Reconfigurable Intelligent Surfaces

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Wireless connectivity is regarded as a fundamental need for our society. Between 2020 and 2030, it is forecast that the data traffic of the global internet protocol will increase by 55% each year, eventually reaching 5016 EB, with data rates scaling up to 1 Tb/s. Besides supporting very high data rates, future wireless networks are expected to offer several other heterogeneous services, which include sensing, localization, low-latency, and ultrareliable communications. Fifth-generation (5G) networks are, however, not designed to meet these requirements. As the demands and needs become more stringent, in fact, fundamental limitations arise, which are ultimately imposed by the inherent nature of the wireless operation.

The articles in this month's special issue provide a comprehensive and complementary treatment of reconfigurable intelligent surfaces for smart and programmable radio environments, by encompassing diverse perspectives.

I. BACKGROUND

A. Current Network Design Assumptions

The first five generations of wireless networks have been conceived by adhering to the postulates that the wireless environment between communicating devices 1) is controlled by nature, 2) cannot be modified, and 3) can be only compensated through the design of sophisticated transmission and reception schemes. After five generations of wireless networks, however, the improvements that can be expected by operating only on the endpoints of a wireless environment may not be enough to fulfill the challenging requirements of future wireless networks. Sixth-generation (6G) networks need a new architectural platform that performs joint communication, sensing, localization, and computing while ensuring ultrahigh throughput, ultralow latency, and ultrahigh reliability that need to be jointly and flexibly customized.

B. Emerging Paradigm: Programming the Environment

Major performance gains can be expected by breaking free from the postulate that regards the wireless environment as an uncontrollable element. For example, a typical base station transmits radio waves of the order of magnitude of Watts while a user equipment detects signals of the order of magnitude of μWatts. The rest of the power is wasted in different ways through the environment by, e.g., generating interference to other network elements or creating security threats, since the propagation of radio waves through the wireless channel cannot be controlled and customized after such radio waves are emitted from the transmitters and before they are detected by the receivers. An intriguing question was recently brought to the attention of the wireless community: *Can this status quo be fundamentally overcome?*

C. Road to Smart Radio Environments

At the time of writing, no precise answer to this question can be given. A plethora of research activities has, however, recently flourished in an attempt of tackling and putting this question in the context of the most promising technologies

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that were developed during the last decades and that are envisioned to constitute the backbone of 5G networks. The current vision to overcome the limitations of 5G networks consists of turning the wireless environment into an optimization variable, which, jointly with the transmitters and receivers, can be controlled and programmed rather than just adapted to. This approach is referred to as smart radio environment (SRE) or "Wireless 2.0," in order to emphasize the conceptual and fundamental difference with the designs and optimization criteria adopted in current and past generations of wireless networks.

D. Reconfigurable Intelligent Surface (RIS): The Enabling Technology

The key enabler to realize the vision of SREs, by making the wireless environment programmable and controllable, is the RIS. The RIS can be thought of as an inexpensive adaptive (smart) thin composite metamaterial sheet, which, like a wallpaper, covers parts of walls, buildings, ceilings, etc., and is capable of modifying the radio waves impinging upon it in ways that can be programmed and controlled using external stimuli. A prominent property of RISs is, therefore, the capability of being reconfigurable after their deployment.

E. State of the Art

During the last three to four years, we have assisted the blooming of research activities on RIS-assisted wireless communications. As an example, the opening article of the first IEEE Special Issue on RISs, which was published in November 2020 in the IEEE Journal on Selected Areas in Communications ("Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead") reported approximately 300 reference papers in this field of research, with a growing trend. The research activities conducted to date encompass different fundamental research issues and several applications, including modulation and encoding, channel estimation, performance evaluation, large-scale network analysis, optimization and resource allocation, physical layer security, nonorthogonal multiple access, the Internet of Things and backscattering communications, aerial communications, wireless power transfer, multiple access edge computing, RIS-assisted millimeter-wave, terahertz, and optical wireless communications, the interplay of RISs with relays and massive multiple-input–multiple-output systems, the integration and synergy with software-defined networking and nanocommunication networks, the role of machine learning for the control and management of SREs, applications beyond communications, such as localization, positioning, and sensing, and the implementation of the first experimental prototypes and testbeds in the field of computer science and communication systems.

F. Fundamental Gap of Knowledge in Research

Despite the large number of research works published on RIS-assisted SREs in just three to four years, current research activities and results are affected by a fundamental limiting factor: the models employed for RISs are often simplistic and are not always compliant with the principles of physics that govern the design and operation of the surfaces at the electromagnetic level and with currently available metamaterial-based implementations. The typical communication model employed for RISs consists of a collection of tiny and independent nearly-passive antenna elements whose response is independent of the incident and scattered radio waves and of the inter-distance and practical implementation of the metamaterial structure that constitutes the RIS. This major limitation often originates from the limited know-how and background on the physics of radio propagation and electromagnetic metamaterials of most researchers working in wireless communications, networks, and signal processing. Likewise, researchers working in the field of metamaterials and electromagnetics are not always familiar with the needs of communication standards The fundamental need of overcoming these oversimplifications and gaps of knowhow is well acknowledged, along with the fact that it can be achieved only through the collaboration among scientists who work across multiple disciplines, including information and communication theories, wireless communications, antennas and propagation, electromagnetics, physics, metamaterials, engineering, devices, computer science, signal processing, and machine learning.

G. Importance of the Topic to the Readers of the Proceedings of the IEEE

The objective of the present special issue is to fill the just mentioned fundamental gap of knowledge among researchers working on RISs across several different disciplines. The present Special Issue provides a multidisciplinary venue where state-of-the-art research results are brought together from different perspectives and applications, which are emerging within the areas of physics, electromagnetics, antennas and propagation, microwave theory and techniques, metamaterials, circuit design, devices, telecommunications, wireless networks, computer science, signal processing, optimization, communication theory, information theory, machine learning, and data science. The present Special Issue is intended to lead, therefore, to a widespread dissemination of state-of-the-art analytical and algorithmic tools, testbed implementations and experimental activities, and research perspectives, and may enable the acceleration in the germination of novel ideas pertaining to the development of RISs for various applications. Given the potential applications that RISs may have in 6G wireless networks and the current prestandardization activities within the European

Telecommunication Standards Institute (https://www.etsi.org/committee/1966-ris), the present Special Issue is aimed to students, practitioners, and researchers from several different disciplines in both industry and academia.

II. OVERVIEW OF THE SPECIAL ISSUE

The different articles of the present Special Issue are put together in order to provide a comprehensive and complementary treatment of RISs for smart and programmable radio environments, by encompassing diverse perspectives including physics, electromagnetics, antennas and propagation, microwave theory and techniques, metamaterials, circuit design, devices, telecommunications, wireless networks, computer science, signal processing, optimization, communication theory, information theory, machine learning, and data science. In particular, the key feature of the present Special Issue is to cast together these different fields in the context of research on RISs, including metamaterials and electromagnetics, software-defined networking and control, testbed implementation and computer science, antennas and propagation, communications, signal processing, optimization, machine learning, and potential applications.

The special issue consists of 14 invited articles, which are here briefly introduced.

Communication Models for Reconfigurable Intelligent Surfaces: From Surface Electromagnetics to Wireless Networks Optimization
by M. Di Renzo, F. H. Danufane, and S. Tretyakov
This article provides an overview of communication models for RISs. The communication models that are most often employed in wireless communications for analyzing and optimizing RISs are introduced, and their advantages and limitations are discussed. Considering the model based on an inhomogeneous sheet of surface impedance, this article offers a step-by-step recipe on how to formulate electromagnetically consistent analytical frameworks for optimizing the surface impedance.

Wavefront Shaping for Wireless Communications in Complex Media: From Time Reversal to Reconfigurable Intelligent Surfaces
by G. Lerosey and M. Fink
This article provides an overview of the research works and enabling technologies that have underpinned the development of RISs. The main challenges for integrating RISs in future telecommunication standards are discussed, with an emphasis on real-time implementations of this emerging technology.

Theory, Analysis, and Design of Metasurfaces for Smart Radio Environments
by E. Martini and S. Maci
This article provides an overview of the fundamental theory behind RISs, with a focus on surface-wave and non-specular reconfigurable reflective surfaces. A ray-based representation of the radiated and scattered fields is discussed, which is convenient for modeling RISs within ray-tracing tools used for network planning.

MIMO Evolution Beyond 5G Through Reconfigurable Intelligent Surfaces and Fluid Antenna Systems
by A. Shojaeifard, K.-K. Wong, K.-F. Tong, Z. Chu, A. Mourad, A. Haghighat, I. Hemadeh, N. Thanh Nguyen, V. Tapio, and M. Juntti
This article provides an overview of the application of RISs for free-space communications and surface-wave communications, in order to realize intelligent propagation media with superior radio propagation efficiency. In addition, this article introduces the operating principles of fluid antennas, which is a novel antenna technology capable of altering its shape.

Reconfigurable Intelligent Surfaces: Simplified-Architecture Transmitters—From Theory to Implementations
by Q. Cheng, L. Zhang, J. Y. Dai, W. Tang, J. C. Ke, S. Liu, J. C. Liang, S. Jin, and T. J. Cui
This article provides an overview of the theoretical models for space-time digital metasurfaces and information metasurfaces, the mechanisms for wavefront shaping, and the signal modulation models in space and time for wave–matter interactions. In addition, this article elaborates on practical issues for implementing RISs and the hardware architectures at microwave frequencies to realize simplified radio frequency transmitters.

Reconfigurable Intelligent Surfaces: Channel Characterization and Modeling
by J. Huang, C.-X. Wang, Y. Sun, R. Feng, J. Huang, B. Guo, Z. Zhong, and T. J. Cui
This article provides an overview of wireless channel models for RISs. Channel measurements and experiments are presented by classifying them as a function of the frequency band, deployment scenario, and system configuration. The features of wireless channels assisted by RISs are discussed in terms of reflection and transmission characteristics, Doppler effect, multipath fading mitigation, channel reciprocity, channel hardening, rank improvement, as well as far-field and near-field propagation.

Channel Estimation With Reconfigurable Intelligent Surfaces—A General Framework
by A. L. Swindlehurst, G. Zhou, R. Liu, C. Pan, and M. Li
This article provides an overview of the identifiability of wireless channels for RISs. The methods overviewed account for the available pilot data and the setup of the surfaces during training. Different case studies are analyzed, including line-of-sight

propagation, single-antenna and multiple-antenna configurations, correlated and sparse channel models, single-carrier, and wideband orthogonal frequency-division multiplexing signals.

Backscatter Communication Assisted by Reconfigurable Intelligent Surfaces
by Y.-C. Liang, Q. Zhang, J. Wang, R. Long, H. Zhou, and G. Yang
This article provides an overview of backscatter communications assisted by RISs that are configured as information transmitters. This article introduces the basics of backscatter communications, by covering antenna scattering, backscatter modulation, and link budget analysis, and it elaborates on the role played by RISs in backscatter communications.

A State-of-the-Art Survey on Reconfigurable Intelligent Surface-Assisted Non-Orthogonal Multiple Access Networks
by Z. Ding, L. Lv, F. Fang, O. A. Dobre, G. K. Karagiannidis, N. Al-Dhahir, R. Schober, and H. V. Poor
This article provides an overview of the recent progress on the synergistic integration of RISs and nonorthogonal multiple access schemes. The basics of both techniques are introduced, and the fundamental challenges and opportunities for their amalgamation are discussed in the context of communication scenarios with different transceiver capabilities.

Intelligent Reflecting Surface-Aided Wireless Networks: From Single-Reflection to Multireflection Design and Optimization
by W. Mei, B. Zheng, C. You, and R. Zhang
This article provides an overview of wireless networks aided by multiple RISs, with an emphasis on addressing the challenges associated with the presence of multiple surfaces, as well as multiple signal reflections and physical routing. Moreover, important directions worth of research and investigation are discussed.

Toward Ubiquitous Sensing and Localization With Reconfigurable Intelligent Surfaces
by H. Zhang, B. Di, Kaigui Bian, Z. Han, H. V. Poor, and L. Song
This article provides an overview of the use of wireless signals for sensing and localization, with a focus on the applications and open challenges of RISs for integrated communication, sensing, and localization. Case studies and open research challenges are discussed.

Nonterrestrial Communications Assisted by Reconfigurable Intelligent Surfaces
by J. Ye, J. Qiao, A. Kammoun, and M.-S. Alouini
This article provides an overview of the concept of nonterrestrial networks assisted by RISs, with a focus on existing works that investigate their integration with advanced technologies. Also, unexplored and promising research directions are discussed.

Software-Defined Reconfigurable Intelligent Surfaces: From Theory to End-to-End Implementation
by C. Liaskos, L. Mamatas, A. Pourdamghani, A. Tsioliaridou, S. Ioannidis, A. Pitsillides, S. Schmid, and I. F. Akyildiz
This article provides an overview of metasurface-based hardware and software components for application to programmable wireless environments. The complete workflow from the user device to the final services is discussed. Also, this article elaborates on the design of SREs that are accessible from various engineering disciplines, facilitating their integration into existing networks, wireless systems, and applications.

Pervasive Machine Learning for Smart Radio Environments Enabled by Reconfigurable Intelligent Surfaces
by G. C. Alexandropoulos, K. Stylianopoulos, C. Huang, C. Yuen, M. Bennis, and M. Debbah
This article provides an overview of online machine learning methods for optimizing wireless networks in the presence of multiple users and multiple RISs. By considering the sum-rate maximization problem as a representative design objective, a complete problem formulation based on deep reinforcement learning is discussed.

Acknowledgment

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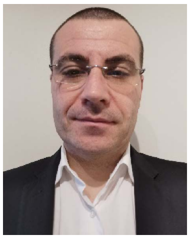
ABOUT THE GUEST EDITORS



Marco Di Renzo (Fellow, IEEE) received the Laurea (*cum laude*) and Ph.D. degrees in electrical engineering from the University of L'Aquila, L'Aquila, Italy, in 2003 and 2007, respectively, and the Habilitation à Diriger des Recherches (Doctor of Science) degree from the University Paris-Sud (now Paris-Saclay University), Gif-sur-Yvette, France, in 2013.

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