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Guest Editorial: Intelligent metasurfaces for smart connectivity

Current 5G wireless systems depend heavily on the quality of the wireless propagation environment, which had conventionally been modelled as an exogenous entity that can only be adapted and not controlled. This is challenged by future wireless networks which integrate communication, sensing, and localisation in a single platform, and where the wireless environment is not treated as part of the network design parameters. This new vision of wireless network design is enabled by an emerging technology of reconfigurable intelligent surfaces (RISs), also known as intelligent reflecting surfaces (IRSs). RISs are thin layers of electromagnetic metamaterials capable of shaping radio waves that impinge upon them in ways that the wireless environment can be customized to fulfil specific system requirements. As a result, metamaterial-based RISs can create favourable propagation conditions by controlling the phase and amplitude of the impinging radio waves through nearly passive and low-cost scattering elements. Recently, metasurfaces have received a surge in research and development interests in wireless communications and are seen as a promising transformative technology with the potential of fundamentally changing how wireless networks are implemented, optimized, and operated.

This special issue aims to create a platform for researchers from both academia and industry to disseminate state-of-the-art results and to advance metasurface-empowered wireless networks. In total, 15 excellent papers were accepted after a rigorous multi-round review process. These papers can be divided into two topics: key techniques for metasurface-enabled multi-input–multi-output (MIMO) systems and integration of metasurfaces and existing wireless techniques. In the following, we will introduce these papers and highlight their contributions.

1 | KEY TECHNIQUES FOR METASURFACE-ENABLED MIMO SYSTEMS

In this topic area, the authors focus on key techniques for metasurface-enabled MIMO systems. Specifically, we have one paper providing a comprehensive survey for the state-of-the-art of RIS-assisted MIMO communications, one paper introducing channel estimation for RIS-assisted MIMO systems, one paper studying equalization with RISs, and four papers dealing with joint beamforming solutions for both the transmitter and the RIS.

In their survey paper ‘Exploring Reconfigurable Intelligent Surfaces for 6G: State-of-the-Art and the Road Ahead’, Basharat et al. explore the state-of-the-art research on different aspects of RIS-assisted communications. Emerging applications of RISs in 6G wireless networks are discussed with their crucial challenges. They also highlight important research directions for RIS-assisted 6G networks.

In their paper ‘Multipath Separation and Parameter Estimation by Single DMA in Fading Channel’, Lou et al. establish a general multipath separation and measurement framework based on a dynamic metasurface antenna which can rapidly change patterns within a single pilot symbol period. As a result, equivalent multidimensional received signals can be obtained. Based on the framework, they propose a multipath channel estimation scheme.

In their paper ‘Over-the-Air Equalization with Reconfigurable Intelligent Surfaces’, Arslan et al. explore performing a sort of virtual equalization over-the-air for frequency-selective channels using an RIS. Specifically, the frequency-selective channel from the transmitter to the RIS is transformed to a frequency-flat channel through the elimination of intersymbol interference (ISI) at the receiver. It is demonstrated that conventional RIS phase alignment methods can successfully eliminate ISI, and the RIS-aided communication channel can be converted from frequency-selective to frequency-flat.

In their paper ‘Joint Optimization Scheme for Intelligent Reflecting Surface Aided Multi-Relay Networks’, Li et al. consider a hybrid network with multiple decode-and-forward relays and an IRS. They maximize the end-to-end transmission rate by jointly optimizing the beamformer at the IRS, relay selection, and power allocation, subject to a total transmit power constraint. Compared with the single relay case, the proposed scheme shows significant performance improvement.

In their paper ‘Dynamic Wireless Networks Assisted by RIS Mounted on Aerial Platform: Joint Active and Passive Beamforming Design’, Zhu et al. design a joint beamforming scheme for a MIMO system assisted by RISs mounted on aerial platforms. Considering the time-varying channels and the mobility of users, they minimize the long-term power consumption using a Lyapunov-based drift-plus-penalty algorithm for stability, under the requirements of the time-averaged minimum rate for users and the total transmit power constraint for the base station.

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In their paper ‘Multiuser Beamforming Optimization for IRS-aided Systems With Discrete Phase Shifts’, Shi et al. design the beamforming for an IRS-aided MIMO network with discrete phase shifts. An alternating optimization algorithm based on the gradient extrapolated majorization–minimization approach is proposed to solve a minimum signal-to-interference-plus-noise-ratio maximization problem. Simulation results show that the proposed algorithm can achieve similar performance as existing methods but with lower complexity.

In their paper ‘Design of Dynamic Active-Passive Beamforming for Reconfigurable Intelligent Surfaces Assisted Hybrid VLC/RF Communications’, Han et al. investigate hybrid visible light communication (VLC)/radio frequency (RF) communications with the aid of RISs in dynamic wireless networks. Under average minimum rate constraints for VLC/RF users and total transmit power constraints for VLC/RF access points, they minimize the average long-term power consumption by joint beamforming.

2 | INTEGRATION OF METASURFACES AND EXISTING WIRELESS TECHNIQUES

In this topic, the authors focus on the integration of metasurfaces and existing wireless techniques. Specifically, we have four papers studying the integrations of RIS and physical layer security, three papers working on the integration of RISs and non-orthogonal multiple access (NOMA), and one paper investigating the integration of RISs and device-to-device (D2D) communications.

In their paper ‘Design of A Novel Wireless Information Surveillance Scheme Assisted by Reconfigurable Intelligent Surface’, Ji et al. investigate an application of an RIS for physical layer security. Especially, they propose a wireless information surveillance scheme aiming at monitoring the information of a suspicious illegal user. They jointly optimize the RIS phase shifts, the combining vector for the legitimate user, the transmit beamformer, and the jamming power to maximize the effective information monitoring rate.

In their paper ‘Artificial Noise Aided Directional Modulation via Reconfigurable Intelligent Surface: Secrecy Guarantee in Range Domain’, Chen et al. provide another case study for integrating RISs and physical layer security. They propose an artificial noise (AN)-aided directional modulation scheme via an RIS. An optimization problem is solved to maximize the secrecy rate.

In their paper ‘Optimal Design for the Artificial-Noise-Aided IRS-MIMO-OFDM Secure Communications’, Ren et al. integrate IRSs and physical layer security as well. An AN-aided IRS MIMO system is discussed for secure communications. They jointly optimize the beamformer at the base station, the AN covariance matrix, and the phase shifts of the IRS to maximize the sum secrecy rate.

In their paper ‘RIS-Assisted Secure UAV Communications with Resource Allocation and Cooperative Jamming’, Guo et al.

combine an RIS with unmanned aerial vehicles (UAVs) to improve the physical layer security of a wireless network. They introduce a friendly UAV jammer with a fixed location to send jamming signals to confuse an eavesdropper with the assistance of an RIS. The average secrecy rate is maximized by jointly optimizing the flight trajectory, the transmit power, and phase shifts of the RIS.

In their paper ‘Performance Analysis for Reconfigurable Intelligent Surface Assisted Downlink NOMA Networks’, Gong et al. investigate the performance of an RIS-assisted downlink NOMA network. In particular, the asymptotic outage probabilities and asymptotic upper bounds at a high signal-to-noise ratio are derived and the diversity order achieved by the network is obtained. They show that the outage probability can be enhanced by increasing the number of reflecting elements.

In their paper ‘Performance Analysis of RIS Aided NOMA Networks With Hardware Impairments’, Lu et al. study the performance of RIS-aided NOMA networks with hardware impairments over Rician fading channels. Exact and asymptotic expressions of the outage probability for a pair of users are derived, where imperfect successive interference cancellation (ipSIC) and perfect SIC (pSIC) are taken into consideration. Moreover, the system throughputs with ipSIC/pSIC are also presented. Their results show that the outage probability decreases when the number of reflecting elements or the Rician factor increases.

In their paper ‘Resource Allocation for IRS-Assisted MC MISO-NOMA System’, Javadi et al. consider a downlink multi-user communication of an IRS-assisted power-domain NOMA system. They optimize the beamforming at the base station, subcarrier allocation, and phase shifts at the IRS to maximize the system throughput. Numerical results illustrate that a higher throughput is obtained by the proposed system compared to the IRS-assisted orthogonal multiple access systems.

In their paper ‘Resource Allocation for Multi-IRS-aided D2D Communication Underlying Cellular Networks’, Forouzanmehr et al. propose a resource allocation scheme for D2D communications underlying cellular networks, which is assisted by multiple IRSs at the cell boundary. They maximize the sum-rate of the D2D pairs and cellular users (CUs) by jointly optimizing the D2D transmission power, the subcarrier assignment, the beamformer at the base station, and beamformers at IRSs. Simulation results reveal a non-trivial trade-off between the sum-rate of CUs and D2D pairs.

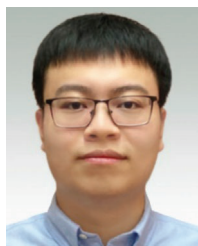
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Hongliang Zhang received the B.S. and Ph.D. degrees from the School of Electrical Engineering and Computer Science, Peking University, Beijing, China, in 2014 and 2019, respectively. He was a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX, USA. He is currently a Postdoctoral Associate with the Department of Electrical and Computer Engineering, Princeton University, Princeton, NJ, USA. His current research interest includes reconfigurable intelligent surfaces, aerial access networks, optimization theory, and game theory. Dr. Zhang received the Best Doctoral Thesis Award from the Chinese Institute of Electronics in 2019. He is an Exemplary Reviewer for IEEE Transactions on Communications in 2020. He was a recipient of the 2021 IEEE Comsoc Heinrich Hertz Award for Best Communications Letters and the 2021 IEEE ComSoc Asia-Pacific Outstanding Paper Award. He has served as a TPC Member for many IEEE conferences, such as Globecom, ICC, and WCNC. He is also an Editor of *IEEE Communications Letters*, *IET Communications*, and *Frontiers in Signal Processing*. He has served as a Guest Editor for several journals, such as *IEEE Internet of Things Journal* and *Journal of Communications and Networks*.




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Marco Di Renzo received the Laurea (cum laude) and Ph.D. degrees in electrical engineering from the University of 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), France, in 2013. Since 2010, he has been with the French National Center for Scientific Research (CNRS), where he is a CNRS Research Director (Professor) with the Laboratory of Signals and Systems (L2S) of Paris-Saclay University – CNRS and CentraleSupélec, Paris, France. In Paris-Saclay University, he serves as the Coordinator of the Communications and Networks Research Area of the Laboratory of Excellence DigiCosme, and as a Member of the Admission and Evaluation Committee of the Ph.D. School on Information and Communication Technologies. He is the Editor-in-Chief of *IEEE Communications Letters* and a Distinguished Speaker of the IEEE Vehicular Technology Society. From 2017 to 2020, he was a Distinguished Lecturer of the IEEE Vehicular Technology Society and IEEE Communications Society. He has received several research distinctions, which include the SEE-IEEE Alain Glavieux Award, the IEEE Jack Neubauer Memorial Best Systems Paper Award, the Royal Academy of Engineering Distinguished Visiting Fellowship, the Nokia Foundation Visiting Professorship, the Fulbright Fellowship, the 2021 EURASIP Journal on Wireless Communications and Networking Best Paper Award, and the 2022 IEEE Communications Society Outstanding Paper Award. He is a Fellow of the UK Institution of Engineering and Technology (IET), a Fellow of the Asia-Pacific Artificial Intelligence Association (AAIA), a Fellow of the Institute of Electrical and Electronics Engineers, an Ordinary Member of the European Academy of Sciences and Arts (EASA), and an Ordinary Member of the Academia Europaea (AE). Also, he is a Highly Cited Researcher.

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