Reconfigurable Intelligent Surfaces for 6G and Beyond: Principles, Applications, and Research Directions

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Abstract

Reconfigurable intelligent surfaces (RIS) or intelligent reflecting surfaces (IRSs), are regarded as one of the most promising and revolutionizing techniques for enhancing the spectrum and/or energy efficiency of wireless systems. These devices are capable of reconfiguring the wireless propagation environment by carefully tuning the phase shifts of a large number of low-cost passive reflecting elements. In this article, we aim for answering four fundamental questions: 1) Why do we need RISs? 2) What is an RIS? 3) What are its applications? 4) What are the relevant challenges and future research directions? In response, ten promising research directions are pointed out.

Index Terms

Intelligent Reflecting Surface (IRS), Reconfigurable Intelligent Surface (RIS), Large Intelligent Surface (LIS), Metasurface.
I. Why Do We Need RIS?

Although fifth-generation (5G) wireless networks are being rolled out worldwide, the key physical layer technology therein is massive multiple-input multiple-output (MIMO) operating in the sub-6 GHz bands, while millimeter wave (mmWave) communication, originally envisioned as one of three main technologies in 5G networks, is still under investigation. The key impediments of mmWave communication include its sensitivity to blockages, limited coverage, and severe path loss. However, some innovative applications such as immersive virtual reality, high-fidelity holographic projections, digital twins, connected robotics and autonomous systems, industrial internet of things (IIoT), intelligent transportation system (ITS) and brain-computer interfaces, are expected to be supported by 6G-and-beyond communications [1]. These applications entail high quality-of-service (QoS) requirements such as extremely high data rates, ultra-high reliability, and ultra-low latency, which cannot be readily supported by the existing systems. Given the large amount of available bandwidth at higher frequencies, communications in the mmWave and even Terahertz bands will be an inevitable trend. The array gain of massive MIMO techniques at the base stations (BSs) mitigates the path loss at high frequencies, but fails to solve the blockage problem. More densely deployed BSs can help eliminate blockages and fill coverage holes, but this is a costly solution both in terms of its infrastructure (and backhaul requirements) and power consumption. Hence, new cost-effective and power-efficient technologies are needed to solve these problems.

Recently, reconfigurable intelligent surfaces (RISs), have been envisioned as a key enabling technology to circumvent the above-mentioned issues. RISs can be installed on large flat surfaces (e.g., walls or ceilings indoors, buildings or signage outdoors) in order to reflect radio-frequency (RF) energy around obstacles and create a virtual line-of-sight (LoS) propagation path between a mmWave source and the destination.

II. What Is An RIS?

An RIS is a planar surface consisting of an array of passive reflecting elements, each of which can independently impose the required phase shift on the incoming signal [2], [3]. By carefully adjusting the phase shifts of all the reflecting elements, the reflected signals can be reconfigured to propagate towards their desired directions. Due to rapid developments in metamaterials [4], the reflection coefficient of each element can be reconfigured in real time to adapt to the dynamically fluctuating wireless propagation environment.
As shown in Fig. 1-(a), a typical RIS architecture mainly consists of a planar surface and a controller. The planar surface may be made of a single or, in general, multiple layers. In [2], for example, a three-later planar surface is designed. The outer layer has a large number of reflecting elements printed on a dielectric substrate to directly act on the incident signals. The middle layer is a copper panel to avoid signal/energy leakage. The last layer is a circuit board that is used for tuning the reflection coefficients of the RIS elements, which is operated by a smart controller such as a field-programmable gate array (FPGA). In a typical scenario envisioned for their operation, the optimal reflection coefficients of the RIS are calculated at the BS, and then sent to the RIS’s controller through a dedicated feedback link. The design of the reflection coefficients depends on the channel state information (CSI), which is only updated when the CSI changes, on a much longer time scale than the data symbol duration. Hence, low-rate information exchange is sufficient for the dedicated control link, which can be implemented using low-cost copper lines or simple cost-efficient wireless transceivers. Fig. 1-(b) shows the structure of each reflecting element, in which a positive-intrinsic negative (PIN) diode is embedded. By controlling the voltage through the biasing line, the PIN can switch between ‘On’ and ‘Off’ modes as shown in the equivalent circuit of Fig. 1-(c), which can realize a phase shift difference of \( \pi \) in radians [2], [4]. To increase the number of phase shift levels, more PINs have to be integrated in each element.

RISs also have important advantages for practical implementations. For example, the RIS reflecting elements only passively reflect the incoming signals without any sophisticated signal processing (SP) operations that require RF transceiver hardware. Hence, compared to conventional active transmitters, RISs can operate with several orders of magnitude lower cost in
TABLE I

RIS vs. Relays

|                  | RIS | AF Relay | DF Relay | FD Relay |
|------------------|-----|----------|----------|----------|
| With RF Chains?  | No  | Yes      | Yes      | Yes      |
| SP Capability?   | No  | No       | Yes      | Yes      |
| Noise?           | No  | Yes      | Yes      | Yes      |
| Duplex           | Full| Half     | Half     | Full     |
| Hardware cost    | Low | Median   | High     | Very high|
| Power Consumption| Low | Median   | High     | Very high|

terms of hardware and power consumption [2], [5]. Additionally, due to the passive nature of the reflecting elements, RISs can be fabricated with light weight and limited layer thickness, hence they can be readily installed on walls, ceilings, signage, street lamps, etc. Furthermore, an RIS naturally operates in full-duplex (FD) mode without self-interference or introducing thermal noise. Therefore, they achieve higher spectral efficiency than active half-duplex (HD) relays, despite their lower signal processing complexity than that of active FD relays requiring sophisticated self-interference cancelation. In Table I, we compare RISs to various kinds of relays, since they both serve to create alternative transmission links. The acronyms of AF and DF in Table I refer to amplify-and-forward and decode-and-forward, respectively.

III. WHAT ARE ITS APPLICATIONS?

In addition to their application in high-frequency communications, RISs are also appealing for applications in conventional sub-6 GHz communications, where blockages are generally not a serious problem, and direct non-LoS signal paths exist. Specifically, by judiciously tuning the phase shifts of the reflecting elements, the reflected signals can be constructively superimposed with those from the direct paths for enhancing the desired signal power. Alternatively, they may be destructively combined for mitigating deleterious effects of multiuser interference or the information leakage to eavesdroppers. Hence, RISs provide additional degrees of freedom (DoFs) to further improve the system performance by reconfiguring the wireless propagation environment.

To clarify the advantages of RIS, below we discuss a simple example of the RIS-aided system of Fig. 2 consisting of a single-antenna source node (denoted ‘S’) and a single-antenna
destination node (denoted ‘D’). An RIS having a single reflecting element is deployed between S and D, which has a reflection coefficient of $\gamma$. Since the RIS is passive, $\gamma$ should satisfy $|\gamma| \leq 1$.

In Fig. 2, $h^{SR}$, $h^{RD}$ and $h^{SD}$ are the scalar channel gains spanning from S to the RIS, from the RIS to D, and from S to D, respectively. The variables $\alpha$, $\beta$ and $\rho$ are the corresponding positive channel gains, and $\theta$, $\varphi$ and $\mu$ are the channel phases. By carefully setting the values of the reflection coefficient $\gamma$, two main functionalities can be provided by the RIS: signal enhancement and signal neutralization.

To evaluate the performance of the RIS-aided system, we consider two cases based on the example of Fig. 2. In Case I, the system parameters are set as $\rho = 0.5, \alpha = 1, \beta = 1$, while in Case II, they are $\rho = 3, \alpha = 1, \beta = 1$. The numerical results of Fig. 3 verify its efficiency in both functionalities of the RIS.

In a more practical setting, the BS may be equipped with multiple antennas, and the RIS is
A. RIS-aided Multicell Networks

To maximize spectrum efficiency (SE), multiple BSs in different cells reuse the same scarce frequency resources, which leads to inter-cell interference, especially for the cell-edge users. Specifically, the desired signal power received by the cell-edge user from its serving BS is comparable to the interference received from its neighbouring cells. Hence, the cell-edge users...
suffer from a low signal-to-interference-plus-noise ratio (SINR). To address this issue, the authors of [6] proposed to deploy an RIS at the cell boundary as shown in Fig. 4-(a). In such a setting, the RIS is able to simultaneously enhance the signal gleaned from the serving BS, and mitigate the interference from the other. The simulation results of [6] showed that the sum rate achieved by an RIS-aided system having 80 reflecting elements may double that without an RIS.

B. RIS-aided SWIPT Networks

SWIPT is a promising technique of providing cost-effective power delivery to energy-limited internet of things (IoT) networks. In SWIPT systems, a BS with constant power supply broadcasts wireless signal to two groups of receivers. One group, referred to as information receivers (IRs), intend to decode the received signal, while the other group, referred to as energy receivers (ERs), harvests energy from the signals. The key challenge in SWIPT systems is that the ERs and IRs operate under different power supply requirements. Explicitly, IRs require a received power on the order of -60 dBm, while ERs can only operate when the minimum power is higher than -10 dBm. As a result, ERs should be deployed in closer proximity to the BS than IRs to harvest sufficient power, since the signal attenuation limits the ERs’ practical operational range. To deal with this problem, the authors of [7] proposed to deploy an RIS in the proximity of the ERs, as shown in Fig. 4-(b). By leveraging the RIS’s signal enhancement capability, increased power can be harvested at the ERs. The simulation results of [7] revealed that to ensure a minimum harvested power of 0.2 mW, the operational range of the ERs can be extended from 5.5 meters to 9 meters, when the RIS is equipped with 40 reflecting elements. Longer ranges are anticipated by installing more elements at the RIS.

C. RIS-aided MEC Networks

In novel future applications such as virtual reality (VR), computation-intensive image and video processing tasks must be executed in real time. However, due to the limited power supply and hardware capabilities of typical VR devices, these tasks cannot be accomplished locally. To tackle this issue, these computationally intensive tasks can be offloaded to powerful computing nodes that are usually deployed at the edge of the network. However, for some special cases where these devices are far from the MEC node, they can suffer from a low data offloading rate due to the severe path loss, which leads to excessive offloading delays. To overcome this impediment, a novel RIS-aided MEC framework was proposed in [8], as shown in Fig. 4-(c).
The simulation results of [8] showed that the overall task latency can be reduced from 115 ms to 65 ms, if a 100-element RIS is employed.

D. RIS-aided Multicast Networks

Multicast transmission based on content reuse has attracted wide research attention, since it is capable of mitigating the tele-traffic, hence it will play a pivotal role in future wireless networks. Some typical examples using multicast transmission include video conferencing, video gaming and TV broadcast. In multi-group multicast communications, identical content is shared within each group, and each group’s data rate is limited by the user with the weakest channel gain. To deal with this issue, an RIS-aided multicast architecture was proposed in [9] as shown in Fig. 4-(d). By carefully tuning the RIS phase shifts, the channel conditions of the weakest link can be enhanced.

E. RIS-aided PLS Networks

Due to the broadcast nature of wireless transmission, wireless links are prone to security threats such as jamming attacks or secure information leakage. Conventional secure communication techniques rely on encryption in the upper layers of the protocol stack. However, complicated security key exchange and management are required, which increases the communication delay and system complexity. Recently, PLS techniques have received extensive research attention, since they can avoid complex key exchange protocols, and are suitable for latency-sensitive applications. In order to maximize the rate of a secure communication link, both artificial noise and multiple antennas have been proposed. However, when both the legitimate users and eavesdroppers have correlated channels or where the eavesdroppers are closer to the BS than the legitimate users, the achievable secure rate remains limited. To tackle this issue, in [10], an RIS was deployed in a network operating in the presence of an eavesdropper as shown in Fig. 4-(e), for mitigating the information leakage to the eavesdroppers, while simultaneously increasing the received signal power at the legitimate users.

F. RIS-aided CR Networks

CRs are capable of enhancing the SE by allowing secondary users (SUs) to reuse the same spectrum with primary users (PUs) while controlling the interference inflicted by the SU transmitters (SU-TXs) on the PU receivers (PU-RXs). A standard approach is to use beamforming for
maximizing the sum-rate of the SUs, while ensuring that the interference power at the PU-RXs remains below the interference temperature (IT) limit. The IT is chosen such that the quality of service (QoS) constraint at the PUs will not be violated. However, the beamforming gain is limited, when the SU-TX to SU-RX link is weak, and the channel gain between the SU-TX and SU-RX is much higher. To handle this issue, the authors of [11] proposed to deploy an RIS in the vicinity of the PU-RXs, as shown in Fig. 4-(f). Signal neutralization by the RIS is used for mitigating the interference towards the PU-TXs, while its signal enhancement improves the signal power at the SU-RXs. The simulation results in [11] showed that the data rate achieved by deploying an RIS having 100 reflecting elements is twice that without the RIS.

IV. WHAT ARE THE RELEVANT CHALLENGES AND RESEARCH DIRECTIONS?

Although RISs are indeed appealing for the above applications, their implementation poses several challenges as well. In the following, we list ten promising future research directions.

**Direction 1: Channel Estimation**

To reap the full potential of RIS-aided wireless networks, CSI should be estimated to enable the design of appropriate transmit beamforming. However, the acquisition of CSI in an RIS-aided scenario is totally different from conventional communication systems. Consider the typical RIS-aided wireless system of Fig. 5, where a multi-antenna BS serves a single-antenna user with the aid of an RIS. By turning off the RIS, the direct channel can be estimated using conventional channel estimation methods. However, the RIS-related channels \( (\mathbf{H} \text{ and } h_r) \) are more challenging to estimate since the RIS is equipped with passive reflecting elements that cannot process the pilot signals from the user/BS and it cannot transmit pilot signals to the BS/user. Fortunately, in most situations having only the cascaded CSI defined as \( \mathbf{G} = \text{diag}(h_r^H)\mathbf{H} \) is sufficient. However, since the number of reflecting elements is usually very large, the cascaded channel \( G \) contains a large number of channel coefficients, hence their estimation entails a large number of pilots.

In RIS-aided mmWave/THz communication systems, the cascaded channel is generally sparse and has a low rank. Thus compressive sensing (CS) techniques can be used for reducing the CSI estimation overhead. However, for RIS-aided sub-6 GHz communication systems, the channels are often not sparse and thus no CS methods can be used. How to reduce the channel estimation overhead for sub-6 GHz communication systems remains an open problem.

**Direction 2: Robust Transmission Design Based on Imperfect CSI**
Given the estimated cascaded CSI, the phase shifts of the reflecting elements have to be jointly designed together with the BS’s active beamforming for achieving either desired signal enhancement or interference cancellation depending on the design objectives. However, most of the existing contributions are based on the assumption of having perfect CSI knowledge for all channels, which is challenging to satisfy in practice. For estimating the cascaded CSI, one should first estimate the direct BS-user channel by switching off the RIS, and then estimate the overall channel by switching on the RIS. The cascaded CSI can be calculated by subtracting the direct BS-user channel response from the overall channel response. Since the direct BS-user channel cannot be perfectly estimated, the subtraction operation will further contaminate the cascaded CSI, similar to the error propagation of successive interference cancellation. Thus, the cascaded CSI error is sizeable and should be taken into account. The authors of [12] proposed a framework for robust transmission design by considering the imperfect cascaded CSI, assuming a bounded channel error model and a statistical channel error model.

**Direction 3: Transmission Design Based on Long-term CSI**

Most of the existing papers concerning the RIS phase shift are based on the availability of instantaneous CSI, which has the following drawbacks. Firstly, for RIS-aided sub-6 GHz communication systems, the channel training overhead becomes excessive when the number of elements is large. Secondly, for each channel coherence interval (roughly 20-100 ms), the BS must compute its beamforming weights as well as the phase shifts at the RIS, which entails solving a large-scale optimization problem. Thirdly, when the number of RIS elements is large and the channel is rapidly varying, the required capacity of the feedback link from the BS to
the RIS also increases, which imposes a high overhead and higher cost.

To address the above challenges, it is appealing to design the phase shifts based on the longer-term CSI relying on both angular and location information, which changes much more slowly. Direction of arrival/departure (DOA/DOD) estimation can be used for determining the long-term CSI, which substantially reduces the channel estimation overhead. Additionally, when the phase shifts are designed based on the long-term CSI, they vary more slowly and less control signaling overhead is required. Hence, the computational complexity can be reduced, and having low-capacity connections between the BS and RIS is sufficient, thereby reducing the implementation cost. The idea of using DOA/DOD information in RIS-aided massive MIMO systems was studied in [13] for Rician channels.

**Direction 4: Angle/Location Estimation**

To facilitate the RIS phase shift design based on long-term CSI, the angle or location information should be available at the BS. Unfortunately, conventional angle/location estimation algorithms may not be applicable for RIS-aided networks when the direct channel spanning from the BS to the user is blocked. This is because a conventional BS can transmit pilot beams for tracking the users, the RIS is passive, hence cannot send pilot signals. Thus, low-complexity yet high-performance angle/location algorithms have to be conceived for RIS-aided networks.

**Direction 5: Robust Design/Performance Analysis for Mitigating Hardware Impairment**

In practical communication systems, in addition to imperfect CSI, we encounter transceiver hardware impairments (HWI), caused by non-linear amplifiers, low-resolution analog-to-digital counters (ADCs) and imperfect oscillators. The strength of these distortions is closely coupled with that of the useful signals. Furthermore, to reduce the hardware cost and power consumption, a limited number of quantized phase-shifts may be used. Compared with conventional MIMO systems without RIS, the impact of HWI in RIS-aided systems is complex due to the presence of quantized phase at the RIS. If not appropriately tackled, the system will suffer from more severe performance losses than in conventional MIMO systems. Hence, robust transmission design is highly needed that takes into account HWI at both the transceivers and RIS. Furthermore, accurate performance analysis is needed for characterizing the performance loss due to HWI.

**Direction 6: Distributed Algorithms with Low Overhead Exchange**

In the RIS-aided multicell scenario of [6], the transmission design is centralized. In particular, the algorithm proposed requires a central processing unit (CPU) for collecting all the complex-valued channel matrices over the network. The CPU computes all the active beamforming
weights and phase shifts, and then sends them back to the corresponding nodes. However, these centralized algorithms suffer from a heavy feedback overhead and high computational complexity, which is an impediment. Note that compared to conventional RIS-free systems, the large-dimensional cascaded channel matrix must additionally be fed back to the CPU for the transmission design.

Hence, it is imperative to design distributed algorithms, where each BS can make transmission decisions based on its local CSI and limited information exchange with other BSs. Distributed algorithms have appealing advantages over centralized algorithms, such as low information exchange overhead, reduced computational complexity and increased scalability.

**Direction 7: System Design for RIS-aided Frequency-division Duplex (FDD) systems**

Most existing contributions related to RIS have considered channel estimation for time-division duplex (TDD)-based implementations due to the appealing feature of channel reciprocity. However, recent results in [14] revealed that the RIS phase-shift model depends on the incident electromagnetic angles, which implies that the assumption of channel reciprocity in TDD systems may not hold in practice. Hence, it is imperative to study channel estimation and transmission design for FDD RIS systems. Due to a large number of reflecting elements at the RIS, large-dimensional channel matrices have to be fed back to the BS in FDD RIS systems, which incurs high feedback overhead.

**Direction 8: Application of RIS in Terahertz Communications**

Compared to mmWave communications, Terahertz (THz) communications can provide more abundant bandwidth and higher data rates. It has been widely envisioned as one of the most important technologies in future 6G networks [11]. Despite its abundant bandwidth, THz frequencies suffer from strong atmospheric attenuation, molecular absorption and extremely severe path loss. Moreover, such high-frequency signals are very prone to blockage effects, and thus they are unable to support reliable communication links, except for short-range LoS scenarios. The use of RISs is a promising remedy to address these issues due to their ability to create alternative signal paths. In the THz band, path-loss peaks appear in different frequency bands, and thus the total bandwidth has to be divided into several sub-bands having different bandwidths. In [15], the location of the RIS, the selection of the sub-bands and the phase shifts were jointly optimized for maximizing the sum rate. In addition to its unique frequency characteristics, THz electronic components can be made compact, and thus the RIS can accommodate a massive number of tiny reflecting elements, allowing us to realize a holographic array having a near-continuous aperture.
Hence, channel estimation and beam pattern design for RIS-aided THz communications is an exciting area for future study.

**Direction 9: Channel Modeling**
Accurate channel modeling is crucial for link budget analysis. Most of the existing channel models used in RIS-aided wireless systems are based on the far-field channel model, where the distances between a BS and all reflecting elements are the same. In practice, to achieve the best performance, the RIS may be deployed in the vicinity of BSs and/or users [6]. Additionally, RIS may cover a large area to capture a large number of incident electromagnetic waves. In this case, the distances from the BS to all the reflecting elements are different, and a near-field channel model should be adopted.

**Direction 10: Mobility Management**
Mobility management is a challenging problem for RIS-aided wireless networks. Due to the rapid movements of users, the BS may lose its connection with them, unless agile mobility management schemes are used. Since RISs are passive, they cannot send pilot signals to track the movement of the users. Hence, it is much more challenging to track roaming users, especially when the direct links between the BS and users are blocked.

**V. Conclusions**
In this article, we have answered four critical questions associated with RIS. Additionally, we have demonstrated that they are capable of mitigating the challenging blockage and coverage issues of mmWave or THz communications. We briefly introduced the basic RIS hardware architecture and its main advantages over relays. We also discussed their desired signal enhancement and undesired signal neutralization capability. These two functionalities make RISs appealing for integration into emerging wireless applications, including multicell, SWIPT, MEC, multicast, PLS, and CR systems. Finally, to provide useful guidance and spark additional research interests, we also formulated ten promising research directions.

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