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

Cunhua Pan, Hong Ren, Kezhi Wang, Jonas Florentin Kolb, Maged Elkashlan, Ming Chen, Marco Di Renzo, Yang Hao, Jiangzhou Wang, A. Lee Swindlehurst, Xiaohu You, and Lajos Hanzo

Reconfigurable intelligent surfaces (RISs) 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.

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Abstract

Reconfigurable intelligent surfaces (RISs) 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 to answer four fundmental questions: 1) Why do we need RISs? 2) What is an RIS? 3) What are RIS's applications? 4) What are the relevant challenges and future research directions? In response, eight promising research directions are pointed out.

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 pivotal technologies in 5G networks, has not been widely adopted. 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, the Industrial Internet of Things, intelligent transportation system, 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 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 in terms of both 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 an mmWave source and the destination.

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]. Based on the specific materials of the reflecting elements, the RIS can be classified into antenna-array-based [4] and metasurface-based structures [5]. By carefully adjusting the phase shifts of all the reflecting elements, the reflected signals can be reconfigured to propagate toward their desired directions. Due to rapid developments in metamaterials, 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. 1a, a typical RIS architecture fabricated with metamaterials mainly consists of a planar surface and a controller. The planar surface may be made of a single layer or, in general, multiple layers. In [2], for example, a three-layer 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

Cunhua Pan, Jonas Florentin Kolb, Maged Elkashlan, and Yang Hao are with Queen Mary University of London; Hong Ren (corresponding author), Ming Chen, and Xiaohu You are with Southeast University; Kezhi Wang is with Northumbria University; Marco Di Renzo is with Université Paris-Saclay; Jiangzhou Wang is with the University of Kent; A. Lee Swindlehurst is with the University of California at Irvine; Lajos Hanzo (corresponding author) is with the University of Southampton.

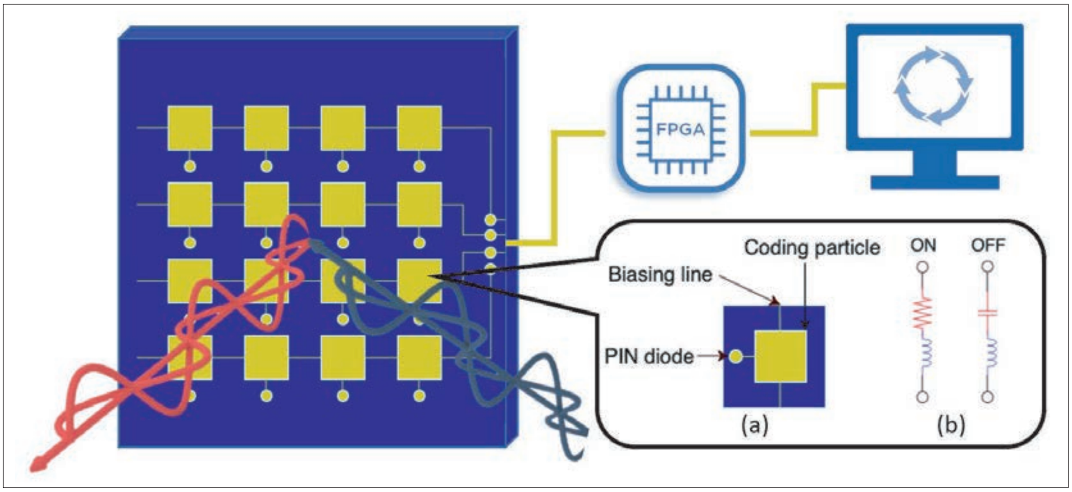

FIGURE 1. Architecture of an RIS.

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 timescale than the data symbol duration. Figure 1a 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. 1b, which can realize a phase shift difference of π in radians [2, 5]. 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 at much lower cost in terms of hardware and power consumption [2, 6]. 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, and so on. 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 cancellation. In Table 1, we compare RISs to various kinds of relays, since they all serve to create alternative transmission links. The acronyms of AF and DF in Table 1 refer to amplify-and-forward and decode-and-forward, respectively.

	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

TABLE 1. RIS vs. relays.

What Are the RIS's Applications?

By judiciously tuning the phase shifts of the reflecting elements of the RIS, the reflected signals can be constructively superimposed with those from the direct paths for enhancing the desired signal power, or destructively combined for mitigating deleterious effects of multiuser interference. Hence, RISs provide additional degrees of freedom to further improve the system performance. In the following, we list some typical RIS applications in various emerging systems.

RIS-Aided mmWave Systems

MmWave techniques have the potential of supporting high data rates given their high bandwidth. However, communication at mmWave frequency also has some drawbacks, such as severe path loss. Fortunately, this can be mitigated by its huge array gain provided by a large antenna array within a compact space, given its short wavelength. Another impediment is that it is vulnerable to blockages by cars, pedestrians, and trees. The penetration loss is also high, which cannot be readily addressed by using a large antenna array. Instead, RISs can be deployed to construct an auxiliary transmission link even when the direct link is blocked.

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 neighboring cells. Hence, the cell edge users suffer from a low signal-to-interference-plus-noise ratio (SINR). To address this issue, the authors of [7] proposed to deploy an RIS at the cell boundary, as shown in Fig. 2. 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 [7] showed

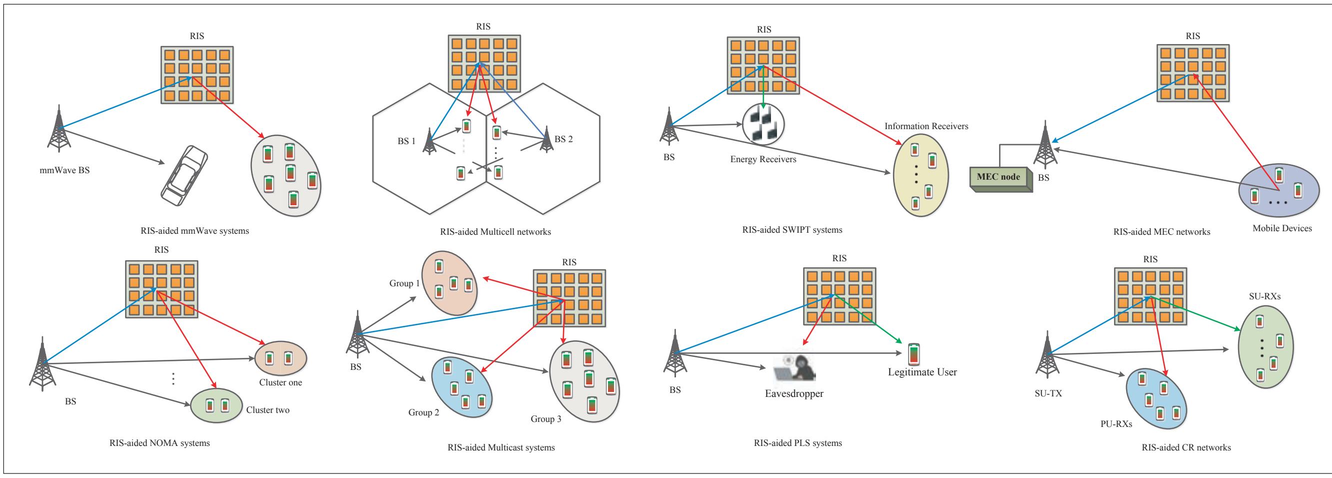

FIGURE 2. Typical applications of RIS in various emerging sub-6 GHz systems.

that the sum rate achieved by an RIS-aided system having 80 reflecting elements may double that without an RIS.

RIS-Aided Simultaneous Wireless Information and Power Transfer Networks

Simultaneous wireless information and power transfer (SWIPT) is a promising technique for providing cost-effective power delivery to energy-limited Internet of Things (IoT) networks, where a BS with constant power supply broadcasts wireless signal to information receivers (IRs) and energy receivers (ERs) simultaneously. The key challenge in SWIPT systems is that the ERs and IRs operate under different power supply requirements. Explicitly, ERs require received power on an order much higher than IRs. 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 [8] proposed to deploy an RIS in the proximity of the ERs, as shown in Fig. 2. The simulation results of [8] revealed that to ensure a minimum harvested power of 0.2 mW, the operational range of the ERs can be extended from 5.5 m to 9 m when the RIS is equipped with 40 reflecting elements.

RIS-Aided Mobile Edge Computing 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 mobile edge computing (MEC) node, they can suffer from a low data offloading rate due to severe path loss, which leads to excessive offloading delays. To overcome this impediment, a novel RIS-aided MEC framework was proposed in [9], as shown in Fig. 2. The simulation results of [9] showed that the overall task latency can be reduced from 115 ms to 65 ms if a 100-element RIS is employed.

RIS-Aided Non-Orthogonal Multiple Access

Non-orthogonal multiple access (NOMA) constitutes a promising future multiple access technique in future wireless networks, in which each orthogonal resource block is shared by multiple simultaneous users. This significantly enhances the spectral efficiency of conventional orthogonal multiple access (OMA). However, in some special cases when the users' channel vectors are orthogonal to each other, NOMA may not be a good option. The ideal implementation scenario for NOMA is when all the users' channel vectors represent the same angular direction. To broaden the application of NOMA, RIS can be introduced into the system to beneficially manipulate the wireless channel vectors of all users so that one user's channel vector can be aligned with another one's [10].

RIS-Aided Multicast Networks

Multicast transmission based on content reuse has attracted wide research attention, since it is capable of mitigating the tele-traffic, and hence will play a pivotal role in future wireless networks. Some typical examples using multicast transmission include videoconferencing, 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 [11], as shown in Fig. 2. By carefully tuning the RIS phase shifts, the channel conditions of the weakest link can be enhanced.

RIS-Aided Physical Layer Security Networks

Due to the broadcast nature of wireless transmission, wireless links are prone to security threats such as jamming attacks and secure information leakage. Recently, physical layer security (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 when the eavesdroppers are closer to the BS than the legitimate users, the achievable secure rate remains limited. To tackle this issue, in [12], an RIS was deployed in a network operating in the presence of an eavesdropper, as shown in Fig. 2, for mitigating the information leakage to the eavesdroppers, while simultaneously increasing the received signal power at the legitimate users.

RIS-Aided Cognitive Radio Networks

Cognitive radios (CRs) are capable of enhancing the SE by allowing secondary users (SUs) to reuse the same spectrum as 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. 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 PU-RX is much higher. To handle this issue, an RIS can be deployed in the vicinity of the PU-RXs, as shown in Fig. 2. The RIS is used for mitigating the interference toward the PU-RXs, while improving the signal power at the SU-RXs.

Case Study

In this section, we present a case study to show the benefits of deploying an RIS in multicell networks. Specifically, we consider the RIS-aided two-cell network shown in Fig. 3. Each cell has two users that are randomly positioned in a circle with radius of 20 m. The path loss exponent between the BS and the users is $\alpha_{BU} = 3.75$. The path loss exponents of the BS-RIS link and the RIS-user link are set to $\alpha_{BI} = \alpha_{IU} \triangleq = \alpha_{RIS} = 2.2$. The small-scale fading is assumed to be Rayleigh fading. All other parameters are given in [7].

Explicitly, in [7], an iterative algorithm was proposed for jointly optimizing the transmit precoding at the BS and the passive beamforming at the RIS for maximizing the weighted sum rate (WSR). In the following, we compare it (called "RIS-aided") to the following two benchmark schemes:

- **RandPhase:** The phase shifts of the RIS are randomly generated from [0, 2π]. The transmit precoding at the BS is designed based on the method of [7].
- **No-RIS:** There is no RIS in the system.

First, we study the impact of the RIS-related path loss exponent α_{RIS} on the WSR performance in Fig. 4. It can be observed from this figure that the WSR achieved by the RIS-aided algorithm decreases with the increase of α_{RIS} and finally converges to the WSR of the no-RIS scheme. The reason for this is that by increasing α_{RIS}, the RIS-related links suffer from severe signal attenuation, and hence the signal reflected by the RIS becomes too weak. However, when α_{RIS} is small, significant performance gains can be achieved by an RIS over the scenario operating without RIS. This provides important design insights indicating that the location of RIS should be carefully chosen for avoiding obstacles in both the BS-IRS link and IRS-user link.

Then the impact of RIS location X_{RIS} on the WSR performance is evaluated in Fig. 5, where the RIS moves from X_{RIS} = 50 m (cell center) to X_{RIS}= 300 m (cell edge). The RIS-aided algorithm is shown to achieve superior performance over the other two benchmark schemes. It is interesting to observe that the WSR obtained by the RIS-aided algorithm first decreases for 50 m < X_{RIS} < 150 m and then increases with X_{RIS}. The minimum WSR value is achieved when the RIS is located midway between BS 1 and the RIS. This is in contrast to the conventional relaying scheme, where the best performance is achieved when the relay is halfway between the transmitter and the receiver. Furthermore, the WSR achieved when the RIS is at the cell edge is much higher than in the case when the RIS is at the cell center. This is because positioning the RIS near BS 1 is only beneficial for users in cell 1, while all users benefit from the RIS when it is at the cell edge.

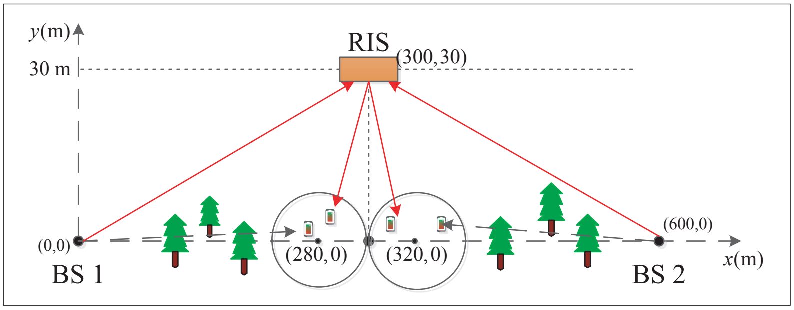

FIGURE 3. Simulation setup.

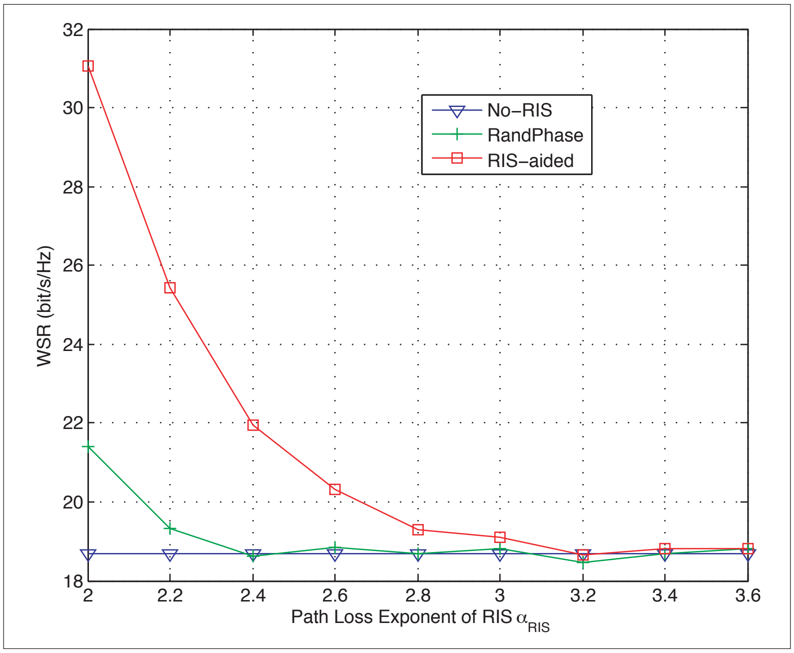

FIGURE 4. Weighted sum rate vs. the path loss exponent α_{RIS}.

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 eight promising future research directions.

Direction 1: Channel Estimation

To reap the full benefits of RIS-aided wireless networks, the CSI should be estimated in support of the phase shift design. We may consider near-instantaneous CSI and long-term CSI.

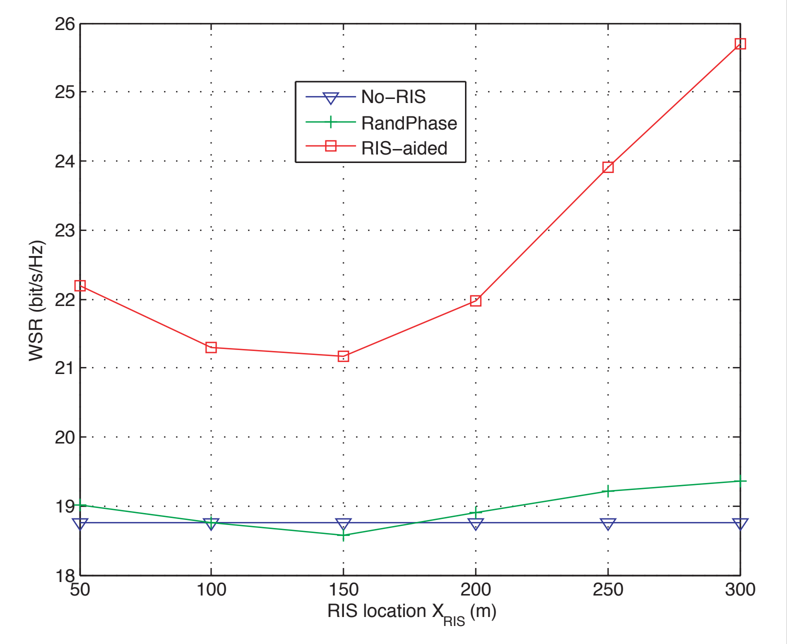

FIGURE 5. Weighted sum rate vs. the RIS location X_{RIS}.

Concerning near-instantaneous CSI estimation, we consider a typical RIS-aided wireless system where a multi-antenna BS serves a single-antenna user with the aid of an RIS. Let us denote the channel spanning from the BS to the RIS and that from the RIS to the user by $\mathbf{H}$ and $\mathbf{h}_r$, respectively. In most situations, having only the cascaded CSI of the two hops defined as $\mathbf{G} = \text{diag}(\mathbf{h}_r^{\mathbf{H}})\mathbf{H}$ is sufficient. However, since the number of reflecting elements is usually very large, the cascaded channel $\mathbf{G}$ contains a large number of channel coefficients. Hence, their estimation requires a large number of pilots, which is proportional to the number of reflecting elements. How to reduce the channel estimation overhead remains an open problem.

To facilitate the 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, while the RIS is passive and hence cannot send pilot signals. Thus, low-complexity but high-performance angle/location estimation algorithms have to be conceived for RIS-aided networks.

Direction 2: Passive Beamforming Design Based on Imperfect Parameters

Given the estimated CSI, the phase shifts have to be jointly designed together with the BS's active beamforming to achieve the desired objectives. However, most of the existing contributions are based on the assumption of perfect instantaneous CSI, which is unrealistic 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. An initial attempt was devoted to a simple RIS-aided multiple-user downlink scenario in [13], and more emerging application scenarios are imperative to be investigated.

Furthermore, in addition to imperfect CSI, we encounter realistic transceiver hardware impairments (HWIs) caused by nonlinear amplifiers, low-resolution analog-to-digital converters (ADCs), and imperfect oscillators. To reduce the hardware cost and power consumption, a limited number of quantized phase shifts may be used. This will impose quantization noise on the phase shifts of the RIS elements. Additionally, the popularly assumed phase-only reflection model is not accurate in practice, since the reflection amplitude tends to depend on the value of the phase shift itself. Compared to conventional systems operating without RIS, the impact of HWIs in RIS-aided systems is complex due to the presence of quantized phase at the RIS. Hence, robust transmission design is needed that takes into account the HWIs at both the transceivers and the RIS.

On the other hand, acquiring the near-instantaneous CSI may be challenging for the following reasons. First, the training overhead is excessive when the number of reflecting elements is large. Second, the BS has to compute its beamforming weights as well as the phase shifts at the RIS, which entails solving a large-scale optimization problem. Third, 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 high overhead and high cost. To address these challenges, it is appealing to design the phase shifts based on the long-term CSI relying on both angular and location information, which changes much more slowly. Unfortunately, only a very few contributions were devoted to this research area [14].

Direction 3: Distributed Algorithms with Low Overhead Exchange

In the RIS-aided multicell scenario of [7], 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 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.

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 4: System Design for RIS-Aided Frequency-Division Duplex 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 [15] 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 frequency-division duplex (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 5: Application of RIS in Terahertz Communications

Compared to mmWave communications, THz communications can provide more abundant bandwidth and higher data rates. Despite its abundant bandwidth, THz frequencies suffer from strong atmospheric attenuation, molecular absorption, and extremely severe path loss, which limits its operational range. Moreover, such high-frequency signals are very prone to blockage effects, and thus they are unable to support reliable communication links. These drawbacks impair its practical implementation. 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. Furthermore, 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 6: 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.

Direction 7: Deployment Issues

The deployment strategy for RIS reflecting elements has a significant impact on the generation of the RIS-related channel coefficients and thus also on the system performance limit. From a practical implementation perspective, RIS deployments have to take into account the hardware cost, location availability, user distributions, and the requested services. There is a fundamental question to be answered: *Given a total number of reflection elements, is centralized deployment better than distributed deployment?* To answer this question, we have to address the following two research issues:

- For centralized deployment, where should the RIS be deployed: in the vicinity of the BS or the users, or where else between the BS and the user?
- For distributed deployment, how many smaller-sized groups of RISs should the total number of reflecting elements be partitioned into? Where should these smaller-sized RISs be deployed?

Direction 8: AI-Driven Design and Optimization

The RIS phase shift matrices have to be optimized for enhancing the system performance. In practical deployments, each RIS is equipped with hundreds of reflecting elements. Most of the existing contributions on phase shift design tend to rely on model-based optimization methods, which require a large number of iterations to find a near-optimal solution, which is due to the non-convexity of phase shift constraints and the non-convex nature of the objective function. Thus, the existing methods will incur high computational complexity, which makes them unsuitable for real-time applications. To address this issue, an artificial-intelligence-based method is an appealing data-driven scheme that can extract system features without a specific mathematical model. Once trained, the optimal solution can be found by simple algebraic calculations. Additionally, the trained model can be quite robust against both imperfect CSI and hardware impairments.

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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 and THz communications. We briefly introduce the basic RIS hardware architecture and its main advantages over relays. We also discuss their potential integration into emerging wireless applications, including multicell, SWIPT, MEC, NOMA, multicast, PLS, CR systems, and mmWave. Finally, to provide useful guidance and spark additional research interest, we also formulate eight promising research directions.

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Biographies

Cunhua Pan (c.pan@qmul.ac.uk) received his Ph.D. from Southeast University, China, in 2015. From 2015 to 2016, he was a research associate at the University of Kent, United Kingdom. He held a postdoctoral position at Queen Mary University of London, United Kingdom, from 2016 to 2019, where he is currently a lecturer. He serves as Lead Guest Editor of the *IEEE JSTSP* Special Issue on RIS, and an Editor of *IEEE CL*, *IEEE WCL*, and *IEEE Access*.

Jonas Florentin Kolb (j.f.kolb@qmul.ac.uk) is a Ph.D. student at Queen Mary University of London.

Maged Elkashlan (maged.elkashlan@qmul.ac.uk) received his Ph.D. from the University of British Columbia, Canada, in 2006. From 2007 to 2011, he was with CSIRO, Australia. In 2011, he joined Queen Mary University of London.

Yang Hao (y.hao@qmul.ac.uk) received his Ph.D. degree from the University of Bristol, United Kingdom, in 1998. He is currently a professor in the Antenna Engineering Group, Queen Mary University of London. He is a former Editor-in-Chief of *IEEE APC* and Editor of *IEEE TAP*.

Hong Ren (hren@seu.edu.cn) received her Ph.D. from Southeast University in 2018. From 2016 to 2018, she was a visiting student at the University of Southampton, United Kingdom, and during 2018–2020, she was a postdoctoral scholar at Queen Mary University of London. Currently, she is an associate professor at Southeast University.

Ming Chen (chenming@seu.edu.cn) received his Ph.D. from Nanjing University in 1996. Then he joined Southeast University, where he is a full professor.

Xiaohu You (xhyu@seu.edu.cn) received his Ph.D. degree from Southeast University in 1988. Since 1990, he has been working at Southeast University. He was a recipient of the National Technological Invention Award of China in 2011.

Marco Di Renzo [F] (marco.direnzo@centralesupelec.fr) is a CNRS research director in the Laboratory of Signals and Systems at Paris-Saclay University, France. He serves as the Editor-in-Chief of *IEEE Communications Letters*. He is as IET Fellow (2020) and a Highly Cited Researcher (2019).

Jiangzhou Wang (J.Z.Wang@kent.ac.uk) is a professor at the University of Kent. He was the TPC Chair of IEEE ICC 2019, the Executive Chair of IEEE ICC 2015, and the TPC Chair of IEEE WCNC 2013.

Kezhi Wang (kezhi.wang@northumbria.ac.uk) received his Ph.D. from the University of Warwick, United Kingdom, in 2015, and then he was appointed a senior research officer at the University of Essex, United Kingdom. Currently, he is a senior lecturer at Northumbria University, United Kingdom.

A. Lee Swindlehurst (windle@uci.edu) received his Ph.D. (1991) degree from Stanford University. He was with Brigham Young University from 1990 to 2007. Since 2007 he has been a professor at the University of California Irvine. He was the inaugural Editor-in-Chief of the *IEEE JSTSP*.

Lajos Hanzo (lh@ecs.soton.ac.uk) received his doctorate in 1983. He holds honorary doctoratse from the Technical University of Budapest (2009) and from the University of Edinburgh (2015). He is a member of the Hungarian Academy of Sciences and a former Editor-in-Chief of IEEE Press.