



(51) International Patent Classification:
H04B 7/026 (2017.01) *H04B 7/06* (2006.01)

(21) International Application Number:
PCT/EP2022/051724

(22) International Filing Date:
26 January 2022 (26.01.2022)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
PCT/CN2021/077059
20 February 2021 (20.02.2021) CN

(71) Applicant: **BRITISH TELECOMMUNICATIONS
PUBLIC LIMITED COMPANY** [GB/GB]; 1 Braham
Street, London E1 8EE (GB).

(71) Applicant (*for UG only*): **HAO, Mo** [CN/CN]; Room
4B, Gate 2, Building 102, Daxiyang Xincheng, Wangjing,
Chaoyang District, Beijing, Beijing Beijing 100102 (CN).

(72) Inventors: **DAI, Linglong**; 163, Building 11, Northwest
Community, Tsinghua University, Haidian District, Bei-
jing, Beijing Beijing 100084 (CN). **LIU, Kunzan**; 163,
Building 11, Northwest Community, Tsinghua Universi-
ty, Haidian District, Beijing, Beijing Beijing 100084 (CN).
ZHANG, Zijian; 163, Building 11, Northwest Community,
Tsinghua University, Haidian District, Beijing, Beijing Bei-
jing 100084 (CN). **MACKENZIE, Richard**; 27 Cordelia
Drive, Colchester CO4 6AZ (GB). **HAO, Mo**; Room
4B, Gate 2, Building 102, Daxiyang Xincheng, Wangjing,
Chaoyang District, Beijing, Beijing Beijing 100102 (CN).

(74) Agent: **BRITISH TELECOMMUNICATIONS PUB-
LIC LIMITED COMPANY, INTELLECTUAL PROP-**

(54) Title: WIRELESS TELECOMMUNICATIONS NETWORK INCLUDING A MULTI-LAYER TRANSMISSIVE RECON-
FIGUREABLE INTELLIGENT SURFACE

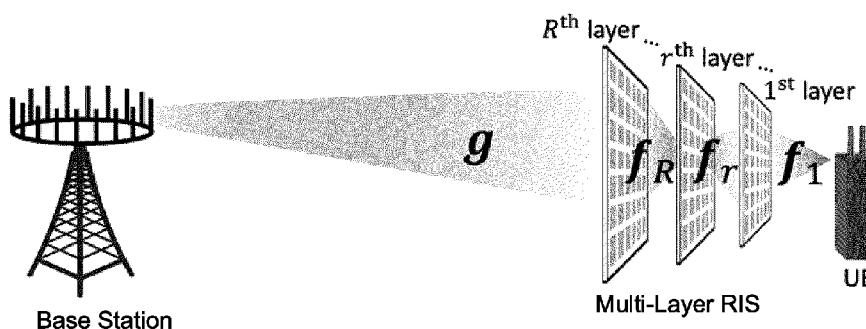


Figure 1

(57) **Abstract:** This invention provides a method of controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a transmitter, a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last transmissive RIS layer, and a receiver, the method comprising the steps of: determining a beamforming vector to be applied by the transmitter, a first phase shift matrix to be applied by the first transmissive RIS layer, a last phase shift matrix to be applied by the last transmissive RIS layer, and a combining vector to be applied by the receiver; and, in a transmission of a wireless signal from the transmitter to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer, causing the transmitter to use the determined beamforming vector, causing the first transmissive RIS layer to use the determined first phase shift matrix, causing the last transmissive RIS layer to use the determined last phase shift matrix, and causing the receiver to use the determined combining vector. This invention also provides a device, and a system including the device, for controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a receiver configured to apply a combining vector to the wireless signal, the device comprising: a transmitter; and a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last

ERTY DEPARTMENT; 9th Floor, One Braham, Braham Street, London E1 8EE (GB).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- with international search report (Art. 21(3))
- in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE

transmissive RIS layer, wherein the transmitter is configured to transmit the wireless signal to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer, the transmitter is configured to apply a beamforming vector to the wireless signal, the first transmissive RIS is configured to apply a first phase shift matrix to the wireless signal, and the last transmissive RIS is configured to apply a last phase shift matrix to the wireless signal.

WIRELESS TELECOMMUNICATIONS NETWORK INCLUDING A MULTI-LAYER TRANSMISSIVE RECONFIGUREABLE INTELLIGENT SURFACE

Field of the Invention

The present invention relates to a wireless telecommunications network having a reconfigurable intelligent surface.

Background

In wireless telecommunications, a wireless signal being transmitted between a transmitter and receiver generally degrades due to interference from other wireless signals and/or other physical phenomena (e.g. fading and blockage). This has generally been addressed by improving the transmission characteristics (e.g. higher power transmissions or repeaters) or transmission processing techniques (e.g. more robust modulation schemes). An emerging concept in wireless telecommunications is the concept of a reconfigurable propagation environment, or “smart radio environment”, which may improve the transmission quality. This may be achieved by use of a surface of electromagnetic material, often known as a Reconfigurable Intelligent Surface (RIS), which may be operated to apply a change to an incident wireless signal, such as a change in phase, amplitude, frequency and polarisation, so as to improve the transmission quality between the transmitter and the receiver.

One use of the RIS is to assist in beamforming between the transmitter and receiver. A conventional method of beamforming in a wireless telecommunications network (that is, a wireless telecommunication network that does not include an RIS) is to use a phased array based hybrid precoder. However, the equipment costs and resource consumption (including energy resource and processing resource) are known to be high compared to wireless telecommunications networks that do not implement beamforming. It has been shown that an RIS may be configured to assist a transmitter to beamform, such as in the Institute of Electrical and Electronics Engineers (IEEE) article, “Reconfigurable Intelligent Surface Based Hybrid Precoding for THz Communications” by Yu Lu and Linglong Dai. As the RIS is nearly passive and easy to deploy, this system is a cost-effective and resource-efficient beamforming solution.

Alternative names for the RIS include large intelligent surface, large intelligent metasurface, programmable metasurface, reconfigurable metasurface, smart reflect-arrays, intelligent reflective surface, software-defined surface, and passive intelligent

surface. The term “reconfigurable” is often used to indicate that the angle of reflection can be configured regardless of the angle of incidence. Although most RISs are implemented as reflective surfaces, an RIS may also be a transmissive surface in which the incident wireless signal is transmitted through the surface. However, these have generally not been considered as a feasible technology, especially for telecommunications, due to the propagation loss that is experienced as the wireless signal passes through the RIS.

Summary of the Invention

According to a first aspect of the invention, there is provided a method of controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a transmitter, a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last transmissive RIS layer, and a receiver, the method comprising the steps of: determining a beamforming vector to be applied by the transmitter, a first phase shift matrix to be applied by the first transmissive RIS layer, a last phase shift matrix to be applied by the last transmissive RIS layer, and a combining vector to be applied by the receiver; and, in a transmission of a wireless signal from the transmitter to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer, causing the transmitter to use the determined beamforming vector, causing the first transmissive RIS layer to use the determined first phase shift matrix, causing the last transmissive RIS layer to use the determined last phase shift matrix, and causing the receiver to use the determined combining vector.

The beamforming vector, first phase shift matrix, second phase shift matrix and combining vector may be determined as a solution to a wireless communications performance optimisation problem. The wireless communications performance optimisation problem may be solved in a series of iterations until a convergence criterion is met. The convergence criterion may be based on a current wireless communication performance for a current iteration of the series of iterations, and the current wireless communications performance is determined based on: a beamforming vector for the current iteration of the series of iterations, based on the first phase shift matrix of a previous iteration of the series of iterations, the last phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations; a first phase shift matrix of the current iteration of the series of

iterations, based on the beamforming vector of the previous iteration of the series of iterations, the last phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations; a last phase shift matrix of the current iteration of the series of iterations, based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations; and a combining vector of the current iteration of the series of iterations, based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations and the last phase shift matrix of the previous iteration of the series of iterations. The previous iteration may be the immediately preceding iteration.

The combining vector for the current iteration of the series of iterations may be determined as:

$$v = \psi_{\max} \left(g^H \left(\prod_{r=R}^1 \Theta_r f_r \right) w w^H \left(\prod_{r=R}^1 \Theta_r f_r \right)^H g \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\psi_{\max}$ is a matrix operator for calculating an eigenvector corresponding to a largest eigenvalue of $(g^H (\prod_{r=R}^1 \Theta_r f_r) w w^H (\prod_{r=R}^1 \Theta_r f_r)^H g)$,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1, and
- w is the beamforming vector of the previous iteration of the series of iterations.

The first phase shift matrix of the first transmissive RIS layer of the current iteration of the series of iterations may be determined as:

$$\theta_1 = \exp \left(j \arg \left(\text{diag}(\mathbf{f}_1 \mathbf{w})^H \left(\prod_{r=R}^2 \mathbf{\Theta}_r \mathbf{f}_r \right)^H \mathbf{g} \mathbf{v} \right) \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\mathbf{f}_1$ is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer,
- $\mathbf{w}$ is the beamforming vector of the previous iteration of the series of iterations,
- $\mathbf{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the $(r-1)$ -th transmissive RIS layer to the r -th transmissive RIS layer,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- $\mathbf{v}$ is the combining vector for the previous iteration of the series of iterations.

The last phase shift matrix of the last transmissive RIS layer of the current iteration of the series of iterations may be determined as:

$$\theta_R = \exp \left(j \arg \left(\text{diag} \left(\mathbf{f}_R \left(\prod_{r=R-1}^1 \mathbf{\Theta}_r \mathbf{f}_r \right) \mathbf{w} \right)^H \mathbf{g} \mathbf{v} \right) \right)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\mathbf{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1,
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,

- $\mathbf{w}$ is the beamforming vector of the previous iteration of the series of iterations,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- $\mathbf{v}$ is the combining vector for the previous iteration of the series of iterations.

5

The beamforming vector of the current iteration of the series of iterations may be determined as:

$$\mathbf{w} = \sqrt{P_{\max}} \frac{(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}}{\|(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}\|_2}$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\boldsymbol{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- $\mathbf{v}$ is the combining vector for the previous iteration of the series of iterations.

The multi-layer transmissive RIS may include one or more intermediate transmissive RIS layers and the transmission of the wireless signal from the transmitter to the receiver passes through the first transmissive RIS layer, each intermediate transmissive RIS layer and the last transmissive RIS layer, and the method further comprises the steps of: determining an intermediate phase shift matrix for each of the one or more intermediate transmissive RIS layers to be applied by each respective intermediate transmissive RIS layer; and causing the first intermediate transmissive RIS layer to use the determined first intermediate phase shift matrix in the transmission of the wireless signal from the transmitter to the receiver, wherein the current wireless communications performance is determined based on: the beamforming vector for the current iteration of the series of

iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations, the first phase shift matrix of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations, each intermediate phase shift matrix for the current iteration of the series of iterations, each intermediate phase shift matrix being based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations, the last phase shift matrix of the previous iteration of the series of iterations, the combining vector of the previous iteration of the series of iterations and, if there is more than one intermediate transmissive RIS layer, each other intermediate phase shift matrix of the previous iteration of the series of iterations, the last phase shift matrix of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations, and the combining vector of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations.

Each intermediate phase shift matrix for the current iteration of the series of iterations may be determined as:

$$\theta_l = \exp \left(j \arg \left(\text{diag} \left(f_l \left(\prod_{r=l-1}^1 \Theta_r f_r \right) w \right)^H \left(\prod_{r=R}^{l+1} \Theta_r f_r \right)^H g v \right) \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers in the multi-layer transmissive RIS,
- l is an element of a set of 2 to $R-1$,
- f_l is a frequency-domain channel matrix from the $(l-1)$ -th transmissive RIS layer to the l -th transmissive RIS layer,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix

from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,

- w is the beamforming vector of the previous iteration of the series of iterations,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- v is the combining vector for the previous iteration of the series of iterations.

The wireless communications performance problem may be a Signal to Noise Ratio, SNR, optimisation problem.

According to a second aspect of the invention, there is provided a computer program comprising instructions which, when the program is executed by a computer, cause the computer to carry out the steps of the first aspect of the invention. The computer program may be stored on a computer readable carrier medium.

According to a third aspect of the invention, there is provided a device for controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a receiver configured to apply a combining vector to the wireless signal, the device comprising: a transmitter; and a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last transmissive RIS layer, wherein the transmitter is configured to transmit the wireless signal to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer, the transmitter is configured to apply a beamforming vector to the wireless signal, the first transmissive RIS is configured to apply a first phase shift matrix to the wireless signal, and the last transmissive RIS is configured to apply a last phase shift matrix to the wireless signal.

The transmitter and multi-layer RIS may be enclosed in a housing having electromagnetic shielding.

The device may further comprise one or more processing modules configured to carry out the steps of the first aspect of the invention.

According to a fourth aspect of the invention, there is provided a system in a wireless telecommunications network comprising a device according to the third aspect of the invention, the system further comprising the receiver.

5 The system may further comprise one or more processing modules configured to carry out the steps of the first aspect of the invention. The one or more processing modules may be disposed on one or more of a group comprising: the device, the receiver, and an external node.

10 Brief Description of the Figures

In order that the present invention may be better understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a schematic diagram of an embodiment of the present invention, illustrating
15 a model of wireless communications performance for a multi-layer transmissive Reconfigurable Intelligent Surface (RIS);

Figure 2 is a schematic diagram of a first embodiment of a cellular telecommunications network having a two-layer transmissive RIS;

Figure 3 is a flow diagram of a first embodiment of a method of the present invention;

20 Figure 4a is a schematic diagram of a simulation setup for the cellular telecommunications network of Figure 2;

Figure 4b is a schematic diagram of a simulation setup for an alternative network having a single-layer RIS;

25 Figure 4c is a schematic diagram of a simulation setup for an alternative network without a RIS;

Figure 5 is a graph illustrating transmission power against SNR;

Figure 6a is a power distribution chart for a single-layer transmissive RIS; and

Figure 6b is a power distribution chart for the two-layer transmissive RIS of Figure 2.

30 Detailed Description of Embodiments

Embodiments of the present invention provide a system and method for beamforming in a wireless telecommunications network having a Reconfigurable Intelligent Surface (RIS). An overview of the system and a model of its wireless communication performance will be described with reference to Figure 1. Figure 1 illustrates a UE, a
35 multi-layer transmissive RIS having R transmissive layers, and a base station. Each

transmissive layer of the multi-layer transmissive RIS, indexed by r , has N_r elements, and we assume that each transmissive layer has the same number of elements for simplicity (such that N_r is equal to N for all values of r). The base station has M antennas and the UE has K antennas.

5

Let $\mathbf{f}_1 \in \mathbb{C}^{N \times K}$ denote the frequency-domain channel matrix from the UE to the first layer of the multi-layer RIS, $\mathbf{f}_r \in \mathbb{C}^{N \times N}$ denote the frequency-domain channel matrix from the $(r-1)$ -th layer of the multi-layer transmissive RIS to r -th layer of the multi-layer transmissive RIS for all $r \in \{2, 3, \dots, R\}$, and $\mathbf{g} \in \mathbb{C}^{N \times M}$ denote the frequency-domain channel matrix from the R -th layer of the multi-layer transmissive RIS to the base station. Denote $\boldsymbol{\Theta}_r = \text{diag}(\boldsymbol{\theta}_r) = \text{diag}(\theta_{r,1}, \dots, \theta_{r,N})$ for all $r \in \{1, 2, \dots, R\}$ as the phase shift matrix at the multi-layer transmissive RIS's r -th layer, where $|\theta_{r,n}| = 1$ for all $n \in \{1, 2, \dots, N\}$. The signal vector received at the BS can be represented as:

10

$$\mathbf{y} = \mathbf{g}^H \left(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r \right) \mathbf{w} s + \mathbf{n}, \quad (1-1)$$

where $\mathbf{w}$ is the beamforming vector with power constraint $\|\mathbf{w}\|_2^2 \leq P_{\max}$ and s is the transmitted symbol. Additive White Gaussian Noise (AWGN) introduced in the base station's decoding satisfies $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_M)$ where σ^2 is the noise power and $\mathbf{I}_M$ is an identity matrix of size M . The communication performance of the device may be evaluated by the decoding Signal to Noise Ratio (SNR) as:

15

$$\text{SNR} = \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r) \mathbf{w}|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2}, \quad (1-2)$$

where $\mathbf{v}$ denotes the combining vector at the base station and $\mathbf{g}^H (\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)$ denotes the equivalent channel between the UE and the base station. In this context, the "equivalent" channel is the overall channel matrix applied to the transmitted signal as it arrives at the base station, based on all channel matrices experienced by the transmitted signal. Assuming that the Channel State Information (CSI) is perfectly known, the beamforming vector $\mathbf{w}$ at the UE, the combining vector $\mathbf{v}$ at the base station, and the phase shift matrix $\boldsymbol{\Theta}_1, \dots, \boldsymbol{\Theta}_R$ of the multi-layer transmissive RIS should be jointly optimized to maximize SNR.

20

25

Based on this model, an SNR optimisation problem may be formulated as:

$$\max_{\mathbf{v}, \boldsymbol{\Theta}_r, \mathbf{w}} \text{SNR} = \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r) \mathbf{w}|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \quad (1-3)$$

$$\begin{aligned} \text{s. t. } \|\mathbf{w}\|_2^2 &\leq P_{\max} \\ |\theta_{r,n}| &= 1, \forall r, n \end{aligned}$$

A first embodiment of a method of the present invention, discussed below, describes an iterative algorithm for obtaining the optimal solution of all variables to this SNR optimisation problem. Before discussing this method, an embodiment of a cellular telecommunications network of the present invention will be described with reference to Figure 2.

The cellular telecommunications network includes a device 10 and a base station 20. The device 10 includes a User Equipment (UE) 11 and a multi-layer RIS 12, all enclosed within a housing 19, and further includes a processor 17. In this embodiment, the UE 11 and each layer of the multi-layer RIS 12 are connected to the processor 17 via a wired communications link. The multi-layer RIS 12 includes a first transmissive RIS 13 (being a first layer of the multi-layer RIS 12) and a second transmissive RIS 15 (being a second layer of the multi-layer RIS 12). In this embodiment, the UE 11 and first transmissive RIS 13 are separated by a distance of around 0.05m, the first transmissive RIS 13 and second transmissive RIS 15 are separated by a distance of around 0.05m, and the second transmissive RIS 15 and base station 20 are separated by a distance of around 20m.

The housing 19 includes a first, second, third and fourth elongate supporting member 19a, 19b, 19c, 19d and a first, second, third and fourth wall 19e, 19f, 19g, 19h, such that the housing 19 has an open-ended rectangular cuboidal shape (the open-ends being the faces of the rectangular cuboidal shape that are not defined by the walls 19e, 19f, 19g, 19h). The first, second, third and fourth walls 19e, 19f, 19g, 19h are constructed of a radio-frequency absorbing material. This radio-frequency absorbing material should be chosen to protect the stability of the internal channels (that is, f_1 to f_R) such as by absorbing any radio-frequencies from external sources that would otherwise cause interference. Furthermore, this absorbing material should avoid undesired diffraction or reflection.

The UE 11 includes a first and second transceiver 11a, 11b arranged as a Uniform Linear Array (ULA). The base station 20 includes a first, second, third, fourth, fifth and sixth transceiver 21a, 21b, 21c, 21d, 21e, 21f, also arranged as a ULA. The UE 11 and base

station 20 may communicate with each other using a cellular telecommunications protocol, such as the 5th Generation (5G) protocol defined by the 3rd Generation Partnership Project (3GPP). An uplink wireless signal from the UE 11 to the base station 20 may be transmitted through the first transmissive RIS 13, then through the second transmissive RIS 15, and then to the base station 20.

The first transmissive RIS 13 includes a plurality of elements 14, each of which may be controlled by processor 17 to apply a particular phase shift to a wireless signal passing through that element 14. Similarly, the second transmissive RIS 15 includes a plurality of elements 16, each of which may be controlled by processor 17 to apply a particular phase shift to the wireless signal passing through that element 16. In this embodiment, a count of elements in the plurality of elements 14 for the first transmissive RIS 13 is equal to a count of elements in the plurality of elements 16 for the second transmissive RIS 15. Figure 2 illustrates the first transmissive RIS 13 and second transmissive RIS 15 both having a square form, but the skilled person will understand that this is non-essential.

The first embodiment of the method of the present invention will now be described with reference to the flow diagram of Figure 3. As noted above, this embodiment provides an iterative algorithm to obtain an optimal solution of all variables of the SNR optimisation problem. This is achieved by decoupling the coupled variables – the beamforming vector $\mathbf{w}$, the combining vector $\mathbf{v}$, and the phase shift matrices Θ_r – and alternately optimising each variable with the other variables fixed. The algorithm will be described for a multi-layer RIS having R layers (including a first layer, a last layer, and optionally one or more intermediate layers between the first and last layers), which can be applied to the two-layer RIS of the first embodiment of the cellular network described above.

In a first step, S101, the processor 17 determines values for a plurality of input parameters, including channel matrices $\mathbf{f}_1 \dots \mathbf{f}_R$ and $\mathbf{g}$ and the maximum transmit power P_{max} , that may be considered as fixed input parameters throughout a single performance of this embodiment. As the space between the UE 11 and the first layer of the multi-layer RIS (that is, the first transmissive RIS 13 in the first embodiment above) and the space between each layer of the multi-layer RIS are fixed and substantially shielded from electromagnetic fields (other than those produced by the UE 11) by the device's housing 19, then channel matrices $\mathbf{f}_1 \dots \mathbf{f}_R$ are considered near-field static channels that are

therefore unchanging following installation. Accordingly, $f_1 \dots f_R$ may be measured and recorded during installation of the device 10. The channel matrix g is a far-field channel which may change with time and/or location. This may be measured by conventional channel estimation and channel feedback mechanisms. The value for the maximum transmit power P_{max} is, in this embodiment, stored in the UE 11 and may be retrieved by the processor 17.

In step S103, the processor 17 sets initial values for a plurality of variable input parameters. In this embodiment, the processor 17 sets w and v at 1 and generates initial values for $\Theta_1 \dots \Theta_R$ randomly. The processor 17 then enters an iterative loop. In step S105, the processor 17 updates its value for the combining vector v based on equation 1-5 below and its current values for all other variable parameters (being the initial values determined in step S103 on the first iteration, or the values determined in the previous iteration of the iterative loop on subsequent iterations). For the combining vector, v , the SNR optimisation problem can be reformulated as:

$$\max_v \text{SNR} = \frac{v^H g^H (\prod_{r=R}^1 \Theta_r f_r) w w^H (\prod_{r=R}^1 \Theta_r f_r)^H g v}{\|v\|_2^2 \sigma^2} := \frac{v^H A v}{\|v\|_2^2 \sigma^2} \quad (1-4)$$

where $A = g^H (\prod_{r=R}^1 \Theta_r f_r) w w^H (\prod_{r=R}^1 \Theta_r f_r)^H g$ is a positive definite matrix. So the maximum of SNR is the largest eigenvalue of A , and the corresponding v is written as

$$v = \psi_{\max} \left(g^H \left(\prod_{r=R}^1 \Theta_r f_r \right) w w^H \left(\prod_{r=R}^1 \Theta_r f_r \right)^H g \right) \quad (1-5)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers in the multi-layer RIS,
- $\psi_{\max}(\cdot)$ is a matrix operator to calculate an eigenvector corresponding to a largest eigenvalue of matrix A ,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the base station,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- f_r is a frequency-domain channel matrix from the UE 11 to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1, and

- $\mathbf{w}$ is the beamforming vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations).

5 In step S107, the processor 17 updates its value for Θ_1 , the phase shift matrix for the first transmissive-RIS layer of the multi-layer RIS, based on equation 1-7 below and its current values for all other variable parameters (being the initial values determined in step S103 on the first iteration, or the values determined in the previous iteration of the iterative loop on subsequent iterations). For Θ_1 , the SNR optimisation problem can be reformulated as:

$$\text{SNR} = \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^1 \Theta_r \mathbf{f}_r) \mathbf{w}|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} = \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^2 \Theta_r \mathbf{f}_r) \text{diag}(\mathbf{f}_1 \mathbf{w}) \boldsymbol{\theta}_1|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \quad (1-6)$$

Because $\boldsymbol{\theta}_1$ is a vector whose components all have norm 1, the optimal value for $\boldsymbol{\theta}_1$ is

$$\boldsymbol{\theta}_1 = \exp \left(j \arg \left(\text{diag}(\mathbf{f}_1 \mathbf{w})^H \left(\prod_{r=R}^2 \Theta_r \mathbf{f}_r \right)^H \mathbf{g} \mathbf{v} \right) \right) \quad (1-7)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers in the multi-layer RIS,
- $\mathbf{f}_1$ is a frequency-domain channel matrix from the UE 11 to the first transmissive RIS layer,
- $\mathbf{w}$ is the beamforming vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the $(r-1)$ -th transmissive RIS layer to the r -th transmissive RIS layer,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the base station, and
- $\mathbf{v}$ is the combining vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations).

If the multi-layer RIS is comprised of two layers only, then the process skips to step S111. If the multi-layer RIS is comprised of three or more layers, then, in step S109, the processor 17 updates its value for θ_l , where $l = 2, \dots, R - 1$, being the phase shift matrix for each intermediate transmissive layer of the multi-layer RIS based on equation 1-9 below and its current values for all other variable parameters (being the initial values determined in step S103 on the first iteration, or the values determined in the previous iteration of the iterative loop on subsequent iterations). For θ_l , the SNR optimization problem can be reformulated as:

$$\begin{aligned} \text{SNR} &= \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r) \mathbf{w}|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \\ &= \frac{|\mathbf{v}^H \mathbf{g}^H (\prod_{r=R}^{l+1} \boldsymbol{\Theta}_r \mathbf{f}_r) \text{diag}(\mathbf{f}_l (\prod_{r=l-1}^1 \boldsymbol{\Theta}_r \mathbf{f}_r) \mathbf{w}) \boldsymbol{\theta}_l|^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \end{aligned} \quad (1-8)$$

Because $\boldsymbol{\theta}_l$ is a vector whose components all have norm 1, the optimal value for $\boldsymbol{\theta}_l$ is

$$\boldsymbol{\theta}_l = \exp \left(j \arg \left(\text{diag} \left(\mathbf{f}_l \left(\prod_{r=l-1}^1 \boldsymbol{\Theta}_r \mathbf{f}_r \right) \mathbf{w} \right)^H \left(\prod_{r=R}^{l+1} \boldsymbol{\Theta}_r \mathbf{f}_r \right)^H \mathbf{g} \mathbf{v} \right) \right) \quad (1-9)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers in the multi-layer RIS,
- l is an element of a set of 2 to $R-1$,
- $\mathbf{f}_l$ is a frequency-domain channel matrix from the $(l-1)$ -th transmissive RIS layer to the l -th transmissive RIS layer,
- $\boldsymbol{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the UE 11 to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- $\mathbf{w}$ is the beamforming vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the base station 20, and

- v is the combining vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations).

5 In step S111, the processor 17 updates its value for Θ_R , the phase shift matrix for the last transmissive layer of the multi-layer RIS, based on equation 1-11 below and its current values for all other variable parameters (being the initial values determined in step S103 on the first iteration, or the values determined in the previous iteration of the iterative loop on subsequent iterations). For Θ_R , the SNR optimization problem can be reformulated as:

$$\text{SNR} = \frac{|v^H g^H (\prod_{r=R}^1 \Theta_r f_r) w|^2}{\|v^H\|_2^2 \sigma^2} = \frac{|v^H g^H \text{diag}(f_R (\prod_{r=R-1}^1 \Theta_r f_r) w) \Theta_R|^2}{\|v^H\|_2^2 \sigma^2} \quad (1-10)$$

Because Θ_R is a vector whose components all have norm 1, the optimal value for Θ_R is

$$\Theta_R = \exp \left(j \arg \left(\text{diag} \left(f_R \left(\prod_{r=R-1}^1 \Theta_r f_r \right) w \right)^H g v \right) \right) \quad (1-11)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer RIS,
- Θ_r is a phase shift matrix of an r -th RIS layer (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- f_r is a frequency-domain channel matrix from the UE 11 to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- w is the beamforming vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the base station 20, and
- v is the combining vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations).

In step S113, the processor 17 updates its value for the beamforming vector $\mathbf{w}$ based on equation 1-13 below and its current values for all other variable parameters (being the initial values determined in step S103 on the first iteration, or the values determined in the previous iteration of the iterative loop on subsequent iterations). The optimal solution of normalized $\mathbf{w}$, that is, $\frac{\mathbf{w}}{\|\mathbf{w}\|_2}$, is:

$$\frac{\mathbf{w}}{\|\mathbf{w}\|_2} = \frac{(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}}{\|(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}\|_2}. \quad (1-12)$$

Considering the constraint $\|\mathbf{w}\|_2^2 \leq P_{\max}$, the optimal solution of $\mathbf{w}$ is

$$\mathbf{w} = \sqrt{P_{\max}} \frac{(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}}{\|(\prod_{r=R}^1 \boldsymbol{\Theta}_r \mathbf{f}_r)^H \mathbf{g} \mathbf{v}\|_2} \quad (1-13)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer RIS,
- $\boldsymbol{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations),
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the UE 11 to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the base station 20, and
- $\mathbf{v}$ is the combining vector (being the initial value determined in step S103 on the first iteration, or the value determined in the previous iteration of the iterative loop on subsequent iterations).

In step S115, the processor 17 estimates the SNR of a transmission from the device 10 to the base station 20 using the values for $\mathbf{w}$, $\mathbf{v}$, and $\boldsymbol{\Theta}_r$ determined in steps S105 to S113 above for the current iteration. This SNR estimate is stored in memory, together with an iteration identifier. In step S117, the processor 17 evaluates the SNR estimates to determine whether a convergence condition has been satisfied. In this embodiment, the convergence condition is that the difference between the estimated SNR for the current iteration and the estimated SNR for the previous iteration is less than or equal to 1%. If the convergence condition has not been satisfied (such as when there has only been one iteration of the algorithm), then the process loops back to step S105 for a

further iteration. Once the convergence condition has been satisfied, then the processor 17 has determined final values of $\mathbf{w}$, $\mathbf{v}$, and Θ_r as those generated in the final iteration of the algorithm. The process then proceeds to step S119 in which the processor 17 causes the UE 11 to use beamforming vector $\mathbf{w}$ in transmissions of wireless signals from the device 10 to the base station 20, causes each layer of the multi-layer RIS to use its respective phase shift matrix Θ_r (that is, causes the first transmissive RIS 13 to use Θ_1 and causes the second transmissive RIS 15 to use Θ_2) to apply phase shifts to the wireless signals passing through that layer, and causes the base station 20 to use the combining vector $\mathbf{v}$ to receive the wireless signals transmitted from the device 10 to the base station 20.

In this embodiment, the processor 17 implements a processor module for the UE and each layer of the multi-layer RIS, wherein the processing modules are configured to apply the beamforming vector to the UE's transmitted wireless signal or apply the respective phase shift matrix to the wireless signal as it passes through a layer of the multi-layer RIS. The base station 20 may also include a processing module for applying the combining vector to the received wireless signal. The processing modules for applying the phase shift matrices may be based on a Field Programmable Gate Array (FPGA) architecture in similar manner to that described in "Programmable artificial intelligence machine for wave sensing and communications", Che Lui et al.

Subsequently, the process may be triggered again (with new input values, particularly for $\mathbf{g}$ as the channel between the multi-layer RIS and the base station 20 changes over time) to determine new values for $\mathbf{w}$, $\mathbf{v}$, and Θ_r . The trigger may be present in a signal from the base station or UE indicating that $\mathbf{g}$ has been updated.

In summary, the iterative algorithm may be defined as:

Iterative Algorithm	
Inputs:	
Channel matrix $\mathbf{f}_1, \dots, \mathbf{f}_R$ and $\mathbf{g}$;	
Maximum transmit power $P_{\max}$.	
Outputs:	
Maximum of SNR.	
1: Initialize $\mathbf{w}, \mathbf{v}, \Theta_1, \dots, \Theta_R$;	

2: while no convergence of SNR do
3: Update ν by (1 – 5);
4: Update Θ_1 by (1 – 7);
5: if $R > 2$, update $\Theta_2, \dots, \Theta_{R-1}$ by (1 – 9);
6: Update Θ_R by (1 – 11);
7: Update w by (1 – 13);
8: end while
9: return SNR

The performance of the above method, when applied to the cellular network of Figure 2 having a two-layer RIS, can be evaluated by simulation, as shown in the Figures 4a, 4b, 4c and Figure 5.

5

Figure 4a illustrates a simulation of the cellular telecommunications network 1 of Figure 2, in which the UE includes two antennas in a ULA, the multi-layer transmissive RIS includes two layers each having 64 elements, and the base station includes 6 antennas in a ULA. The UE and first layer of the multi-layer RIS are separated by 0.05m, the first layer of the multi-layer RIS and the second layer of the multi-layer RIS are separated by 0.05m, and the second layer of the multi-layer RIS and the base station are separated by 20m (such that the UE and base station are separated by 20.1m). The UE transmits at a frequency of 1.5GHz. The loss factor when a wireless signal passes through each layer of the multi-layer RIS is 0.8.

10

15

Figure 4b illustrates a simulation of an alternative cellular telecommunications network, for the purposes of comparison, in which the UE includes two antennas in a ULA, the RIS is a single-layer RIS having 256 elements, and the base station includes 6 antennas in a ULA. The UE and single-layer RIS are separated by 0.05m, and the single-layer RIS and base station are separated by 20.05m (such that the UE and base station are again separated by 20.1m). The UE transmits at a frequency of 1.5GHz. This simulation may be used for both a single-layer transmissive RIS (in which the loss factor when the wireless signal passes through the single-layer transmissive RIS is 0.8) or a single-layer reflective RIS, as the channel models are the same.

20

25

Figure 4c illustrates a simulation of another alternative cellular telecommunications network, for the purposes of comparison, in which the UE includes two antennas in a

ULA and the base station includes 6 antennas in a ULA. There is no RIS in this alternative network. The UE and base station are again separated by 20.1m.

Figure 5 is a graph illustrating the decoding SNR against the power constraint, P_{max} for the four scenarios covered by these simulations, 1) the alternative network having no RIS, 2) the alternative network having a single-layer transmissive RIS, 3) the alternative network having a single-layer reflective RIS, and 4) the first embodiment of the network of the present invention having a two-layer transmissive RIS. It can be seen that the cellular network of the embodiment of the present invention has the best wireless communication performance with a SNR improvement of around 4dB above the next best performing scenario (the alternative network having a single-layer reflective RIS). The alternative network having a single-layer transmissive RIS scenario had an SNR around 2dB lower than the alternative network having a single-layer reflective RIS, and the alternative network having no RIS was the worst performing scenario. These simulation results illustrate the improvement in wireless communication performance provided by the above embodiments of the invention relative to traditional RIS-based networks. Furthermore, these simulations are based on a two-layer RIS having half the number of elements compared to the single-layer reflective RIS and single-layer transmissive RIS, illustrating the cost-efficiency and power-efficiency benefits of the present invention (as the material costs and power requirements of a RIS are proportional to the number of elements).

The benefits of the two-layer transmissive RIS relative to a single-layer RIS architecture can also be understood on review of the power distribution of each architecture. Figure 6a includes a power distribution chart of a single-layer transmissive RIS and Figure 6b includes a first power distribution chart of a first layer of the two-layer transmissive RIS and a second power distribution chart of a second layer of the two-layer transmissive RIS. It can be seen by comparison of Figures 6a and 6b that the element utilisation of the RIS is comparatively low for the single-layer transmissive RIS compared to the two-layer transmissive RIS. In other words, only a small proportion of the elements of the single-layer transmissive RIS are utilised compared to the proportion of elements of both layers of the two-layer transmissive RIS. It can also be seen from Figure 6b that the power distribution on the second layer of the two-layer transmissive RIS is relatively smooth compared to the first layer.

In the above embodiments, the processor communicates with the UE and each layer of the multi-layer RIS by a wired connection. However, this is non-essential and the processor may communicate with the UE and each layer of the multi-layer RIS via a wireless connection. It is also non-essential that the steps of the method of the present invention are carried out by a single processor. That is, the processing may be performed by the UE, by the base station, by an external node, or in a distributed manner, with suitable wired or wireless communication links between the various elements.

The skilled person will also understand that the present invention may be applied to a downlink communication (that is, from the base station to the UE) where the UE receives the downlink communication through each layer of the multi-layer RIS. Furthermore, the present invention is not limited to a cellular telecommunications example, such that it may be applied to a wireless signal between a transmitter and a receiver in other forms of wireless telecommunications network, such as between a transmitter and receiver of a wireless local area network or a wireless wide area network. Nonetheless, the present invention has particular benefits when applied to a wireless signal being transmitted from a low-powered and/or low-cost device, such as a UE, where conventional beamforming techniques are prohibitively costly and/or resource intensive. Furthermore, the skilled person will understand that this invention may be applied to transmissions from a single transmitter to multiple receivers.

In the above embodiments, the UE had two antennas in a ULA and the base station had six antennas in a ULA. The skilled person will understand that this is non-essential and different antenna configurations are possible. That is, the channel matrices between the UE and first transmissive RIS layer of the multi-layer RIS is sufficiently static such that the channel matrix may be measured and recorded at installation and thereafter used in the algorithm. Furthermore, the channel matrix between the last transmissive RIS layer and the base station is sufficiently far field that it is not affected by a change in antenna configuration and, in any event, are measured by a channel estimation process.

The skilled person will also understand that the present invention is not limited to optimising SNR performance, and other wireless communications performance metrics may be used, such as latency or throughput.

In the above embodiment, each layer of the multi-layer transmissive RIS had the same number of elements. The skilled person will understand that the present invention is not limited in this way and can be applied to multi-layer RISs where one or more layers have a differing number of elements. This would merely result in a change in the dimensions of the matrices and potentially a change in the form of the device housing (e.g. from a cuboidal shape to a flared structure).

The skilled person will understand that any combination of features is possible within the scope of the invention, as claimed.

CLAIMS

1. A method of controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a transmitter, a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last transmissive RIS layer, and a receiver, the method comprising the steps of:

determining a beamforming vector to be applied by the transmitter, a first phase shift matrix to be applied by the first transmissive RIS layer, a last phase shift matrix to be applied by the last transmissive RIS layer, and a combining vector to be applied by the receiver; and, in a transmission of a wireless signal from the transmitter to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer,

causing the transmitter to use the determined beamforming vector,
causing the first transmissive RIS layer to use the determined first phase shift matrix,
causing the last transmissive RIS layer to use the determined last phase shift matrix, and
causing the receiver to use the determined combining vector.

2. A method as claimed in Claim 1, wherein the beamforming vector, first phase shift matrix, second phase shift matrix and combining vector are determined as a solution to a wireless communications performance optimisation problem.

3. A method as claimed in Claim 2, wherein the wireless communications performance optimisation problem is solved in a series of iterations until a convergence criterion is met.

4. A method as claimed in Claim 3, wherein the convergence criterion is based on a current wireless communication performance for a current iteration of the series of iterations, and the current wireless communications performance is determined based on:

a beamforming vector for the current iteration of the series of iterations, based on the first phase shift matrix of a previous iteration of the series of iterations, the last

phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations;

a first phase shift matrix of the current iteration of the series of iterations, based on the beamforming vector of the previous iteration of the series of iterations, the last phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations;

a last phase shift matrix of the current iteration of the series of iterations, based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations; and

a combining vector of the current iteration of the series of iterations, based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations and the last phase shift matrix of the previous iteration of the series of iterations.

5. A method as claimed in Claim 4, wherein the combining vector for the current iteration of the series of iterations is determined as:

$$v = \psi_{\max} \left(g^H \left(\prod_{r=R}^1 \Theta_r f_r \right) w w^H \left(\prod_{r=R}^1 \Theta_r f_r \right)^H g \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\psi_{\max}$ is a matrix operator for calculating an eigenvector corresponding to a largest eigenvalue of $(g^H (\prod_{r=R}^1 \Theta_r f_r) w w^H (\prod_{r=R}^1 \Theta_r f_r)^H g)$,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1, and

- w is the beamforming vector of the previous iteration of the series of iterations.

6. A method as claimed in Claim 4 or Claim 5, wherein the first phase shift matrix of the first transmissive RIS layer of the current iteration of the series of iterations is determined as:

$$\theta_1 = \exp \left(j \arg \left(\text{diag}(\mathbf{f}_1 \mathbf{w})^H \left(\prod_{r=R}^2 \mathbf{\Theta}_r \mathbf{f}_r \right)^H \mathbf{g} \mathbf{v} \right) \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\mathbf{f}_1$ is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer,
- w is the beamforming vector of the previous iteration of the series of iterations,
- $\mathbf{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- $\mathbf{f}_r$ is a frequency-domain channel matrix from the $(r-1)$ -th transmissive RIS layer to the r -th transmissive RIS layer,
- $\mathbf{g}$ is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- v is the combining vector for the previous iteration of the series of iterations.

7. A method as claimed in any one of Claims 4 to 6, wherein the last phase shift matrix of the last transmissive RIS layer of the current iteration of the series of iterations is determined as:

$$\theta_R = \exp \left(j \arg \left(\text{diag} \left(\mathbf{f}_R \left(\prod_{r=R-1}^1 \mathbf{\Theta}_r \mathbf{f}_r \right) \mathbf{w} \right)^H \mathbf{g} \mathbf{v} \right) \right)$$

Where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- $\mathbf{\Theta}_r$ is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1,

- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- w is the beamforming vector of the previous iteration of the series of iterations,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- v is the combining vector for the previous iteration of the series of iterations.

8. A method as claimed in any one of Claims 4 to 7, wherein the beamforming vector of the current iteration of the series of iterations is determined as:

$$w = \sqrt{P_{\max}} \frac{(\prod_{r=R}^1 \Theta_r f_r)^H g v}{\|(\prod_{r=R}^1 \Theta_r f_r)^H g v\|_2}$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers of the multi-layer transmissive RIS,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- v is the combining vector for the previous iteration of the series of iterations.

9. A method as claimed in any one of Claims 4 to 8, wherein the multi-layer transmissive RIS includes one or more intermediate transmissive RIS layers and the transmission of the wireless signal from the transmitter to the receiver passes through the first transmissive RIS layer, each intermediate transmissive RIS layer and the last transmissive RIS layer, and the method further comprises the steps of:

determining an intermediate phase shift matrix for each of the one or more intermediate transmissive RIS layers to be applied by each respective intermediate transmissive RIS layer; and

causing the first intermediate transmissive RIS layer to use the determined first intermediate phase shift matrix in the transmission of the wireless signal from the transmitter to the receiver,

wherein the current wireless communications performance is determined based on:

the beamforming vector for the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations,

the first phase shift matrix of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations,

each intermediate phase shift matrix for the current iteration of the series of iterations, each intermediate phase shift matrix being based on the beamforming vector of the previous iteration of the series of iterations, the first phase shift matrix of the previous iteration of the series of iterations, the last phase shift matrix of the previous iteration of the series of iterations and the combining vector of the previous iteration of the series of iterations,

the last phase shift matrix of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations, and

the combining vector of the current iteration of the series of iterations, that is further based on each intermediate phase shift matrix of the previous iteration of the series of iterations.

10. A method as claimed in Claim 9, wherein each intermediate phase shift matrix for the current iteration of the series of iterations is determined as:

$$\theta_l = \exp \left(j \arg \left(\text{diag} \left(\mathbf{f}_l \left(\prod_{r=l-1}^1 \boldsymbol{\Theta}_r \mathbf{f}_r \right) \mathbf{w} \right)^H \left(\prod_{r=R}^{l+1} \boldsymbol{\Theta}_r \mathbf{f}_r \right)^H \mathbf{g} \mathbf{v} \right) \right)$$

where:

- r is an element of a set of 1 to R , where R is a count of transmissive RIS layers in the multi-layer transmissive RIS,
- l is an element of a set of 2 to $R-1$,

- f_l is a frequency-domain channel matrix from the $(l-1)$ -th transmissive RIS layer to the l -th transmissive RIS layer,
- Θ_r is a phase shift matrix of an r -th transmissive RIS layer of the previous iteration of the series of iterations, including the first phase shift matrix of the first transmissive RIS layer of the previous iteration of the series of iterations when r equals 1 and the last phase shift matrix of the last transmissive RIS layer of the previous iteration of the series of iterations when r equals R ,
- f_r is a frequency-domain channel matrix from the transmitter to the first transmissive RIS layer when r equals 1 and is a frequency-domain channel matrix from an $(r-1)$ -th transmissive RIS layer to an r -th transmissive RIS layer when r is greater than 1,
- w is the beamforming vector of the previous iteration of the series of iterations,
- g is a frequency-domain channel matrix from the last transmissive RIS layer to the receiver, and
- v is the combining vector for the previous iteration of the series of iterations.

11. A method as claimed in any one of Claims 2 to 10, wherein the wireless communications performance problem is a Signal to Noise Ratio, SNR, optimisation problem.

12. A computer program comprising instructions which, when the program is executed by a computer, cause the computer to carry out the steps of any one of Claims 1 to 11.

13. A computer readable carrier medium comprising the computer program of Claim 12.

14. A device for controlling a transmission of a wireless signal in a wireless telecommunications network, the wireless telecommunications network including a receiver configured to apply a combining vector to the wireless signal, the device comprising:

a transmitter; and

a multi-layer transmissive Reconfigurable Intelligent Surface, RIS, including a first transmissive RIS layer and a last transmissive RIS layer,

wherein the transmitter is configured to transmit the wireless signal to the receiver, the wireless signal passing through the first transmissive RIS layer and the last transmissive RIS layer, the transmitter is configured to apply a beamforming vector to the wireless signal, the first transmissive RIS is configured to apply a first phase shift matrix to the wireless signal, and the last transmissive RIS is configured to apply a last phase shift matrix to the wireless signal.

15. A device as claimed in Claim 14, wherein the transmitter and multi-layer RIS are enclosed in a housing having electromagnetic shielding.

16. A device as claimed in Claim 14 or Claim 15, further comprising one or more processing modules configured to carry out the steps of any one of Claims 1 to 11.

17. A system in a wireless telecommunications network comprising a device as claimed in either Claim 14 or Claim 15, further comprising the receiver.

18. A system as claimed in Claim 17, further comprising one or more processing modules configured to carry out the steps of any one of Claims 1 to 11.

19. A system as claimed in Claim 18, wherein the one or more processing modules are disposed on one or more of a group comprising: the device, the receiver, and an external node.

1/6

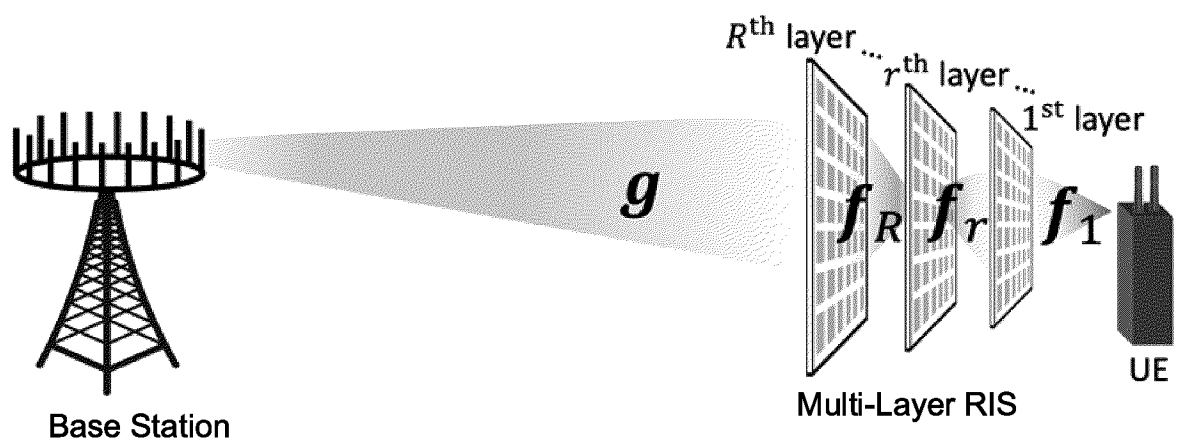


Figure 1

2/6

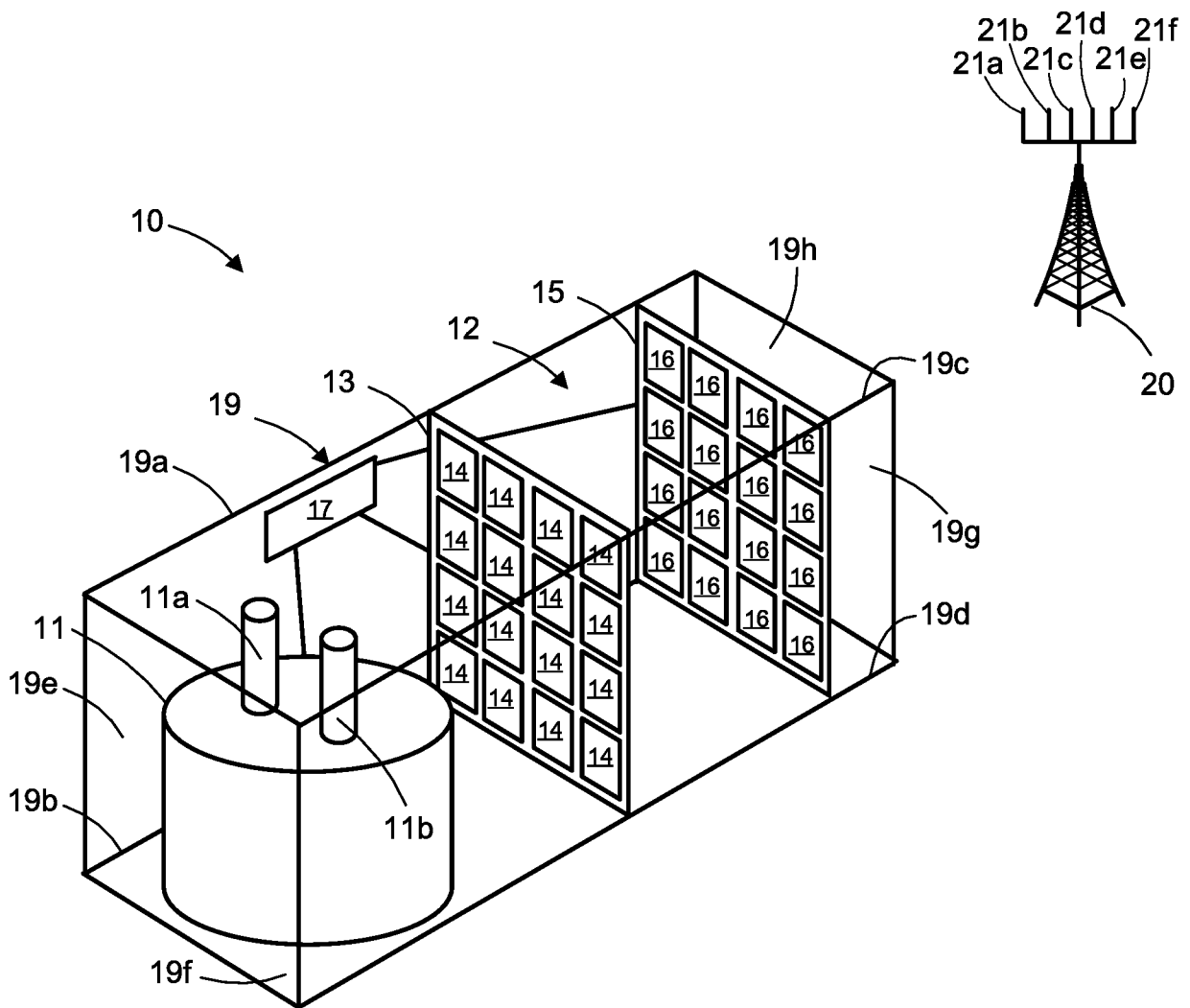
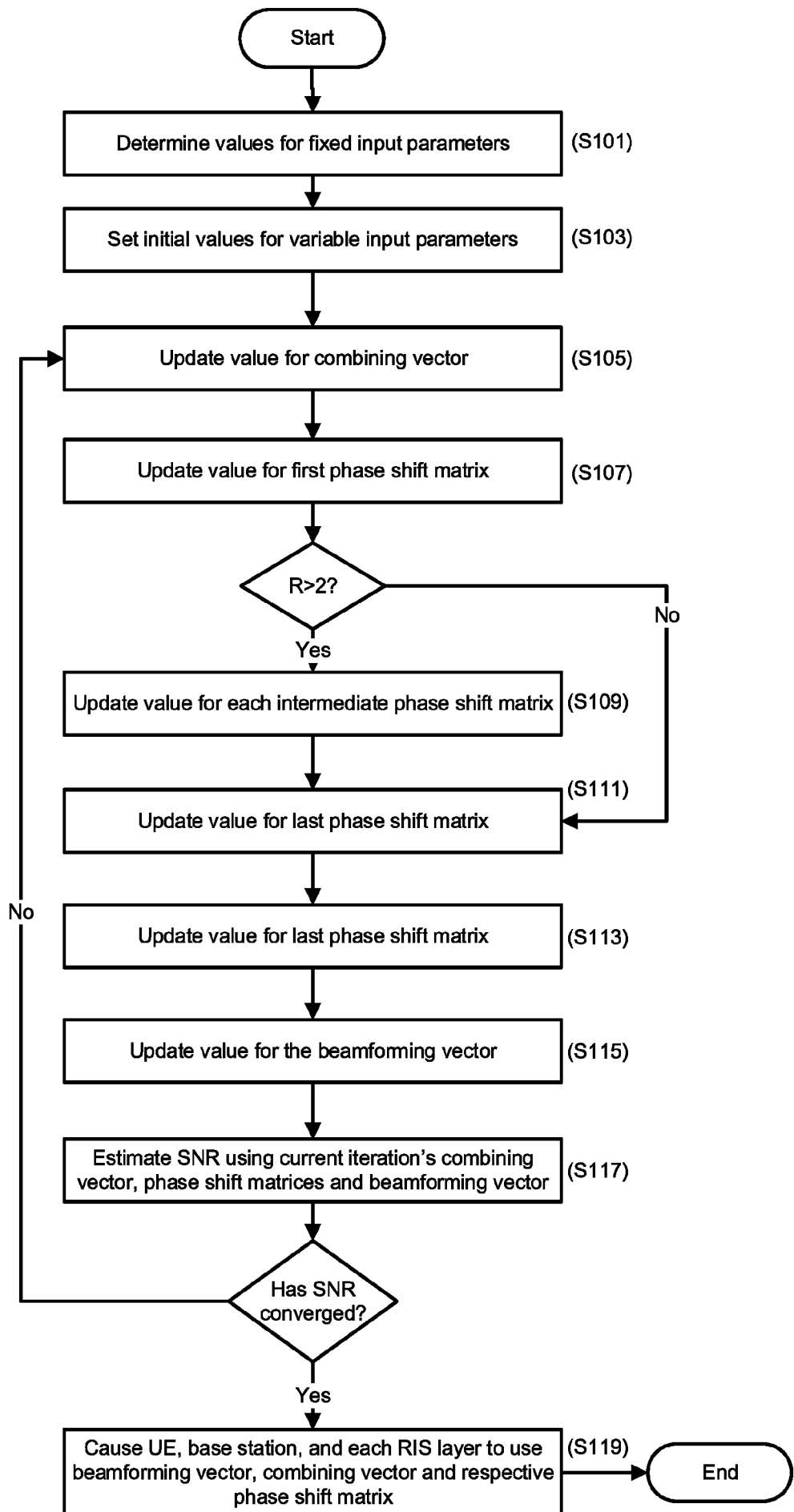


Figure 2

**Figure 3**

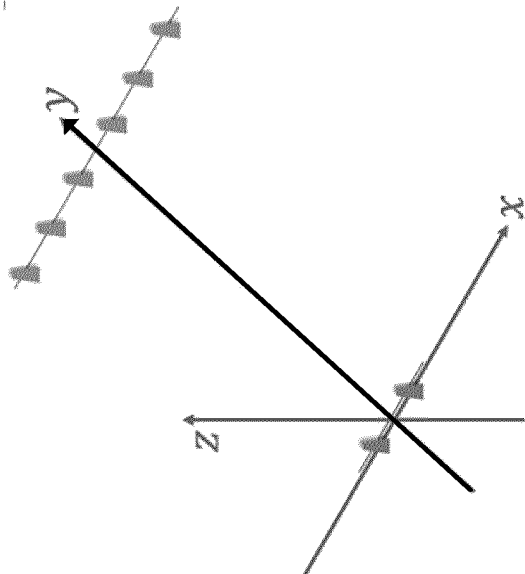


Figure 4a

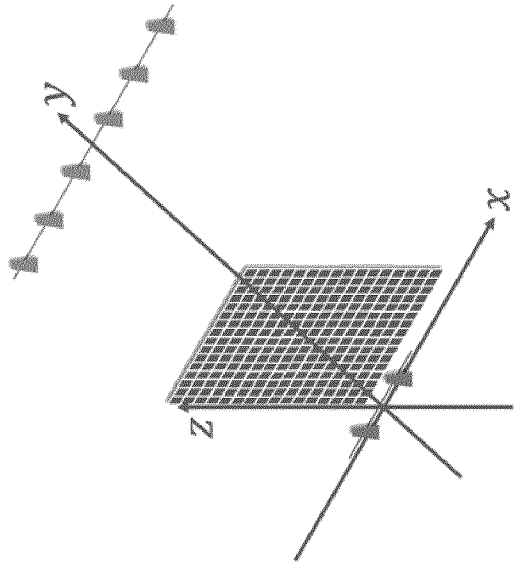


Figure 4b

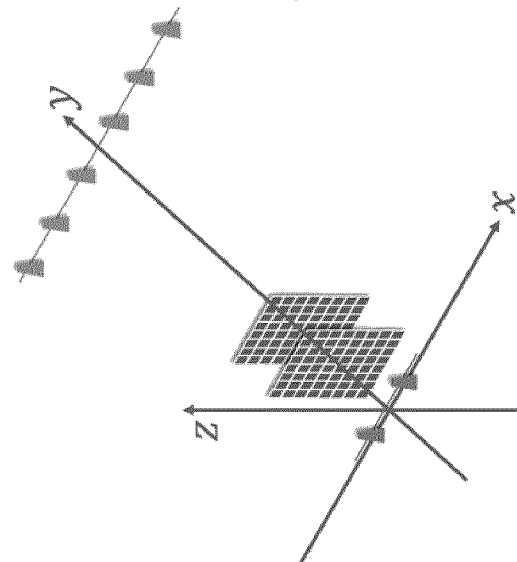


Figure 4c

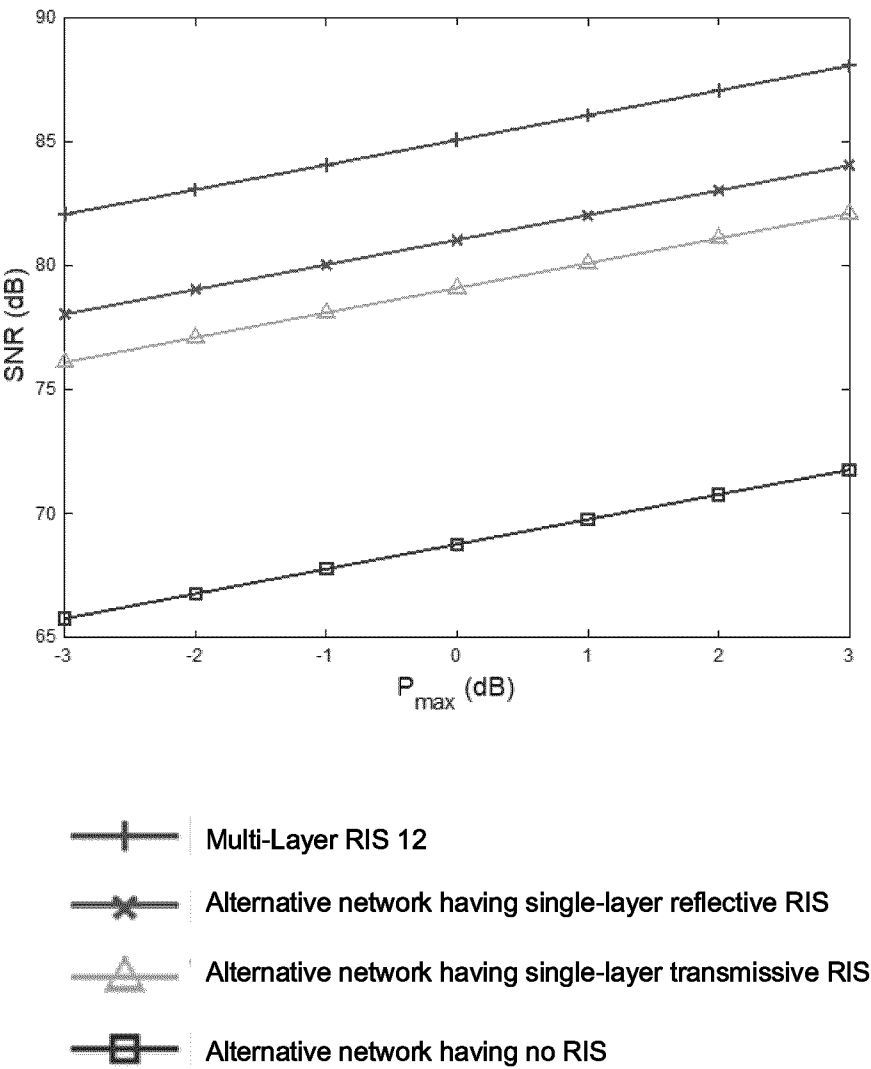


Figure 5

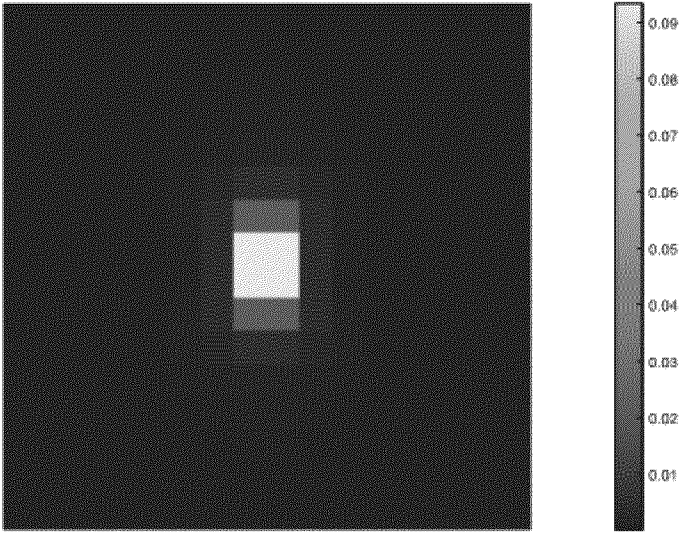


Figure 6a

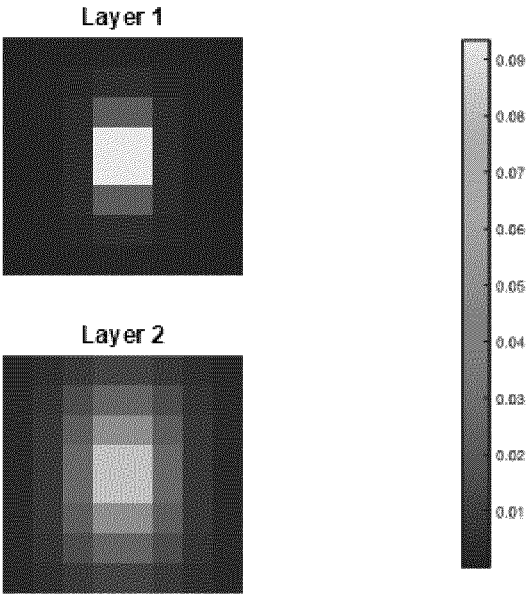


Figure 6b

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2022/051724

A. CLASSIFICATION OF SUBJECT MATTER INV. H04B7/026 H04B7/06 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		
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, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SHUHANG ZHANG ET AL: "Intelligent Omni-Surface: Ubiquitous Wireless Transmission by Reflective-Transmissive Metasurface", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 2 November 2020 (2020-11-02), XP081805288, abstract page 8; figure 3 pages 10,12 ----- -/--	1-19
☒ 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
13 May 2022		31/05/2022
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Oana, Andrei

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2022/051724

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	RUITIANYI LU: "Joint Beamforming and Phase Optimization in a Multi-user Communication System Composed of Dual Reconfigurable Intelligent Surfaces", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 1 February 2021 (2021-02-01), XP081872385, figure 1 abstract -----	1-19
A	CN 111 464 223 A (UNIV ELECTRONIC SCI & TECH CHINA) 28 July 2020 (2020-07-28) paragraphs [0049], [0050]; figure 1 paragraphs [0076], [0077] -----	1-19
A	SHUHAO ZENG ET AL: "Reconfigurable Intelligent Surfaces in 6G: Reflective, Transmissive, or Both?", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 13 February 2021 (2021-02-13), XP081885196, abstract; figure 1 -----	1-19

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2022/051724

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 111464223	A	28-07-2020	NONE
