

A RECONFIGURABLE INTELLIGENT SURFACE SYSTEM FOR WIRELESS COMMUNICATIONS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to Singapore patent application no. 10202300754W which was filed on 21 March 2023, the contents of which are hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] This application relates to a Reconfigurable Intelligent Surface (RIS) system for wireless communications. This application also relates to a 2-bit phase-quantized unit cell for manipulating properties of received electromagnetic waves whereby the unit cell may be utilized in a RIS system.

BACKGROUND

[0003] Reconfigurable Intelligent Surface (RIS) systems have emerged as a promising technology for future wireless communication. RIS systems usually comprise numerous reconfigurable elements that have been integrated into a two-dimensional structure. Such systems may be applied to various applications, including smart transportation systems, internet of things networks, wireless mobile communication systems, and any other systems that implement simultaneous wireless information and power transfer. The appeal of RIS systems lies in their capacity to transform wireless environments with their cost-effectiveness, ease of deployment, and adaptability. These characteristics create the foundation for artificial, programmable control of the electromagnetic (EM) environment, aligning with the worldwide movement towards more intelligent, adaptive, and sustainable communication networks.

[0004] With the rapid deployment and adoption of Fifth Generation (5G) mobile networks, wireless communication technologies have been rapidly propelled forward, resulting in unprecedented advancements in technology in this area. By creating a smart and adaptable wireless environment, RIS systems are well placed to meet the evolving demands of future wireless communication systems, even in Sixth Generation (6G) mobile networks. RIS systems utilize novel programmable subwavelength two-dimensional metamaterials, digitally encoded to control EM waves actively and intelligently. This control extends to adjusting amplitude,

phase, polarization, or frequency response, effectively bridging the physical EM world with the digital information world.

[0005] One of the factors that determine the capability of a RIS system to manipulate EM waves is the number of reconfigurable states per RF unit cell used in the RIS system. Traditional RF unit cells used in RIS systems are designed based on resonant principles, where the EM wave's phase and amplitude are controlled and/or modified by adjusting the resonant frequency of the RF unit cell by manipulating the impedance and reactance of active components in the unit cell. However, as the number of reconfigurable states increases, the complexity of the unit cell's design escalates. Moreover, nonlinear coupling between different states impacts the independence and stability of state transitions within the unit cell. These problems present significant challenges for both the design and practical implementation of the overall RIS system. Due to system complexity constraints, those skilled in the art have resorted to limiting the number of adjustable states per unit cell, often resorting to 1-bit reconfigurable structures whereby these 1-bit systems can generally only achieve a 180-degree phase shift for incident EM waves. Due to this limitation, this results in the RIS system suffering from quantization losses.

[0006] Additionally, to combat EM wave propagation path loss, RIS systems are typically positioned within the visible range of Base Stations (BS), i.e., the wireless channel between the RIS system and the BS is usually defined as Line-of-Sight (LoS). In order to achieve beam steering, the amplitude and phase of each RF unit cell of the RIS has to be adjusted based on the principle of the calculation of geometric optics under the LoS channel assumption. While the relatively static LoS channel simplifies the computation of both channel estimation and beamforming from the base station to the RIS system, it poses limitations on the diversity and multiplexing performance of Multiple-Input Multiple-Output (MIMO) communication systems. With limited scattering occurring in the propagation environment, the LoS channel responses tend to exhibit high correlations, and this leads to a severe decrease in the degree of freedom of a multiple antennas system. Consequently, the additional copy of the BS signal reflected by the RIS primarily provides only energy gain.

[0007] To address this problem, those skilled in the art have proposed a cooperative double-RIS aided MIMO system. Through the spatial multiplexing gain and reflected signal power

gain brought by the two cooperative RISs in the system, it was shown that the double-RIS system was able to improve the data rate in the LoS transmission scenario. However, when the number of RISs in the system are increased, this will inevitably lead to increased costs and system complexity. Moreover, the multiple RISs in the system would have to cooperate and operate in synchrony in order to ensure efficient operation of the MIMO system. This results in an increase in the overheads of the pilot and control signals while also causing the effective data rate to reduce to a certain extent.

[0008] Despite the efforts of those skilled in the art, existing RIS systems still possess significant challenges when deployed in wireless communication systems that involve the redirection of transmitted vortex beams with multiple modes into blind zones, whereby the redirected beams are re-radiated as plane waves.

SUMMARY

[0009] In one aspect of the present disclosure, a 2-bit phase-quantized unit cell for manipulating received electromagnetic waves is disclosed. The unit cell comprises an antenna provided on the first surface of the unit cell, a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via. It is also disclosed that the quadrature phase shifter circuit is configured to selectively provide a phase shift of 0-degrees, 90-degrees, 180-degrees, or 270-degrees to an electromagnetic wave received by the antenna based on control signals received from a control module and then to provide a phase shifted electromagnetic signal to the antenna to be re-radiated. It is further disclosed that the control signals were computed based on a phase compensation factor of a transmitter that transmitted the electromagnetic wave at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell.

[0010] In embodiments of the aspect, the quadrature phase shifter circuit of the 2-bit phase-quantized unit cell comprises a first delay line having an end coupled to the via and another end coupled to a first switch, a second switch and a third switch. In this embodiment, the first delay line is configured to provide a 0-degree phase shift to the electromagnetic wave received by the antenna. The quadrature phase shifter circuit also has a second delay line having an end coupled to the first switch and having a section coupled to a first control line whereby the second delay line is configured to provide a 90-degree phase shift to the electromagnetic wave

received by the antenna, a third delay line having an end coupled to the second switch and having a section coupled to a second control line whereby the third delay line is configured to provide a 180-degree phase shift to the electromagnetic wave received by the antenna, and a fourth delay line having an end coupled to the third switch and having a section coupled to a third control line whereby the fourth delay line is configured to provide a 270-degree phase shift to the electromagnetic wave received by the antenna.

[0011] In another aspect of the present disclosure, a reconfigurable intelligent surface (RIS) system for wireless communication is disclosed. The disclosed RIS system has a layer comprising a plurality of 2-bit phase-quantized unit cells that are each configured to receive electromagnetic waves from a transmitter and a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells. The control module is further configured to, for each of the plurality of 2-bit phase-quantized unit cells, compute a phase shift to be provided by the unit cell based on a phase compensation factor of the transmitter at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell, and then to provide control signals to the unit cell such that the unit cell is triggered to provide the computed phase shift to the electromagnetic wave received by the unit cell, and provide a phase shifted electromagnetic signal to the unit cell to be re-radiated.

[0012] In yet another aspect of the present disclosure, a method for manipulating received electromagnetic waves using a 2-bit phase-quantized unit cell is disclosed. The disclosed method comprises the steps of receiving an electromagnetic wave using an antenna provided on a first surface of the unit cell, selectively providing, using a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via, a phase shift of 0-degrees, 90-degrees, 180-degrees or 270-degrees to the electromagnetic wave received by the antenna, based on control signals received from a control module and providing a phase shifted electromagnetic signal to the antenna to be re-radiated. It is also disclosed that the control signals were computed based on a phase compensation factor of a transmitter that transmitted the electromagnetic wave at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell.

[0013] In yet another aspect of the present disclosure, a method for wireless communication using a reconfigurable intelligent surface system comprising a layer having a plurality of 2-bit phase-quantized unit cells and a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells is disclosed whereby the method comprises the steps of receiving, using the plurality of 2-bit phase-quantized unit cells, electromagnetic waves transmitted from a transmitter, whereby for each of the plurality of 2-bit phase-quantized unit cells, the method comprises the steps of computing, using the control module, a phase shift to be provided by the unit cell based on a phase compensation factor of the transmitter at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell, and providing, using the control module, control signals to the unit cell such that the unit cell is triggered to provide the computed phase shift to the electromagnetic wave received by the antenna and to provide a phase shifted electromagnetic signal to the antenna to be re-radiated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Various embodiments of the present disclosure are described below with reference to the following drawings:

Figure 1 illustrates a block diagram representative of the RIS system for facilitating conversion and reflection of vortex beams having multiple modes to independent plane-wave beams in accordance with embodiments of the present disclosure;

Figure 2 illustrates a block diagram representative of a processing system for performing embodiments of the present disclosure;

Figure 3 illustrates a cross-sectional view of a 2-bit phase-quantized unit cell in accordance with embodiments of the present disclosure;

Figures 4(a) and 4(b) illustrate the layouts of the circuits on the front surface and a back surface of a 2-bit phase-quantized unit cell in accordance with embodiments of the present disclosure;

Figures 5(a)-(d) illustrate four states of the 2-bit phase-quantized unit cells in accordance with embodiments of the present disclosure;

Figure 6(a) illustrates the phase-response of the four states of the 2-bit phase-quantized unit cells illustrated in Figures 5(a)-(d) when the frequency-domain response is varied, with particular emphasis on their performance at 10.7 GHz in accordance with embodiments of the present disclosure;

Figure 6(b) illustrates the magnitude-response of the four states of the 2-bit phase-quantized unit cells illustrated in Figures 5(a)-(d) when the frequency-domain response is varied, with

particular emphasis on their performance at 10.7 GHz in accordance with embodiments of the present disclosure;

Figure 7 illustrates an arrangement of the RIS in accordance with embodiments of the present disclosure;

Figure 8 illustrates a flowchart of a process for manipulating electromagnetic waves using a 2-bit phase-quantized unit cell in accordance with embodiments of the disclosure;

Figure 9 illustrates a flowchart of a process for wireless communication using a reconfigurable intelligent surface system comprising a layer having a plurality of 2-bit phase-quantized unit cells and a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells in accordance with embodiments of the disclosure;

Figure 10 illustrates an exemplary arrangement pattern on the RIS for converting a Mode +1 vortex beam to a plane wave in accordance with embodiments of the disclosure;

Figure 11 illustrates an exemplary arrangement pattern on the RIS for converting a Mode +2 vortex beam to a plane wave in accordance with embodiments of the disclosure; and

Figure 12 illustrates an exemplary arrangement pattern on the RIS for converting a Mode +1 and +2 vortex beam to a plane wave in accordance with embodiments of the disclosure.

DETAILED DESCRIPTION

[0015] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0016] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0017] In the context of various embodiments, the term “about” or “approximately” as applied to a numeric value encompasses the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0018] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0019] As used herein, “comprising” means including, but not limited to, whatever follows the word “comprising”. Thus, use of the term “comprising” indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0020] As used herein, “consisting of” means including, and limited to, whatever follows the phrase “consisting of”. Thus, use of the phrase “consisting of” indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0021] As used herein, the terms “first,” “second,” and the like in the description, in the claims, and in the figures are used for distinguishing between similar objects and not necessarily for describing a particular sequential or chronological order.

[0022] As used herein, the term “multi-mode vortex beam” and the like in the description refers to a specific type of electromagnetic wave that carries orbital angular momentum (OAM) and possesses multiple distinct phase profiles, or modes (i.e., twist profiles), within its cross-section. Each mode of a multi-mode vortex beam corresponds to a different twist rate, resulting in a beam with multiple intertwined helical wavefronts.

[0023] Further, one skilled in the art will recognize that certain functional units in this description have been labelled as modules, sub-modules or sets of processing elements throughout the specification. The person skilled in the art will also recognize that a module, a sub-module or a set of processing elements may be implemented as circuits, logic chips or any sort of discrete component. Still further, one skilled in the art will also recognize that a module, a sub-module or a set of processing elements may be implemented in software which may then be executed by a variety of processor architectures. In embodiments of the disclosure, a module, a sub-module or a set of processing elements may also comprise computer instructions, computations or executable code that may instruct a computer processor to carry out a sequence of events based on instructions received. The choice of the implementation of the modules, the sub-modules or the sets of processing elements is left as a design choice to a person skilled in the art and does not limit the scope of the claimed subject matter in any way.

[0024] A reconfigurable intelligent surface (RIS) is a system that is designed to receive electromagnetic (EM) waves and to re-radiate the EM waves after the EM waves have been modified by the RF unit cells of the RIS. In embodiments of the disclosure, the RIS may be configured to receive multi-mode vortex beams and re-radiate them as plane waves. The RIS may comprise an array of programmable subwavelength elements, such as meta-atoms or RF unit cells, that may be arranged in a two-dimensional configuration to form the surface of the RIS. Through the use of these elements, the RIS would be able to dynamically adjust the phase and amplitude of each element to reconfigure the surface, and subsequently emit plane waves with the desired characteristics, effectively transforming the vortex beams into plane waves. This capability would enable the RIS to adaptively manipulate and control the propagation of electromagnetic waves, allowing for advanced beamforming, signal steering, and communication enhancement in various applications.

[0025] Figure 1 illustrates a block diagram of a RIS system in accordance with embodiments of the present disclosure. RIS system 100 comprises of RIS 105 that is configured to receive multi-mode vortex beams 108 carrying orbital angular momentum (OAM) from transmitter 106. The multi-mode vortex beams 108 are then converted by RIS 105 into plane waves 109 that are then re-radiated in the direction of receiver 111. RIS 105 comprises a plurality of phase-quantized unit cells 110 that are each configured to operate on the electromagnetic waves and/or multi-mode vortex beams that pass through it. In RIS applications, phase-quantized unit cells 110 are designed to operate over a specific frequency band and can be configured to manipulate the phase of the incoming EM waves and multi-mode vortex beams in a variety of ways. By adjusting the phase shift to be applied by each of the unit cells 110, RIS 105 is able to selectively modify the direction and pattern of the transmitted waves and/or beams, enabling a range of applications such as wireless communication, sensing, and imaging. In the subsequent sections, for ease of reading, when reference is made to EM waves, it should be understood that this term may encompass both conventional electromagnetic waves and multi-mode vortex beams.

[0026] Control module 104, which may be provided on RIS 105 or at a separate location from RIS 105, is communicatively coupled to each of phase-quantized unit cells 110 through a plurality of control lines (not shown in Figure 1). In embodiments of the disclosure, control module 104 is configured to compute a phase shift to be provided by each of the unit cells 110

to received EM waves 108. This computation is done based on a phase compensation factor of transmitter 106 at each of the unit cells, a beamforming factor of transmitter 106 at each of the unit cells and a conversion compensation factor of each of the unit cells. Control module 104 then provides a control signal to the control lines of each of the unit cells so that the respective computed phase shifts are applied to EM wave 108 by each of the unit cells, before the phase shifted EM wave is then re-radiated as plane wave 109 in the direction of receiver 111. As illustrated in Figure 1, computer 102 is communicatively connected to control module 104 to perform any calculations or computations that may be required.

[0027] In accordance with embodiments of the present disclosure, a block diagram representative of components of processing system 200 that may be provided within, control module 104, computer 102, transmitters 106 and/or receiver 111 to carry out the digital signal processing functions or computations in accordance with embodiments of the disclosure, or any other modules or sub-modules of the system is illustrated in Figure 2. One skilled in the art will recognize that the exact configuration of each processing system provided within these modules may be different and the exact configuration of processing system 200 may vary and the arrangement illustrated in Figure 2 is provided by way of example only.

[0028] In embodiments of the disclosure, processing system 200 may comprise controller 201 and user interface 202. User interface 202 is arranged to enable manual interactions between a user and the computing module as required and for this purpose includes the input/output components required for the user to enter instructions to provide updates to each of these modules. A person skilled in the art will recognize that components of user interface 202 may vary from embodiment to embodiment but will typically include one or more of display 240, keyboard 235 and optical device 236.

[0029] Controller 201 is in data communication with user interface 202 via bus 215 and includes memory 220, processing unit, processing element or processor 205 mounted on a circuit board that processes instructions and data for performing the method of this embodiment, an operating system 206, an input/output (I/O) interface 230 for communicating with user interface 202 and a communications interface, in this embodiment in the form of a network card 250. Network card 250 may, for example, be utilized to send data from these modules via a wired or wireless network to other processing devices or to receive data via the

wired or wireless network. Wireless networks that may be utilized by network card 250 include, but are not limited to, Wireless-Fidelity (Wi-Fi), Bluetooth, Near Field Communication (NFC), cellular networks, satellite networks, telecommunication networks, Wide Area Networks (WAN) and etc.

[0030] Memory 220 and operating system 206 are in data communication with processor 205 via bus 210. The memory components include both volatile and non-volatile memory and more than one of each type of memory, including Random Access Memory (RAM) 223, Read Only Memory (ROM) 225 and a mass storage device 245, the last comprising one or more solid-state drives (SSDs). One skilled in the art will recognize that the memory components described above comprise non-transitory computer-readable media and shall be taken to comprise all computer-readable media except for a transitory, propagating signal. Typically, the instructions are stored as program code in the memory components but can also be hardwired. Memory 220 may include a kernel and/or programming modules such as a software application that may be stored in either volatile or non-volatile memory.

[0031] Herein the term “processor” is used to refer generically to any device or component that can process such instructions and may include: a microprocessor, a processing unit, a plurality of processing elements, a microcontroller, a programmable logic device or any other type of computational device. That is, processor 205 may be provided by any suitable logic circuitry for receiving inputs, processing them in accordance with instructions stored in memory and generating outputs (for example to the memory components or on display 240). In this embodiment, processor 205 may be a single core or multi-core processor with memory addressable space. In one example, processor 205 may be multi-core, comprising—for example—an 8 core CPU. In another example, it could be a cluster of CPU cores operating in parallel to accelerate computations.

[0032] Figure 3 illustrates a cross-sectional view of a 2-bit phase-quantized unit cell of a reconfigurable intelligent surface for manipulating a received EM wave in accordance with embodiments of the present disclosure. 2-bit phase-quantized unit cell 300 comprises ground layer 304 sandwiched between substrate layer 302 and substrate layer 306. Further, an adhesion layer (not shown) comprising, but not limited to, Rogers RO4450F may be provided between ground layer 304 and substrate layer 302. In embodiments of the disclosure, substrate layers

302 and/or 306 may comprise, but are not limited to, 1mm thick Taconic TLX-8 dielectric substrates and ground layer 304 may comprise a copper layer having a thickness of 0.035mm.

[0033] As shown in Figure 3, antenna 308 is located on one surface of substrate layer 302 while quadrature phase shifter circuit 309 is provided on a surface of substrate layer 306. Antenna 308 is electrically connected to quadrature phase shifter circuit 309 through via 314, and antenna 308 is also electrically connected to ground layer 302 through via 316.

[0034] Quadrature phase shifter circuit 309 may comprise delay lines 312 which are connected to each other through switches 310. In embodiments of the disclosure, antenna 308 may comprise, but is not limited to, a single polarization antenna, a dual polarization antenna, a rectangular copper patch antenna, or any other types of planar antennas. In certain embodiments, switches 310 may comprise, but are not limited to, PIN diodes that are biased through a plurality of control lines (not shown in Figure 3), or any other types of similar switching elements. Further, delay lines 312 may comprise, but are not limited to, quarter-wavelength transformers or transmission lines such as microstrip lines whereby the physical dimensions (e.g., lengths and/or widths) and/or choice of materials of the lines are dependent on the frequency of the EM wave received by antenna 308 and the required phase delays.

[0035] Figure 4(a) illustrates a front surface of the 2-bit phase-quantized unit cell and Figure 4(b) illustrates a back surface of the 2-bit phase-quantized unit cell. In particular, with reference to Figure 3, surface 400 in Figure 4(a) represents the surface of substrate layer 302 on which antenna 308 is formed and surface 420 in Figure 4(b) represents the surface of substrate layer 306 on which quadrature phase shifter circuit 309 is formed.

[0036] As illustrated in Figure 4(a), surface 400 comprises patch antenna 308, and via 314 which is electrically connected to patch antenna 308 through transmission line 404. Further, as shown in Figure 4(b), via 314 electrically connects patch antenna 308 to delay line 421 of quadrature phase shifter circuit 309. Additionally, via 316 is provided at the centre of patch antenna 308 to connect patch antenna 308 to the ground layer of the 2-bit phase-quantized unit cell, thereby completing the electrical circuit.

[0037] Referring to Figure 4(b), surface 420 includes quadrature phase shifter circuit 309 that comprises switches 425, 426, 427 and delay lines 421, 422, 423, 424 whereby delay line 421 is connected to patch antenna 308 through via 314. Additionally, delay lines 422, 423, and 424 are connected to delay line 421 through switches 425, 426, and 427, respectively. Control lines 428a-c, which are communicatively connected to a control module (not shown), are provided on surface 420 to provide control signals to the switches, with control line 428a being linked to a portion of delay line 422, control line 428b to a part of delay line 423, and control line 428c to a section of delay line 424. In embodiments of the disclosure, filtering elements (not shown), such as inductors, can be included on each of the control lines 428a-c to eliminate any noise from biasing voltages and/or currents that may be applied to these control lines. In some other embodiments, radio frequency (RF) absorbers like ferrite absorbers or carbon-based absorbers may be used in place of the filtering elements.

[0038] When the control module provides a biasing signal to control line 428a, switch 425 turns on thereby electrically connecting delay line 422 to delay line 421. Similarly, when a biasing signal is applied to control line 428b, switch 426 switches on thereby electrically connecting delay line 423 to delay line 421 and when a biasing signal is applied to control line 428c, switch 427 turns on thereby electrically connecting delay line 423 to delay line 421.

[0039] In embodiments of the disclosure, the physical dimensions of delay line 421 may be chosen to provide about a 0-degree phase shift to an EM signal provided by antenna 308, the dimensions of delay line 422 may be chosen to provide about a 90-degree phase shift to the EM signal provided by antenna 308, the dimensions of delay line 423 may be designed to provide about a 180-degree phase shift to the EM signal provided by antenna 308, and the dimensions of delay line 424 may be selected to provide about a 270-degree phase shift to the EM signal provided by antenna 308. This may be done by varying the physical dimensions such as the length and/or width of each of the respective delay lines in view of the frequency of the EM signal received by antenna 308. In embodiments of the disclosure, delay line 421 may be designed to have a length that is equivalent to about 1/4 of the wavelength of the EM signal provided by antenna 308, delay line 422 may be designed to have a length that is equivalent to about 1/4 of the wavelength of the EM signal provided by antenna 308, delay line 423 may be designed to have a length that is equivalent to about 1/2 of the wavelength of the EM signal provided by antenna 308 and delay line 424 may be designed to have a length that

is equivalent to about 3/4 of the wavelength of the EM signal provided by antenna 308. In other words, in embodiments of the disclosure, the four phase shifted states are designed to be uniformly distributed within 360-degrees.

[0040] In operation, antenna 308 is configured to receive an EM wave from a transmitter, and the EM wave may comprise a traditional electromagnetic wave or a multi-mode vortex beam. Upon receiving the EM wave, antenna 308 will convert the EM wave into an electrical signal that is then provided to quadrature phase shifter circuit 309 through via 314.

[0041] In embodiments of the disclosure, quadrature phase shifter circuit 309 may be configured to selectively provide a phase shift of about 0-degrees, 90-degrees, 180-degrees or 270-degrees to the EM signal provided by the antenna. The selection of the phase shift to be provided may be done through the provision of appropriate control/biasing signals to switches 425, 426, 427 through control lines 428a-c respectively.

[0042] The four states of the 2-bit phase-quantized unit cells in accordance with embodiments of the present disclosure are illustrated in Figures 5(a)-(d). Figure 5(a) illustrates the first state of the 2-bit phase-quantized unit cell whereby the quadrature phase shifter circuit has been selected to provide a phase shift of 0-degrees to the EM signal that was provided by the antenna to the circuit. In this embodiment, control signals are provided via the control lines to turn switches 425, 426, 427 off so that the EM signal will only pass through delay line 421 which has been designed to provide a 0-degree phase shift. Hence, after the EM signal provided by the antenna of the unit cell has been reflected by delay line 421, the reflected EM signal will then be re-radiated by the antenna.

[0043] Figure 5(b) illustrates the second state of the 2-bit phase-quantized unit cell whereby the quadrature phase shifter circuit has been selected to provide a phase shift of 90-degrees to the EM signal that was provided by the antenna to the circuit. In this embodiment, control signals are provided via the control lines to turn switches 426, 427 off and switch 425 on, so that the EM signal will pass through delay lines 421 and 422, where delay line 422 has been designed to provide a 90-degree phase shift. Hence, after the EM signal provided by the antenna of the unit cell has been reflected by delay lines 421 and 422, the reflected 90-degree phase shifted EM signal will then be re-radiated by the antenna.

[0044] Figure 5(c) illustrates the third state of the 2-bit phase-quantized unit cell whereby the quadrature phase shifter circuit has been selected to provide a phase shift of 180-degrees to the EM signal that was provided by the antenna to the circuit. In this embodiment, control signals are provided via the control lines to turn switches 425, 427 off and switch 426 on, so that the EM signal will pass through delay lines 421 and 423, where delay line 423 has been designed to provide a 180-degree phase shift. Hence, after the EM signal provided by the antenna of the unit cell has been reflected by delay lines 421 and 423, the reflected 180-degree phase shifted EM signal will then be re-radiated by the antenna.

[0045] Figure 5(d) illustrates the fourth state of the 2-bit phase-quantized unit cell whereby the quadrature phase shifter circuit has been selected to provide a phase shift of 180-degrees to the EM signal that was provided by the antenna to the circuit. In this embodiment, control signals are provided via the control lines to turn switches 425, 426 off and switch 427 on, so that the EM signal will pass through delay lines 421 and 424, where delay line 424 has been designed to provide a 270-degree phase shift. Hence, after the EM signal provided by the antenna of the unit cell has been reflected by delay lines 421 and 424, the reflected 270-degree phase shifted EM signal will then be re-radiated by the antenna.

[0046] **Exemplary embodiment of a unit cell**

[0047] In an exemplary embodiment of the present disclosure, a 2-bit phase-quantized unit cell was designed with a copper ground layer having a thickness of 0.035mm sandwiched between two 1 mm-thick Taconic TLX-8 dielectric substrates. A copper patch antenna having dimensions of 13.8 mm x 8.3 mm was formed on a surface of one of the dielectric substrates while four delay lines with three PIN diodes acting as switches were formed on the surface of the other dielectric substrate. A via was provided in the middle of the antenna to connect the antenna to the middle ground layer, thereby completing the electrical circuit of the unit cell.

[0048] As the unit cell was designed to receive an EM wave having a frequency of 10.7 GHz with a bandwidth of 200 MHz, the lengths of the first, second, third and fourth delay lines were set to be 2.78 mm, 2.78 mm, 4.64 mm and 7.05 mm respectively with the second, third and fourth delay lines being connected to the first delay line through individual PIN diodes, as

previously illustrated in Figure 4(b). Each of the PIN diodes are independently controlled by separate control lines, each having an inductor to isolate any AC RF signals that may interfere with the operation of the unit cell or the biasing of the unit cell.

[0049] When the appropriate control signals were provided to the PIN diodes via the respective control lines, it was determined that the phase delay of the EM wave captured by the antenna of the unit cell may be dynamically adjusted as shown in Figure 6(a). In particular, the phase-response of the four states of the 2-bit phase-quantized unit cell (i.e., 0-degree, 90-degree, 180-degree and 270-degree phase shifts) when the frequency-domain response was varied in accordance with this example is illustrated in Figure 6(a) and its corresponding amplitude response is illustrated in Figure 6(b).

[0050] As shown in Figure 6(a), when the unit cell was shown to provide a phase-shift of about 140-degrees, it is then to be quantized to 270-degrees (i.e., unit state 1), when the unit cell was shown to provide a phase-shift of about 45-degrees it is to be quantized to 180-degrees (i.e., unit state 2), when the unit cell was shown to provide a phase-shift of about -40-degrees it is to be quantized to 90-degrees (i.e., unit state 3) and when the unit cell was shown to provide a phase-shift of about -118-degrees it is to be quantized to 0-degrees (i.e., unit state 4) which corresponds to the various states of the unit cell. Additionally, as shown in Figure 6(b), the amplitude attenuations of the re-radiated EM wave of the four states of the unit cell were found to be less than 0.6 dB within a 200 MHz bandwidth.

[0051] In accordance with other embodiments of the disclosure, a reconfigurable intelligent surface (RIS) system for wireless communication may include a layer that has a plurality of 2-bit phase-quantized unit cells that are each configured to receive EM waves from a transmitter, where modified EM waves are re-radiated to a receiver. Such a system is illustrated in Figure 7.

[0052] Figure 7 illustrates RIS system which has layer 701 that comprises a total of $M \times N$ 2-bit phase-quantized unit cells 706, transmitter 702 that is configured to transmit EM waves 703, which may comprise traditional EM waves or multi-mode vortex beams, to layer 701 and receiver 705 that is configured to receive re-radiated EM waves 704 from layer 701. The physical length and widths of each of unit cells 706 in layer 701 are dy and dz respectively as

shown in Figure 7 and layer 701 is defined by z - and y -axes that are parallel to the surface of layer 701 and a y -axis that is in a normal direction to the surface of layer 701. As shown, it can be seen that central point 'O' is at the centre of layer 701 and in a Cartesian coordinate system, has the coordinate $O = [0, 0, 0]^T$ while transmitter u_T 702 is assumed to have a coordinate of $u_T = [x_T, y_T, z_T]^T$. Based the information that layer 701 comprises a total of $M \times N$ of unit cells 706, the coordinate of each unit cell 706 in layer 701 can be calculated individually, e.g., the coordinate of unit cell 707, located at the bottom corner of layer 701, may be denoted as $[0, \frac{M}{2}dy, \frac{N}{2}dz]^T$. Further, without the loss of generality, it can be seen that the coordinate of a (M^{th} , N^{th}) unit cell in layer 701 may be defined as $[0, y_{m,n}, z_{m,n}]^T$.

[0053] In view of the above, the distance d_{T-RIS} between transmitter 702 and any one of unit cells 706 may thus be defined as:

$$d_{T-RIS} = \sqrt{(0 - x_T)^2 + (y_{m,n} - y_T)^2 + (z_{m,n} - z_T)^2} \quad \dots \text{equation (1)}$$

[0054] An Azimuth angle of each of unit cells 706 may then be computed in the Cartesian coordinate system based on an axis perpendicular to a plane of layer 701 (i.e., from the y -axis as shown in Figure 7) as:

$$\phi_{m,n} = \arctan\left(\frac{z_{m,n}}{y_{m,n}}\right) \quad \dots \text{equation (2)}$$

where it is assumed that transmitter 702, receiver 705 and centre point 'O' of layer 701 are all located on the same flat plane. The beamforming factor $\varphi_{deflect}$ can then be obtained as:

$$\varphi_{deflect} = -k(y_{m,n}\sin * (\Theta_R) \cos(\Phi_R) + z_{m,n}\sin * (\Theta_R) \sin(\Phi_R)) \quad \dots \text{equation (3)}$$

where k is the wave vector, and (Θ_R, Φ_R) defines a re-radiation direction of the reflected EM wave. Hence, when EM waves 703 comprise multi-mode vortex beams, the mode number of the multi-mode vortex beams may be defined as $l_{OAM} \in \{1, 2, \dots, N\}$. The convert compensation factor φ_{OAM} at each unit cell (i.e., where vortex beams are converted to plane waves) can then be calculated as:

$$\varphi_{OAM} = -l_{OAM}\phi_{m,n} \quad \dots \text{equation (4)}$$

[0055] Similarly, the phase compensation factor φ_{feed} from transmitter 702 to each unit cell at layer 701 can be calculated as

$$\varphi_{feed} = -kd_{T-RIS} \quad \dots \text{equation (5)}$$

[0056] In view of the above, the total phase compensation of each unit cell in layer 701 may be computed as:

$$\varphi_{m,n} = \varphi_{feed} + \varphi_{deflect} + \varphi_{OAM} \quad \dots \text{equation (6)}$$

[0057] In this embodiment, all the calculations above may be carried out by a control module (not shown in Figure 7) that is communicatively connected to each of the unit cells 706 in layer 701. The control module may be configured to provide control signals to unit cells in layer 701 such that each unit cell is triggered to provide a phase shift computed for the unit cell to the electromagnetic wave received by the unit cell, and re-radiate the phase shifted electromagnetic signal to receiver 705.

[0058] In embodiments of the disclosure, the phase shift computed for each unit cell may then be quantized into four different discrete phase values, i.e., 0-degrees, 90-degrees, 180-degrees and 270-degrees. Hence, using equations (1)-(6) above, the unit-cell pattern on layer 701 may be computed based on Algorithm 1 as set out below:

Algorithm 1: Calculation of the arrangement of the unit-cell pattern on the RIS

Input: Setup the basic parameters link $[x_T, y_T, z_T]^T$, $[0, y_{m,n}, z_{m,n}]^T$, M, N, dy, dz, k ,

$l_{OAM}, \{\Theta_R, \Phi_R\}$, and confirm the geometric coordinates of the transmitters and the RIS board.

Output: $\varphi_{m,n}$, then the whole unit-cell phase-quantized distribution pattern on the RIS can be obtained.

1: **for:** $m = 1, 2, \dots, M$; Calculate the unit cells of each row on RIS in turn;

2: **for:** $n = 1, 2, \dots, N$; Calculate the unit cells of each column on RIS in turn;

3: Calculate $d_{T-RIS} = \sqrt{(0 - x_T)^2 + (y_{m,n} - y_T)^2 + (z_{m,n} - z_T)^2}$ for each unit cell,

which means the distance between the transmitter and each unit cell on the RIS;

4: Calculate $\phi_{m,n} = \arctan\left(\frac{z_{m,n}}{y_{m,n}}\right)$ for each unit cell, then we obtain the Azimuth angle of each unit cell in Cartesian coordinates;

5: Calculate $\varphi_{\text{deflect}} = k(y_{m,n} \sin(\Theta_R) \cos(\Phi_R) + z_{m,n} \sin(\Theta_R) \sin(\Phi_R))$ for each unit cell, which means the direction of the reflected beam;

6: Calculate $\varphi_{\text{OAM}} = -l_{\text{OAM}} \phi_{m,n}$ based on the result obtained in **Step 4**, which means the modes of vortex beams using in this transmission system;

7: Calculate $\varphi_{\text{feed}} = -kd_{\text{T-RIS}}$ based on the result obtained in **Step 3**, which means the phase compensation according to the position between the transmitter and each unit cell;

8: Calculate $\varphi_{m,n} = \varphi_{\text{feed}} + \varphi_{\text{deflect}} + \varphi_{\text{OAM}}$ based on the results obtained in **Step 5**, **Step 6** and **Step 7**, which means the specific amount of phase compensation that should be done on each unit cell on the whole RIS board;

9: **end for**

10: **end for**

[0059] A process for manipulating received electromagnetic waves is illustrated in Figure 8, whereby process 800 may be carried out using a 2-bit phase-quantized unit cell of a reconfigurable intelligent surface in accordance with embodiments of the disclosure.

[0060] Process 800 begins at step 802 with process 800 receiving an electromagnetic wave using an antenna provided on the first surface of the unit cell. At step 804, process 800 then selectively provides, using a quadrature phase shifter circuit provided on the second surface of the unit cell and communicatively connected to the antenna through a via, a phase shift of 0-degrees, 90-degrees, 180-degrees or 270-degrees to the electromagnetic wave received by the antenna, based on control signals received from a control module. Process 800 then provides the phase shifted electromagnetic signal to the antenna to be re-radiated and this takes place at step 806. In embodiments of the disclosure, process 800 may compute the control signals based on a phase compensation factor of a transmitter that transmitted the electromagnetic wave at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell.

[0061] In embodiments of the disclosure, the quadrature phase shifter circuit may comprise a first delay line having an end coupled to the via and another end coupled to a first switch, a second switch and a third switch, the first delay line being configured to provide a 0-degree phase shift to the electromagnetic wave received by the antenna, a second delay line having an end coupled to the first switch and having a section coupled to a first control line, the second

delay line being configured to provide a 90-degree phase shift to the electromagnetic wave received by the antenna, a third delay line having an end coupled to the second switch and having a section coupled to a second control line, the third delay line being configured to provide a 180-degree phase shift to the electromagnetic wave received by the antenna, and a fourth delay line having an end coupled to the third switch and having a section coupled to a third control line, the fourth delay line being configured to provide a 270-degree phase shift to the electromagnetic wave received by the antenna.

[0062] In embodiments of the disclosure, the antenna may comprise a single polarization antenna, a dual polarization antenna, or a patch antenna and the first switch may include a first PIN diode that is biased by the first control line, the second switch comprises a second PIN diode that is biased by the second control line, and the third switch comprises a third PIN diode that is biased by the third control line.

[0063] In embodiments of the disclosure, the received electromagnetic wave may comprise a multi-mode vortex beam and whereby the phase compensation factor of the transmitter to the unit cell is computed by process 800 based on a wave vector of the multi-mode vortex beam transmitted by the transmitter and a distance between the transmitter and the unit cell, the beamforming factor of the transmitter at the unit cell may be computed by process 800 based on the wave vector of the multi-mode vortex beam transmitted by the transmitter, a spatial location of the unit cell on the reconfigurable intelligent surface, and a direction of a modified electromagnetic wave as re-radiated from the antenna of the unit cell and the conversion compensation factor of the unit cell may be computed by process 800 based on a mode number of the multi-mode vortex beam transmitted by the transmitter and an azimuth angle of the unit cell as computed from an axis perpendicular to a plane of the first surface of the unit cell.

[0064] A process for wireless communication using a reconfigurable intelligent surface system comprising a layer having a plurality of 2-bit phase-quantized unit cells and a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells, is shown in Figure 9 in accordance with embodiments of the disclosure.

[0065] Process 900 begins at step 902 by receiving, using the plurality of 2-bit phase-quantized unit cells, electromagnetic waves transmitted from a transmitter. In embodiments of

the disclosure, the electromagnetic waves may comprise traditional EM waves or multi-mode vortex beams. Process 900 then proceeds to step 904 where for each of the plurality of 2-bit phase-quantized unit cells, process 900 proceeds to compute, using the control module, a phase shift to be provided by the unit cell based on a phase compensation factor of the transmitter at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell, and then provides, using the control module, control signals to the unit cell such that the unit cell is triggered to provide the computed phase shift to the electromagnetic wave received by the unit cell. At step 906, the control signals then cause the unit cell to re-radiate the phase shifted electromagnetic signal.

[0066] **Numerical Simulation**

[0067] In a first embodiment of the present disclosure, the input parameters of a RIS system which is configured to convert a multi-mode vortex beam having a mode number $l_{OAM} = +1$ to a plane wave is shown in Table 1 below. The arrangement of the 4 different states of the unit cells on a layer of the RIS is illustrated in Figure 10.

Parameters	$[x_T, y_T, z_T]^T$	M	N	dy	dz	k	l_{OAM}	$\{\Theta_R, \Phi_R\}$
Values	$[0, -0.25, -0.3]^T$ m	36	36	12 mm	12 mm	228	+1	$\{30^\circ, 0^\circ\}$

TABLE 1

[0068] In a second embodiment of the present disclosure, the input parameters of a RIS system which is configured to convert a multi-mode vortex beam having a mode number $l_{OAM} = +2$ to a plane wave is shown in Table 2 below. The arrangement of the 4 different states of the unit cells on a layer of the RIS is illustrated in Figure 11.

Parameters	$[x_T, y_T, z_T]^T$	M	N	dy	dz	k	l_{OAM}	$\{\Theta_R, \Phi_R\}$
Values	$[0, -0.25, -0.3]^T$ m	36	36	12 mm	12 mm	228	+2	$\{30^\circ, 0^\circ\}$

TABLE 2

[0069] In a third embodiment of the present disclosure, the input parameters of a RIS system which is configured to convert a multi-mode vortex beam having a mode number $l_{OAM} =$

+1 & +2 to a plane wave is shown in Table 3 below. The arrangement of the 4 different states of the unit cells on a layer of the RIS is illustrated in Figure 12.

Parameters	$[x_T, y_T, z_T]^T$	M	N	dy	dz	k	l_{OAM}	$\{\Theta_R, \Phi_R\}$
Values	$[0, -0.25, -0.3]^T$ m for Mode +1, $[0, 0.25, -0.3]^T$ m for Mode +2	36	36	12 mm	12 mm	228	+1&+2	$\{0^\circ, -45^\circ\}$ for +1, $\{0^\circ, 10^\circ\}$ for +2

TABLE 3

[0070] From the embodiments above, it was determined that a RIS system designed in accordance with the present disclosure was able to convert multi-mode vortex beams to independent plane-wave beams for wireless communication applications. The RIS was then able to be used to receive multiple signals from multiple base stations and convert them to independent plane waves for multiple users thereby significantly improving the channel capacity of wireless communications in line-of-sight scenarios.

[0071] Numerous other changes, substitutions, variations, and modifications may be ascertained by the skilled in the art and it is intended that the present application encompass all such changes, substitutions, variations, and modifications as falling within the scope of the appended claims.

CLAIMS

1. A 2-bit phase-quantized unit cell of a reconfigurable intelligent surface for manipulating a received electromagnetic wave comprising:
 - an antenna provided on a first surface of the unit cell;
 - a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via, the quadrature phase shifter circuit being configured to selectively provide a phase shift of 0-degrees, 90-degrees, 180-degrees, or 270-degrees to the electromagnetic wave received by the antenna based on control signals received from a control module and provide a phase shifted electromagnetic signal to the antenna to be re-radiated,
 - whereby the control signals were computed based on a phase compensation factor of a transmitter that transmitted the electromagnetic wave at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell.
2. The 2-bit phase-quantized unit cell according to claim 1 wherein the quadrature phase shifter circuit comprises:
 - a first delay line having an end coupled to the via and another end coupled to a first switch, a second switch and a third switch, the first delay line being configured to provide a 0-degree phase shift to the electromagnetic wave received by the antenna;
 - a second delay line having an end coupled to the first switch and having a section coupled to a first control line, the second delay line being configured to provide a 90-degree phase shift to the electromagnetic wave received by the antenna;
 - a third delay line having an end coupled to the second switch and having a section coupled to a second control line, the third delay line being configured to provide a 180-degree phase shift to the electromagnetic wave received by the antenna; and
 - a fourth delay line having an end coupled to the third switch and having a section coupled to a third control line, the fourth delay line being configured to provide a 270-degree phase shift to the electromagnetic wave received by the antenna.
3. The 2-bit phase-quantized unit cell according to claims 1 or 2, wherein the antenna comprises a single polarization antenna, a dual polarization antenna, or a patch antenna.

4. The 2-bit phase-quantized unit cell according to any one of claims 2 to 3, wherein the first switch comprises a first PIN diode that is biased by the first control line, the second switch comprises a second PIN diode that is biased by the second control line, and the third switch comprises a third PIN diode that is biased by the third control line.
5. The 2-bit phase-quantized unit cell according to any one of claims 1 to 4, whereby the quadrature phase shifter circuit is configured to provide an attenuation of less than 0.6dB to an amplitude of the electromagnetic signal provided by the antenna.
6. The 2-bit phase-quantized unit cell according to claim 1, wherein the received electromagnetic wave comprises a multi-mode vortex beam and whereby the phase compensation factor of the transmitter to the unit cell is computed based on a wave vector k of the multi-mode vortex beam transmitted by the transmitter and a distance d_{T-RIS} between the transmitter and the unit cell.
7. The 2-bit phase-quantized unit cell according to claim 6, whereby the beamforming factor of the transmitter at the unit cell is computed based on the wave vector k of the multi-mode vortex beam transmitted by the transmitter, a spatial location of the unit cell on the reconfigurable intelligent surface, and a direction of a modified electromagnetic wave as re-radiated from the antenna of the unit cell.
8. The 2-bit phase-quantized unit cell according to claim 7, whereby the conversion compensation factor of the unit cell is computed based on a mode number of the multi-mode vortex beam transmitted by the transmitter and an azimuth angle of the unit cell as computed based on an axis perpendicular to a plane of the first surface of the unit cell.
9. A reconfigurable intelligent surface system for wireless communication, the system comprising:
 - a layer comprising a plurality of 2-bit phase-quantized unit cells that are each configured to receive electromagnetic waves from a transmitter;
 - a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells, the control module configured to:
 - for each of the plurality of 2-bit phase-quantized unit cells,

compute a phase shift to be provided by the unit cell based on a phase compensation factor of the transmitter at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell, and

provide control signals to the unit cell such that the unit cell is triggered to provide the computed phase shift to the electromagnetic wave received by the unit cell, and re-radiate a phase shifted electromagnetic signal.

10. The reconfigurable intelligent surface system according to claim 9, whereby each of the 2-bit phase-quantized unit cells comprise:

an antenna provided on a first surface of the unit cell,

a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via, the quadrature phase shifter circuit being configured to selectively provide a phase shift of 0-degrees, 90-degrees, 180-degrees, or 270-degrees to an electromagnetic wave received by the antenna based on control signals received from the control module.

11. The reconfigurable intelligent surface system according to claim 10, wherein each of the received electromagnetic waves comprises a multi-mode vortex beam and whereby the phase compensation factor of the transmitter to the unit cell is computed based on a wave vector k of the multi-mode vortex beam transmitted by the transmitter and a distance d_{T-RIS} between the transmitter and the unit cell.

12. The reconfigurable intelligent surface system according to claim 11, whereby the beamforming factor of the transmitter at the unit cell is computed based on the wave vector k of the multi-mode vortex beam transmitted by the transmitter, a spatial location of the unit cell on the layer, and a direction of a modified electromagnetic wave as re-radiated from the antenna of the unit cell.

13. The reconfigurable intelligent surface system according to claim 12, whereby the conversion compensation factor of the unit cell is computed based on a mode number of the multi-mode vortex beams transmitted by the transmitter and an azimuth angle of the unit cell as computed based on an axis perpendicular to a plane of the layer.

14. A method for manipulating received electromagnetic waves using a 2-bit phase-quantized unit cell of a reconfigurable intelligent surface, the method comprising:

receiving an electromagnetic wave using an antenna provided on a first surface of the unit cell;

selectively providing, using a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via, a phase shift of 0-degrees, 90-degrees, 180-degrees or 270-degrees to the electromagnetic wave received by the antenna, based on control signals received from a control module and providing a phase shifted electromagnetic signal to the antenna to be re-radiated,

whereby the control signals were computed based on a phase compensation factor of a transmitter that transmitted the electromagnetic wave at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell.

15. The method according to claim 14, whereby the quadrature phase shifter circuit comprises:

a first delay line having an end coupled to the via and another end coupled to a first switch, a second switch and a third switch, the first delay line being configured to provide a 0-degree phase shift to the electromagnetic wave received by the antenna;

a second delay line having an end coupled to the first switch and having a section coupled to a first control line, the second delay line being configured to provide a 90-degree phase shift to the electromagnetic wave received by the antenna;

a third delay line having an end coupled to the second switch and having a section coupled to a second control line, the third delay line being configured to provide a 180-degree phase shift to the electromagnetic wave received by the antenna; and

a fourth delay line having an end coupled to the third switch and having a section coupled to a third control line, the fourth delay line being configured to provide a 270-degree phase shift to the electromagnetic wave received by the antenna.

16. The method according to claims 14 or 15, wherein the antenna comprises a single polarization antenna, a dual polarization antenna, or a patch antenna.

17. The method according to any one of claims 15 to 16, wherein the first switch comprises a first PIN diode that is biased by the first control line, the second switch comprises a second PIN diode that is biased by the second control line, and the third switch comprises a third PIN diode that is biased by the third control line.
18. The method according to any one of claims 14 to 17, whereby the quadrature phase shifter circuit is configured to provide an attenuation of less than 0.6dB to an amplitude of the electromagnetic wave received by the antenna.
19. The method according to claim 14, wherein the received electromagnetic wave comprises a multi-mode vortex beam and whereby the phase compensation factor of the transmitter to the unit cell is computed based on a wave vector k of the multi-mode vortex beam transmitted by the transmitter and a distance d_{T-RIS} between the transmitter and the unit cell.
20. The 2-bit phase-quantized unit cell according to claim 19, whereby the beamforming factor of the transmitter at the unit cell is computed based on the wave vector k of the multi-mode vortex beam transmitted by the transmitter, a spatial location of the unit cell on the reconfigurable intelligent surface, and a direction of a modified electromagnetic wave as re-radiated from the antenna of the unit cell.
21. The 2-bit phase-quantized unit cell according to claim 20, whereby the conversion compensation factor of the unit cell is computed based on a mode number of the multi-mode vortex beam transmitted by the transmitter and an azimuth angle of the unit cell as computed based on an axis perpendicular to a plane of the first surface of the unit cell.
22. A method for wireless communication using a reconfigurable intelligent surface system comprising a layer having a plurality of 2-bit phase-quantized unit cells and a control module communicatively coupled to each of the plurality of 2-bit phase-quantized unit cells, the method comprising:
 - receiving, using the plurality of 2-bit phase-quantized unit cells, electromagnetic waves transmitted from a transmitter;
 - for each of the plurality of 2-bit phase-quantized unit cells,

computing, using the control module, a phase shift to be provided by the unit cell based on a phase compensation factor of the transmitter at the unit cell, a beamforming factor of the transmitter at the unit cell and a conversion compensation factor of the unit cell, and

providing, using the control module, control signals to the unit cell such that the unit cell is triggered to provide the computed phase shift to the electromagnetic wave received by the unit cell and to re-radiate a phase shifted electromagnetic signal.

23. The method according to claim 22, whereby each of the 2-bit phase-quantized unit cells comprise:

an antenna provided on a first surface of the unit cell,

a quadrature phase shifter circuit provided on a second surface of the unit cell and communicatively connected to the antenna through a via, the quadrature phase shifter circuit being configured to selectively provide a phase shift of 0-degrees, 90-degrees, 180-degrees, or 270-degrees to an electromagnetic wave received by the antenna based on control signals received from the control module.

24. The method according to claim 22, wherein each of the received electromagnetic waves comprises a multi-mode vortex beam and whereby the phase compensation factor of the transmitter to the unit cell is computed based on a wave vector k of the multi-mode vortex beam transmitted by the transmitter and a distance d_{T-RIS} between the transmitter and the unit cell.

25. The method according to claim 24, whereby the beamforming factor of the transmitter at the unit cell is computed based on the wave vector k of the multi-mode vortex beam transmitted by the transmitter, a spatial location of the unit cell on the layer, and a direction of a modified electromagnetic wave as re-radiated from the antenna of the unit cell.

26. The method according to claim 25, whereby the conversion compensation factor of the unit cell is computed based on a mode number of the multi-mode vortex beam transmitted by the transmitter and an azimuth angle of the unit cell as computed based on an axis perpendicular to a plane of the layer.