. a HRIS, comprising an array of hybrid meta-atoms, which are able to simultaneously reflect and absorb (i.e., sense the power of) incident signals, each reflective element may be coupled with a sampling waveguide that propagates the absorbed (i.e., sensed) power of the incident electromagnetic (EM) waves towards some downstream RF hardware for enabling digital signal processing (DSP). To reduce the complexity and cost of the required hardware with respect to conventional HRIS and enable energy harvesting (EH), the proposed reflective device may not be equipped with fully-fledged RF chains, but only with an RF power detector and an RF energy harvester. The signals absorbed by each metasurface element are summed together by means of RF combiners, which may be implemented as lumped components throughout the metasurface RF circuit. The resulting signal may be fed into an RF switch, which routes it to either the above-mentioned power detector or the energy harvester. The power detector, which may be made by, e.g., a thermistor or a diode detector, may be configured to convert the RF power into a measurable direct current (DC) or a low frequency (LF) signal.

According to an embodiment, the method may comprise the following steps:

1) using, when the first operational state is set, the probing signal to obtain a power profile of the incident RF signal;
2) performing a CSI, Channel State Information, estimation based on the obtained power profile;
3) using the estimated CSI to extract the angle of arrival of the incident RF signal; and
4) computing an optimized absorption configuration that enhances the absorption properties of the reflective elements towards the angle of arrival of the incident RF signal.

Based thereupon, the optimized absorption configuration may be enforced in such a way that each of the reflective elements applies the computed optimized

absorption configuration on the second portion of the RF signal by means of a phase shifter. In the considered hardware architecture, the reflected and absorbed signals may be subject to a phase shift applied by the metasurface elements. In particular, each signal may be fed to its corresponding phase shifter bank, which is optimized independently of the other, allowing to simultaneously control the signal reflection and power absorption properties of the reflective element. In other words, the reflective element implements two branches – reflection branch and absorption branch – that enable independent signal routes with different phase shift banks. While the reflective element continuously reflects the impinging signals through the reflection branch, the absorption branch is involved in two fundamental operations, i.e. probing and EH, and may leverage on power-based indirect beamforming, which is described below. As will be appreciated, instead of an independent optimization, the phase shifts optimization can also be performed in a dependent way, in which the same phase shifter bank operates on both the reflected and absorbed signals.

According to an embodiment, the computed optimized absorption configuration may be communicated to the reflective elements by means of a push module of the control element via a control link.

According to an embodiment, it may be provided that, after the optimized absorption configuration has been determined and enforced, a switch from the first operational state to the second operational state is performed, wherein the system may remain in the second operational state for a certain time interval of predetermined or configurable length.

According to an embodiment, a state of charge of the energy storage system may be monitored, continuously or in regular time intervals, and the operational mode may be adjusted based on whether the state of charge is above or below a predefined threshold. For instance, in case the state of charge of the energy storage system is above the threshold, an operational mode may be executed in which the reflective device regularly switches between the first operational state and the second operational state. On the other hand, in case the state of charge of the energy storage system is below the given threshold, an operational mode may be executed in which the reflective device remains in the second operational state for

a certain time interval of predetermined or configurable length without any determination of an optimized absorption configuration.

According to an embodiment, the energy storage system may be dimensioned (with regard to its storage capacity) based on conditions for energy self-sufficiency of the reflective device. For instance, these conditions may be derived by means of a model of the energy storage system, in which the energy storage in the energy storage system (i.e. the battery charge and discharge processes) is represented as a homogeneous Markov process. Specifically, the energy storage in the battery of the reflective device may be represented as a homogeneous Markov process, in which the next battery state-of-charge (SoC) depends only on the current one, satisfying the so-called Markov memorylessness property.

There are several ways how to design and further develop the teaching of the present invention in an advantageous way. To this end, it is to be referred to the dependent claims on the one hand and to the following explanation of preferred embodiments of the invention by way of example, illustrated by the figure on the other hand. In connection with the explanation of the preferred embodiments of the invention by the aid of the figure, generally preferred embodiments and further developments of the teaching will be explained. In the drawing

Fig. 1 is a diagram schematically illustrating an example of HRIS hardware architecture with self-configuring capabilities,

Fig. 2 is a diagram schematically illustrating a HRIS with energy harvesting capabilities according to an embodiment of the present disclosure,

Fig. 3 is a diagram schematically illustrating an operational work-flow including sensing, channel estimation and energy harvesting according to an embodiment of the present disclosure,

Fig. 4 is a diagram schematically illustrating operation of a low power consumption mode according to an embodiment of the present disclosure, and

Fig. 5 is a diagram illustrating a reference Markov-chain-based battery state transition diagram used according to an embodiment of the present disclosure.

Fig. 1 depicts an example of HRIS hardware 10 with self-configuring capabilities. In accordance with the basic RIS concept, the hardware 10 comprises a surface 12 including a number of reflective elements 14. In the illustrated example, the reflective elements 14_1, ..., 14_N are arranged in form of a 4x4 array (i.e., N=16). Each reflective element 14, also known as meta-atom, comprises an antenna element (not shown) and a directional coupler 16. The directional coupler 16 provides (after applying an adjustable reflection configuration θ) a portion η of a signal incident on the respective reflective element 14 as reflection signal and steers a remaining portion $1-\eta$ of the incident signal towards a CSI (Channel State Information) estimation module 18. For instance, the CSI estimation module 18 may be in charge of estimating the CSI of a BS-RIS channel and RIS-UEs channels. As shown, such module can be either a signal-based module 18a, hence comprising RF-chains 20 and digital signal processing units (DSP) 22 to digitally perform the CSI estimation, or a power-based module 18b, hence exploiting RF-combiners 24 and power detection of a RF-power detector 26 to perform CSI estimation. Once CSI of the channels is available, the results are provided to a HRIS controller 28 that is configured to optimize the HRIS reflection based on the received information.

The HRIS hardware concept as describe above is in general, due to its quasi-passive behaviour, characterized by a very limited operational power consumption. Hence, compact batteries may be sufficient to power HRISs for a reasonably long period of time, which depends on the overall battery capacity and power consumption of the device. Nonetheless, in order to keep the device operational, the use of batteries requires unavoidable periodic maintenance to substitute or recharge them when out of charge. Alternatively, HRISs could be supplied with an external power source, e.g. power plug, which however would limit their deployment agility and flexibility.

As explained above with reference to Fig. 1, HRISs are capable of absorbing a fraction of the impinging signal in order to process it. Such a portion of the signal is dependent on the physical design of the respective meta-atom and cannot be modulated over time. This means that the HRIS elements are absorbing the signal also when no processing is needed, which leads to a waste of energy.

Embodiments of the present invention provide a modified HRIS hardware architecture that provides the HRIS with radio frequency (RF) energy harvesting (EH) capabilities in order to convert the absorbed signal into useful energy to operate the device. In particular, energy harvesting may be activated when no signal processing is performed, thus saving precious energy, which would be otherwise wasted. This energy harvesting capability is potentially providing the HRIS with unlimited power to operate, thus eliding the need for an external power source or periodic maintenance for battery substitution.

According to an embodiment, the present disclosure provides a HRIS hardware architecture that is configured to provide the HRIS with RF energy harvesting capabilities. This architecture provides the advantageous feature of converting the absorbed signal into energy to operate the device. The harvested energy, once collected, can be directly used to operate the device or can be stored in an energy storage system for later use, e.g., in a rechargeable battery.

According to an embodiment, it may be provided that the energy harvesting capabilities can be switched on and off or can be activated and deactivated. For instance, it may be provided that energy harvesting is activated when no signal processing is performed, thus saving precious energy that otherwise would be wasted, and potentially providing the RIS with unlimited power availability. This feature removes the need for an external power source and for periodic maintenance to substitute the device‘s battery.

According to an embodiment, the energy storage system configured to store the harvested energy may include a capacitor, either in addition or as an alternative to a rechargeable battery. Capacitors present the benefit of a longer lifespan and lower production cost than batteries. However, they tend to discharge faster than batteries

and hence need for more frequent charging. Nonetheless, since HRIS are low-power devices, RF energy harvesting may be sufficient to maintain the capacitor's charge.

Fig. 2 schematically illustrates a HRIS hardware architecture in accordance with an embodiment of the present disclosure. Like reference numbers denote like or similar components as in Fig. 1.

Like in the example of Fig. 1, the HRIS hardware 10 comprises a surface 12 including a number of reflective elements 14. In the illustrated embodiment, the reflective elements 14_1, ..., 14_N are arranged in form of a 4x4 array (i.e., N=16). However, it is appreciated that any other number and arrangement of reflective elements 14 is likewise possible.

Each reflective element 14 comprises an antenna element 30 and a directional coupler 16. The directional coupler 16 is configured to split a signal incident on the respective reflective element 14 (i.e., the signal received via antenna element 30) in reflection and absorption branches of the HRIS RF circuits. More specifically, the directional coupler 16 may be configured to provide a first portion η of the received signal as reflection signal that is sent out via transmitter 32 after that a reflection configuration ϑ is applied (e.g., by means of phase shifters 34). It should be noted that although antenna element 30 and transmitter 32 are shown as separate devices in Fig. 2, both can be integrated into a single transceiver device.

At the same time, the remaining portion $1-\eta$ of the received signal is fed to the absorption branch of the HRIS, where an absorption configuration φ is applied (e.g., by means of phase shifters 36). The absorbed portions of the signals coming from each element 14 are summed up by means of one or more RF combiners 38.

According to the illustrated embodiment, an RF switch 40 is placed downstream the RF combiners 38. The RF switch 40 is configured to steer the signal received from the RF combiners 38 either towards a RF-power detector 26 or towards an RF-energy harvester 42.

As already mentioned in connection with Fig. 1, the RF-power detector 26 allows to sense the received power in different directions, hence obtaining a power profile describing the angle of arrival of the signal from BS and UEs. Based on the sensed power, the CSI information can be estimated locally at the HRIS, as described in detail in A. Albanese, F. Devoti, V. Sciancalepore, M. Di Renzo and X. Costa-Pérez, "MARISA: A Self-configuring Metasurfaces Absorption and Reflection Solution Towards 6G", *IEEE INFOCOM 2022 – IEEE Conference on Computer Communications*, 2022, pp. 250-259, doi: 10.1109/INFOCOM48880.2022.9796976, which is hereby incorporated herein by reference.

On the other hand, the RF-energy harvester 42 may be configured to allow to capture the absorbed RF energy and reuse it for powering the HRIS hardware 10. For instance, the power harvested by the RF-energy harvester 42 may be fed into a rechargeable battery (or any other power storage means), which powers the active components of the hardware. Accordingly, the proposed architecture according to the embodiment of Fig. 2 enhances the one proposed in the document referenced above with additional components including one or more of the following components: the components highlighted within the dashed box, namely i) the RF switch 40 and ii) the RF energy harvester 42, as well as iii) the phase shifters 36 of the absorption branch, and iv) a rechargeable battery (not shown in Fig. 2).

The additional hardware components provide the following capabilities to the HRIS 10:

As explained above, the RF switch 40 allows to steer the absorbed signal towards the RF-detector 36 or towards the RF-energy harvester 42. As such, the RF switch 40 controls the operational function of the absorption branch, i.e., power sensing or energy harvesting. According to an embodiment, the RF switch 40 may be implemented by means of CMOS technology.

The RF-energy harvester 42 may be configured to transform the absorbed portion of the RF signal into energy to power the device 10. According to an embodiment, the RF-energy harvester 42 may be configured to extract energy from the EM fields in the form of DC voltage. For instance, the RF-energy harvester 42 may be

implemented by means of a rectifier or a voltage multiplier that boots the output DC by stacking multiple rectifiers, such as in the Cockcroft-Walton or Dickson configurations (as described, e.g., in Tran, L.-G., Cha, H.-K., and Park, W.-T., "RF power harvesting: a review on designing methodologies and applications", Micro and Nano Systems Letters, vol. 5, no. 1, 2017. doi:10.1186/s40486-017-0051-0, which is hereby incorporated herein by reference).

The phase shifters 36 of the absorption branch may be configured to allow enhancing the absorption properties of the HRIS 10 towards the angle of the arrival of the incident signal and optimize the absorption properties to maximize the energy input, without affecting the reflection properties of the device. In particular, given the CSI estimation, the HRIS absorption configuration can be optimized to focus the absorption properties of the HRIS towards the directions of arrival of the signal, and maximize the absorbed power. Moreover, the optimization can leverage the intensity of the sensed power at different directions to increase the gain towards devices that are providing more power, i.e., that might be closer to the HRIS or transmitting at higher power levels, to further increase the energy harvesting performance.

While the architecture depicted in Fig. 2 refers to a HRIS architecture with power-based processing (by means of RF-power detector 26), it will be appreciated that likewise the core novel elements as described above can be seamlessly integrated into a HRIS architecture with signal-based processing (e.g., by means of RF-chains 20 and DSP units 22, as described above in connection with Fig. 1).

With reference to Fig. 3, an operational workflow for performing sensing, channel estimation, and energy harvesting is described in accordance with an embodiment of the present disclosure. Again, like reference numbers denote like or similar components as in Figs. 1 and 2.

In the illustrated situation, the RF switch 40 is set to steer the absorbed signal to the power detector 26. For instance, the absorbed signal may be the signal summed up by the RF combiner 38 from the absorption branches of the reflective elements 14_1, ..., 14_N as described above with reference to Fig. 2. In this situation, the power detector 26 may start measuring the absorbed power, while the RIS controller 28

sweeps over the probing beam patterns, e.g., as described in Albanese, F. Devoti, V. Sciancalepore, M. Di Renzo and X. Costa-Pérez, "MARISA: A Self-configuring Metasurfaces Absorption and Reflection Solution Towards 6G", *IEEE INFOCOM 2022 – IEEE Conference on Computer Communications*, 2022, pp. 250-259, doi: 10.1109/INFOCOM48880.2022.9796976. The RIS controller 28 comprises a CSI estimation module 44 that may be configured to process the power profile and obtain the CSI estimation, as is known for itself in prior art. The CSI estimation can then be used by optimization module 46 to optimize the absorption and the reflection configuration of the reflective elements 14. To this end, the optimization module 46 may collect the CSI estimated by the CSI estimation module 44, extract the angle of arrival of the signal, and compute the optimal absorption branch configuration to maximize the absorbed power. In this step, the intensity of the power sensed at a given direction can be used to give more absorption gain in the directions with higher sensed power intensity.

The optimized RIS configuration may then be communicated to the reflective elements 14 by push module 48 via control link 50. In this context, it may be provided that the RIS controller 28 enforces the optimized reflection (ϑ) and absorption (φ) configuration on the HRIS.

After determination and enforcement of the optimized RIS configuration, the RF switch 40 is set to steer the absorbed signal to the RF-energy harvester 42. The energy collected by the RF-energy harvester 42 may be directly consumed by the HRIS or may be stored in a battery 52 for later use, as depicted in Fig. 3.

The system remains in this state of energy harvesting for a certain time interval, which may have a predetermined or a configurable length, before the RF switch 40 is switched back to the previous setting to again perform CSI estimation and RIS configuration optimization.

According to an embodiment of the present disclosure, the energy harvesting technology described herein can be integrated in the hardware, e.g., the HRIS can be connected to solar panels 54 to collect additional energy during daytime or when no devices are communicating, as depicted in Fig. 3. Nonetheless, solar panels

would require additional deployment space, as they cannot be collocated on the HRIS surface. Moreover, this alternative solution is not feasible for every HRIS deployment setup, e.g., in indoor deployments.

To address this issue, according to an embodiment, during the operational phases described above the level of the battery 52 may be kept monitored by the HRIS controller 28 through a battery level monitor module 56.

Based on such monitoring, in accordance with an embodiment of the present disclosure, Fig. 4 schematically illustrates a process for selecting a low power consumption mode to prevent battery 52 from being fully discharged.

The left side of Fig.4 shows the "normal" operational mode 62, which is executed as long as the battery level, i.e., the state of charge (SoC) of the battery 52, is above a given threshold, THR, as determined at reference 60 in Fig. 4. The battery's 52 SoC may be monitored by the battery level monitor module 56 shown in Fig. 3. In operational mode 62, operation basically follows the concepts described above with reference to Fig. 3. Accordingly, the operational mode 62 may include the steps of steering energy to RF-power detector 26 (as shown at step 62_1), performing CSI estimation (step 62_2), performing reflection and absorption optimization based on the estimated CSI (step 62_3), and setting RIS configurations according to the optimized absorption and the reflection configuration (step 62_4). After that, the RF switch 40 is set to steer the absorbed signal to the RF-energy harvester 42 (step 62_5).

Operational mode 62 is maintained until the end of the reflection phase of the HRIS (as illustrated at reference 63), whereupon it is determined again whether the battery's 52 SoC value is above the given threshold THR (as illustrated at reference 60). If it is determined that the SoC value is below the threshold THR, the RIS controller 28 may enforce a non-optimized RF-energy harvesting mode 64 including a low consumption configuration on the reflection and absorption. For instance, in this low consumption configuration, the diodes of the meta-atoms that function as the phase shifters 34, 36 may be switched off/deactivated (idle configuration) and the switch 40 may be set to steer the energy to the harvester 42 (resulting in a non-

optimized energy harvesting). As such, in operational mode 64, the HRIS behaves as a scatterer, while it keeps absorbing from the direction enhanced by the idle configuration. Therefore, it absorbs a limited amount of power to refill the battery 52. Once the battery 52 has received enough energy, i.e. SoC>THR, the system returns to "normal" operational mode 62, as depicted in Fig. 4.

According to another aspect, the present disclosure provides a solution for proper HRIS battery dimensioning. In this context, it may be provided that the conditions for energy self-sufficiency of a HRIS are derived by means a model for the HRIS battery. For instance, in such a model the energy storage in the HRIS battery may be represented as a homogeneous Markov process, in which the next battery state-of-charge (SoC) depends only on the current one, satisfying the so-called Markov *memorylessnes* property. A respective Markov-chain-based battery state transition diagram is illustrated in Fig. 5. It is worth highlighting that state 0 is prevented from being an absorbing state for the Markov Chain (MC), namely a state that once entered cannot be left, by assuming that a HRIS with a low battery SoC defaults to an idle configuration that does not consume power while enabling power absorption, just at a lower efficiency. To achieve negligible power consumption, all phase shifters may be deactivated when the battery SoC falls below a minimum guard threshold Γ, thereby making the HRIS only capable of harvesting power from signals incoming from within the solid angle enhanced by the idle beamforming configuration.

Embodiments of the present disclosure define as p_{LoC} the probability of loss of charge (LoC), namely the probability of the MC not being able to meet a negative net stored energy without falling below Γ given its current SoC. In other words, considering all the possible mutually exclusive events leading to a LoC, one can write

$$p_{LoC} = \sum_{j=0}^{s_\Gamma} \sum_{i=0}^{S-1} p_{i,j}\pi_i$$

where S is the number of discrete states corresponding to the possible HRIS battery SoCs, $p_{i,j}$ is the probability of transitioning from SoC i to SoC j and π_i is the probability of being in SoC i, and we denote as S_Γ the state of the MC corresponding to the minimum SoC guard threshold. p_{LoC} depends on the stationary probabilities π and the transition probabilities, which in turn are affected by the number of states S, the energy difference between subsequent states Δ, and the statistics of the net stored energy ΔE, which is given by the difference between the harvested and the consumed energy. Therefore, for a given ΔE distribution, in order to dimension the battery, it may be provided to perform a linear search on S and a set of feasible Δ's and to derive π and the transition probabilities to approach the design p_{LoC}. The corresponding minimal battery capacity is then given by $C = (S-1)\Delta$.

Many modifications and other embodiments of the invention set forth herein will come to mind to the one skilled in the art to which the invention pertains having the benefit of the teachings presented in the foregoing description and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

Claims

1. A method of operating a reflective device (10) comprising an array of reflective elements (14), each reflective element (14) being under control of a control element (28), the method comprising:

dividing, for each of the reflective elements (14), an incident RF signal into at least a first portion and at least a second portion;

providing the first portion of the RF signal as reflection signal of the respective reflective element (14); and

selectively setting either a first operational state, in which the second portion of the RF signal is provided as probing signal for performing an analysis of the incident RF signal, or a second operational state, in which the second portion of the RF signal is fed into an energy harvester (42) configured to collect the RF-energy of the RF signal.

2. The method according to claim 1, further comprising:

converting the RF-energy collected by the energy harvester (42) into useful energy to operate the reflective device (10).

3. The method according to claim 2, further comprising:

providing the useful energy for direct use and/or storing the useful energy in an energy storage system of the reflective device (10) for later use.

4. The method according to any of claims 1 to 3, further comprising:

summing up the second portions of the RF signal from all reflective elements (14) of the reflective device (10) by means of one or more RF combiners (38).

5. The method according to claim 4, further comprising:

using an RF switch (40) to selectively steer the summed up RF signal either to an RF-power detector (26) configured to obtain a power profile of the signal or to the energy harvester (42).

6. The method according to any of claims 1 to 5, further comprising:

using, when the first operational state is set, the probing signal to obtain a power profile of the incident RF signal;

performing a CSI, Channel State Information, estimation based on the obtained power profile;

using the estimated CSI to extract the angle of arrival of the incident RF signal; and

computing an optimized absorption configuration that enhances the absorption properties of the reflective elements (14) towards the angle of arrival of the incident RF signal.

7. The method according to claim 6, further comprising:

applying, for each of the reflective elements (14), the computed optimized absorption configuration on the second portion of the RF signal by means of a phase shifter (36).

8. The method according to claim 7, wherein the computed optimized absorption configuration is communicated to the reflective elements (14) by a push module (48) of the control element (28) via a control link (50).

9. The method according to any of claims 6 to 8, further comprising:

performing, after determining and enforcing the optimized absorption configuration, a switch from the first operational state to the second operational state and remaining in the second operational state for a certain time interval of predetermined or configurable length.

10. The method according to any of claims 3 to 9, further comprising:

monitoring a state of charge of the energy storage system; and

executing, in case the state of charge of the energy storage system is above a given threshold, an operational mode (62) in which the reflective device (10) regularly switches between the first operational state and the second operational state.

11. The method according to claim 10, further comprising:

executing, in case the state of charge of the energy storage system is below the given threshold, an operational mode (64) in which the reflective device (10) remains in the second operational state for a certain time interval of predetermined or configurable length without any determination of an optimized absorption configuration.

12. The method according to any of claims 3 to 11, further comprising:

dimensioning the energy storage system in terms of storage capacity based on conditions for energy self-sufficiency of the reflective device (10), wherein said conditions are derived by means of a model of the energy storage system, in which the energy storage in the energy storage system is represented as a homogeneous Markov process.

13. A reflective device (10), comprising:

a control element (28);

an energy harvester (42) configured to collect the RF-energy of a received RF signal;

an array of reflective elements (14), wherein each reflective element (14) is under control of the control element (28) and comprises means for dividing an incident RF signal into at least a first portion and at least a second portion and for providing the first portion of the RF signal as reflection signal of the respective reflective element (14); and

a switching mechanism configured to allow to selectively set either a first operational state, in which the second portion of the RF signal is provided as probing signal for performing an analysis of the incident RF signal, or a second operational state, in which the second portion of the RF signal is fed into the energy harvester (42).

14. The device according to claim 13, wherein the means for dividing the incident RF signal into at least a first portion and at least a second portion include a directional coupler (16), and/or

wherein the switching mechanism includes an RF switch (40) configured to selectively steer a received RF signal either to an analysis tool configured to obtain a power profile of the incident RF signal or to the energy harvester (42).

15. The device according to claim 13 or 14, wherein each of the reflective elements (14) has an associated phase shifter (36) configured to apply an absorption configuration on the second portion of the RF signal.

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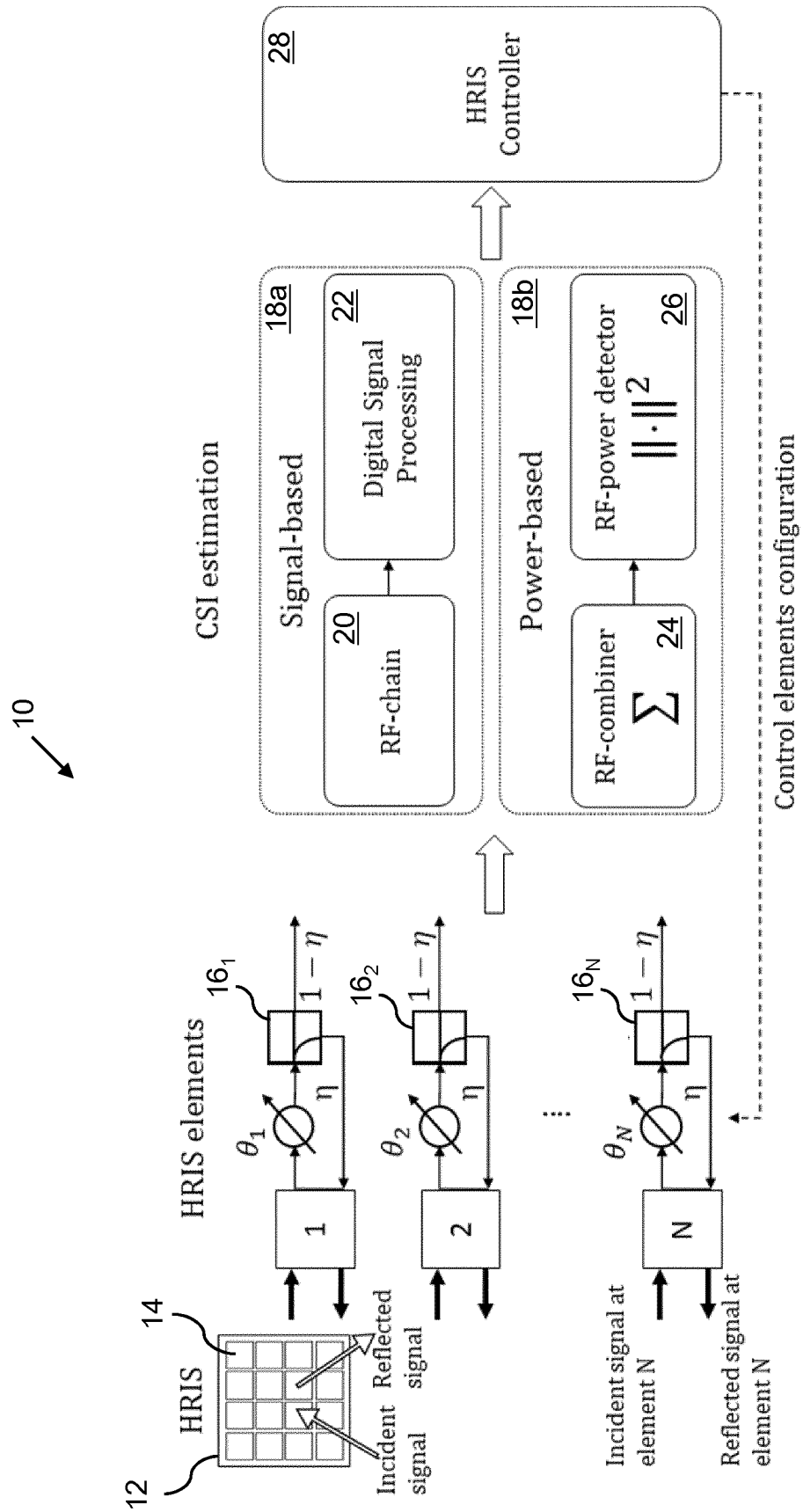

10
12
HRIS
14
HRIS elements
16_1
16_2
16_N
θ_1
θ_2
θ_N
$1-\eta$
η
1
2
N
Incident signal
Reflected signal
Incident signal at element N
Reflected signal at element N
CSI estimation
18a
Signal-based
20
RF-chain
22
Digital Signal Processing
18b
Power-based
RF-combiner
24
RF-power detector
$\|\cdot\|^2$
26
28
HRIS Controller
Control elements configuration

Fig. 1

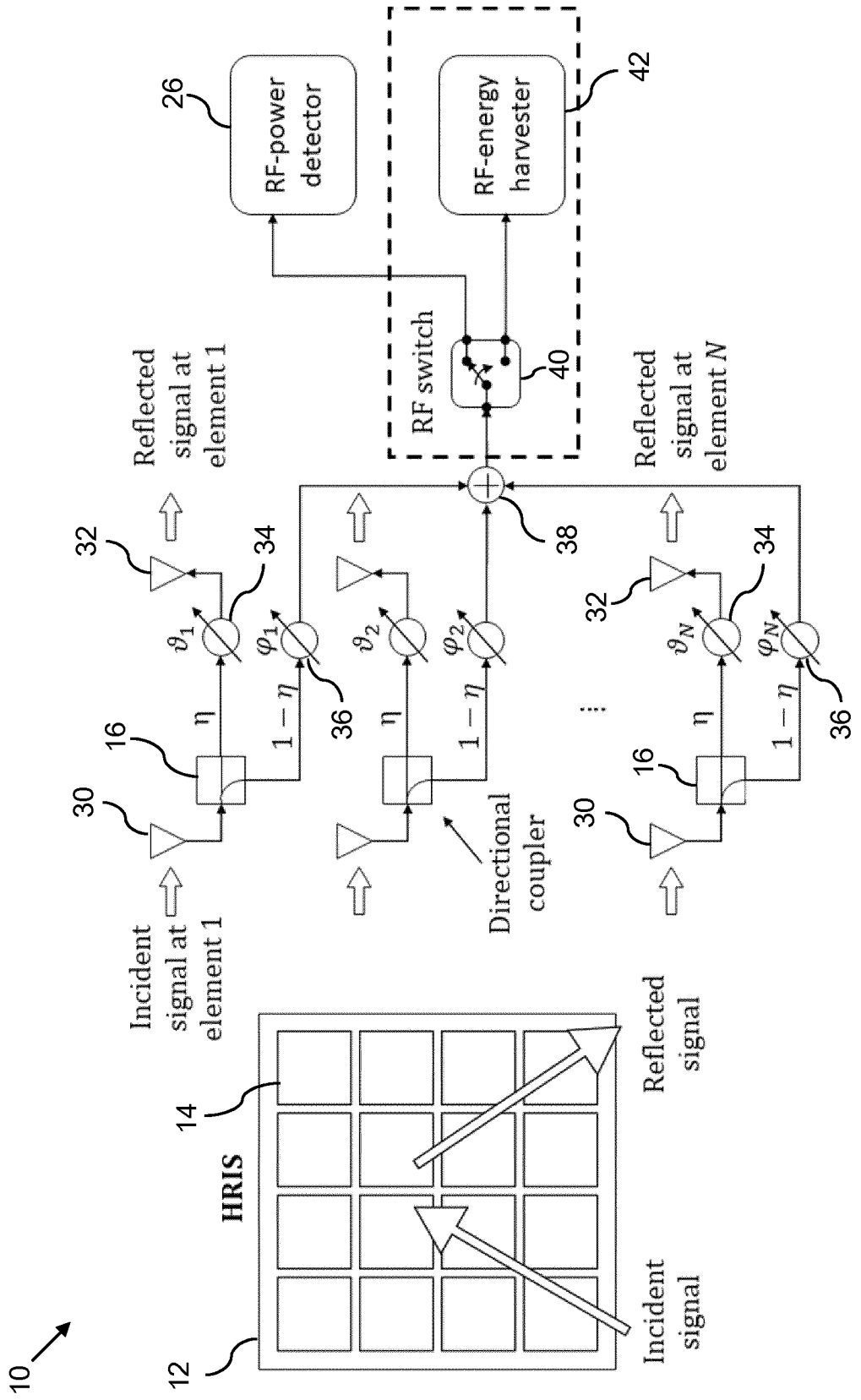

10
12
HRIS
14
Incident signal
Reflected signal
Incident signal at element 1
Reflected signal at element 1
Reflected signal at element N
Directional coupler
RF switch
RF-power detector
RF-energy harvester
26
30
32
34
36
38
40
42
16
η
1 − η
ϑ_1
φ_1
ϑ_2
φ_2
ϑ_N
φ_N

Fig. 2

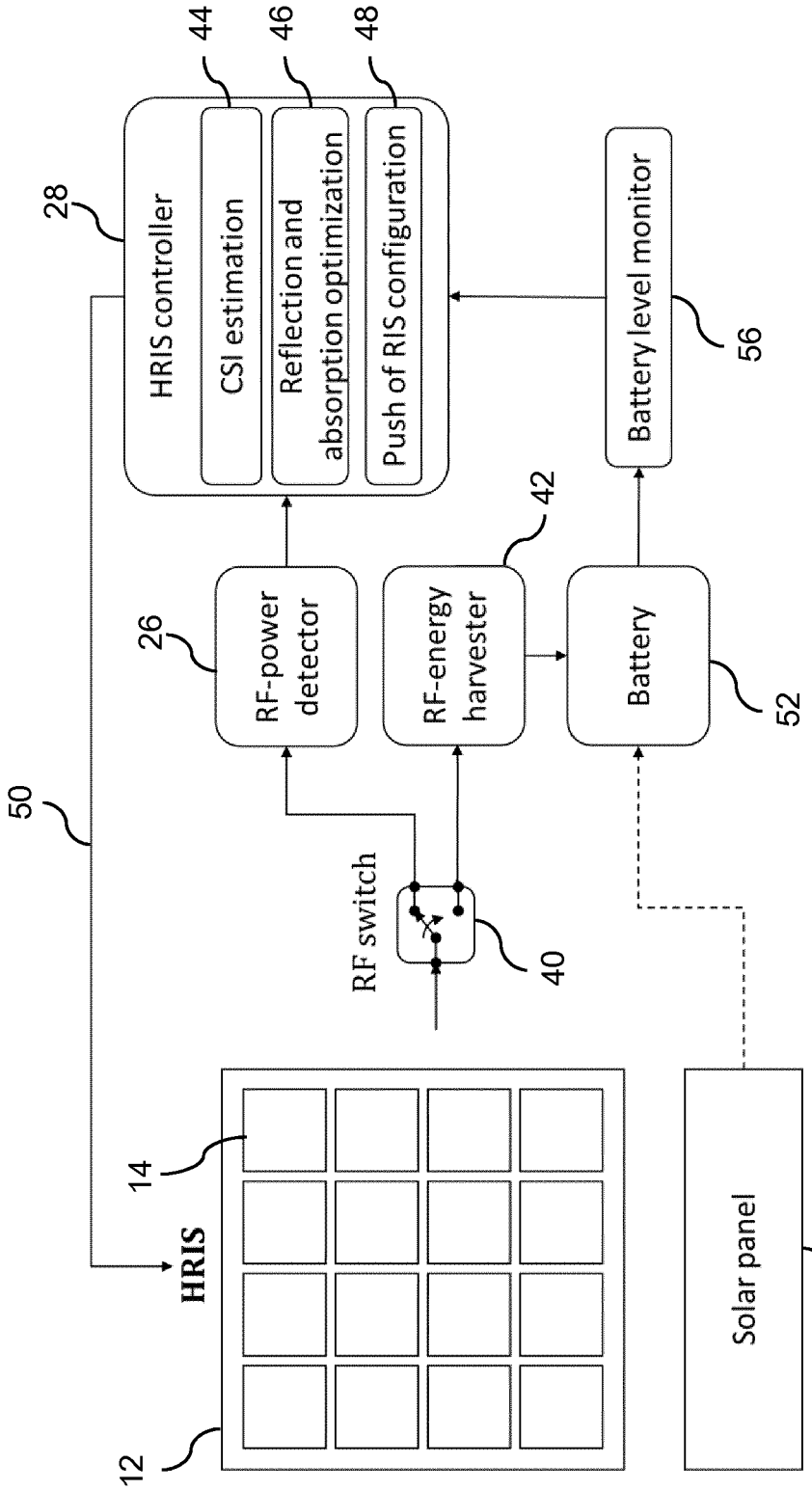

HRIS
12
14
Solar panel
54
RF switch
40
50
RF-power detector
26
RF-energy harvester
42
Battery
52
Battery level monitor
56
HRIS controller
28
CSI estimation
44
Reflection and absorption optimization
46
Push of RIS configuration
48

Fig. 3

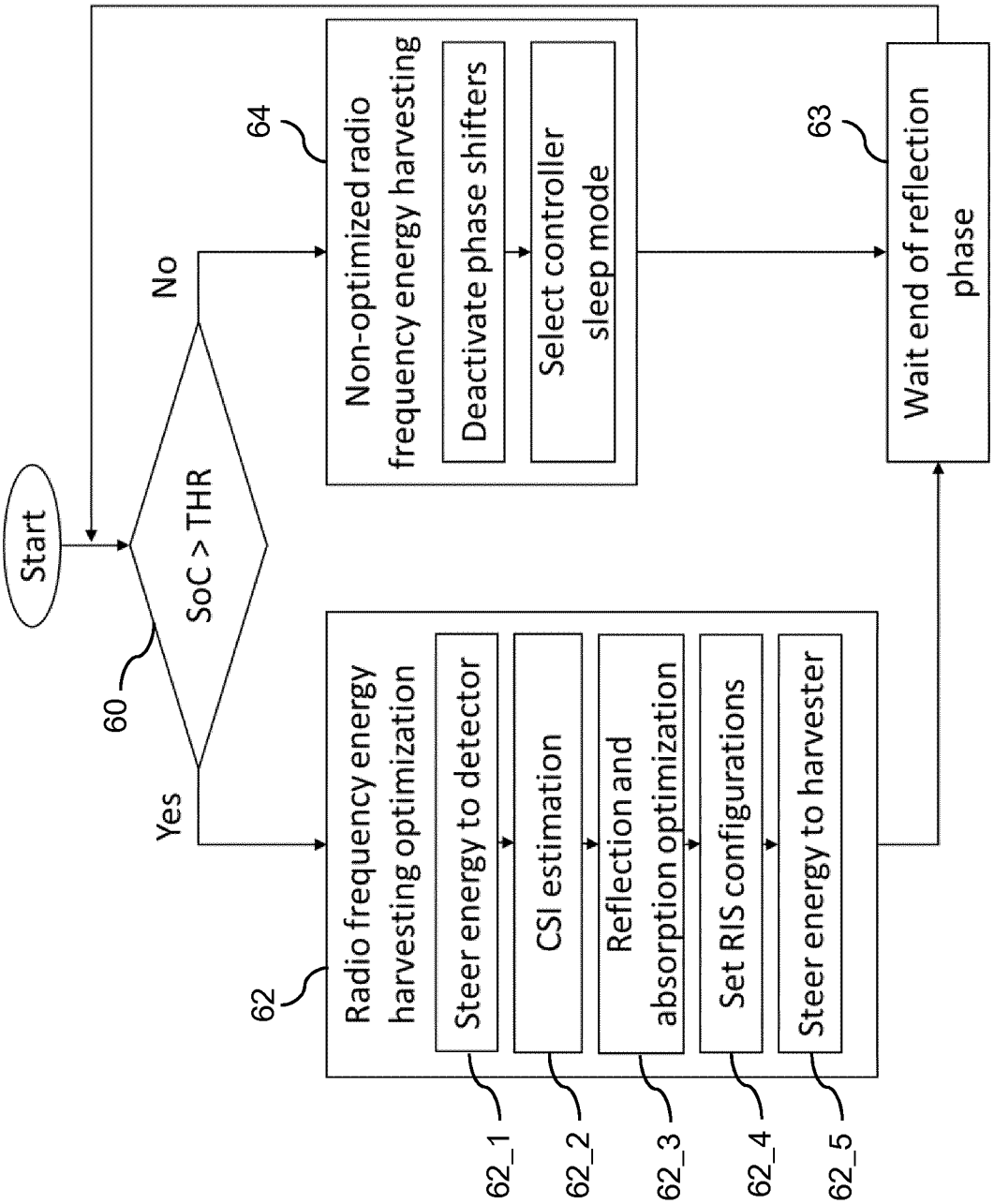

Start
SoC > THR
60
No
Yes
64
Non-optimized radio frequency energy harvesting
Deactivate phase shifters
Select controller sleep mode
63
Wait end of reflection phase
62
Radio frequency energy harvesting optimization
Steer energy to detector
CSI estimation
Reflection and absorption optimization
Set RIS configurations
Steer energy to harvester
62_1
62_2
62_3
62_4
62_5

Fig. 4

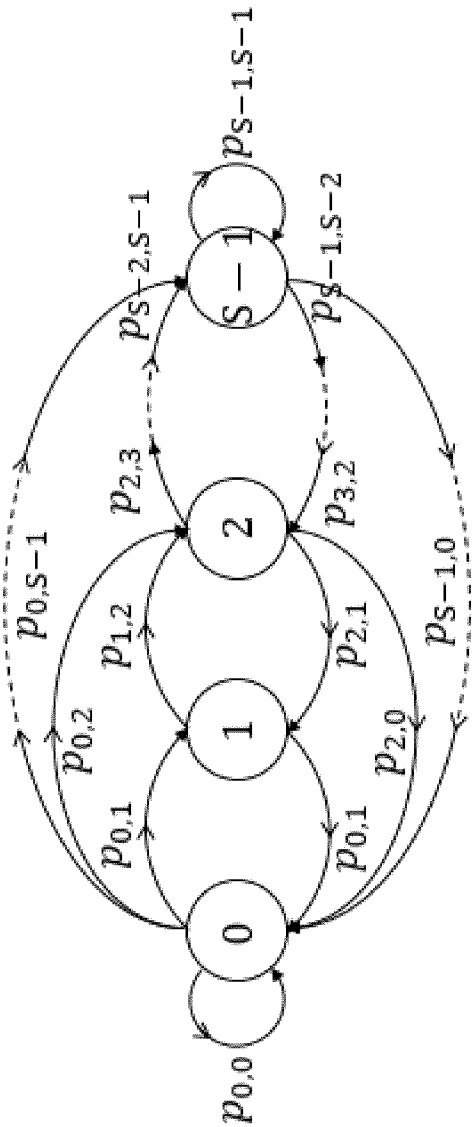

$p_{0,0}$
$p_{0,1}$
$p_{0,2}$
$p_{0,S-1}$
$p_{1,2}$
$p_{2,3}$
$p_{S-2,S-1}$
$p_{S-1,S-1}$
$p_{S-1,S-2}$
$p_{3,2}$
$p_{2,1}$
$p_{2,0}$
$p_{S-1,0}$
$p_{0,1}$
0
1
2
S − 1

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2023/080569

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B7/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04B H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ANTONIO ALBANESE ET AL: "ARES: Autonomous RIS solution with Energy harvesting and Self-configuration towards 6G", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 2 March 2023 (2023-03-02), XP091450527, page 3 - page 9; figures 1,2,4 -----	1-15

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 January 2024	12/02/2024

Name and mailing address of the ISA/	Authorized officer
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