Guest Editorial Special Issue on "Wireless Networks Empowered by Reconfigurable Intelligent Surfaces"

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I. Introduction

FUTURE wireless networks will be as pervasive as the air we breathe, not only connecting us but embracing us through a web of systems that support personal and societal well-being. That is, the ubiquity, speed and low latency of such networks will allow currently disparate devices and services to become a distributed intelligent communications, sensing, and computing platform.

Small cells, massive multiple-input-multiple-output (MIMO), millimeter-wave communications are three fundamental technologies that will spearhead the emergence of 5G wireless networks – Their advantages are undeniable. The question is, however, whether these technologies will be sufficient to meet the requirements of future wireless networks that integrate communications, sensing, and computing in a single platform. Wireless networks, in addition, are rapidly evolving towards a software-defined design paradigm, where every part of the network can be configured and controlled via software. In this optimization process, however, the wireless environment itself – the medium or channel – is generally assumed uncontrollable and often an impediment to be reckoned with. For example, signal attenuation limits the network connectivity, multi-path propagation results in fading phenomena, reflections and refractions from objects are a source of uncontrollable interference.

Recently, a new concept called Reconfigurable Intelligent Surfaces (RISs) has emerged wherein every environmental object is coated with man-made intelligent surfaces of configurable electromagnetic materials [1]–[5]. These materials contain integrated electronic circuits and software that enable the control of the wireless medium. RISs can be realized in different ways, which include: (i) large arrays of inexpensive antennas that are usually spaced half of the wavelength apart; and (ii) metamaterial-based planar or conformal large surfaces whose scattering elements have sizes and inter-distances much smaller than the wavelength. Compared with other transmission technologies, e.g., phased arrays, multi-antenna transmitters, and relays, RISs require the largest number of scattering elements, but each of them needs to be backed by the fewest and least costly components. Also, no power amplifiers are usually needed.

For these reasons, RISs constitute a promising software-defined architecture that can be realized at reduced cost, size, weight, and power (C-SWaP design), which could potentially enable telecommunication operators to sculpt the communication medium that comprises the network. As such, RISs have the potential to change how wireless networks are designed, usher in that hoped-for wireless future, and are regarded as an enabling technology for realizing the emerging concept of smart radio environments (SREs). But, RISs are not currently well-understood.

II. On the Special Issue

With the above vision, a Call for Papers for the Special Issue (SI) on "Wireless Networks Empowered by Reconfigurable Intelligent Surfaces", IEEE Journal on Selected Areas in Communications, was published in the summer of 2019. The SI was aimed at gathering the latest and most promising research advances on the modeling, analysis, design, and implementation of RIS-empowered wireless networks, and at envisioning new research directions in this emerging field of research.

The SI attracted 51 high quality submissions from authors distributed over different countries. All articles received at least three reviews and the accepted articles went through at least one revision round. Eventually, 13 technical articles were accepted covering various aspects of RISs for application to wireless communications and networks. In addition, a survey/tutorial paper from the Guest Editors was reviewed by the team of Senior Editors of IEEE Journal on Selected Areas in Communications.

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In the following section, we briefly outline the contribution of each accepted article.

III. Summary of Accepted Articles

In the invited article titled "Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How it Works, State of Research, and the Road Ahead," the authors introduce the emerging research field of RIS-empowered SREs, overview the most suitable applications of RISs in wireless networks; present an electromagnetic-based communication-theoretic framework for analyzing and optimizing metamaterial-based RISs; provide a comprehensive overview of the current state of research; and discuss the most important research issues to tackle. Owing to the interdisciplinary essence of RIS-empowered SREs, in addition, the authors put forth the need of reconciling and reuniting C. E. Shannon's mathematical theory of communication with G. Green's and J. C. Maxwell's mathematical theories of electromagnetism for appropriately modeling, analyzing, optimizing, and deploying future wireless networks empowered by RISs.

In the article titled "Communicating with Large Intelligent Surfaces: Fundamental Limits and Models," the author analyzes communication-related issues of RISs from the electromagnetic viewpoint. In particular, the author derives simple but accurate analytical expressions for the link gain, and the available degrees-of-freedom (DoF) for the communication between two RISs. It is shown that the achievable DoF and gain are determined only by geometric factors, and that the Friis's formula is no longer valid in scenarios in which the transmitter and receiver operate in the near-field regime. Furthermore, the authors show that, in contrast to classic MIMO systems, RISs can exploit all the potentially available DoF even in strong line-of-sight channel conditions, which is shown to correspond to a significant increase of the spatial capacity density.

In the article titled "Reconfigurable Intelligent Surfaces: Bridging the Gap Between Scattering and Reflection," the authors investigate the scaling law of the received power as a function of the distance in RIS-assisted communications. In particular, the authors focus their attention on characterizing the array near-field, which unveils the promising potential of RISs. The authors show that the point-like (or zero-dimensional) conventional scattering characterization of RISs results in the well-known dependence of the received power with the fourth power of the distance. On the contrary, the scaling law is different in the near-field of the array, and the received power is shown to decay with the second power of the distance for planar array structures. By appropriately optimizing the phase of the RIS, the authors show that it may be possible to obtain a scaling law of the received power that depends on the fourth power of the distance in the near-field regime, which provides better performance. In this latter case, the RIS operates as a lens that focuses the signal towards a given location. Therefore, the authors show that, by appropriately optimizing the phase of the RISs, different operating regimes, each associated with a different implementation complexity, can be obtained.

In the article titled "Reflecting Modulation," the authors introduce a reflecting modulation (RM) scheme for RIS-based communications, where both the reflecting patterns and transmit signals can carry information. Depending on whether the transmitter and RIS jointly or independently deliver information, RM is further classified into two categories: jointly mapped RM (JRM) and separately mapped RM (SRM). JRM and SRM are shown to be naturally superior to existing schemes, because the transmit signal vectors, reflecting patterns, and bit mapping methods of JRM and SRM are more flexibly designed. To enhance the transmission reliability, the authors propose a discrete optimization-based joint signal mapping, shaping, and reflecting (DJMSR) design for JRM and SRM, in order to minimize the bit error rate (BER) with a given transmit signal candidate set and a given reflecting pattern candidate set. To further improve the performance, the authors optimize multiple reflecting patterns and their associated transmit signal sets. Numerical results show that JRM and SRM with the proposed system optimization methods considerably outperform existing schemes in term of BER.

In the article titled "Large Intelligent Surface Assisted Wireless Communications with Receive Spatial Modulation and Antenna Selection," the authors introduce a novel transmission scheme based on RISs and receive spatial modulation (RSM). The authors derive the theoretical average bit error rate (ABER) performance of the proposed scheme. To further decrease the ABER and to obtain spatial diversity gains, the authors generalize the proposed scheme by leveraging receive antenna subset selection (RASS). In particular, a low-complexity antenna selection algorithm is designed based on the minimum squared Euclidean distance (MSED) and the signal-to-leakage-and-noise ratio (SLNR). The analysis of the proposed schemes shows that the RASS-aided RIS-RSM scheme is more robust than conventional RIS-RSM systems. Moreover, the authors show that the proposed low-complexity antenna selection algorithm can be realized at low complexity.

In the article titled "Reconfigurable Intelligent Surface Aided NOMA Networks," the authors conceive an RIS-aided system for serving paired power-domain non-orthogonal multiple access (NOMA) users, by designing the passive beamforming weights at the RIS. To evaluate the network performance, the authors derive best-case and worst-case channel statistics for characterizing the effective channel gains. Furthermore, the authors investigate the outage probability, the ergodic rate, the spectral efficiency, and the energy efficiency of the proposed system. The obtained results demonstrate that the links between the transmitter and the user have almost no impact on the diversity order, provided that the number of elements of the RIS is large enough. Also, numerical results show that the proposed RIS-aided NOMA network has superior network performance compared to its orthogonal counterpart.

In the article titled "Joint Design of Reconfigurable Intelligent Surfaces and Transmit Beamforming under Proper and Improper Gaussian Signaling," the authors consider a network scenario in which a multiple-antenna access point (AP) serves multiple single-antenna downlink users with the assistance of an RIS. The authors tackle the joint design of the programmable reflecting coefficients of the RIS and the transmit beamforming, in order to maximize the users' worst rate. Under a proper Gaussian signaling (PGS) and an improper Gaussian signaling (IGS), the optimization problem is computationally challenging and non-convex. By leveraging a penalized reformulation of the optimization problem, which incorporates the unit-modulus constraints for the reflecting coefficients into the optimization objectives, the authors introduce iterative algorithms at low computational complexity. Numerical results are illustrated in order to show the performance of the proposed optimized designs.

In the article titled "Progressive Channel Estimation and Passive Beamforming for Intelligent Reflecting Surface with Discrete Phase Shifts," the authors analyze an RIS-aided single-user communication system with discrete phase shifts and propose a new joint design framework for progressive RIS channel estimation and passive beamforming. Specifically, the authors consider a practical block-based transmission scheme, in which each block has a finite number of training symbols for channel estimation. In contrast to conventional channel estimation methods in which the channels of all RIS elements are estimated at one time, which inevitably causes long delay for data transmission, the authors introduce a hierarchical training reflection design by properly partitioning the reflecting elements into groups/subgroups by assigning each group/subgroup of elements differently-combined discrete phase shifts over multiple blocks. Furthermore, the authors design a progressive passive beamforming design with discrete phase shifts in order to improve the achievable rate. With the aid of numerical results, the authors confirm the good performance provided by the proposed schemes as compared with benchmark methods.

In the article titled "Matrix-Calibration-Based Cascaded Channel Estimation for Reconfigurable Intelligent Surface Assisted Multiuser MIMO," the authors investigate the channel acquisition problem in an RIS-assisted multiuser MIMO system. State-of-the-art channel acquisition methods, which assume fully passive RIS elements, may require excessively long training sequences. To estimate the cascaded channels with an affordable training overhead, the authors formulate the channel estimation problem as a matrix-calibration-based matrix factorization task. By exploiting information on the slow-varying channel components and the channel sparsity, the authors introduce a novel message-passing based algorithm that factorizes the cascaded channels. Furthermore, the authors propose an analytical framework in order to characterize the theoretical performance of the proposed estimator in the large-system regime. The performance of the proposed algorithms are analyzed with the aid of numerical simulations.

In the article titled "Robust and Secure Wireless Communications via Intelligent Reflecting Surfaces," the authors investigate RISs for enhancing the physical layer security in challenging radio environments. The authors, in particular, consider a multi-antenna AP that serves multiple single-antenna legitimate users, which do not have line-of-sight communication links, in the presence of multiple multi-antenna potential eavesdroppers whose channel state information (CSI) is not perfectly known. Artificial noise (AN) is transmitted from the AP to deliberately impair the eavesdropping channels for security provisioning. The authors study the joint design of the beamformers and AN covariance matrix at the AP, as well as the phase shifts at the RISs in order to maximize the system sum-rate while limiting the maximum information leakage to the potential eavesdroppers. To this end, the authors formulate a robust non-convex optimization problem that accounts for the impact of the imperfect CSI of the eavesdropping channels. To address the non-convexity of the optimization problem, an efficient algorithm is developed by capitalizing on alternating optimization, a penalty-based approach, successive convex approximation, and semidefinite relaxation. Simulation results show that RISs can significantly improve the system secrecy performance compared to conventional architectures.

In the article titled "Adaptive Transmission Protocol for Reconfigurable Intelligent Surface-Assisted OFDM," the authors propose an adaptive transmission protocol for wideband RIS-assisted single-input multiple-output (SIMO) orthogonal frequency division multiplexing (OFDM) systems. In the considered system, each transmission frame is divided into multiple sub-frames in order to execute channel estimation and data transmission in each sub-frame. Since multiple training symbols are distributed over multiple sub-frames, the user-RIS-access point cascaded channel cannot be estimated at once. Therefore, the authors propose a progressive channel estimation method by updating the CSI in a sub-frame-by-sub-frame manner, based on which progressive passive beamforming is implemented at the RIS. Based on the partially estimated CSI, the authors formulate an optimization problem in order to maximize the average achievable rate of each sub-frame by designing the passive beamforming vector, which needs to balance the received signal power over different sub-carriers and different receive antennas. As the formulated problem is non-convex and difficult to solve optimally, the authors propose two efficient algorithms to find a high-quality sub-optimal solution. Simulation results validate the effectiveness of the proposed channel estimation and beamforming optimization methods, as well as the superiority of the proposed protocol over existing transmission protocols.

In the article titled "Latency Minimization for Intelligent Reflecting Surface Aided Mobile Edge Computing," the authors analyze the research problem of computation off-loading in mobile edge computing (MEC) systems, which is an efficient paradigm for supporting resource-intensive applications on mobile devices. However, the benefit of MEC cannot be fully exploited if the communications link used for offloading computational tasks are not reliable. The authors investigate the application of RISs in MEC systems, where single-antenna devices may opt for off-loading a fraction of their computational tasks to the edge computing node via a multi-antenna access point with the aid of an RIS. The authors formulate latency-minimization problems for single-device and multi-device scenarios, subject to practical constraints imposed on both the edge computing capability and the RIS phase shift design. To solve the optimization problems, the authors use block coordinate descent (BCD) methods in order to decouple the original problem into two sub-problems, and then alternatively optimize the computing and communication settings. The authors demonstrate that an RIS-aided MEC system is capable of significantly outperforming conventional MEC systems that operate without using RISs.

In the article titled "MIMO Transmission Through Reconfigurable Intelligent Surface: System Design, Analysis, and Implementation," the authors propose an RIS-based architecture in order to achieve amplitude-and-phase-varying modulation, which facilitates the design of MIMO quadrature amplitude modulation (QAM) transmission. The proposed solution overcomes the limitations of current implementations of RISs in which only their phase response is adjustable, which may limit the achievable rate of RIS-based transmitters. The hardware constraints of the proposed implementation of RIS and their impact on the system design are discussed and analyzed. Furthermore, the proposed approach is evaluated using and advanced prototype that implements RIS-based MIMO-QAM transmission over the air.

In the article titled "Reconfigurable Intelligent Surfaces Based Radio-frequency Sensing: Design, Optimization, and Implementation," the authors use radio-frequency (RF) sensing techniques for human posture recognition based on RISs. Conventional RF sensing techniques are constrained by their radio environments, which limit the number of transmission channels to carry multi-dimensional information about human postures. The proposed system can actively customize the environment to provide the desirable propagation properties and diverse transmission channels. However, achieving high recognition accuracy requires the optimization of the RIS configuration, which is a challenging problem. To tackle this challenge, the authors formulate an optimization problem, decompose it into two sub-problems, and propose algorithms to solve them. Based on the developed algorithms, the authors implement the system and carry out practical experiments. Simulation and experimental results verify the effectiveness of the designed algorithms and system. Compared to the benchmark scenario in which RISs are not used, the designed system is shown to greatly improve the recognition accuracy.

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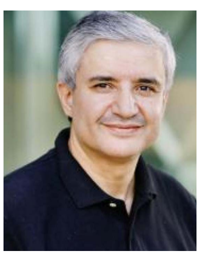

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