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Reconfigurable Intelligent Surface Aided Multi-User Communications: State-of-the-Art Techniques and Open Issues

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ABSTRACT Reconfigurable intelligent surface (RIS)-aided communication is considered as an exciting research topic in academic and industrial communities since it provides an emerging affordable solution to achieve high quality and secure next-generation wireless systems. Especially, the deployment of RIS in multi-user wireless networks promises to reduce system hardware costs, signal processing complexity, as well as energy consumption due to small size, lightweight and ability to actively shape the wireless propagation environment. Further, by realizing a cost-effective radio environment, RIS-aided communication can be implemented to be an appealing technology for future integration with other emerging wireless applications and communication systems. Despite the positive appeal, RISs face new challenges that hinder integrating efficiently into wireless networks, such as network secrecy performance and system sum-rates, as well as achieving efficient deployment design in highly dynamic and time-varying wireless environments. To this end, we overview recent state-of-the-art techniques to address the above issues faced in the integration of RISs with various emerging multi-user communication techniques, such as Unmanned Aerial Vehicles (UAVs), Non-Orthogonal Multiple Access (NOMA), Millimeter Wave (mmWave) and Terahertz (THz) communications, Physical Layer Security (PLS), massive antennas, and Simultaneous Wireless Information and Power Transfer (SWIPT). Finally, we highlight promising future research directions of RIS-aided communication in Cell-Free Massive Multiple-Input-Multiple-Output (MIMO) systems, Rate-Splitting Multiple Access (RSMA), Light Fidelity (LiFi), and Cognitive Radio (CR) systems.

INDEX TERMS Reconfigurable intelligent surface, UAV communications, NOMA, mmWave and THz communications, physical layer security (PLS), massive antenna, cell-free massive MIMO, rate-splitting multiple access (RSMA), cognitive radio (CR), simultaneous wireless information and power transfer (SWIPT), light fidelity (LiFi).

I. INTRODUCTION

The idea of integrating reconfigurable intelligent surfaces (RISs), also known as Intelligent Reflecting Surface (IRS), with various next-generation multi-user technologies is based on the principal idea of migrating beamforming usually executed at the radio front-end of base stations (BS), Access Points (APs), and user terminals, to the environment [1]. Conventionally, RISs are reconfigurable meta-surfaces equipped with low-cost passive reflecting elements that can effectively adjust phase shifts, frequency, polarization and even amplitude of incident radio waves [2]–[6]. Due to this ability to suitably adjust the phase shifts according to the dynamic wireless environment. The signals reflected by the passive

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RIS can constructively combine with signals from other paths to boost the desired receiver Signal-to-Interference-plus-Noise Ratio (SINR), or destructively suppress signal power at undesired eavesdroppers in physical layer security (PLS) networks [1], [3], [7], [11], [12]. However, recent research in [13] and [14] demonstrated that RISs can be equipped with active reflecting elements, where each element reflects and amplifies the incident signal instead of only reflecting it as in the case of passive RIS. One of the differences between passive and active RIS is that the former introduces negligible thermal noise while the latter amplifies the noise as verified by experiments in [13], [14]. Table 1 provides a summary of the key differences between active and passive RIS.

TABLE 1. Active versus passive RIS.

Active RIS	Passive RIS
Reflects signals with amplification	Reflects signals without amplification
Achieves significant capacity gain when the transmitter-receiver direct link is strong	Achieves negligible capacity gain when the transmitter-receiver direct link is strong
Introduces thermal noise	Introduces negligible thermal energy
Consumes additional power	Consumes negligible power
No RF chains	No RF chains
Overcomes double fading	Suffers from double fading

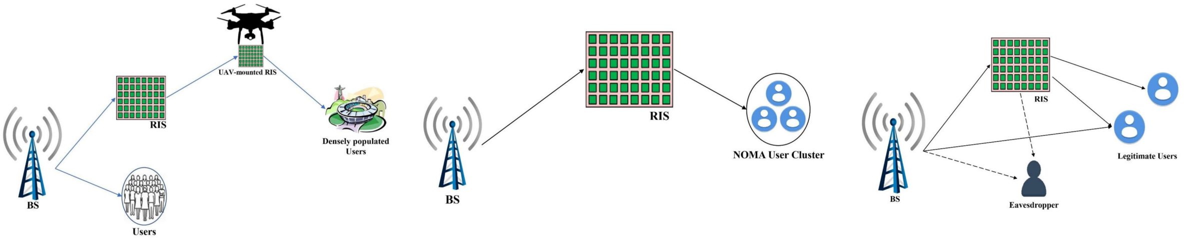
Due to this difference in noise introduction when reflecting signals, passive RIS can provide full-duplex transmission with full-band response [1], [7]. Therefore, eliminating the need for complex signal processing as well as costly and energy-consuming radio frequency (RF) chains in future/beyond-5G wireless networks [3], [8]–[10]. Moreover, the lack of RF chains leads to passive RIS providing a smaller signal coverage than BS/relays, enabling them to be deployed on building facades and other environmental objects, thus, providing an extra line-of-sight (LoS) link between the BS (transmitter) and the user terminal (receiver) [3]. In addition, the absence of RF chains complicates the channel acquisition capability of RIS. Practical passive RIS systems resolve this issue by relying on uplink pilots to estimate the aggregate BS channels. However, a majority of studies just assume perfect channel state information (CSI) availability to avoid the huge pilot overhead in RIS systems with massive N elements. To overcome this, the authors in [15], proposed a two-timescale beamforming approach as a possible solution to reduce the channel estimation overhead. The works in [16], [17] and references therein, highlighted recent proposed techniques to tackle the channel acquisition problem in various multi-user RIS-aided systems.

In addition to the above benefits, there are also other fundamental benefits provided by RIS, such as the squared power gain of RIS for the single user case [2]–[5]. Which is a result of the negligible thermal noise discussed previously [2]–[5], [13], [14]. For example, if an N-element RIS is deployed in a wireless network, the expected array gain is proportional to N^2, this is N times larger than what would be achieved in existing massive multiple-input multiple-output (MIMO) [13], [14]. Despite the significant theoretical capacity gains, actual gains are only obtained in uncommon scenarios where complete blockage exists between the direct link from the BS to the receiver. This means that, if the direct link is strong and unobstructed, passive RIS with many elements achieves negligible capacity gains [13], [14]. This phenomenon is termed "double fading" where the path-loss of the BS-RIS-receiver link is a thousand times larger than the direct link [13]–[16]. To solve the "double fading" impact on RIS, the authors in [13]–[16] suggested active RIS with simulation results showing significant capacity gains over passive RIS. In addition, most existing works choose to ignore the "double fading" effect by only considering the scenario where the direct link is obstructed or very weak [14].

For the multi-user scenario, the SINR can be enhanced by the joint beamforming of the RIS phase shifts and the BS beamforming vectors as discussed in [2]–[5]. While a majority of existing works on RIS assume continuous adjustment of amplitude and phase shift, in practice it is difficult and costly to be implemented due to the finite resolution of practical phase shifters [3], [4], [18], [19]. On the other hand, the authors in [19] showed that random discrete phase shifting avoids the huge pilot overhead caused by CSI acquisition. Further, in [4], the authors demonstrated that energy-efficient communication can be achieved in IRS-aided Multiple-Input Single-Output (MISO) multi-user communication. Where the objective is to minimize the transmit power via jointly optimizing the continuous transmit beamforming and IRS discrete phase shifts subject to individual signal-to-noise ratio (SNR) at the receivers. Similarly, in [4], the authors via simulation results proved that IRS with discrete phase shifts obtains the same asymptotic squared power gain as IRS with continuous phase shifts.

In [20], the authors demonstrated that including RIS in a MISO downlink communication system maximizes the sum-rate under a multi-user scenario, while utilizing Zero-Forcing (ZF) precoding at the BS. However, ZF precoding can amplify background noise, and if the channel is ill-conditioned, the system performance can be severely impacted [21]. In contrast, the authors in [21], maximized the weighted sum-rate of multi-users by jointly designing the beamforming at the BS and RIS phase shifts subject to transmit power. Moreover, in [22], the authors claimed that IRS also enhances the sum-rate in downlink multigroup multicast MISO systems. The authors jointly optimized the BS Transmit Precoding (TPC) matrix and IRS reflection coefficients subject to transmit power and unit-modulus constraints. On the other hand, in [23], the authors also proved numerically that IRS can maximize the Secondary User (SU) rate in the presence of strong cross-link Primary User (PU) interference in Cognitive Radio (CR) systems. By jointly optimizing the IRS continuous phase shifts and the SU transmit power subject to the PU link target SINR.

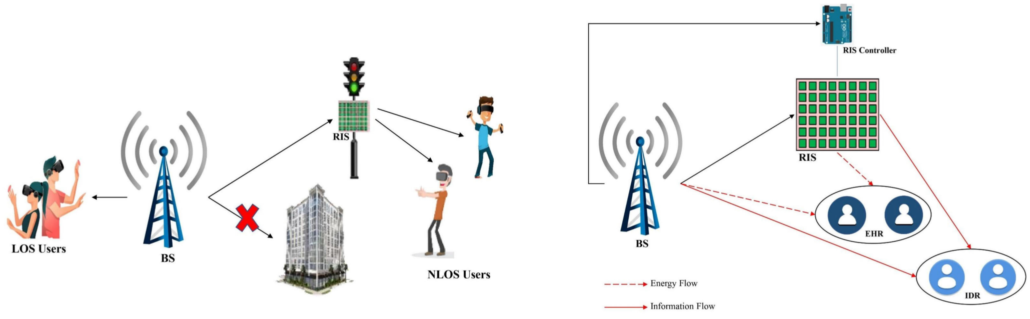
The authors in [24], proposed IRS-aided Simultaneous Wireless Information and Power Transfer (SWIPT) as a potential solution to address energy consumption in future wireless systems. The authors studied the weighted



a) UAV-assisted RIS system

b) RIS-assisted NOMA communications

c) RIS-assisted PLS communications



d) RIS-assisted mmWave communications

e) RIS-assisted SWIPT

FIGURE 1. Integration of RIS with next-generation communication technologies.

sum-power optimization problem by jointly designing the transmit TPC matrices and IRS continuous phase shifts subject to individual receiver Quality-of-Service (QoS) constraints. The study also showed that wireless coverage and battery life of SWIPT devices is enhanced by the introduction of IRS. Also, in the writing of this survey, we observe that most works adopted a linear energy harvesting model based on the assumption that RIS can reflect impinging signals from different directions with unit gain. However, in practice, depending on the angle of incidence, polarization of the electromagnetic wave, and the reflection angle, results in RIS reflecting incident signals from different directions with different gains [25]. Therefore, most of paper assumed that the RIS-aided SWIPT system follows a linear energy harvesting model as reported in [26], [27].

In [28], the authors proved numerically that in RIS-aided cell-free networks, the joint design of the beamforming BS vector and the discrete RIS phase shifts indeed maximizes the weighted sum-rate of users facing transmit power and RIS phase shift constraints. Moreover, in [29], the authors also proved that deploying IRS at the cell boundary of multi-cells mitigates inter-cell interference which is beneficial to cell-edge users downlink transmission.

To aid researchers and telecommunication operators fully understand the benefits of RIS deployment in wireless communications, in the upcoming sections, we discuss the proposed benefits and state-of-the-art solutions in the integration of RIS with the following next-generation communication systems such as Unmanned Aerial Vehicles (UAVs), Non-Orthogonal Multiple Access (NOMA), Millimeter Wave (mmWave) and Terahertz (THz) communications, PLS, multiple antennas systems, and SWIPT.

The integration of RIS with UAVs is advantageous since RISs can efficiently direct radio signals through joint beamforming with ground-based BS, to reduce interference with UAVs in adjacent cells [7]. The addition of RIS into NOMA promises to be mutually beneficial, as desirable channel gain differences among users are introduced and inter-user interference is removed by Successive Interference Cancellation (SIC) [7], [30]. In another context of RIS-aided systems, the applications of RIS in mmWave and THz are essential, as RIS can provide additional LoS links to mmWave and THz communications that are susceptible to blockage from trees, buildings, cars and even the human body [1], [31], [32]. This becomes even more important as conventional relaying technology is unavailable in mmWave and THz frequency bands [33]. Moreover, the integration of RIS into multi-user communications provides advanced PLS of legitimate users in the presence of eavesdroppers [7], [32]-[37]. Thus, RIS is expected to achieve higher spectrum energy efficiency in future wireless communications. In fact, RIS can operate similar to the role played by massive MIMO, by realizing a low-cost and energy-efficient MIMO 2.0 [38].

This article aims to provide a survey on the latest techniques and challenges in RIS-aided multi-user communications research. Furthermore, we only focus on the scenarios where RIS is integrated with next-generation communication technologies, such as UAV, NOMA, mmWave and THz, PLS, multiple antenna systems, and SWIPT as shown in Fig. 1. Finally, we highlight potential areas of RIS integration with Cognitive Radio (CR), Rate-Splitting Multiple Access (RSMA), Cell-Free Massive MIMO, and Light Fidelity (LiFi). Furthermore, we hope that this work will make it easier for researchers and industry practitioners to have an appreciation of the current progress on RIS-aided communication and gain insights into the design of more sophisticated optimization algorithms which can achieve higher spectrum energy efficiency, than that found in the current literature. To highlight our contributions, Table 2 provides a comparison of existing surveys on RIS-aided communications for those interested in reading more on RIS.

The remaining parts of this paper are organized as follows. Section II presents the integration of the RIS with emerging techniques. As the main goal, this study focuses on the analytical results of RIS-aided wireless networks. Section III discusses some practical challenges and future research directions, and then concludes the paper in Section IV. The main techniques covered in this paper are shown in Fig. 1. A list of recent studies and key findings are presented in Tables 2, 3, 5 - 9.

TABLE 2. **Summary of existing surveys on RIS-aided communications.**

Theme	Reference	Major Contributions
Mathematical frameworks	[8]	Tutorial on IRS-aided communications.
	[9]	RIS modeling and algorithm design.
	[18]	Optimization and performance analysis techniques for RIS in 6G
General concepts and research directions	[1], [3], [7], [32], [36], [2]	Survey on RIS-aided wireless communications and open research problems.
Industrial viewpoints on RIS	[10]	Key use cases, challenges from industrial viewpoints, and standardizations.
Security and privacy	[78], [79]	PLS concepts, applications, and open research problems.
	[80]	Security in energy harvesting networks.
	[39]	PLS in LiFi-enabled networks
	[103]	IRS-aided covert communications
RIS with emerging 6G technologies	[33], [175]	Discuss the coverage of a RIS-assisted large-scale mmWave cellular network using stochastic geometry.
	[38]	Compare RIS with massive MIMO, MIMO 2.0
	[39]	Combines RIS with light fidelity (LiFi) networks
RIS-aided Localization and mapping	[65]	Integration of RIS with mmWave to enable localization.
Integration with other transmission technologies	Our survey	Integration of RIS with UAV, NOMA, mmWave, PLS, CR, RSMA, Massive Antenna, Cell-Free Massive MIMO, SWIPT, and LiFi.

II. INTEGRATION OF RIS WITH NEXT-GENERATION COMMUNICATION TECHNOLOGIES

A. RIS-AIDED UAV COMMUNICATIONS

1) WHY UAV?

UAVs have gained tremendous significance over the last decade. An UAV is generally known as an aircraft without a human pilot on board. In most of well-known system models, RIS surfaces are installed on building walls to reflect the radio waves, the introduction of UAV integration with RIS, either by attaching it to RIS or to transmit the signal, is proven to be advantageous in communicating with the devices. The ability of the UAV to establish an Ad-Hoc network will make communication possible in deserted areas and mountains. Combining various techniques like NOMA, Visible Light Communication (VLC), etc., with UAV RIS will allow the systems to extend the coverage area of communication.

TABLE 3. **Summary of RIS-aided UAV communications.**

References	Main Contributions
[40]	Performance of the system in terms of BER and OP.
[41]	Utilize UAV - RIS in Visible Light Communications to reduce energy consumption by 35 percent approximately.
[44]	UAV assisted RIS with IoT enabled for data collection to increase coverage probability and improve energy efficiency of the system.
[45]	To maximize the average achievable rate by passive beamforming and trajectory optimization.
[46]	Maximizes the secure energy efficiency by optimising continuous phase shift, user optimization, transmit power and the UAV trajectory.
[47]	An UAV-assisted RIS system with TDMA communication network with an efficient algorithm is proposed to improve the system secrecy rate.
[48]	An UAV-assisted RIS system with Terahertz (THz) communication network to improve the performance of the system.

2) STATE-OF-THE-ART

In [40], the authors designed a system model where the UAV acts as a relay between the RIS transmitter and ground receiver. The authors aimed to maximize the coverage area and improve the reliability of the system. The authors have derived the probability density function (PDF) using the instantaneous SNR. Utilizing the PDF, the analytical expressions of outage probability (OP), average bit error rate, and average capacity are derived for considering N number of meta-surfaces. The simulations are performed to compare the proposed system with minimum number of RIS meta-surfaces to traditional system without RIS. The simulations have shown that, for constant SNR, the RIS can significantly reduce the bit error rate (BER) and improve the coverage, and reliability of the system. In [41], the authors considered a system model similar to [40] assisted by VLC. Compared to the limitations of radio waves, the VLC provides high bandwidth and immunity to the interference from the electromagnetic signals [42]. The considered model system is motivated to minimize the energy consumption, as the energy efficiency plays major role in deploying the UAV for long time. It is achieved by adjusting the phase shift, UAV deployment, and user – RIS association. The phase shift optimization is adopted in discrete mode using the phase alignment method and semi-definite program algorithm, and UAV deployment optimization can be achieved using a successive convex approximation (SCA) algorithm. A greedy algorithm is proposed to optimize the RIS association. Numerical results and simulation have demonstrated that the performance of the proposed algorithms is efficient when compared to the cases without RIS. The minimum transmit power is achieved when each RIS is associated with its nearest UAV.

The evolution of 5G networks has introduced smart cities with lots of useful applications. Applications for smart cities mainly depend on Internet-of-Things (IoT) devices which generate a huge quantity of data that needs to be collected and processed. The integration of IoT with UAV can extends the coverage area possible for the communication between the IoT devices and transmitters [43]. Utilizing this concept, the authors in [44] designed a system model that integrates RIS and UAV to collect the data from IoT devices. The research work considered the time-constrained data collection problem from a network of IoT sensing devices with the assistance of UAV and RIS, which helped to improve the multiple device connectivity. The trajectory of the UAV was modeled as a Markov Decision Process (MDP) and approached by Proximal Policy Optimization (PPO) to invoke it. The simulation results showed that the suggested model is 50 percent more efficient when compared to the traditional systems and the increase in the number of RIS elements significantly improves the UAV energy efficiency.

To introduce optimization, the work in [45] investigated RIS-assisted UAV communication systems to maximize the average achievable rate. In particular, the authors decomposed the non-convex problem into two sub-problems, passive beamforming and trajectory optimization. The authors proposed a joint UAV trajectory and passive RIS beamforming optimization algorithm for obtaining a sub-optimal solution. The simulation results demonstrated that the proposed system and algorithm is efficient enough to improve the communication quality of UAV networks. The authors in [46] considered a system model in which the UAV is installed with RIS assisted uplink wireless communication system and investigated the problem of maximizing the secure energy efficiency of RIS. The maximization problem is tackled by jointly optimizing the user association, transmit power, UAV's trajectory and phase shift in continuous mode at both RIS and UAV. The SCA method is used to solve the problems. As the main finding, the proposed design exhibits the improvement of the secure energy efficiency by 38 percent gains, compared to non-RIS traditional systems.

To maximize the average worst-case secrecy rate of the proposed system, the system secrecy rate was analysed in the context of the UAV-assisted RIS system with Time Division Multiple Access (TDMA) protocol [47]. In particular, the authors focused on the joint and CSI-robust design of a UAV's trajectory, passive RIS beamforming, discrete phase shift design, and transmit power of the legitimate user. To solve the non-convex problem, an efficient algorithm was proposed to solve it by Alternating Optimization (AO), SCA S-Procedure, and semi-definite relaxation (SDR) techniques. Simulation results showed that the secrecy performance rate was improved using the proposed system and the robustness of the proposed algorithm is also confirmed. To maximize the minimum average achievable rate of all users, the study in [48] presented the joint optimization of UAV's trajectory, the continuous phase shift of RIS, the power control, and the allocation of THz sub-bands. An algorithm based on SCA with rate constraint penalty was developed by the authors to determine the UAV trajectory and IRS phase-shift as closed-form expressions. Simulation results showed that the performance rate of the whole system can be enhanced. To summarize main ideas, Table 3 provides a summary of the contributions made by recent studies focusing deployment of UAV in RIS systems.

B. RIS-AIDED NOMA COMMUNICATIONS

1) THE KEY ROLE OF NOMA

The future of wireless networks needs more strict requirements, such as low latency, high data rates, mass connectivity. Beyond 5G (B5G) and 6G wireless systems deal with several issues that 5G has not been able to satisfy. Though we have advantages and it is good enough to be used, the new multiple access technique that arises is 6G capable of being called a future generation network.

Wireless networks have been rapidly evolving and recently, smart radio environments have been playing a major role in these networks. The propagation medium of a wireless network signal has always been uncontrollable. Because of this kind of nature, the attenuation of the signal always limits its network connectivity. The multi-path propagation results in fading of the signal strength. We can assume that the reflections and the refractions caused by the obstacles in between are the sources for this so-called uncontrolled behavior of the environment. Recently, new technology has been evolved which can control the propagation of the signal in any environment the communication can happen. RIS is a meta-surface that can reflect and refract a radio signal according to the requirement of the user. These meta-surfaces contain integrated electronic circuits and software that can control the wireless medium [49]. It just sounds like a mirror that can reflect and refract light rays according to the incident angle. The control of the wireless signals in the medium is possible by adjusting the phase shift of the signal according to the user requirement or the position. This way, a lot of signal wasted in the environment because of external factors, can be saved and utilized, which can increase the efficiency of present-day wireless networks.

Since multiple access techniques play a major role in B5G and 6G wireless networks, the studies in [26]–[53] considered the concept along with performance analysis of promising multiple access technique, namely NOMA. NOMA is an extended version of Orthogonal Multiple Access (OMA) rather than a competitor in the field. In general, NOMA has two categories, i.e., Power Domain NOMA and Code Domain NOMA. Power Domain NOMA utilizes the same frequency, time, and phase domain with different power coefficient levels to perform communication between multiple users at the same time. This stands as the foremost advantage of NOMA. Multiple users can utilize the same non-orthogonal resources at the same time by permitting high spectral efficiency, with allowable user interference [54]–[55]. The Code Domain NOMA utilizes the Sparse Code Multiple Access (SCMA) techniques and various other techniques to perform the communication between the transmitter and the receiver. To sum up, Table 4 compares the primary advantages and disadvantages of NOMA and OMA networks.

TABLE 4. Summary of RIS-aided NOMA communications.

Techniques	Advantages	Disadvantages
OMA	Receiver detection is simpler	Inequity for users Limiting the number of users Limited spectral efficiency
NOMA	High Spectral efficiency Equity for users Lower latency	Increased complexity at receivers Highly sensitive to channel uncertainty

Considering the advantages of NOMA, integrating the NOMA technique with RIS technology provides enhanced communications possibility, since the RIS possess the ability to control the radio waves propagation in the environment. This integration leads to enhanced spectral efficiency, energy efficiency, QoS, and maximization of performance rate of the system. This has motivated several researchers to study the performance of the system under various parameters. The notable research articles are studied in the state-of-the-art section which describes the considered system model, optimized parameter and enhanced system performance. Despite the several advantages NOMA has over OMA, various challenges need to solved before bringing it to real-time implementation. Although recent studies in [62]–[64] explored RIS-NOMA systems, there are several open problems to investigate on how RIS benefits NOMA-aided systems.

2) STATE-OF-THE-ART

In [26], the authors have adopted a single-input-single-output (SISO) NOMA network to illustrate the advanced performance of the NOMA-aided systems. The best and worst cases of the system performance are analyzed in the various parameters such as OP. To get benefits of NOMA [26], both downlink and uplink RIS-aided NOMA scenarios are considered in [50]. They adopted links with Nakagami-m fading channel distribution. The authors found that the diversity order is affected by the reflecting elements in IRS and Nakagami-m fading parameters, but these parameters do not affect the high-SNR slope.

Authors in [37] discussed the impact of Residual Hardware Impairments (RHI) on RIS-aided NOMA system. The research shows that RHI shows a primary impact on system secrecy performance. Therefore, the authors have proposed a single eavesdropper RIS-assisted downlink NOMA system with RHI. To evaluate the performance, the closed-form expressions of secrecy outage probability (SOP) are derived. The simulation results show that the main factors that affect SOP are reflective units in RIS, transmit SNR and target data rate. Simulation results showed that the secrecy outage performance of the system will be majorly affected by the RHI, and the severity of the impact of RHI on the system performance depends on the transmit SNR, and target data rates.

To explore the impact of RHI on a RIS-aided NOMA system, [37], [51] studied two-user downlink NOMA, where each user is distinguished by the distance and position of the user. In this scenario, hardware impairments are considered as the residual noise either at the transmitter or the receiver or both, considering the real-time environment, which affects the performance of the system. It is also found that the number of RIS elements, transmit power at the BS and power allocation factors play a major role in improving the performance of the system. The destination users have more chances to receive better signals from the BS [52], [53] which is different from a RIS-NOMA system reported in [51]. They designed a RIS-NOMA system with two links i.e. backscatter link and direct link. The numerical results indicate that in the high-SNR regime and with a higher number of reflecting elements, the RIS-NOMA can outperform RIS-OMA in terms of OP, while the ergodic capacity (EC) of the near user case remains the best case.

RIS has the power to turn the highly probabilistic natured environment into a human-controlled propagation environment, which means it can also be an emerging technology that can achieve energy-efficient wireless communication. Authors in [53] focused on beamforming, joint clustering, and power allocation for downlink RIS assisted NOMA system which is targeted to maximize energy efficiency. Sub-optimal solutions were identified utilizing the efficient iterative algorithms developed by the authors. The simulation and numerical analysis illustrated that the proposed system can enhance the energy efficiency significantly, comparing the traditional NOMA and OMA system without RIS.

Moreover, it is possible to achieve higher diversity if multiple antennas are enabled in RIS-aided systems. In [54], the authors considered MIMO assisted NOMA-RIS for serving multiple users simultaneously, employing noise cancellation-based design. The authors also compared the proposed system to zero-forcing design and signal-alignment design and it turns out that the role played by reflecting antennas is not important anymore. The analytical results show that inter-cluster interference can be eliminated by employing a large number of RIS elements. Furthermore, the authors designed MIMO RIS-NOMA by enabling passive beamforming weight at RISs and Signal Cancellation Based (SCB) design is employed as well. The minimal required number of RISs can be determined in both anomalous reflector and the diffuse scattering scenarios to deploy the proposed SCB design. For the case of multiple users, a multi-cluster MISO NOMA downlink network is considered by the authors in [55]. The primary goal of this research was to minimize the transmit power by jointly optimizing the active beamforming matrices at the BS and reflective coefficient vectors at RIS. Here the authors have proposed a second-order cone programming altering the direction method of multipliers-based algorithm instead of conventional semi-definite programming, to obtain a locally optimal solution. It is shown that the proposed algorithm achieves significant performance gain over the traditional algorithm. The main result minimizes the transmit power by considering joint optimization of the reflection coefficient vector at the RISs and the active beamforming matrices at the BS.

The authors in [56]–[61] also evaluated the performance improvement of various system models of NOMA-RIS systems. For example, the interesting work in [56] designed a backscatter communication RIS system similar to [52] which investigated the joint power reflection coefficients and phase shift optimization. To solve these non-convex problems, the authors proposed a low complexity algorithm which, in the presence of a large number of meta-surfaces, outperforms the traditional NOMA Backscatter Communication (NOMABC) and OMA Backscatter Communication (OMABC) networks without RIS. With the similar systems designed in [53], [55], authors in [57] have proposed a machine learning approach based on double decaying deep-Q network (D-DQN) to maximize the energy efficiency of the system. The approach was taken in steps in which the first step is supposed to predict the data traffic demands of the users by utilizing a real-time dataset. Secondly, a position acquisition and phase-control algorithm are proposed to solve the problem of deployment and design of RIS. The results show that the proposed algorithm outperforms the traditional algorithm and NOMA enhanced RIS system has better performance when compared to the OMA enabled RIS system. Table 5 highlights the system setup and key contributions of the above works.

C. RIS-AIDED mmWave AND THz COMMUNICATIONS

1) The BENEFITS OF RIS TO BEYOND 6 GHz COMMUNICATIONS

The ever increasing demand for higher data rates and seamless wireless connectivity has forced both academic and industrial strategists of wireless communications to consider exploring higher frequency bands other than the heavily utilized sub-6 GHz radio spectrum. The millimeter and THz spectrum of electromagnetic waves are two of the most preferred choices. However, when the carrier frequency increases, the propagation conditions become more challenging due to the increased penetration losses and lower scattering levels, leading to fewer propagation paths between the BS and the receiver. Further, antenna arrays become challenging to design since the size of each antenna element shrinks with the wavelength. Under these conditions, deploying RISs can enhance the propagation conditions by introducing additional scattering and control of the scattering characteristics, to create passive beamforming towards the desired receivers to achieve high beamforming gain and suppression of the co-channel interference.

TABLE 5. Summary of RIS-aided NOMA communications.

Scheme	Reference	Main Contributions
SISO	[26], [50]	Compared the performance analysis of RIS-Aided NOMA system with OMA and identified the role played by number of elements, effect on diversity order and power allocation factor.
MIMO	[54]	RIS-Aided NOMA MIMO with noise cancellation system is designed which was able to eliminate the inter-cluster interference using a large number of RIS elements.
Hardware Impairment effect	[37], [51]	Evaluated the performance of the system in terms of OP and SOP, in the presence of hardware impairments at the transceiver, where severe impact is shown and also compared NOMA with OMA system.
Energy efficiency and optimization	[53], [55], [57]	Authors have focused on energy optimization and minimization of transmit power and proposed an iterative non-complex algorithm and machine learning approach, which was able to boost up the performance of suggested system by 23 percent.
Backscatter communication	[52], [56]	Authors have designed a multi-user system with direct link and backscatter link to evaluate the performance of the system and proposed a low complexity algorithm to deal with non-convex problems like phase optimization and power reflection coefficients.
Reliability	[54]	Authors have designed a RIS-Aided NOMA system to check the reliability in terms of BER.

As such, deployment and utilization of RIS increases propagation conditions by providing an additional propagation path in mmWave and THz frequency bands where conventional relaying technology is not available [33]. In light of these benefits, the goal of this section becomes one of unveiling and discussing the benefits associated with integrating RISs into mmWave and THz wireless communications. Therefore, in the following section, we introduce several state-of-the-art techniques achieved by the introduction of RIS into mmWave and THz communications. The section covers communication coverage and performance analysis perspectives. Including, RIS placement, quantization error reduction, channel acquisition, beamforming design, and user localization strategies [65].

2) STATE-OF-THE-ART

In [31], the authors study how RIS can outperform Amplify-and-Forward (AF) relays over a fluctuating two-ray (FTR) channel model. The authors derived exact end-to-end SNR expressions for the RIS-aided system and AF relay system. To maximize the SNR, the authors proposed an optimal phase shift design method to obtain optimal phase shifts at the RIS elements. Furthermore, the optimal power allocation algorithm for the AF relay system is also derived. Consequently, Monte-Carlo simulations validate the OP and the average bit-error probability of the two systems. The simulation results show that the RIS-aided system can achieve the same performance as the AF relay system with low transmit power.

In [66], the authors explored the utilization of RISs to assist the BS to localize the user equipment (UE) in mmWave MIMO systems. The authors proposed a two-stage positioning method where dual RISs are used. In the first stage, a suitable RIS is chosen to reflect signals and in the second stage angle information and the difference in the delay is utilized to estimate the location of the UE. Numerical results show that the proposed method reaches a localization accuracy up to $10^{-5} \sim 10^{-4}$ which is an order of magnitude lower than the single-RIS-aided method. In [67], the authors investigated the use of the cross-entropy (CE) method to maximize the sum-rate performance of RIS-aided indoor THz transmission. The CE method greatly reduces the complexity of selecting the optimal phase shift for each reflecting element when compared with the local search and exhaustive search (ES) methods. The work in [68] evaluated the coverage of a RIS-assisted large-scale mmWave cellular network using stochastic geometry and obtained the peak reflection power expression of a RIS and the downlink Signal-to-Interference ratio (SIR) coverage expression in closed forms. Simulation results proved the tightness of the closed-form expressions, showing that the deployment of passive RISs is effective in enhancing mmWave coverage. Different from work in [68], the authors in [69] examined a robust technique for mitigating undesired side lobes or quantization lobes in single-bit mmWave RISs under plane-wave illumination using random phase delays. These lobes are caused by the periodicity of the errors due to the limited number of phase quantization bits. Phase randomization breaks the periodicity of quantization errors. Finally, Radar Cross-Section (RCS) characterization results show that the proposed randomization technique mitigates the quantization lobes. For deployment of MIMO, a RIS-aided multi-user THz MIMO system with orthogonal frequency division multiple access (OFDMA) is studied, where the sparse radio frequency chain antenna structure is adopted for reducing the power consumption [70]. While downlink RIS-aided mmWave systems are conducted in [67]-[70], the closed-form expression of uplink achievable rate expression were derived, taking into consideration the phase noise at the RIS and the quantization error at the BS [71]. The authors analyzed the performance loss caused by the phase noise at the RIS and the quantization error at the BS. As insight of the considered system, asymptotic results are presented when the number of RIS phase shifts approaches infinity.

In the presence of random blockages, the work in[72] studied the enhancement of network reliability and connectivity of multi-user mmWave RISs-aided communication system. The authors formulated a sum-outage probability minimization problem subject to total transmit power constraint and unit modulus constraint. The proposed stochastic optimization problem is solved using the Block Stochastic Gradient Descent (BSGD) method. In [73], the authors proposed a Geometric Mean Decomposition (GMD)-based beamforming for single-user RIS-aided wideband hybrid mmWave MIMO systems. The GMD-based hybrid beamforming achieves better BER performance without resorting to complicated bit/power allocation on different spatial domain sub-channels. Leading to multiple parallel data streams in the spatial domain having the same channel gain. Also, the authors exploited the common angular-domain sparsity of mmWave massive MIMO (mMIMO) channels over different subcarriers, to design a simultaneous orthogonal matching pursuit algorithm. The algorithm obtains optimal multiple beams from an oversampling two Dimensional Discrete Fourier Transform (2D-DFT) codebook. Moreover, the authors' design phase shifters for RIS by maximizing the array gain for the LoS channel. Simulation results show that the proposed scheme achieves good performance in wideband hybrid mmWave MIMO systems with the aid of RIS. In [74], the ranging performance of RIS-aided mmWave systems is considered in the presence of blockages. The authors proposed an optimal RIS deployment strategy that minimizes the joint blockage probability of the UE to the BS link and the UE to the RIS link. Moreover, the authors derived a Cramer-Rao Lower Bound (CRLB) characterization of the localization strategy of users in the network.

To design a practical beam alignment and channel parameter estimation method for single-user RIS-aided mmWave MIMO networks, the results in [75] show that the proposed method outperforms the standard beam alignment in terms of mean square error and spectrum efficiency. To reduce the pilot overhead, Compressive Sensing (CS)-based algorithm is developed that exploits the dual sparsity of THz MIMO channels in both the angular and delay domain [76]. In [77], the authors presented an optimal RIS placement in mmWave networks, that maximizes the SNR performance of highly directional single-user RIS-aided mmWave links of fixed topology under blockage. Table 6 provides a summary of the preceding discussion.

TABLE 6. State-of-the-art proposed solutions for RIS-aided mmWave and THz communications.

Reference	Main Contributions
[31]	Derivation of exact end-to-end SNR expressions for the RIS-aided system and AF relay system
[66]	Provide a two-stage positioning with dual RIS in mmWave MIMO systems
[67]	Introduce the cross-entropy method to maximize the sum-rate performance of RIS-aided indoor THz transmission
[68]	Discuss the coverage of an RIS-assisted large-scale mmWave cellular network using stochastic geometry
[69]	Present a robust technique for mitigating quantization errors in low resolution mmWave RISs under plane-wave illumination using random phase delays
[70]	Investigate an IRS-aided multi-user THz MIMO system with OFDMA, where the sparse radio frequency chain antenna structure is adopted for reducing the power consumption
[71]	Formulate the closed-form expression of uplink achievable rate expression of RIS-aided mmWave systems
[72]	Study the enhancement of network reliability and connectivity of mmWave RISs-aided communication system in the presence of random blockages
[73]	Discuss Geometric Mean Decomposition (GMD)-based beamforming for RIS-aided wideband hybrid mmWave MIMO systems
[74]	Study the ranging performance of RIS-aided mmWave systems in the presence of blockages
[75]	Present a design of a practical beam alignment and channel parameter estimation method for RIS-aided mmWave MIMO networks via atomic norm minimization
[76]	Discuss a holographic version of an RIS and its use in THz mMIMO systems
[77]	Present the optimal RIS placement in mmWave networks

D. RIS-AIDED PHYSICAL LAYER SECURITY

1) WHY PHYSICAL LAYER SECURITY?

With the introduction of wireless communication networks in security-sensitive scenarios such as banking, military, healthcare, Smart City, and environmental surveillance. As well as in emerging wireless networks such as IoT, massive machine-type communication (mMTC), 5G-Tactile Internet, wireless vehicle technology, remote surgery and sensitive IoT actuators. This has created an urgent need to study ways to protect these networks against malicious attackers. The use of encryption techniques for network security may not be suitable due to stringent delay requirements [2], [7], and [78]. As a result, there is now more research interest in the development of secure data transmission based on the physical layer of the wireless channel. Mathematically, the integration of RISs with PLS brings about new communication system models and optimization techniques beneficial to enhancing Secrecy Rate Maximization (SRM), secrecy capacity, and SOP in wireless communications without relying on encryption techniques [79], [80]. We next briefly discuss the RIS-enabled state-of-the-art solutions proposed by several authors along these lines, and Table 7 provides a summary of the main system setup, key contributions and proposed technical solutions.

TABLE 7. **State-of-the-art proposed solutions for RIS-aided physical layer security.**

System Setup	Reference	Contributions	Proposed Techniques
SISO	[81], [35], [101]	Closed-form SOP and average SR expressions	Fox's H transform, mellin-barnes integrals, asymptotic analysis
Full-duplex jamming-underlay D2D	[84]	Achievable SR maximization	AO algorithms
MISO-Energy efficient jamming	[85]	Energy efficiency maximization	AO based S procedure, SDR algorithm
Inband underlay D2D	[86]	SOP, non-zero secrecy capacity probability	Asymptotic analysis
UAV	[87]	Jamming minimization	AO, SCA algorithms
SISO-NOMA	[89]	SOP	Asymptotic analysis
SISO-mmWave and THz	[97]	Non-convex secrecy rate solutions	SDP, BCD algorithms
MISO	[95] [102]	PLS feasibility Secrecy rate	AO, SDR SCA algorithms
MISO-Multicast	[90]	Secrecy multicast capacity	Inequality constrained optimization, logarithmic Barrier
MISO-SWIPT	[91]	Harvested power maximization	Low-complexity AO, SDR algorithm
MISO-NOMA	[94]	Secure beamforming	SROCR based AO algorithm
MIMO	[82], [88] [99]	Non-convex secrecy rate maximization Spectral efficiency	BCD, lagrangian multiplier, MM, AO, SCA algorithms Asymptotic analysis
MIMO-Wiretap	[93]	Secrecy rate maximization	Fractional programming, manifold optimization
MIMO-mmWave	[100]	Non-convex secrecy rate maximization solutions	AO, SCA, BCD algorithms
V2I	[92]	Closed-form average secret capacity expression	Asymptotic analysis
IoT	[96]	Closed-form average secrecy capacity and SOP expressions	Fischer-Snedecor, Asymptotic analysis
Dual-hop	[98]	Closed-form OP and sum-rate expressions	Asymptotic analysis
NOMA-IoT	[37]	Closed-form SOP expressions	Asymptotic analysis
SISO-Covert Communication	[104]	Covert rate maximization	PSCA, low-complexity two-stage algorithm
MISO-Covert communication	[105]	Covert rate maximization	AO, low-complexity sub-optimal algorithm, triangle, Cauchy-Schwarz inequalities, SDR, Gaussian randomization
SISO-Covert communication	[106]	Covert rate maximization	AO algorithm, SDR technique

2) STATE-OF-THE-ART

In [81], the authors studied the performance analysis of RIS-aided communications in the presence of discrete phase shifts and derived exact SOP in the presence of non-colluding and colluding eavesdroppers. In addition, the authors employed Fox's H transform theory and the Mellin-Barnes integrals to obtain closed-form expressions of the SOP and Average Secrecy Rate (ASR) with discrete phase noise. In the interesting work of [35], the authors examined the achievable SOP of a RIS-aided wireless communication system, in which a single-antenna communicates with a single-antenna receiver in the presence of a single-antenna eavesdropper. Accurate and closed-form analytical expressions for the SOP are derived by asymptotic analysis. The security performance of adding RISs in an Artificial Noise (AN)-aided secure MIMO wireless communication system is analysed in [82]. The RIS-aided system consists of a BS, a legitimate receiver and an eavesdropper, all of which are equipped with multiple antennas. The BS transmits AN to jam the eavesdropper's received signal. To maximize the Secrecy Rate (SR), the authors jointly optimize the BS TPC matrix, the AN matrix, and continuous phase shifts at the RIS subject to constraints of transmit power limit and unit-modulus of RIS phase shifts. The resultant SRM problem is non-convex with multiple coupled variables. To solve this non-convex problem, the authors develop a BCD algorithm to alternately update the variables while keeping SR non-decreasing. The TPC matrix and AN covariance matrix are derived by the Lagrangian multiplier method, and the closed-form optimal phase shifts are obtained by an efficient Majorization-Minimization (MM) algorithm. Simulation results show that security gains can be achieved by the addition of RISs in AN-aided secure MIMO wireless communication system.

Further, in [83], the authors studied the usefulness of AN or jamming as a way to enhance the SR of an IRS-aided wireless communication network consisting of a legitimate multi-antenna transmitter in the presence of multiple single-antenna eavesdroppers. The authors maximized the achievable secrecy rate via joint design of the transmit beamforming with jamming or AN and IRS continuous phase shifts subject to transmit power. The authors proposed an AO to solve the non-convex problem. Using numerical results, the authors demonstrated that transmit and IRS reflect beamforming alone fails to improve the SR when the number of eavesdroppers is larger than that of the transmit antennas due to lack of sufficient Degrees-of-Freedom (DoF). Therefore, in such a scenario, AN or jamming can effectively enhance the SR.

Recently, AN or jamming has been introduced into new RIS-aided network setups. The authors in [84], examined the integration of RIS and full-duplex jamming receivers in underlay device-to-device (D2D) systems. The authors derived novel approximate expressions of the proposed system achievable ergodic SR. In [85], the authors studied the achieved energy-efficiency via IRS-aided MISO with independent jamming. Here, the authors maximized the energy efficiency by jointly optimizing the transmit and jamming beamforming as well as the continuous IRS phase shift matrix. The authors considered both perfect and imperfect CSI scenarios. Further, the authors proposed a SDR algorithm to solve the formulated non-convex fractional problem under perfect CSI conditions as well as an AO algorithm based on the S procedure for the imperfect CSI condition. Simulation results demonstrated that IRS can enhance energy efficiency even under imperfect CSI conditions. Differently, in [86], the authors studied RIS-assisted inband underlay D2D communication where the direct link between D2D users is absent. The RIS device is used to improve the D2D communication while enhancing the network's secrecy performance. The authors derived asymptotically the SOP, the non-zero secrecy capacity probability, and D2D OP. Moreover, in [87], the authors investigated the deployment of an RIS-aided UAV deployed to eliminate jamming attacks and improve legitimate transmissions. The authors jointly optimized the RIS-aided UAV deployment and RIS continuous phase shifts subject to the aerial RIS location and the unit-modulus constraint. The authors tackle the non-convex problem via AO where SCA obtains the RIS-aided UAV location and manifold optimization is used to obtain the RIS phase shifts.

To benefit from multiple antennas design, the authors in [88] considered a scenario where an AP communicates with a legitimate user in the presence of an eavesdropper. To maximize the SR, the authors jointly optimized the AP transmit covariance matrix, and reflecting coefficients at RIS under the assumption of continuous and discrete reflecting coefficients. To solve this non-convex problem, the authors developed an algorithm based on AO and SCA. The more complex scenario of multiple RISs, multiple near and far legitimate users was explored in [89]. Analytical results for the SOP are derived, and numerical and simulation results show that secrecy performance can be improved by using group selection, and increasing the number of reflecting elements also enhances the system secrecy performance. In [90], the authors proposed securing multicast communication with the help of RISs. A multiple antenna multicasts a common message to a group of single-antenna receivers in the presence of a single-antenna eavesdropper. The authors, first derived the equivalent multicast and wiretap channels, next the channels capacity maximization problem was formulated by jointly optimizing the optimal covariance matrix and continuous phase shifts subject to the transmit power budget and RIS phase shift constraints. The problem is an inequality constrained optimization problem, which is continuously differentiable. Then, a logarithmic barrier algorithm is developed to obtain a locally optimal solution.

From another aspect, the authors in [91], presented how the deployment of RIS maximizes harvested power at an energy harvesting receiver (EHR) in a MISO SWIPT wireless network. The proposed network consists of a multi-antenna AP serving an EHR and an information receiver with the help of a RIS in the presence of an eavesdropper. To maximize the harvested power, the authors optimize the transmit beamforming at the AP and continuous phase shifts at the RIS subject to the SR and the reflecting RIS phase shifts constraints. Since the resultant problem is non-convex with multiple coupled variables, the authors address this problem by developing AO algorithms. The non-convex problem is first converted into a SDR problem. However, the proposed SDR method is high in complexity, therefore, a Low-Complexity Alternating Optimization (LC-AO) algorithm is designed to reduce the computational complexity. Simulation results show that the integration of RIS into a MISO-SWIPT network approximately doubles the harvested power at the EHR. For vehicle-to-infrastructure (V2I) communications, the work in [92] characterized the PLS problem in the presence of malicious eavesdroppers. The authors compared the Average Secret Capacity (ASC) performance between the Decode-and-Forward (DF) and Amplify-and-Forward (AFFG) relays and RIS when employed in V2I communications. The numerical results show that RIS-aided V2I communications in the presence of an eavesdropper provide higher security than both DF and AFFG relays.

In respect of the AO algorithm, the authors in [93] considered a RIS-assisted wiretap communication system consisting of a multiple-antenna BS, a single-antenna legitimate user, one RIS, and one multiple-antenna eavesdropper. The authors designed an AO algorithm to optimize the beamforming vector at the BS under fixed RIS phase shifts. In contrast with the work in [93], a robust beamforming scheme for secure RIS-aided NOMA transmissions relying on AN was explored [94].

In [95], the authors investigated the feasibility of providing PLS via RISs in a RIS-aided communication system in which a multiple-antenna BS serves a single-antenna legitimate user in the presence of a passive single-antenna eavesdropper. The authors adopt linear precoders, based on cascaded BS-to-RIS and RIS-to-user channels, with optimization of the continuous phase-shifts at the RIS. An alternating algorithm is developed to iteratively update the phase shifts of the RIS. This optimal phase-shifts problem is modeled as a relaxed semi-definite program. Gaussian randomization techniques are used to achieve a close approximation of the optimal phase shifts. Numerical results show that the proposed techniques offer a low-complexity alternative to joint optimization of the BS precoder and RIS phase shifts.

In [96], the authors studied the PLS of a RIS-aided IoT system over generalized fading channels. The Fischer-Snedecor is employed to analyze the composite fading and shadowing channel in a system modeled concerning a source node and a legitimate destination node in the presence of a passive eavesdropper. The authors derived closed-form expressions of the ASC and SOP of the system. Monte Carlo simulations show that there is a clear secrecy benefit of utilizing a RIS-assisted AP for various fading and shadowing conditions. As similar to these studies, the authors in [97] examined the secure transmission for RIS-assisted mmWave and THz systems, in which a multiple-antenna BS communicates with a single-antenna user in the presence of a single-antenna eavesdropper. In [98], the authors considered a dual-hop cooperative network aided by multiple RISs. In [99], the authors presented a point-to-point anti-eavesdropping system in which a RIS secures transmission from a multiple-antenna transmitter to a multiple-antenna legitimate receiver in the presence of a passive eavesdropper, with completely unknown channel state information.

In the perspective of multiple antennas design, the authors in [100] investigated the SR of a RIS-aided MIMO mmWave network with Low-Resolution Digital-to-Analog Converters (LDACs), where the multiple-antenna AP with multiple RF chains serves a single-antenna legitimate user in the presence of a single-antenna eavesdropper. The authors maximized the SR under hardware impairments by jointly optimizing the discrete RIS phase shifts and the transmit beamforming. In the work of [101], the Ergodic Secrecy Rate (ESR) of RIS-aided communication systems was considered in the presence of discrete phase shifts and multiple eavesdroppers.

To raise the impact of imperfect hardware, the authors in [102] studied the transmission design for a RIS-aided secure MISO communication system in the presence of transceiver hardware impairments. In [37], the authors also examined the impact of RHI on system secrecy performance of RIS-assisted NOMA technology integrated with IoT. The authors derived an approximate closed-form expression of the user's SOP.

The aforementioned techniques focused on protecting the transmitted information against eavesdroppers, however, these techniques do not address the privacy issues faced when the position, movement and even existence of wireless transmissions is easily discoverable by malicious users [103]. Covert communication has been proposed by several works in [104]–[106] and others, as an effective solution to hide the existence of wireless transmission, thus, enhancing privacy and data security. In [104], the authors investigated the performance gain obtained by IRS-enabled covert wireless communication system consisting of a single antenna legitimate transmitter, covert user, and warden. The authors jointly designed the transmit power and IRS continuous phase shifts subject to the covertness constraint (for the cases of global CSI availability and without the warden's instantaneous CSI), transmit power constraint and IRS phase shift constraints. Considering the case of global CSI availability first, the authors proved via numerical results that IRS-aided single antenna transmitters can achieve effective covertness. The authors then designed a penalty based SCA (PSCA) algorithm to tackle the formulated non-convex problem. To reduce the complexity of the PSCA algorithm, the authors developed a low-complexity two-stage algorithm to aid the derivation of analytical formulas for Alice's transmit power and IRS phase shifts. Then for without the warden's instantaneous CSI case, the authors derived analytically the covertness constraint, thus, enabling the optimal design of the IRS phase shifts.

Differently, in [105], the authors jointly optimized transmit beamforming vectors and IRS continuous phase shift subject to transmit power constraints and covertness constraints for IRS-aided single and multiple antenna transmitter scenarios. Both scenarios consider the case of either instantaneous or partial CSI of the warden's link. For the multiple antenna scenario, the authors developed an optimal AO algorithm and two low-complexity sub-optimal algorithms to solve the problem. For the case of partial CSI of the warden's link, the authors used the triangle and the Cauchy-Schwarz inequalities to reorganize the optimization problem. An AO algorithm, SDR and Gaussian randomization methods are used to solve the reformulated problem.

Moreover, in [106], the authors examined covert communication in IRS-aided NOMA systems consisting of a single antenna legitimate transmitter, covert user, and public user. Here, IRS-aided downlink and NOMA-aided uplink techniques hide the existence of a covert user from a warden. The authors maximized the covert rates of the covert user by jointly designing the transmit power and IRS continuous phase shifts subject to covertness constraints and QoS requirements of a public user. The authors developed an efficient AO algorithm to optimize the power allocation and IRS phase shifts of the non-convex problem. The closed-form optimal power allocation solutions for given IRS reflection coefficients are obtained after each iteration. Then the SDR technique was used to derive the optimal IRS phase shifts for given power allocation.

E. RIS-AIDED MULTIPLE ANTENNAS SYSTEM

1) DESIGN OF MULTIPLE ANTENNAS IN RIS

For future wireless communication technology, MIMO has been recognised as a key enabling technology. With a sufficiently large number of antennas at the BS, MIMO has the potentiality to significantly increase the spectral and energy efficiency [107]. To meet the requirements of 5G and 6G communication networks, multi-antenna system utilization has begun, which utilizes high hardware cost and energy consumption. Though the MIMO technology is promising, some limitations need to be taken care of for practical implementation [10]. There are promising approaches given by different authors for limitations of MIMO technologies in [108]–[110]. Utilization of RIS assisted by MIMO systems with careful selection of antennas provides a way to improve the performance of the system while reducing the hardware cost. Table 8 contains a summary of the referenced state-of-the-art works.

TABLE 8. Summary of RIS-aided multiple antennas system.

Reference	Main Contributions
[104]	MIMO based RIS system with cosine-similarity-theorem-based-low-complexity-algorithm to enhance path gain of communicating channel
[112]	AIRS based multiple access point system with either single or multiple antennas to maximize the achievable user rate
[113] [114]	MIMO-assisted RIS system to enhance communication and transferring additional information using on-off reflection technique and maximizing the achievable user sum rate
[115]	RIS assisted mmWave system to maximize the achievable rate of the system by independently optimizing various parameters
[116]	RIS-assisted SWIPT system to enhance the secrecy rate performance of the system
[117]	RIS-assisted SWIPT system to enhance the performance of energy receivers and information receivers

2) STATE-OF-THE-ART

The authors in [111] have designed a RIS-assisted MIMO system with a cosine-similarity-theorem-based-low-complexity-algorithm to understand and adapt the continuous and discrete phase shifts of the RIS system and to enhance the path gain of the communicating channel. A semi-analytic approach is performed to derive the average BER of the system. Computer simulations are performed under different circumstances and investigated the performance of the system including discrete phase reflection, imperfect CSI, and path loss effect. An Aerial Intelligent Reflecting Surface (AIRS) aided downlink system was introduced in [112], where multiple access points with either a single antenna or multiple antennas served a group of a small number of users with single antenna receivers with the help of AIRS. Both the AP and the AIRS are being controlled by a Central Processing Unit (CPU). The main goal of the research was to maximize the achievable user rate and studied the rate optimization problem. The authors have proposed an algorithm by optimizing the power allocation vector and discrete phase shift matrix. The optimization algorithm improves the achievable rate performance and simulations were generated to explain it.

In similar work, the authors in [113] studied the passive beamforming and information transfer technique for multiuser MIMO system-aided RIS which enhances the communication via passive beamforming, meanwhile also carrying additional information using on-off reflection modulation technique [114]. The research was focused on the maximization of achievable user sum rate. The authors developed a sample average approximation-based algorithm for efficient passive beamforming and the complexity of the algorithm is further reduced by considering AO problems. The authors in [115] considered an IRS-assisted mmWave system in which massive antenna arrays are equipped at the transceivers. The main aim of this research was to maximize the achievable rate of the system while providing an optimal solution for power allocation, precoding & combining, phase shift at the RIS. The authors have derived asymptotic expressions for sum rate. The results have manifested that joint optimization of the parameters is no more required as compared to other researches.

To implement green communications, a MIMO-based SWIPT aided RIS system was introduced to provide better performance in terms of secrecy rate when non-convex iterative algorithms are applied [116]–[118]. Authors in [116] considered a SWIPT aided IRS system equipped with multiple antennas aiming to maximize the secrecy rate of the system by joint designing AN covariance and phase shift matrix. To tackle these non-convex problems, the author proposed an inexact BCD method. The simulation results show that the proposed system enhances security. Whereas authors in [117] have considered a similar system for enhancing the performance of Information Receivers and Energy Receivers. To tackle the non-convex problems, the authors have considered the classic BCD method. The proposed method enhances the performance of the system in this case.

Since CSI plays a major role in obtaining the properties of the communication channel in MIMO, achieving perfect CSI is still challenging due to limited signal processing. The authors in [119]–[122] considered RIS-aided MIMO system by assuming imperfect CSI. The authors in [120] studied the worst-case robust beamforming design for the proposed system. The imperfect CSI increases the complexity of solving non-convex problems like minimizing the transmit power and achieving the QoS for the requirement for each user.

F. RIS-AIDED SWIPT

1) The BENEFITS OF RIS IN SWIPT NETWORKS

The rapid increase in wireless devices such as IoT devices and UAVs in various applications has been beneficial and convenient to many communication users [123]–[140]. However, these devices suffer from limited battery life which hampers their performance in different fields [141]–[143]. SWIPT is a desirable technique to provide energy over the air, thus, avoiding frequent battery replacement or recharging in hard to access areas like inside the human body for implanted medical sensors or inside concrete structures for embedded monitoring sensors [144]. In [117], SWIPT enabled networks are described as a BS transmitting signals to a group of devices, where some devices act as information receivers and others behave as energy receivers. Some energy receivers such as humidity sensors require higher operational energy than required by a typical information receiver [117]. To realize SWIPT in practice, there are various utilized receiver protocols, such as Power Splitting (PS), Time Switching (TS), and hybrid versions of the two [145], [153].

Conventional SWIPT systems are limited by the proportional relationship between path loss and transmission distance. Therefore, considerable amounts of energy can only be harvested in the vicinity of the energy transmitter [146]. Moreover, obstacles between the BS and energy receiver as well as channel randomness can impact SWIPT performance.

Hence, deploying RISs closer to energy receivers can remedy this by providing additional LoS links to enhance the harvested power [117].

The authors in [147] also showed that in far-field scenarios, the path loss of the transmitter-RIS-receiver link is larger than that of the unobstructed direct transmitter-receiver link. Therefore, for the two links to have the same path loss, the RIS should be equipped with a massive number of phase shift elements [25]. However, for carrier frequencies in the mmWave and THz range, according to the RIS double fading model, the massive number of equipped RIS elements complicates channel estimation (due to the high overhead of N pilots) and real-time beamforming. The massive number of required elements might make RIS undesirable and unpractical to manufacture and deploy, however, this is not the case as noted in [33], that RIS elements are spread out over the planar two-dimensional surface and are sub-wavelength in size, hence more than 1000 elements can be equipped into a 1 × 1m surface. Moreover, based on the measurements identified in [26], [27], practical RIS devices require good resource allocation schemes to effectively enhance the energy efficiency of SWIPT systems.

Based on the above, several authors have exploited the favorable communication environment created by RIS to propose enhancements to the existing wireless techniques such as efficiency, weighted sum-power and sum-rates maximization, max-min fairness, resource allocation etc, to benefit SWIPT. Next, we discuss the state-of-the-art techniques proposed by several authors. Table 9 contains a summary of the referenced state-of-the-art works.

2) STATE-OF-THE-ART

In [24], the authors proposed a weighted sum power maximization algorithm for IRS-aided MISO SWIPT system with linear energy harvesting (EH) model. The system consists of an IRS assisting a multi-antenna AP serving several single-antenna information decoding receivers (IDRs) and EHRs. Here the authors maximized the weighted sum-power received by the EHRs via jointly optimizing the AP TPC matrices and IRS continuous phase shifts while subject to the individual SINR constraints of the IDRs. Due to the non-convex SINR constraints, the authors proposed efficient AO and SDR algorithms to obtain sub-optimal solutions for the non-convex optimization problem. The authors also confirmed that dedicated energy beamforming for IRS-aided SWIPT systems is unnecessary just as in the case of conventional SWIPT systems without IRS as first investigated in [146].

Different from [24], the authors in [148] extended [24] by introducing multiple IRSs to assist the multi-antenna AP serve several single-antenna information receivers and energy receivers. Here the authors minimized the AP transmit power by jointly optimizing the AP TPCs and the IRS reflect continuous phase shifts, subject to the individual information receiver SINR constraints and energy receiver harvesting constraints. To solve this non-convex QoS-constrained joint active and passive beamforming optimization problem with intricately coupled QoS constraints, the authors first decoupled the QoS constraints via proper transformations then the resultant problem was solved iteratively using the penalty-based method and BCD algorithm.

TABLE 9. State-of-the-art proposed solutions for RIS-aided SWIPT.

System Setup	Reference	Contributions	Proposed Techniques
MISO-SWIPT with linear EH model	[24]	Weighted sum-power maximization	AO, SDR algorithms
MISO-SWIPT with linear EH model	[148]	Transmit power minimization	BCD algorithm, Penalty-based method
Multi-user MISO-SWIPT with linear EH model	[149]	Max-min harvested power	AO, SDR algorithms
Secure MISO-SWIPT with non-linear EH model	[150]	Energy efficiency maximization	AO, SDR algorithms
Secure MIMO-SWIPT with linear EH model	[116]	Secrecy rate maximization	Inexact BCD method, penalty-based MM, CCM
MIMO-SWIPT with linear EH model	[117]	Weighted sum-rate maximization	AO, BCD algorithm
Multi-user PS-MISO-SWIPT with co-located receivers and linear EH model	[151]	Maximum energy efficiency indicator	MM method, fractional programming, AO, SDR, manifold method, Dinklebach algorithm
TS-MISO-SWIPT with non-linear EH model	[152]	Max-min energy rate fairness	AO algorithm
MIMO-IoT-SWIPT with linear EH model	[153]	Max-min SINR fairness	SOS1, RL methods
PS-MISO-SWIPT with co-located receivers and non-linear EH model	[154]	Max-min energy efficiency fairness	AO, penalty-based method, IA method, SDR, SCA DC programming, MM method, fractional programming
PS-MIMO-SWIPT with co-located receivers and non-linear EH model	[155]	Transmit power minimization	BCD, SCA, SDP
PS-SISO-SWIPT with non-linear EH model	[156], [157]	Closed-form OP, average harvested energy performance	Asymptotic analysis
MISO-SWIPT with non-linear EH model	[158]	Resource allocation	Penalty-based method, SCA,SDR
Multi-user MISO-SWIPT with linear EH model	[159]	Resource allocation	ϵ- constraint method, MM, IA methods

Similarly, in [149], the authors studied joint active and passive beamforming optimization for IRS-aided multiuser MISO SWIPT network with linear EH model. The authors developed an AO and SDR algorithm to obtain a sub-optimal solution for the formulated non-convex max-min harvested power problem at all the EH receivers, under a given set of individual information receiver SINR-constraints, BS transmit power, and continuous IRS phase shifts. Also, in [150], the authors formulated an optimization problem to maximize the energy efficiency in a secure IRS-assisted MISO SWIPT system with non-linear EH model. The authors jointly optimized the AP transmit beamforming vectors, the AP AN covariance matrix, and IRS continuous phase shifts subject to transmit power budget constraints, IRS phase shifts, individual information receivers SINR constraints, EH constraints and information receivers security requirements. The authors also utilized AO and SDR methods to tackle the non-convex problem. Differently, in [116], the authors considered a secure IRS-enabled MIMO SWIPT system where the EHRs are potential eavesdroppers. The authors maximized the secrecy rate by jointly optimizing the TPC matrix, AN, and IRS continuous phase shift matrix, subject to the constraints of harvested energy and unit modulus reflect coefficient. To solve the non-convex SRM problem with several coupled variables, the authors proposed an inexact BCD method as well as the penalty-based MM and complex circle manifold (CCM) to address the unit modulus constraint.

Unlike in [116], the authors in [117] investigated the EH performance of an IRS-enabled MIMO SWIPT network consisting of a multi-antenna BS communicating with several multi-antenna information receivers and energy receivers. The authors jointly optimized the BS TPC matrices and IRS passive continuous phase shifts to maximize the weighted sum rate of the information receivers, subject to the EH constraints of the energy receivers. The EH constraint is non-convex, therefore, complicating the optimization problem. To solve this challenging optimization problem, the authors utilized the BCD algorithm to break down the problem into several sub-problems where the TPC matrices and phase shift matrix are alternately optimized. Further, the authors designed a low-complexity iterative algorithm to enable each sub-problem to converge to the Karush-Kuhn-Tucker (KKT) point of each sub-problem.

Moreover, a recent study by the authors in [151], introduced the energy efficiency indicator to trade off between data rate and harvested energy when a multi-antenna BS transmits data along with energy via PS in a MISO IRS-assisted SWIPT network with co-located receivers. The authors maximized the energy efficiency indicator by jointly optimizing the BS beamforming vectors, individual user's PS ratio, and IRS continuous phase shifts, subject to unit modulus constraints imposed by the IRS passive reflection. To solve the non-convex problem, the authors proposed adopting the MM method to develop a concave-convex fractional function, that is handled by the Dinkelbach algorithm. Further, the AO, SDR and manifold techniques are also used to solve the formulated sub-problems.

The authors in [152] investigated the max-min fairness-based energy-rate trade-off among devices in a IRS-aided time-switching MISO SWIPT system with non-linear EH model. The authors first used linear maximal-ratio transmission (MRT) to set the precoder for both direct and cascaded channels, and then jointly optimized the transmit BS power allocation coefficients and continuous IRS phase shifts to maximize the minimum harvested energy and achievable user rates, subject to the total transmit BS power, and the modulus constraint imposed by the IRS elements. The authors then adopted an AO algorithm to obtain sub-optimal solutions for the formulated non-convex problem.

Another recent study in [153] attempted to solve the max-min fairness of the IRS-assisted MIMO SWIPT IoT networks consisting of a multi-antenna BS, an IRS with discrete phase shifts and two groups of IoT SWIPT devices, i.e, multiple single-antenna information receivers and multiple multi-antenna energy receivers. To simplify the problem, the authors considered the max-min SINR problem of a single information receiver via jointly optimizing the transmit beamforming vector and IRS reflection matrix subject to the EH constraints of the energy receivers. Due to the coupling of the transmit beamforming vectors and IRS discrete phase shifts in both the objective function and max-min SINR problem, the resultant combinatorial optimization problem is non-convex and NP-hard, therefore, deriving the globally optimal solution is computationally challenging. The authors attempted to solve this intractable problem by using classical combinatorial optimization techniques such as special ordered set of type 1 (SOS1) and the reformulation-linearization (RL) methods to handle the max-min SINR design put in place by the optimization of IRS discrete phase shift variables.

Moreover, another recent study on the topic of max-min energy-efficiency fairness in [154], proposed a different fairness algorithm for IRS-aided MISO SWIPT network with non-linear EH model. Here, the authors considered co-located receivers relying on PS. The authors jointly optimized the BS transmit information and energy beamforming, IRS continuous phase shifts, and PS ratio at each user subject to a minimum required data rate, minimum EH, transmit power constraints, and unit modulus constraints. The authors proposed two AO algorithms based on the penalty-based and inner approximation (IA) methods to solve the formulated non-convex problem. To solve this, the non-convex problem is divided into two sub-problems. For the first sub-problem, the penalty-based algorithm exploits SDR, SCA, difference of convex functions (DC) programming, MM method, and fractional programming to transform the non-convex sub-problem into a concave-convex form. Here, the BS information and energy beamforming, and PS ratios are jointly optimized. In the second sub-problem, a penalty-based method is developed to handle the design of the IRS phase shifts unit modulus constraints. For the IA algorithm, PS ratios are designed in the first sub-problem, and in the second sub-problem, the BS information and energy beamforming, and IRS phase shifts are jointly designed.

The works discussed so far in this section have assumed perfect CSI availability, however, this assumption does not hold in practical systems. In [155], the authors designed a joint optimization of the BS's transmit power, and active data, IRS continuous phase shifts, and receivers' PS ratio subject to the minimum rate and EH constraints at each receiver in a MISO IRS-assisted PS-SWIPT network with a nonlinear EH model with co-located receivers. Here the authors considered both perfect and imperfect CSI conditions. For the perfect CSI case, the authors exploited BCD to iteratively design the active and passive beamformers. SCA is used to solve the formulated problem to achieve semidefinite relaxation. For the imperfect CSI case, the problem is reformulated with many constraints. In this case, the BCD method was used iteratively to solve the active and passive beamformers. SDP is used to transform the resulting nonlinear matrix inequalities into linear matrix inequalities. Then SCA is used to solve the inequalities.

In [156], [157], the authors studied the impact of channel correlations between multiple IRS elements on OP and average harvested energy in IRS-aided PS-SISO SWIPT systems with non-linear EH model. Specifically, the OP and average harvested energy performance is evaluated for equal, random and no phase shifts. The authors derived exact average harvested energy formulas as well as exact approximations for the OP for both the uncorrelated and fully correlated cases. The authors via simulation results proved that correlation is beneficial for EH but has a detrimental impact on OP under random and equal phase shifts.

In [158], the authors proposed a resource allocation scheme for large IRS-aided MISO SWIPT systems with non-linear EH model. The authors adopted a physics-based IRS model proposed in [25] and partitioned the IRS into a finite number of phase shift equipped tiles. Based on the above, the authors minimized the total transmit power of the IRS-aided SWIPT network via jointly optimizing the transmit beamforming vectors and the IRS transmission mode tile selection subject to the QoS needs of both the non-linear energy receivers and information receivers. To solve the formulated non-convex problem, the authors exploited a penalty-based method, SCA and SDR to design a low-complexity and efficient algorithm which asymptotically converges to a locally optimal solution.

The authors in [159] extended the work in [158] to study resource allocation in multi-user IRS-assisted MISO SWIPT systems with linear EH. The authors formulate a Multi-Objective Optimization (MOOP) scheme to study the overall system performance in terms of data sum-rate maximization and total harvested energy maximization, via jointly designing the BS active and passive beamforming and IRS continuous phase shifts subject to the information receiver SINR and minimum harvested energy constraints. The formulated non-covex MOOP problem is converted to a single-objective optimization problem (SOOP) by the $\epsilon-$ constraint method. To obtain a locally optimal solution, the authors applied MM and IA techniques.

III. OPEN CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although numerous results on RIS are reported in the literature, there are still several challenging problems to be solved, some of them are presented as follows.

A. RIS-AIDED RATE-SPLITTING MULTIPLE ACCESS (RSMA)

A significant design challenge of RISs is the acquisition of CSI due to the lack of RF chains. This leads to interference in the communications channel due to imperfect Channel State Information at the Transmitter (CSIT). Thus, channel estimation is a crucial issue to be addressed in nearly-passive RISs. In contrast to relays, which are equipped with powerful signal processing units, RISs have limited signal processing capabilities. Therefore, new algorithms are necessary to perform CSI acquisition, while keeping the complexity of RISs as low as possible and avoiding on-board complex signal processing operations as much as possible. In [3], the authors discuss the IRS channel acquisition problem and introduce several solutions.

One of the proposed solutions is applying the sub-array technique to reduce the number of receive RF chains at the IRS. Here the sub-array technique enables the IRS array to be arranged into clusters with each cluster equipped with one RF chain for channel estimation. Similar to [3], in [160], [161], the authors propose a hybrid RIS with a few active elements connected to a RF chain for channel estimation. However, the proposed solutions are hindered by the power budget at the RIS/IRS, as each receive RF chain requires extra power to support the channel estimation operations [6] as well as increased RIS implementation complexity [161].

Another solution is designing the reflection coefficients for IRS's passive beamforming directly based on the feedback from the BSs/users instead of estimating the IRS BS/user channels explicitly [3]. However, this solution is suitable for indoor environments where the IRS to AP/receiver channels are correlated. Recent work in [162] proposed a cascaded channel estimator with low pilot overhead for mmWave massive MISO systems. The proposed solution exploits the sparsity and correlation of cascaded channels in mmWave massive MISO systems. Another recent work in [17], also proposed a channel estimator for RIS-aided massive MIMO based on exploiting spatial correlations at both the RIS and BS and random phase-shifts on the dominant paths in mobile environments. Different solutions can be found in [2], [163]–[189] and the references therein. The assortment and variety of channel estimations techniques ranging from cascaded channels, minimum variance estimators, neural networks, etc, indicates that the research community is still in pursuit of the holy grail of channel estimators suitable for RIS.

In this paper we propose adding RSMA into the mix of possible channel estimators for RIS. RSMA divides user information into two parts which are common and private parts. The common parts are encoded into one or several common streams while the privates parts are encoded into separate streams. The available CSIT (perfect or imperfect) is used to precode the streams. Therefore it is a possible candidate to be used in systems employing RIS since it is designed to be robust to imperfect CSIT [174]. The combination of RIS and RSMA is an exciting and promising area, and more research is needed to develop practical and low complexity RIS-aided communication systems.

B. RIS-AIDED COGNITIVE RADIO SYSTEMS

In [175], [176], the authors proposed robust CR beamforming as a solution to tackle the CSI uncertainty. CR is an effective solution to improve spectrum utilization by allowing the unlicensed SUs to share the spectrum with licensed PUs [175]. Also, RIS has been proposed as a promising approach to enhance Energy Efficiency (EE), achievable rate of the secondary system, physical layer security, resource allocation and spectrum sensing problems of CR networks through intelligently controlling the channel environment as mentioned in the following works [23], [175], [177]–[181]. In addition, RIS-enhanced energy detection has been proposed by the authors in [182] as a potential technique to enhance spectrum sensing in CR networks. Also, the integration of RIS in CR networks has the potential to provide robustness against imperfect CSI. Further studies need to be carried out to confirm this.

C. RIS-AIDED CELL-FREE MASSIVE MIMO SYSTEMS

Cell-Free mMIMO and RIS are two promising technologies for application to future 6G networks [28], [183]–[188]. Cell-free mMIMO systems promise to eliminate inter-cell interference by enabling multiple randomly distributed BS to cooperatively serve users without cell boundaries at the expense of high costs of hardware and power sources due to the large-scale deployment of BSs. To address this issue, the deployment of low-cost RIS can serve as a promising technology to reduce the high costs of hardware and improve the capacity and energy efficiency of cell-free mMIMO systems [28], [185]–[188]. One way RIS can enhance network capacity is via joint precoding. In [28], the authors proposed a precoding framework for wideband RIS-assisted cell-free systems. Specifically, the proposed framework maximized the weighted sum-rate subject to BS power constraint and RIS phase shift constraint. Similarly, in [29], the authors also maximized the weighted sum-rate of IRS-aided multicell MIMO systems via the joint design of TPC and the IRS continuous phase shifts subject to the individual BS power constraint and unit modulus constraint. Motivated by these works, the integration of RIS and cell-free mMIMO is an exciting and promising area of research. Therefore, more research is needed to explore the advantages and disadvantages of this integration.

D. RIS-AIDED LiFi

Due to the rapid increase in wireless data traffic, radio spectrum below 10 GHz is inadequate to satisfy such demand [189], [190]. Therefore, researchers and industry specialists have proposed exploiting higher frequency bands - mmWave (30 - 300 GHz) and VLC communication (430 - 770 THz) [189], [190]. LiFi which is based on VLC offers a complete short-range bidirectional multi-user wireless networking solution, has been indicated as a possible key component in achieving 6G technology [191]. In addition, the bi-directionality and short-range makes it attractive for secure, energy and cost effective indoor, vehicular and underwater communication [191]. However, the achievable rate achieved by LiFi is hindered by the modulation bandwidth of light-emitting diodes (LEDs) and blockages due to non-LoS [191]. The application of RIS to LiFi is a promising solution to address these limitations. The authors in [192] investigated the benefits of using RIS to maintain LoS in free space optical systems. Moreover, in [193]–[197] the authors studied the integration of RIS and VLC. But no studies at present apart from [191], have investigated the benefits of adding RIS into LiFi networks. Hence, further studies are needed to also understand the potential and limitations of the merger between RIS and LiFi in the areas of PLS, modulation, and LoS blockages as proposed in [191].

IV. CONCLUSION

In this paper, we survey recent methodologies of RIS integration with other emerging technologies and identify future research directions for RIS. In addition, this paper provides broad topics of research regarding RIS and the benefits of RIS to existing wireless networks. This study considers lots of perspectives from physical characterization and channel modeling, to key results reported in recent studies, mainly focusing on system performance metrics including outage probability, ergodic capacity, throughput, BER. Further, optimization along with solution methods are introduced for RIS-aided wireless systems. The current papers have identified existing problems and solution methods for RIS-assisted wireless systems, such as imperfect hardware, partial CSI channel information, and security. In the current literature, lots of applications are studied but more practical scenarios need to be further addressed. The system models and performance analysis are provided through significant performance improvement which can be verified by numerical results and simulations, but these results need more comparisons. In future work, by exploring more sophisticated optimization algorithms, the RIS-assisted wireless systems are expected to achieve a higher spectrum, energy efficiency, than that in the current literature. This will open a significantly larger space to explore than the research scope in the current literature. We hope that this survey will create more interest and direction for researchers and industry practitioners in the area of RIS for 6G.

REFERENCES

[1] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753–116773, 2019, doi: 10.1109/ACCESS.2019.2935192.

[2] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. De Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450–2525, Nov. 2020, doi: 10.1109/JSAC.2020.3007211.

[3] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020, doi: 10.1109/MCOM.001.1900107.

[4] Q. Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," *IEEE Trans. Commun.*, vol. 68, no. 3, pp. 1838–1851, Mar. 2020, doi: 10.1109/TCOMM.2019.2958916.

[5] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019, doi: 10.1109/TWC.2019.2936025.

[6] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4157–4170, Aug. 2019, doi: 10.1109/TWC.2019.2922609.

[7] M. Zeng, E. Bedeer, X. Li, Q.-V. Pham, O. A. Dobre, P. Fortier, and L. A. Rusch, "IRS-empowered wireless communications: State-of-the-art, key techniques, and open issues," 2021, *arXiv:2101.07394*. [Online]. Available: http://arxiv.org/abs/2101.07394

[8] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3313–3351, May 2021, doi: 10.1109/TCOMM.2021.3051897.

[9] X. Yu, V. Jamali, D. Xu, D. W. K. Ng, and R. Schober, "Smart and reconfigurable wireless communications: From IRS modeling to algorithm design," 2021, *arXiv:2103.07046*. [Online]. Available: http://arxiv.org/abs/2103.07046

[10] R. Liu, Q. Wu, M. Di Renzo, and Y. Yuan, "A path to smart radio environments: An industrial viewpoint on reconfigurable intelligent surfaces," 2021, *arXiv:2104.14985*. [Online]. Available: http://arxiv.org/abs/2104.14985

[11] S. Zhang, H. Zhang, B. Di, Y. Tan, Z. Han, and L. Song, "Beyond intelligent reflecting surfaces: Reflective-transmissive metasurface aided communications for full-dimensional coverage extension," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 13905–13909, Nov. 2020, doi: 10.1109/TVT.2020.3024756.

[12] S. Zeng, H. Zhang, B. Di, Y. Tan, Z. Han, H. V. Poor, and L. Song, "Reconfigurable intelligent surfaces in 6G: Reflective, transmissive, or both?" 2021, *arXiv:2102.06910*. [Online]. Available: http://arxiv.org/abs/2102.06910

[13] R. Long, Y.-C. Liang, Y. Pei, and E. G. Larsson, "Active reconfigurable intelligent surface-aided wireless communications," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 4962–4975, Aug. 2021, doi: 10.1109/TWC.2021.3064024.

[14] Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. Vincent Poor, "Active RIS vs. passive RIS: Which will prevail in 6G?" 2021, *arXiv:2103.15154*. [Online]. Available: http://arxiv.org/abs/2103.15154

[15] M.-M. Zhao, Q. Wu, M.-J. Zhao, and R. Zhang, "Intelligent reflecting surface enhanced wireless networks: Two-timescale beamforming optimization," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 2–17, Jan. 2021, doi: 10.1109/TWC.2020.3022297.

[16] E. Björnson, Ö. Özdogan, and E. G. Larsson, "Reconfigurable intelligent surfaces: Three myths and two critical questions," *IEEE Commun. Mag.*, vol. 58, no. 12, pp. 90–96, Dec. 2020, doi: 10.1109/MCOM.001.2000407.

[17] Ö. T. Demir and E. Björnson, "Is channel estimation necessary to select phase-shifts for RIS-assisted massive MIMO?" 2021, *arXiv:2106.09770*. [Online]. Available: http://arxiv.org/abs/2106.09770

[18] R. Alghamdi, R. Alhadrami, D. Alhothali, H. Almorad, A. Faisal, S. Helal, R. Shalabi, R. Asfour, N. Hammad, A. Shams, N. Saeed, H. Dahrouj, T. Y. Al-Naffouri, and M.-S. Alouini, "Intelligent surfaces for 6G wireless networks: A survey of optimization and performance analysis techniques," *IEEE Access*, vol. 8, pp. 202795–202818, 2020.

[19] Z. Ding, R. Schober, and H. V. Poor, "On the impact of phase shifting designs on IRS-NOMA," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1596–1600, Oct. 2020, doi: 10.1109/LWC.2020.2991116.

[20] C. Huang, A. Zappone, M. Debbah, and C. Yuen, "Achievable rate maximization by passive intelligent mirrors," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Apr. 2018, pp. 3714–3718, doi: 10.1109/ICASSP.2018.8461496.

[21] H. Guo, Y.-C. Liang, J. Chen, and E. G. Larsson, "Weighted sum-rate maximization for reconfigurable intelligent surface aided wireless networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 5, pp. 3064–3076, May 2020, doi: 10.1109/TWC.2020.2970061.

[22] G. Zhou, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "Intelligent reflecting surface aided multigroup multicast MISO communication systems," *IEEE Trans. Signal Process.*, vol. 68, pp. 3236–3251, 2020, doi: 10.1109/TSP.2020.2990098.

[23] X. Guan, Q. Wu, and R. Zhang, "Joint power control and passive beamforming in IRS-assisted spectrum sharing," *IEEE Commun. Lett.*, vol. 24, no. 7, pp. 1553–1557, Jul. 2020, doi: 10.1109/LCOMM.2020.2979709.

[24] Q. Wu and R. Zhang, "Weighted sum power maximization for intelligent reflecting surface aided SWIPT," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 586–590, May 2020, doi: 10.1109/LWC.2019.2961656.

[25] M. Najafi, V. Jamali, R. Schober, and H. V. Poor, "Physics-based modeling and scalable optimization of large intelligent reflecting surfaces," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2673–2691, Apr. 2021, doi: 10.1109/TCOMM.2020.3047098.

[26] D.-T. Do, M.-S. Van Nguyen, M. Voznak, A. Kwasinski, and J. N. de Souza, "Performance analysis of clustering car-following V2X system with wireless power transfer and massive connections," *IEEE Internet Things J.*, early access, Apr. 2, 2021, doi: 10.1109/JIOT.2021.3070744.

[27] D.-T. Do, C.-B. Le, and F. Afghah, "Enabling full-duplex and energy harvesting in uplink and downlink of small-cell network relying on power domain based multiple access," *IEEE Access*, vol. 8, pp. 142772–142784, 2020.

[28] Z. Zhang and L. Dai, "A joint precoding framework for wideband reconfigurable intelligent surface-aided cell-free network," *IEEE Trans. Signal Process.*, vol. 69, pp. 4085–4101, 2021, doi: 10.1109/TSP.2021.3088755.

[29] C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Multicell MIMO communications relying on intelligent reflecting surfaces," *IEEE Trans. Wireless Commun.*, vol. 19, no. 8, pp. 5218–5233, Aug. 2020, doi: 10.1109/TWC.2020.2990766.

[30] Z. Ding and H. V. Poor, "A simple design of IRS-NOMA transmission," *IEEE Commun. Lett.*, vol. 24, no. 5, pp. 1119–1123, May 2020, doi: 10.1109/LCOMM.2020.2974196.

[31] H. Du, J. Zhang, J. Cheng, and B. Ai, "Millimeter wave communications with reconfigurable intelligent surfaces: Performance analysis and optimization," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2752–2768, Apr. 2021, doi: 10.1109/TCOMM.2021.3051682.

[32] S. Gong, X. Lu, D. T. Hoang, D. Niyato, L. Shu, D. I. Kim, and Y.-C. Liang, "Toward smart wireless communications via intelligent reflecting surfaces: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2283–2314, 4th Quart., 2020, doi: 10.1109/COMST.2020.3004197.

[33] N. Rajatheva *et al.*, "Scoring the terabit/s goal: Broadband connectivity in 6G," 2020, *arXiv:2008.07220*. [Online]. Available: http://arxiv.org/abs/2008.07220

[34] M. Di Renzo, K. Ntontin, J. Song, F. H. Danufane, X. Qian, F. Lazarakis, J. De Rosny, D.-T. Phan-Huy, O. Simeone, R. Zhang, M. Debbah, G. Lerosey, M. Fink, S. Tretyakov, and S. Shamai, "Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 798–807, 2020, doi: 10.1109/OJCOMS.2020.3002955.

[35] L. Yang, J. Yang, W. Xie, M. O. Hasna, T. Tsiftsis, and M. Di Renzo, "Secrecy performance analysis of RIS-aided wireless communication systems," *IEEE Trans. Veh. Technol*, vol. 69, no. 10, pp. 12296–12300, Oct. 2020, doi: 10.1109/TVT.2020.3007521.

[36] X. Yuan, Y.-J.-A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-intelligent-surface empowered wireless communications: Challenges and opportunities," *IEEE Wireless Commun.*, vol. 28, no. 2, pp. 136–143, Apr. 2021, doi: 10.1109/MWC.001.2000256.

[37] Q. Chen, M. Li, X. Yang, R. Alturki, M. D. Alshehri, and F. Khan, "Impact of residual hardware impairment on the IoT secrecy performance of RIS-assisted NOMA networks," *IEEE Access*, vol. 9, pp. 42583–42592, 2021, doi: 10.1109/ACCESS.2021.3065760.

[38] J. Zhao and Y. Liu, "A survey of intelligent reflecting surfaces (IRSs): Towards 6G wireless communication networks," Jul. 2019, *arXiv:1907.04789*. [Online]. Available: http://arxiv.org/abs/1907.04789

[39] H. Abumarshoud, L. Mohjazi, O. A. Dobre, M. Di Renzo, M. A. Imran, and H. Haas, ''LiFi through reconfigurable intelligent surfaces: A new frontier for 6G?'' 2021, *arXiv:2104.02390*. [Online]. Available: http://arxiv.org/abs/2104.02390

[40] L. Yang, F. Meng, J. Zhang, M. O. Hasna, and M. Di Renzo, ''On the performance of RIS-assisted dual-hop UAV communication systems,'' *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10385–10390, Sep. 2020, doi: 10.1109/TVT.2020.3004598.

[41] Y. Cang, M. Chen, Z. Yang, M. Chen, and C. Huang, ''Optimal resource allocation for multi-UAV assisted visible light communication,'' 2020, *arXiv:2012.13200*. [Online]. Available: http://arxiv.org/abs/2012.13200

[42] L. U. Khan, ''Visible light communication: Applications, architecture, standardization and research challenges,'' *Digit. Commun. Netw.*, vol. 3, no. 2, pp. 78–88, 2017, doi: 10.1016/j.dcan.2016.07.004.

[43] A. Moheddine, F. Patrone, and M. Marchese, ''UAV and IoT integration: A flying gateway,'' in *Proc. 26th IEEE Int. Conf. Electron., Circuits Syst. (ICECS)*, Genoa, Italy, Nov. 2019, pp. 121–122, doi: 10.1109/ICECS46596.2019.8965135.

[44] A. Al-Hilo, M. Samir, M. Elhattab, C. Assi, and S. Sharafeddine, ''RIS-assisted UAV for timely data collection in IoT networks,'' 2021, *arXiv:2103.17162*. [Online]. Available: http://arxiv.org/abs/2103.17162

[45] S. Li, B. Duo, X. Yuan, Y.-C. Liang, and M. Di Renzo, ''Reconfigurable intelligent surface assisted UAV communication: Joint trajectory design and passive beamforming,'' *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 716–720, May 2020, doi: 10.1109/LWC.2020.2966705.

[46] H. Long, M. Chen, Z. Yang, Z. Li, B. Wang, X. Yun, and M. Shikh-Bahaei, ''Joint trajectory and passive beamforming design for secure UAV networks with RIS,'' in *Proc. IEEE Globecom Workshops (GC Wkshps*, Taipei, Taiwan, Dec. 2020, pp. 1–6, doi: 10.1109/GCWkshps50303.2020.9367542.

[47] L. Sixian, D. Bin, M. Di Renzo, T. Meixia, and Y. Xiaojun, ''Robust secure UAV communications with the aid of reconfigurable intelligent surfaces,'' 2020, *arXiv:2008.09404*. [Online]. Available: http://arxiv.org/abs/2008.09404

[48] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, ''UAV-assisted and intelligent reflecting surfaces-supported terahertz communications,'' *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1256–1260, Jun. 2021.

[49] M. Di Renzo, M. Debbah, M.-S. Alouini, C. Yuen, T. Marzetta, and A. Zappone, ''Guest editorial special issue on 'wireless networks empowered by reconfigurable intelligent surfaces,''' *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2445–2449, Nov. 2020, doi: 10.1109/JSAC.2020.3007048.

[50] Y. Cheng, K. Hung Li, Y. Liu, K. C. Teh, and H. V. Poor, ''Downlink and uplink intelligent reflecting surface aided networks: NOMA and OMA,'' 2020, *arXiv:2005.00996*. [Online]. Available: http://arxiv.org/abs/2005.00996

[51] A. Hemanth, K. Umamaheswari, A. C. Pogaku, D.-T. Do, and B. M. Lee, ''Outage performance analysis of reconfigurable intelligent surfaces-aided NOMA under presence of hardware impairment,'' *IEEE Access*, vol. 8, pp. 212156–212165, 2020, doi: 10.1109/ACCESS.2020.3039966.

[52] C.-B. Le, D.-T. Do, X. Li, Y.-F. Huang, H.-C. Chen, and M. Voznak, ''Enabling NOMA in backscatter reconfigurable intelligent surfaces-aided systems,'' *IEEE Access*, vol. 9, pp. 33782–33795, 2021, doi: 10.1109/ACCESS.2021.3061429.

[53] M. Zhang, M. Chen, Z. Yang, H. Asgari, and M. Shikh-Bahaei, ''Joint user clustering and passive beamforming for downlink NOMA system with reconfigurable intelligent surface,'' in *Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor Mobile Radio Commun.*, London, U.K., Aug. 2020, pp. 1–6, doi: 10.1109/PIMRC48278.2020.9217212.

[54] T. Hou, Y. Liu, Z. Song, X. Sun, and Y. Chen, ''MIMO-NOMA networks relying on reconfigurable intelligent surface: A signal cancellation-based design,'' *IEEE Trans. Commun.*, vol. 68, no. 11, pp. 6932–6944, Nov. 2020.

[55] Y. Li, M. Jiang, Q. Zhang, and J. Qin, ''Joint beamforming design in multi-cluster MISO NOMA reconfigurable intelligent surface-aided downlink communication networks,'' *IEEE Trans. Commun.*, vol. 69, no. 1, pp. 664–674, Jan. 2021.

[56] J. Zuo, Y. Liu, L. Yang, L. Song, and Y.-C. Liang, ''Reconfigurable intelligent surface enhanced NOMA assisted backscatter communication system,'' 2020, *arXiv:2012.10111*. [Online]. Available: http://arxiv.org/abs/2012.10111

[57] X. Liu, Y. Liu, Y. Chen, and H. V. Poor, ''RIS enhanced massive non-orthogonal multiple access networks: Deployment and passive beamforming design,'' *IEEE J. Sel. Areas Commun.*, vol. 39, no. 4, pp. 1057–1071, Apr. 2021, doi: 10.1109/JSAC.2020.3018823.

[58] Z. Wei, J. Guo, D. W. K. Ng, and J. Yuan, ''Fairness comparison of uplink NOMA and OMA,'' in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–6, doi: 10.1109/VTCSpring.2017.8108680.

[59] B. Wang, K. Wang, Z. Lu, T. Xie, and J. Quan, ''Comparison study of non-orthogonal multiple access schemes for 5G,'' in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2015, pp. 1–5, doi: 10.1109/BMSB.2015.7177186.

[60] D.-T. Do, M.-S.-V. Nguyen, T. N. Nguyen, X. Li, and K. Choi, ''Enabling multiple power beacons for uplink of NOMA-enabled mobile edge computing in wirelessly powered IoT,'' *IEEE Access*, vol. 8, pp. 148892–148905, 2020.

[61] D.-T. Do, M.-S.-V. Nguyen, A.-T. Le, K. M. Rabie, and J. Zhang, ''Joint full-duplex and roadside unit selection for NOMA-enabled V2X communications: Ergodic rate performance,'' *IEEE Access*, vol. 8, pp. 140348–140360, 2020.

[62] M. Elhattab, M.-A. Arfaoui, C. Assi, and A. Ghrayeb, ''Reconfigurable intelligent surface assisted coordinated multipoint in downlink NOMA networks,'' *IEEE Commun. Lett.*, vol. 25, no. 2, pp. 632–636, Feb. 2021.

[63] A.-T. Le, N.-D.-X. Ha, D.-T. Do, A. Silva, and S. Yadav, ''Enabling user grouping and fixed power allocation scheme for reconfigurable intelligent surfaces-aided wireless systems,'' *IEEE Access*, vol. 9, pp. 92263–92275, 2021.

[64] C. Zhang, W. Yi, Y. Liu, Z. Qin, and K. K. Chai, ''Downlink analysis for reconfigurable intelligent surfaces aided NOMA networks,'' in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2020, pp. 1–6.

[65] H. Wymeersch, J. He, B. Denis, A. Clemente, and M. Juntti, ''Radio localization and mapping with reconfigurable intelligent surfaces: Challenges, opportunities, and research directions,'' *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 52–61, Dec. 2020, doi: 10.1109/MVT.2020.3023682.

[66] J. Zhang, Z. Zheng, Z. Fei, and X. Bao, ''Positioning with dual reconfigurable intelligent surfaces in millimeter-wave MIMO systems,'' in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Chongqing, China, Aug. 2020, pp. 800–805, doi: 10.1109/ICCC49849.2020.9238887.

[67] W. Chen, X. Ma, Z. Li, and N. Kuang, ''Sum-rate maximization for intelligent reflecting surface based terahertz communication systems,'' in *Proc. IEEE/CIC Int. Conf. Commun. Workshops China (ICCC Workshops)*, Changchun, China, Aug. 2019, pp. 153–157, doi: 10.1109/ICCChinaW.2019.8849960.

[68] M. Nemati, J. Park, and J. Choi, ''RIS-assisted coverage enhancement in millimeter-wave cellular networks,'' *IEEE Access*, vol. 8, pp. 188171–188185, 2020, doi: 10.1109/ACCESS.2020.3031392.

[69] B. G. Kashyap, P. C. Theofanopoulos, Y. Cui, and G. C. Trichopoulos, ''Mitigating quantization lobes in mmWave low-bit reconfigurable reflective surfaces,'' *IEEE Open J. Antennas Propag.*, vol. 1, pp. 604–614, 2020, doi: 10.1109/OJAP.2020.3034049.

[70] W. Hao, G. Sun, M. Zeng, Z. Chu, Z. Zhu, O. A. Dobre, and P. Xiao, ''Robust design for intelligent reflecting surface-assisted MIMO-OFDMA terahertz IoT networks,'' *IEEE Internet Things J.*, vol. 8, no. 16, pp. 13052–13064, Aug. 2021, doi: 10.1109/JIOT.2021.3064069.

[71] K. Zhi, C. Pan, H. Ren, and K. Wang, ''Uplink achievable rate of intelligent reflecting surface-aided millimeter-wave communications with low-resolution ADC and phase noise,'' *IEEE Wireless Commun. Lett.*, vol. 10, no. 3, pp. 654–658, Mar. 2021, doi: 10.1109/LWC.2020.3044989.

[72] G. Zhou, C. Pan, H. Ren, K. Wang, M. Elkashlan, and M. D. Renzo, ''Stochastic learning-based robust beamforming design for RIS-aided millimeter-wave systems in the presence of random blockages,'' *IEEE Trans. Veh. Technol.*, vol. 70, no. 1, pp. 1057–1061, Jan. 2021, doi: 10.1109/TVT.2021.3049257.

[73] K. Ying, Z. Gao, S. Lyu, Y. Wu, H. Wang, and M. Alouini, ''GMD-based hybrid beamforming for large reconfigurable intelligent surface assisted millimeter-wave massive MIMO,'' *IEEE Access*, vol. 8, pp. 19530–19539, 2020, doi: 10.1109/ACCESS.2020.2968456.

[74] G. Ghatak, ''On the placement of intelligent surfaces for RSSI-based ranging in mm-wave networks,'' *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 2043–2047, Jun. 2021, doi: 10.1109/LCOMM.2021.3063918.

[75] J. He, H. Wymeersch, and M. Juntti, ''Leveraging location information for RIS-aided mmWave MIMO communications,'' *IEEE Wireless Commun. Lett.*, vol. 10, no. 7, pp. 1380–1384, Jul. 2021, doi: 10.1109/LWC.2021.3067474.

[76] Z. Wan, Z. Gao, F. Gao, M. Di Renzo, and M.-S. Alouini, "Terahertz massive MIMO with holographic reconfigurable intelligent surfaces," *IEEE Trans. Commun.*, vol. 69, no. 7, pp. 4732–4750, Jul. 2021, doi: 10.1109/TCOMM.2021.3064949.

[77] K. Ntontin, A.-A.-A. Boulogeorgos, D. G. Selimis, F. I. Lazarakis, A. Alexiou, and S. Chatzinotas, "Reconfigurable intelligent surface optimal placement in millimeter-wave networks," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 704–718, 2021, doi: 10.1109/OJCOMS.2021.3068790.

[78] J. M. Hamamreh, H. M. Furqan, and H. Arslan, "Classifications and applications of physical layer security techniques for confidentiality: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1773–1828, 2nd Quart., 2019, doi: 10.1109/COMST.2018.2878035.

[79] A. Almohamad, A. M. Tahir, A. Al-Kababji, H. M. Furqan, T. Khattab, M. O. Hasna, and H. Arslan, "Smart and secure wireless communications via reflecting intelligent surfaces: A short survey," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1442–1456, 2020, doi: 10.1109/OJCOMS.2020.3023731.

[80] P. Tedeschi, S. Sciancalepore, and R. Di Pietro, "Security in energy harvesting networks: A survey of current solutions and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2658–2693, 2020, doi: 10.1109/COMST.2020.3017665.

[81] I. Trigui, W. Ajib, and W.-P. Zhu, "Secrecy outage probability and average rate of RIS-aided communications using quantized phases," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 1820–1824, Jun. 2021, doi: 10.1109/LCOMM.2021.3057850.

[82] S. Hong, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "Artificial-noise-aided secure MIMO wireless communications via intelligent reflecting surface," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7851–7866, Dec. 2020, doi: 10.1109/TCOMM.2020.3024621.

[83] X. Guan, Q. Wu, and R. Zhang, "Intelligent reflecting surface assisted secrecy communication: Is artificial noise helpful or not?" *IEEE Wireless Commun. Lett.*, vol. 9, no. 6, pp. 778–782, Jun. 2020, doi: 10.1109/LWC.2020.2969629.

[84] W. Khalid, H. Yu, D.-T. Do, Z. Kaleem, and S. Noh, "RIS-aided physical layer security with full-duplex jamming in underlay D2D networks," *IEEE Access*, vol. 9, pp. 99667–99679, 2021, doi: 10.1109/ACCESS.2021.3095852.

[85] Q. Wang, F. Zhou, R. Q. Hu, and Y. Qian, "Energy efficient robust beamforming and cooperative jamming design for IRS-assisted MISO networks," *IEEE Trans. Wireless Commun.*, vol. 20, no. 4, pp. 2592–2607, Apr. 2021, doi: 10.1109/TWC.2020.3043325.

[86] M. H. Khoshafa, T. M. N. Ngatched, and M. H. Ahmed, "Reconfigurable intelligent surfaces-aided physical layer security enhancement in D2D underlay communications," *IEEE Commun. Lett.*, vol. 25, no. 5, pp. 1443–1447, May 2021, doi: 10.1109/LCOMM.2020.3046946.

[87] X. Tang, D. Wang, R. Zhang, Z. Chu, and Z. Han, "Jamming mitigation via aerial reconfigurable intelligent surface: Passive beamforming and deployment optimization," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 6232–6237, Jun. 2021, doi: 10.1109/TVT.2021.3077662.

[88] W. Jiang, Y. Zhang, J. Wu, W. Feng, and Y. Jin, "Intelligent reflecting surface assisted secure wireless communications with multiple-transmit and multiple-receive antennas," *IEEE Access*, vol. 8, pp. 86659–86673, 2020, doi: 10.1109/ACCESS.2020.2992613.

[89] L. Yang and Y. Yuan, "Secrecy outage probability analysis for RIS-assisted NOMA systems," *Electron. Lett.*, vol. 56, no. 23, pp. 1254–1256, Nov. 2020. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/el.2020.2284, doi: 10.1049/el.2020.2284.

[90] L. Du, C. Huang, W. Guo, J. Ma, X. Ma, and Y. Tang, "Reconfigurable intelligent surfaces assisted secure multicast communications," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1673–1676, Oct. 2020, doi: 10.1109/LWC.2020.3001119.

[91] W. Shi, X. Zhou, L. Jia, Y. Wu, F. Shu, and J. Wang, "Enhanced secure wireless information and power transfer via intelligent reflecting surface," *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1084–1088, Apr. 2021, doi: 10.1109/LCOMM.2020.3043475.

[92] N. Mensi, D. B. Rawat, and E. Balti, "Physical layer security for V2I communications: Reflecting surfaces vs. Relaying," 2020, *arXiv:2010.07216*. [Online]. Available: http://arxiv.org/abs/2010.07216

[93] K. Feng, X. Li, Y. Han, S. Jin, and Y. Chen, "Physical layer security enhancement exploiting intelligent reflecting surface," *IEEE Commun. Lett.*, vol. 25, no. 3, pp. 734–738, Mar. 2021, doi: 10.1109/LCOMM.2020.3042344.

[94] Z. Zhang, L. Lv, Q. Wu, H. Deng, and J. Chen, "Robust and secure communications in intelligent reflecting surface assisted NOMA networks," *IEEE Commun. Lett.*, vol. 25, no. 3, pp. 739–743, Mar. 2021, doi: 10.1109/LCOMM.2020.3039811.

[95] G. Amarasuriya, R. F. Schaefer, and H. V. Poor, "Linear precoder design for physical layer security via reconfigurable intelligent surfaces," in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Atlanta, GA, USA, May 2020, pp. 1–5, doi: 10.1109/SPAWC48557.2020.9153886.

[96] A. Makarfi, K. Rabie, O. Kaiwartya, O. Badarneh, G. Nauryzbayev, and R. Kharel, "Physical layer security in RIS-assisted networks in Fisher–Snedecor composite fading," in *Proc. 12th Int. Symp. Commun. Syst., Netw. Digit. Signal Process. (CSNDSP)*, Porto, Portugal, Jul. 2020, pp. 1–6, doi: 10.1109/CSNDSP49049.2020.9249611.

[97] J. Qiao and M.-S. Alouini, "Secure transmission for intelligent reflecting surface-assisted mmWave and terahertz systems," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1743–1747, Oct. 2020, doi: 10.1109/LWC.2020.3003400.

[98] L. Yang, Y. Yang, D. B. D. Costa, and I. Trigui, "Outage probability and capacity scaling law of multiple RIS-aided networks," *IEEE Wireless Commun. Lett.*, vol. 10, no. 2, pp. 256–260, Feb. 2021, doi: 10.1109/LWC.2020.3026712.

[99] J. Luo, F. Wang, S. Wang, H. Wang, and D. Wang, "Reconfigurable intelligent surface: Reflection design against passive eavesdropping," *IEEE Trans. Wireless Commun.*, vol. 20, no. 5, pp. 3350–3364, May 2021, doi: 10.1109/TWC.2021.3049312.

[100] Y. Xiu, J. Zhao, W. Sun, and Z. Zhang, "Secrecy rate maximization for reconfigurable intelligent surface aided millimeter wave system with low-resolution DACs," *IEEE Commun. Lett.*, vol. 25, no. 7, pp. 2166–2170, Jul. 2021, doi: 10.1109/LCOMM.2021.3057379.

[101] P. Xu, G. Chen, G. Pan, and M. D. Renzo, "Ergodic secrecy rate of RIS-assisted communication systems in the presence of discrete phase shifts and multiple eavesdroppers," *IEEE Wireless Commun. Lett.*, vol. 10, no. 3, pp. 629–633, Mar. 2021, doi: 10.1109/LWC.2020.3044178.

[102] G. Zhou, C. Pan, H. Ren, K. Wang, and Z. Peng, "Secure wireless communication in RIS-aided MISO system with hardware impairments," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1309–1313, Jun. 2021, doi: 10.1109/LWC.2021.3064992.

[103] X. Lu, E. Hossain, T. Shafique, S. Feng, H. Jiang, and D. Niyato, "Intelligent reflecting surface enabled covert communications in wireless networks," *IEEE Netw.*, vol. 34, no. 5, pp. 148–155, Sep. 2020, doi: 10.1109/MNET.011.1900579.

[104] X. Zhou, S. Yan, Q. Wu, F. Shu, and D. W. K. Ng, "Intelligent reflecting surface (IRS)-aided covert wireless communication with delay constraint," 2020, *arXiv:2011.03726*. [Online]. Available: http://arxiv.org/abs/2011.03726

[105] J. Si, Z. Li, Y. Zhao, J. Cheng, L. Guan, J. Shi, and N. Al-Dhahir, "Covert transmission assisted by intelligent reflecting surface," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5394–5408, Aug. 2021, doi: 10.1109/TCOMM.2021.3082779.

[106] L. Lv, Q. Wu, Z. Li, Z. Ding, N. Al-Dhahir, and J. Chen, "Covert communication in intelligent reflecting surface-assisted NOMA systems: Design, analysis, and optimization," 2020, *arXiv:2012.03244*. [Online]. Available: http://arxiv.org/abs/2012.03244

[107] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013, doi: 10.1109/MSP.2011.2178495.

[108] A. Konar and N. D. Sidiropoulos, "A simple and effective approach for transmit antenna selection in multiuser massive MIMO leveraging submodularity," *IEEE Trans. Signal Process.*, vol. 66, no. 18, pp. 4869–4883, Sep. 2018, doi: 10.1109/TSP.2018.2863654.

[109] J. Chen, S. Chen, Y. Qi, and S. Fu, "Intelligent massive MIMO antenna selection using Monte Carlo tree search," *IEEE Trans. Signal Process.*, vol. 67, no. 20, pp. 5380–5390, Oct. 2019, doi: 10.1109/TSP.2019.2940128.

[110] M. O. K. Mendonça, P. S. R. Diniz, T. N. Ferreira, and L. Lovisolo, "Antenna selection in massive MIMO based on greedy algorithms," *IEEE Trans. Wireless Commun.*, vol. 19, no. 3, pp. 1868–1881, Mar. 2020, doi: 10.1109/TWC.2019.2959317.

[111] Z. Yigit, E. Basar, and I. Altunbas, "Low complexity adaptation for reconfigurable intelligent surface-based MIMO systems," *IEEE Commun. Lett.*, vol. 24, no. 12, pp. 2946–2950, Dec. 2020, doi: 10.1109/LCOMM.2020.3014820.

[112] T. Zhou, K. Xu, X. Xia, W. Xie, and X. Yang, "Achievable rate maximization for aerial intelligent reflecting surface-aided cell-free massive MIMO system," in *Proc. IEEE 6th Int. Conf. Comput. Commun. (ICCC)*, Dec. 2020, pp. 623–628, doi: 10.1109/ICCC51575.2020.9344963.

[113] W. Yan, X. Yuan, Z.-Q. He, and X. Kuai, "Passive beamforming and information transfer design for reconfigurable intelligent surfaces aided multiuser MIMO systems," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1793–1808, Aug. 2020, doi: 10.1109/JSAC.2020.3000811.

[114] S. Guo, S. Lv, H. Zhang, J. Ye, and P. Zhang, "Reflecting modulation," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2548–2561, Nov. 2020.

[115] D.-W. Yue, H. H. Nguyen, and Y. Sun, "mmWave doubly-massive-MIMO communications enhanced with an intelligent reflecting surface: Asymptotic analysis," *IEEE Access*, vol. 8, pp. 183774–183786, 2020, doi: 10.1109/ACCESS.2020.3029244.

[116] N. Hehao and L. Ni, "Intelligent reflect surface aided secure transmission in MIMO channel with SWIPT," *IEEE Access*, vol. 8, pp. 192132–192140, 2020, doi: 10.1109/ACCESS.2020.3032759.

[117] C. Pan, H. Ren, K. Wang, M. Elkashlan, A. Nallanathan, J. Wang, and L. Hanzo, "Intelligent reflecting surface aided MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1719–1734, Aug. 2020, doi: 10.1109/JSAC.2020.3000802.

[118] J. Yang, X. Ji, K. Huang, X. Sun, and Y. Wang, "Enhanced secure SWIPT in heterogeneous network via intelligent reflecting surface," *Secur. Commun. Netw.*, vol. 2021, pp. 1–12, Mar. 2021.

[119] L. You, J. Xiong, Y. Huang, D. W. K. Ng, C. Pan, W. Wang, and X. Gao, "Reconfigurable intelligent surfaces-assisted multiuser MIMO uplink transmission with partial CSI," *IEEE Trans. Wireless Commun.*, early access, Apr. 1, 2021, doi: 10.1109/TWC.2021.3068754.

[120] G. Zhou, C. Pan, H. Ren, K. Wang, M. Di Renzo, and A. Nallanathan, "Robust beamforming design for intelligent reflecting surface aided MISO communication systems," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1658–1662, Oct. 2020, doi: 10.1109/LWC.2020.3000490.

[121] J. He, M. Leinonen, H. Wymeersch, and M. Juntti, "Channel estimation for RIS-aided mmWave MIMO systems," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2020, pp. 1–6.

[122] J. Xiong, L. You, Y. Huang, D. W. K. Ng, W. Wang, and X. Gao, "Reconfigurable intelligent surfaces assisted MIMO-MAC with partial CSI," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2020, pp. 1–6.

[123] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014, doi: 10.1109/JIOT.2014.2306328.

[124] S. M. R. Islam, D. Kwak, M. H. Kabir, M. Hossain, and K.-S. Kwak, "The Internet of Things for health care: A comprehensive survey," *IEEE Access*, vol. 3, pp. 678–708, 2015, doi: 10.1109/ACCESS.2015.2437951.

[125] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015, doi: 10.1109/COMST.2015.2444095.

[126] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016, doi: 10.1109/COMST.2016.2532458.

[127] L. Da Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014, doi: 10.1109/TII.2014.2300753.

[128] S. Chen, H. Xu, D. Liu, B. Hu, and H. Wang, "A vision of IoT: Applications, challenges, and opportunities with China perspective," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 349–359, Aug. 2014, doi: 10.1109/JIOT.2014.2337336.

[129] S. B. Baker, W. Xiang, and I. Atkinson, "Internet of Things for smart healthcare: Technologies, challenges, and opportunities," *IEEE Access*, vol. 5, pp. 26521–26544, 2017, doi: 10.1109/ACCESS.2017.2775180.

[130] C. Zhu, V. C. M. Leung, L. Shu, and E. C.-H. Ngai, "Green Internet of Things for smart world," *IEEE Access*, vol. 3, pp. 2151–2162, 2015, doi: 10.1109/ACCESS.2015.2497312.

[131] J. A. Stankovic, "Research directions for the Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 3–9, Feb. 2014, doi: 10.1109/JIOT.2014.2312291.

[132] V. Chamola, V. Hassija, V. Gupta, and M. Guizani, "A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, blockchain, and 5G in managing its impact," *IEEE Access*, vol. 8, pp. 90225–90265, 2020, doi: 10.1109/ACCESS.2020.2992341.

[133] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin, "Smart factory of industry 4.0: Key technologies, application case, and challenges," *IEEE Access*, vol. 6, pp. 6505–6519, 2018, doi: 10.1109/ACCESS.2017.2783682.

[134] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5G networks for the Internet of Things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018, doi: 10.1109/ACCESS.2017.2779844.

[135] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016, doi: 10.1109/MCOM.2016.7470933.

[136] H. Shakhatreh, A. H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, "Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges," *IEEE Access*, vol. 7, pp. 48572–48634, 2019, doi: 10.1109/ACCESS.2019.2909530.

[137] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2nd Quart., 2016, doi: 10.1109/COMST.2015.2495297.

[138] M. Gharibi, R. Boutaba, and S. L. Waslander, "Internet of drones," *IEEE Access*, vol. 4, pp. 1148–1162, 2016, doi: 10.1109/ACCESS.2016.2537208.

[139] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2334–2360, 3rd Quart., 2019, doi: 10.1109/COMST.2019.2902862.

[140] S. Hayat, E. Yanmaz, and R. Muzaffar, "Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2624–2661, 4th Quart., 2016, doi: 10.1109/COMST.2016.2560343.

[141] Y. Zeng and R. Zhang, "Energy-efficient UAV communication with trajectory optimization," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3747–3760, Jun. 2017, doi: 10.1109/TWC.2017.2688328.

[142] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, "Wireless energy harvesting for the Internet of Things," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015, doi: 10.1109/MCOM.2015.7120024.

[143] N. B. Carvalho, A. Georgiadis, A. Costanzo, H. Rogier, A. Collado, J. A. García, S. Lucyszyn, P. Mezzanotte, J. Kracek, D. Masotti, and A. J. S. Boaventura, "Wireless power transmission: R&D activities within Europe," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 1031–1045, Apr. 2014, doi: 10.1109/TMTT.2014.2303420.

[144] H. Yang, C. Cai, X. Yuan, and Y. Liang, "RIS-aided constant-envelope beamforming for multiuser wireless power transfer: A max-min approach," *China Commun.*, vol. 18, no. 3, pp. 80–90, Mar. 2021, doi: 10.23919/JCC.2021.03.007.

[145] D. Gunasinghe and G. A. A. Baduge, "Performance analysis of SWIPT for intelligent reflective surfaces for wireless communication," *IEEE Commun. Lett.*, vol. 25, no. 7, pp. 2201–2205, Jul. 2021, doi: 10.1109/LCOMM.2021.3073093.

[146] J. Xu, L. Liu, and R. Zhang, "Multiuser MISO beamforming for simultaneous wireless information and power transfer," *IEEE Trans. Signal Process.*, vol. 62, no. 18, pp. 4798–4810, Sep. 2014, doi: 10.1109/TSP.2014.2340817.

[147] M. Di Renzo, F. H. Danufane, X. Xi, J. de Rosny, and S. Tretyakov, "Analytical modeling of the path-loss for reconfigurable intelligent surfaces—Anomalous mirror or scatterer?" in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, May 2020, pp. 1–5, doi: 10.1109/SPAWC48557.2020.9154326.

[148] Q. Wu and R. Zhang, "Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1735–1748, Aug. 2020, doi: 10.1109/JSAC.2020.3000807.

[149] Y. Tang, G. Ma, H. Xie, J. Xu, and X. Han, "Joint transmit and reflective beamforming design for IRS-assisted multiuser MISO SWIPT systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Dublin, Ireland, Jun. 2020, pp. 1–6, doi: 10.1109/ICC40277.2020.9148892.

[150] J. Liu, K. Xiong, Y. Lu, D. W. K. Ng, Z. Zhong, and Z. Han, "Energy efficiency in secure IRS-aided SWIPT," *IEEE Wireless Commun. Lett.*, vol. 9, no. 11, pp. 1884–1888, Nov. 2020, doi: 10.1109/LWC.2020.3006837.

[151] S. Zargari, A. Khalili, and R. Zhang, "Energy efficiency maximization via joint active and passive beamforming design for multiuser MISO IRS-aided SWIPT," *IEEE Wireless Commun. Lett.*, vol. 10, no. 3, pp. 557–561, Mar. 2021, doi: 10.1109/LWC.2020.3037750.

[152] D. Kudathanthirige, D. Gunasinghe, and G. Amarasuriya, "Max-min fairness-based IRS-aided SWIPT," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Taipei, Taiwan, Dec. 2020, pp. 1–6, doi: 10.1109/GLOBECOM42002.2020.9322484.

[153] S. Gong, Z. Yang, C. Xing, J. An, and L. Hanzo, "Beamforming optimization for intelligent reflecting surface-aided SWIPT IoT networks relying on discrete phase shifts," *IEEE Internet Things J.*, vol. 8, no. 10, pp. 8585–8602, May 2021, doi: 10.1109/JIOT.2020.3046929.

[154] S. Zargari, A. Khalili, Q. Wu, M. Robat Mili, and D. W. K. Ng, "Max-min fair energy-efficient beamforming design for intelligent reflecting surface-aided SWIPT systems with non-linear energy harvesting model," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 5848–5864, Jun. 2021, doi: 10.1109/TVT.2021.3077477.

[155] S. Zargari, S. Farahmand, B. Abolhassani, and C. Tellambura, "Robust active and passive beamformer design for IRS-aided downlink MISO PS-SWIPT with a nonlinear energy harvesting model," *IEEE Trans. Green Commun. Netw.*, early access, Jun. 30, 2021, doi: 10.1109/TGCN.2021.3093825.

[156] C. Psomas and I. Krikidis, "On the effect of correlation in IRS-aided SWIPT networks," in *Proc. IEEE Wireless Power Transf. Conf. (WPTC)*, Seoul, South Korea, Nov. 2020, pp. 460–462, doi: 10.1109/WPTC48563.2020.9295572.

[157] C. Psomas and I. Krikidis, "SWIPT with intelligent reflecting surfaces under spatial correlation," *IEEE Wireless Commun. Lett.*, early access, Jun. 3, 2021, doi: 10.1109/LWC.2021.3086430.

[158] D. Xu, X. Yu, V. Jamali, D. W. K. Ng, and R. Schober, "Resource allocation for large IRS-assisted SWIPT systems with non-linear energy harvesting model," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Nanjing, China, Mar. 2021, pp. 1–7, doi: 10.1109/WCNC49053.2021.9417357.

[159] A. Khalili, S. Zargari, Q. Wu, D. W. K. Ng, and R. Zhang, "Multi-objective resource allocation for IRS-aided SWIPT," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1324–1328, Jun. 2021, doi: 10.1109/LWC.2021.3065844.

[160] G. C. Alexandropoulos and E. Vlachos, "A hardware architecture for reconfigurable intelligent surfaces with minimal active elements for explicit channel estimation," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, May 2020, pp. 9175–9179, doi: 10.1109/ICASSP40776.2020.9053976.

[161] R. Schroeder, J. He, and M. Juntti, "Passive RIS vs. hybrid RIS: A comparative study on channel estimation," in *Proc. IEEE 93rd Veh. Technol. Conf. (VTC-Spring)*, Apr. 2021, pp. 1–7, doi: 10.1109/VTC2021-Spring51267.2021.9448802.

[162] G. Zhou, C. Pan, H. Ren, P. Popovski, and A. L. Swindlehurst, "Channel estimation for RIS-aided multiuser millimeter-wave systems," 2021, *arXiv:2106.14792*. [Online]. Available: http://arxiv.org/abs/2106.14792

[163] M. A. El Mossallamy, H. Zhang, L. Song, K. G. Seddik, Z. Han, and G. Y. Li, "Reconfigurable intelligent surfaces for wireless communications: Principles, challenges, and opportunities," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 3, pp. 990–1002, Sep. 2020, doi: 10.1109/TCCN.2020.2992604.

[164] B. Zheng, C. You, and R. Zhang, "Fast channel estimation for IRS-assisted OFDM," *IEEE Wireless Commun. Lett.*, vol. 10, no. 3, pp. 580–584, Mar. 2021, doi: 10.1109/LWC.2020.3038434.

[165] C. You, B. Zheng, and R. Zhang, "Wireless communication via double IRS: Channel estimation and passive beamforming designs," *IEEE Wireless Commun. Lett.*, vol. 10, no. 2, pp. 431–435, Feb. 2021, doi: 10.1109/LWC.2020.3034388.

[166] Z. Wang, L. Liu, and S. Cui, "Channel estimation for intelligent reflecting surface assisted multiuser communications: Framework, algorithms, and analysis," *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6607–6620, Oct. 2020, doi: 10.1109/TWC.2020.3004330.

[167] G. Zhou, C. Pan, H. Ren, K. Wang, and A. Nallanathan, "A framework of robust transmission design for IRS-aided MISO communications with imperfect cascaded channels," *IEEE Trans. Signal Process.*, vol. 68, pp. 5092–5106, 2020, doi: 10.1109/TSP.2020.3019666.

[168] C. You, B. Zheng, and R. Zhang, "Channel estimation and passive beamforming for intelligent reflecting surface: Discrete phase shift and progressive refinement," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2604–2620, Nov. 2020, doi: 10.1109/JSAC.2020.3007056.

[169] S. Liu, Z. Gao, J. Zhang, M. D. Renzo, and M.-S. Alouini, "Deep denoising neural network assisted compressive channel estimation for mmWave intelligent reflecting surfaces," *IEEE Trans. Veh. Technol.*, vol. 69, no. 8, pp. 9223–9228, Aug. 2020, doi: 10.1109/TVT.2020.3005402.

[170] Q.-U.-A. Nadeem, H. Alwazani, A. Kammoun, A. Chaaban, M. Debbah, and M.-S. Alouini, "Intelligent reflecting surface-assisted multi-user MISO communication: Channel estimation and beamforming design," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 661–680, 2020, doi: 10.1109/OJCOMS.2020.2992791.

[171] B. Zheng and R. Zhang, "Intelligent reflecting surface-enhanced OFDM: Channel estimation and reflection optimization," *IEEE Wireless Commun. Lett.*, vol. 9, no. 4, pp. 518–522, Apr. 2020, doi: 10.1109/LWC.2019.2961357.

[172] T. L. Jensen and E. De Carvalho, "An optimal channel estimation scheme for intelligent reflecting surfaces based on a minimum variance unbiased estimator," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Barcelona, Spain, May 2020, pp. 5000–5004, doi: 10.1109/ICASSP40776.2020.9053695.

[173] Z.-Q. He and X. Yuan, "Cascaded channel estimation for large intelligent metasurface assisted massive MIMO," *IEEE Wireless Commun. Lett.*, vol. 9, no. 2, pp. 210–214, Feb. 2020, doi: 10.1109/LWC.2019.2948632.

[174] O. Dizdar, Y. Mao, W. Han, and B. Clerckx, "Rate-splitting multiple access: A new frontier for the PHY layer of 6G," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Victoria, BC, Canada, Nov. 2020, pp. 1–7, doi: 10.1109/VTC2020-Fall49728.2020.9348672.

[175] J. Yuan, Y. C. Liang, J. Joung, G. Feng, and E. G. Larsson, "Intelligent reflecting surface-assisted cognitive radio system," *IEEE Trans. Commun.*, vol. 69, no. 1, pp. 675–687, Jan. 2021, doi: 10.1109/TCOMM.2020.3033006.

[176] L. Zhang, Y. C. Liang, Y. Xin, and H. V. Poor, "Robust cognitive beamforming with partial channel state information," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 4143–4153, Aug. 2009, doi: 10.1109/TWC.2009.080698.

[177] L. Zhang, Y. Wang, W. Tao, Z. Jia, T. Song, and C. Pan, "Intelligent reflecting surface aided MIMO cognitive radio systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11445–11457, Oct. 2020, doi: 10.1109/TVT.2020.3011308.

[178] D. Xu,X. Yu, Y. Sun, D. W. K. Ng, and R. Schober, "Resource allocation for IRS-assisted full-duplex cognitive radio systems," *IEEE Trans. Commun.*, vol. 68, no. 12, pp. 7376–7394, Dec. 2020, doi: 10.1109/TCOMM.2020.3020838.

[179] Y. Wu, F. Zhou, Q. Wu, Y. Huang, and R. Q. Hu, "Resource allocation for IRS-assisted sensing-enhanced wideband CR networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Jun. 2021, pp. 1–6, doi: 10.1109/ICCWorkshops50388.2021.9473640.

[180] A. U. Makarfi, R. Kharel, K. M. Rabie, O. Kaiwartya, X. Li, and D.-T. Do, "Reconfigurable intelligent surfaces based cognitive radio networks," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Mar. 2021, pp. 1–6, doi: 10.1109/WCNCW49093.2021.9419976.

[181] L. Dong, H.-M. Wang, and H. Xiao, "Secure cognitive radio communication via intelligent reflecting surface," *IEEE Trans. Commun.*, vol. 69, no. 7, pp. 4678–4690, Jul. 2021, doi: 10.1109/TCOMM.2021.3073028.

[182] W. Wu, Z. Wang, L. Yuan, F. Zhou, F. Lang, B. Wang, and Q. Wu, "IRS-enhanced energy detection for spectrum sensing in cognitive radio networks," *IEEE Wireless Commun. Lett.*, early access, Jul. 26, 2021, doi: 10.1109/LWC.2021.3099121.

[183] T. Van Chien, H. Q. Ngo, S. Chatzinotas, M. Di Renzo, and B. Ottersten, "Reconfigurable intelligent surface-assisted cell-free massive MIMO systems over spatially-correlated channels," 2021, *arXiv:2104.08648*. [Online]. Available: http://arxiv.org/abs/2104.08648

[184] M. Bashar, K. Cumanan, A. G. Burr, P. Xiao, and M. Di Renzo, "On the performance of reconfigurable intelligent surface-aided cell-free massive MIMO uplink," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2020, pp. 1–6, doi: 10.1109/GLOBECOM42002.2020.9322151.

[185] Y. Zhang, B. Di, H. Zhang, J. Lin, C. Xu, D. Zhang, Y. Li, and L. Song, "Beyond cell-free MIMO: Energy efficient reconfigurable intelligent surface aided cell-free MIMO communications," *IEEE Trans. Cogn. Commun. Netw.*, vol. 7, no. 2, pp. 412–426, Jun. 2021, doi: 10.1109/TCCN.2021.3058683.

[186] Z. Zhang and L. Dai, "Capacity improvement in wideband reconfigurable intelligent surface-aided cell-free network," in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, May 2020, pp. 1–5.

[187] Q. N. Le, V.-D. Nguyen, O. A. Dobre, and R. Zhao, "Energy efficiency maximization in RIS-aided cell-free network with limited backhaul," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 1974–1978, Jun. 2021.

[188] B. Al-Nahhas, M. Obeed, A. Chaaban, and M. J. Hossain, "RIS-aided cell-free massive MIMO: Performance analysis and competitiveness," 2021, *arXiv:2105.02986*. [Online]. Available: http://arxiv.org/abs/2105.02986

[189] H. Haas, L. Yin, Y. Wang, and C. Chen, "What is LiFi?" *J. Lightw. Technol.*, vol. 34, no. 6, pp. 1533–1544, Mar. 15, 2016, doi: 10.1109/JLT.2015.2510021.

[190] L. Yin and H. Haas, "Non-orthogonal multiple access in LiFi networks," in *Multiple Access Techniques for 5G Wireless Networks and Beyond*. Cham, Switzerland: Springer, 2019, pp. 609–638.

[191] H. Abumarshoud, L. Mohjazi, O. A. Dobre, M. Di Renzo, M. A. Imran, and H. Haas, "LiFi through reconfigurable intelligent surfaces: A new frontier for 6G?" 2021, *arXiv:2104.02390*. [Online]. Available: http://arxiv.org/abs/2104.02390

[192] M. Najafi, B. Schmauss, and R. Schober, "Intelligent reflecting surfaces for free space optical communication systems," *IEEE Trans. Commun.*, early access, May 28, 2021, doi: 10.1109/TCOMM.2021.3084637.

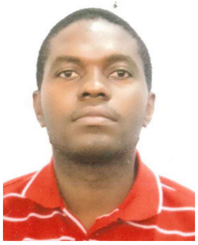
[193] A. M. Abdelhady, A. K. S. Salem, O. Amin, B. Shihada, and M. S. Alouini, "Visible light communications via intelligent reflecting surfaces: Metasurfaces vs mirror arrays," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1–20, Dec. 2021.

[194] B. Cao, M. Chen, Z. Yang, M. Zhang, J. Zhao, and M. Chen, "Reflecting the light: Energy efficient visible light communication with reconfigurable intelligent surface," in *Proc. IEEE 92nd Veh. Technol. Conf. (VTC-Fall)*, Victoria, BC, Canada, Nov. 2020, pp. 1–5.

[195] L. Yang, X. Yan, D. B. da Costa, T. A. Tsiftsis, H.-C. Yang, and M.-S. Alouini, "Indoor mixed dual-hop VLC/RF systems through reconfigurable intelligent surfaces," *IEEE Wireless Commun. Lett.*, vol. 9, no. 11, pp. 1995–1999, Nov. 2020, doi: 10.1109/LWC.2020.3010809.

[196] A. R. Ndjiongue, T. M. N. Ngatched, O. A. Dobre, and H. Haas, "Re-configurable intelligent surface-based VLC receivers using tunable liquid-crystals: The concept," *J. Lightw. Technol.*, vol. 39, no. 10, pp. 3193–3200, May 15, 2021, doi: 10.1109/JLT.2021.3059599.

[197] P. P. Jativa, F. Seguel, and P. Adasme, "Evaluation of intelligent reflecting surfaces for diffuse visible light communications link," in *Proc. IEEE Latin-Amer. Conf. Commun. (LATINCOM)*, Nov. 2020, pp. 1–5, doi: 10.1109/LATINCOM50620.2020.9282298.



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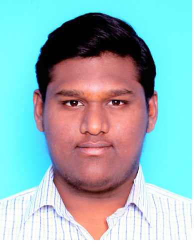

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