Reconfigurable Intelligent Surfaces for 5G and beyond technologies

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With possible new use cases and demanding requirements of future 5th generation (5G) and beyond cellular networks, the future of mobile communications sounds promising. However, the propagation medium has been considered a randomly acting agent between the transmitter and the receiver. With the advent of the digital age of wireless communications, the received signal quality is degrading due to the uncontrollable interactions of the transmitted radio waves with the surrounding artifacts.

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1. Introduction

There has been a flurry of studies on the utilization of reconfigurable intelligent surfaces (RISs) in wireless remote networks to develop intelligent radio environments. In RIS, surfaces can control the propagation of electromagnetic incident waves in a programmable smart radio environment [1]. It provides a way of consciously changing the realization of the channel, which transforms the channel into a block of a controllable device that can be optimized to maximize system performance overall. Therefore, RIS is an artificial surface of electromagnetic (EM) material, electronically controlled with integrated electronics. It is a novel and cost-effective solution to obtain enhanced energy and spectral efficiency for wireless communications.

These surfaces have unique wireless communication capabilities. Recent studies on RIS are based on estimation of theoretical signal to noise ratio (SNR), signal to interference ratio (SINR) maximization, physical layer security solutions, cognitive radio applications, and artificial intelligence solutions (such as deep learning) [2]. Many scholars have published numerous studies and novel solutions related to RISs in the last few months. Reconfigurable intelligent surfaces, intelligent reflecting surfaces, artificial radio space, and other concepts have been used by different writers to describe RISs [3]. Scholars have also looked into machine learning methods, physical layer protection solutions, and the ability of intelligent surfaces for millimeter-wave (mmWave), visible light communication (VLC), and free-space optics (FSO). Furthermore, recently, the first attempt to integrate RISs with OFDM and SM/space shift keying (SSK) schemes have been reported in [4]. Researchers have evaluated the Theoretical SNR and SEP derivations, channel estimation, signal-to-interference-ratio (SINR) improvement for RIS, and joint active and passive beamforming optimization problems in the past few years [5].

Moreover, researchers have studied outage probability, asymptotic data rate, and uplink spectral efficiency when using RISs for transmission and reception in many novel research areas such as mmWave, FSO, VLC system, and unmanned aerial vehicles (UAV), as mentioned earlier. Additionally, the use of machine learning tools, physical layer security solutions, and the potential of intelligent surfaces for mmWave/terahertz applications have been examined in recent years [6][7].

By supporting MIMO transmission with better throughput and increasing spectrum efficiency in mmWave communication, RIS brings up new opportunities in mmWave communication. A RIS can alter radio propagation for mmWave MIMO Channels by passively adjusting the directions of impinging electromagnetic waves. Due to their higher performance over traditional MIMO systems, RIS has recently attracted much attention as a potential technique for FSO and hybrid RF/FSO communications. Furthermore, RIS as a wireless transmission technique in combination with hybrid RF/FSO can achieve significantly higher gain while decreasing design complexity and cost compared to multi-antenna amplify and forward relaying networks with fewer antennas.

RIS-Assisted VLC and Hybrid VLC-RF Networks show remarkable capacity, throughput, and coverage augmentation potential. This integration has the potential to provide a powerful solution for future wireless applications as it can efficiently overcome line-of-sight blockage in highly dynamic settings, such as vehicle application scenarios. Furthermore, it helps to avoid bottlenecks while allowing for intricate interactions between network elements [8][9]. According to recent studies, RIS can significantly improve UAVs' energy efficiency and connectivity, mainly when multiple devices are supported simultaneously, and channel impairments vary. The authors in [10][11] focused on improving the system's secure energy efficiency by maximizing the UAV's direction, the RIS's phase shift, user association, and transmit power all at once.

The main contribution of this paper is to provide a detailed state-of-the-art survey for RIS-assisted technologies and metasurfaces based on large surfaces with their merits and demerits. Further, various novel implementations of RIS, such as active RISs and their signal models, are presented and compared with their performance with a passive one. Their differences are discussed concerning the link budget for the connectivity.

To benefit the overall system performance, we then address the challenges in RIS implementation and highlight the possible opportunities if the challenges can be overcome. Furthermore, we review some novel field-programmable gate array (FPGA) based dynamically controlled RIS structures. Finally, we provide a detailed overview of RIS-assisted communication systems, their performance parameters comparison, applications, and ongoing and future research.

2. Field-Programmable Gate Array (FPGA) Based RIS and Integrated Architectures

RISs can be reconfigured electrically, mechanically, or thermally, based on the tuning mechanisms. The electromagnetic properties of the RIS, such as phase discontinuities, can be controlled by tuning the surface impedance through various techniques. In addition to electrical voltage, other processes for tuning are thermal excitation, optical pump, and physical stretching. Electrical control is the most suitable way as the electrical voltage is easier to quantize and control with FPGA chips. In another way, it is possible to consider the RIS as a broad disjoint beamformer from the transmitter. One appealing feature of some of these approaches is that they do not need improvements to the wireless protocol used. The digital description of coding metasurfaces is well adapted to integrating active elements such as PIN diodes, varactors, and micro-electro-mechanical systems (MEMS). As a result, an FPGA may control all coding elements of a digital coding metasurface separately. Many different functionalities can be switched in real-time by modifying the coding sequences stored in the FPGA, leading to programmable metasurfaces. An FPGA-based dynamically controlled RIS structure is demonstrated in **Figure 1**, and its related work is discussed next.

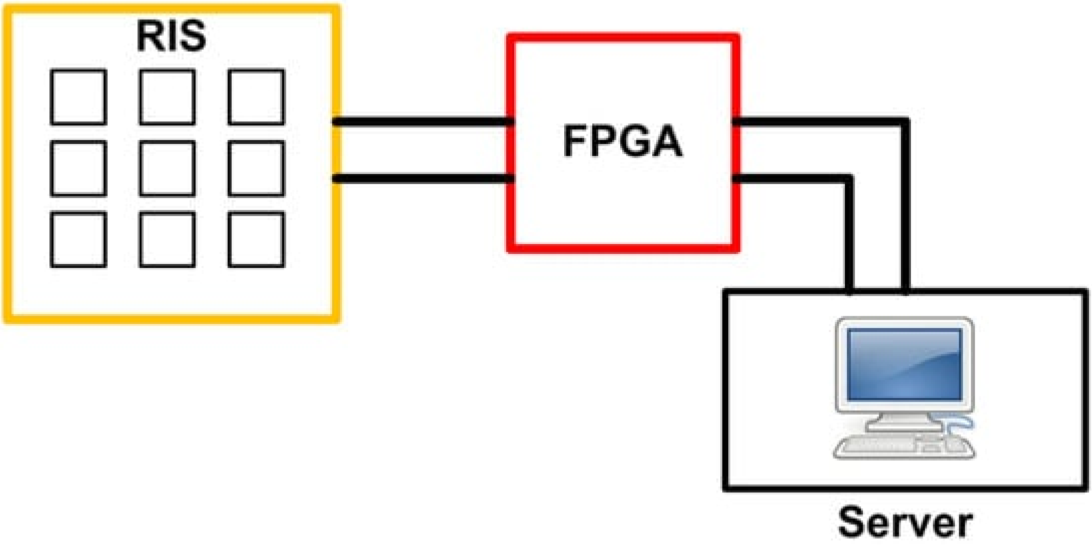

Figure 1. FPGA based dynamically controlled RIS structure.

A system based on a microcontroller unit (MCU), DACs board, and FPGA is commonly used to dynamically control the RIS [12][13]. The RIS in [13] is made up of 328 REs, each of which is loaded with two varactor diodes to achieve a 450-phase reflection range. The varactor is then tuned for the appropriate phase distribution using a central controller, FPGA, and DAC to provide bias voltage. When the RIS reflects the incident wave, the signal is placed onto the carrier.

The reflection phase of each RE in the proposed RIS is controlled by an upper computer (UC) through FPGA. The UC first codes the designed quantized phase before sending it to the FPGA, which uses its output pin to link the PIN diodes on the RIS. Then, to achieve the appropriate phase distribution, each PIN diode loaded on the RE is switched to the ON or OFF states. As a result, the reflected radiation pattern can be dynamically modified using different codes given to the FPGA (**Figure 1**). The simulated radiation pattern of beam scanning is obtained using this control mechanism [14].

In [15], the authors employed the on/off status of PIN diodes to alter the phase responses of meta-material elements. Finally, the authors developed FPGA hardware that uses PIN diodes to control programmable meta-surfaces. The authors claim that these programmable metamaterials can be used to lower the scattering properties of targets and modify antenna radiation beams. In [16], to control the scattered EM waves using the coding metasurface, in which each unit cell loads a pin diode to produce binary coding states of “1” and “0”, the authors presented a direct digital modulation scheme. Instant communications between the coding metasurface and the internal memory of FPGA are established via data lines. As a result, electromagnetic wave digital modulation is achieved, and it offers a field-programmable reflecting antenna with good measurement performance. The proposed method and functional device have a lot of potential for use in next-generation radar and communication systems. Basically, the binary units are realized by loading pin diodes to sub-wavelength artificial structures in a field-programmable reflective antenna based on the coding metasurface in the microwave frequency.

A field-programmable reflective array antenna made up of a horn antenna, and a reflective coding metasurface is presented in this paper. The coding metasurface is built using a binary-phase element and a chessboard configuration approach. The binary codes of the metasurface are controlled directly by field-programmable gate arrays (FPGA) by loading a pin diode in each element. The role of FPGA is to configure the code distributions on the coding metasurface. As a result, the scattered major lobes can be digitally reconfigured at the same frequency. Additionally, it is worthwhile to point out that a real-time switch among these functionalities is also achieved by using an FPGA. In [17], the authors proposed dynamic multi-functional properties of a digitally controlled metasurface (relatively large aperture size >20 wavelengths). The proposed programmable metasurface can be used for a variety of future applications, such as smart stealth missions and novel phased array techniques without expensive phase-shifting components. Each sub-metasurface consists of 320 active unit cells and the proposed metasurface is made up of 5 similar sub-metasurfaces.

A reconfigurable phase for a single polarization is achieved by incorporating one PIN diode into each unit cell. The reconfigurable polarisation conversion is achieved first by utilizing this anisotropic characteristic. Then, a FPGA is used to switch between these functionalities in real-time. In contrast to earlier work that typically controls a lattice and focuses on a single sort of steerable function, each unit cell in the proposed metasurface can be controlled individually, allowing for more versatile functions to be achieved simultaneously. In ref. [18], a prototype of the proposed coding metasurface is validated by building an FPGA-controlled prototype. The coding metasurface uses an FPGA hardware control board (ALTERA Cyclone IV) to generate dynamic biassing voltages, with each column sharing a control voltage. The FPGA is a low-cost system with a clock speed of 50 MHz and a preloaded code that generates eight control voltages according to time-coding sequences. By modifying the coding components on a 2D plane with predesigned coding sequences, reconfigurable meta-surface structures may be used to manipulate EM waves simply and effectively [19]. A Field Programmable Gate Array (FPGA) is used to regulate and construct multiple coding sequences independently. As a result, many distinct functionalities can be swapped in real-time by modifying the coding sequences recorded in the FPGA, resulting in programmable metasurfaces. In ref. [20], a similar approach has been used to formulate the exact features of a meta-surface for vehicular communication applications in the frequency band of 5–5.9 GHz.

An Intelligent metasurface imager and recognizer is proposed in which a network of artificial neural networks (ANNs) is used for adaptively controlling data flow. It transforms the measured microwave data into images of the whole human body, classifying specifically designated spots (hand and chest) within the entire image. Thus, it recognizes human hand signs instantly at a Wi-Fi frequency of 2.4 GHz. An FPGA with its changing coding sequences, the large-aperture programmable metasurface is designed to dynamically and adaptively regulate ambient EM wavefields. First, FPGA acts as an information relay station or an electrically controllable random mask, sending EM signals with finer information about the specimen to the receivers. Secondly, the programmable metasurface with optimized coding patterns can focus EM wavefields on the desired areas while suppressing irrelevant interference and clutter, allowing body language recognition and respiration monitoring to be realized [21]. In [13], a reconfigurable reflectarray with the feature of fast steerable monopulse patterns has been proposed and tested at X-band. To reconfigure the reflective phase between 0° and 180°, the reflectarray element integrates one PIN diode. One hundred sixty field-programmable gate arrays (FPGAs) are used to regulate the “ON/OFF” states of every PIN diode connected in parallel to provide quick beam steering. This FPGA-based reflectarray design approach is proved to be feasible for fast beam-switching.

3. Applications and Future Research Directions of RIS

3.1. RIS Assisted Unmanned Aerial Vehicles (UAV) in IoT Networks

Unmanned aerial vehicles (UAVs) might be considered as an alternative for providing and strengthening connection in contexts where direct communication is hampered by, for example, blockages, such as big centers, especially when IoT devices (IoTD) are resource constrained. A RIS is used to improve the UAV’s energy efficiency and connectivity, especially when numerous devices are supported simultaneously and have varying channel impairments. In [10], the authors focused on enhancing the system’s secure energy efficiency by optimizing the UAV’s trajectory, the RIS’s phase shift, user association, and transmit power all at the same time. From simulation results, authors showed their suggested algorithm converges quickly. The proposed architecture can improve secure energy efficiency by up to 38% compared to standard schemes that don’t use RIS.

In [22], the authors show that integrating a RIS with a UAV in IoT networks can significantly enhance UAV energy efficiency. For example, when employing a RIS of 100 pieces, UAV energy efficiency is boosted five times. Authors in [11] suggested a RIS-assisted UAV method, in which a RIS mounted on a building is used to reflect signals broadcast from a ground source to a UAV. The UAV is deployed as a relay to transfer the decoded signals to the destination. According to the findings, the usage of RISs can significantly increase the coverage and reliability of UAV communication systems.

A novel framework for integrating RIS in UAV-enabled wireless networks is proposed in [23], in which a RIS is deployed to improve the UAV’s service quality. While mobile users (MUs) are deemed to be traveling continually, the non-orthogonal multiple access (NOMA) technique is used to increase the network’s spectrum efficiency. Minimizing energy consumption is formulated by concurrently planning the UAV’s movement, RIS phase changes, power allocation policy from the UAV to the MUs, and setting the dynamic decoding order. Results revealed that by using RISs in UAV-enabled wireless networks, the energy dissipation of the UAV could be greatly reduced. Therefore, it can be stated from the literature that by integrating UAV with RIS-assisted system, coverage and reliability of UAV communication systems is improved. Additionally, by incorporating RIS in UAV, secure energy efficiency maximization, the significant improvement in processing time and throughput performance, enhanced service quality, and decreased energy dissipation of the UAV with optimized energy efficiency is possible.

3.2. RIS-Aided Millimeter (mmWave) MIMO Systems

RIS enabled new possibilities in mmWave communication by supporting MIMO transmission with improved throughput by increasing the spectral efficiency in mmWave communication. Authors in [24] proposed a mmWave system with low-precision analog-to-digital converters (ADCs) and numerous RIS arrays containing many reflectors with a discrete phase shift. These arrays produce a synthetic channel with higher spatial variety and power gain, allowing MIMO transmission using linear spatial processing.

3.2.1. Channel Estimation for mmWave MIMO Channels Using RIS

By passively modifying the directions of impinging electromagnetic waves, a RIS can shape radio propagation for mmWave MIMO Channels. However, perfect channel state information (CSI) of all links between the BS and the MS via the RIS is required for optimal RIS control. As a result, channel (parameter) estimation and the associated message feedback mechanism are required at the BS/MS. The authors in [25] suggested a two-stage channel estimation approach for RIS-aided mmWave MIMO channels, which uses an iterative reweighted method to estimate the channel parameters sequentially.

3.2.2. Coverage Improvement of mmWave Communications

There are a lot of barriers to interacting at millimeter-wave frequencies. The channel is slightly more aggressive at these frequencies than it is at sub 6 GHz frequencies. This implies that shadowing has a significant negative impact on the average received power to create a link. While adaptive beam steering techniques can enhance the reliability of millimeter-wave connections, communication at these frequencies remains very demanding. Therefore, the capacity of millimeter-wave channels for spatial multiplexing is limited. In several examples, e.g., LOS, there is only a single feasible direction of propagation, and spatial multiplexing is not viable. By exploiting the strength of RISs, the above difficulties can be overcome. The RISs will act as a centralized beamformer in low-received power scenarios to increase channel gains. The power coverage of mmWave communications has gotten a lot of attention in recent years due to its large spectrum availability. The RIS is proposed as a promising novel solution to address the issue of power coverage in mmWave communication systems. To improve the coverage area of RIS-assisted mmWave, a variety of strategies have been proposed in the literature as stated below:

(1) A component of the Blockages: The primary concept behind this method is to provide several helpful system levels. It can improve the coverage probability of the cellular network by providing additional indirect line-of-sight (LOS) links to objects that operate as communication link blockers, such as buildings or trees [26].

(2) An achievable rate region: It derives a capacity region outer bound for centralized deployment and a capacity region in closed form for distributed deployment using RIS. The main idea is to investigate the capacity region of a multiple access channel (MAC) with two users sending independent messages to an access point (AP) [27].

(3) Probability of Reflection: Authors in [28] proposed a new analytical framework that provides the probability of reflection of a reconfigurable metasurface. The RIS is regarded as a reflector for a given transmitter and receiver, given environmental objects modeled with the modified random line process of fixed length and random orientations and locations.

Further, the usage of mmWave bandwidth is one of the primary enablers for 5G and beyond cellular systems to deliver significant data rates. However, due to their high directivity and sensitivity to blockages, mmWave signals suffer from severe route loss, which limits their use in small-scale deployments. In order to enhance the coverage in Millimeter-Wave Cellular Networks, a large number of RISs are deployed, which passively reflect mmWave signals towards desired directions and therefore improve the range of mmWave communication.

3.3. RIS-Assisted Free Space Optics (FSO) and Hybrid RF/FSO Communications

Free space optics (FSO) may find a place in situations where fiber is too expensive or impossible to install, when high data rates are needed, and in cases when the RF spectrum becomes congested. RIS has recently received much interest as a viable technology for FSO and hybrid RF/FSO communications due to its superior performance over typical MIMO systems [29]. Furthermore, compared to multi-antenna amplification and forward relaying networks with fewer antennas, RIS as a wireless transmission technique can achieve significant performance while reducing system complexity and budget. Recently, a new wireless transmission technique based on RIS for hybrid RF/FSO communications has been presented in [30]. Two hops are used to transmit the signal. The first hop is based on FSO channel communication, whereas the second hop is based on RF throughput RIS. Compared to conventional RF/FSO communications, the proposed RIS-based RF/FSO communications offer a 25–50 dB gain. This analysis is valid when RIS is taken as a reflector or transmitter.

The authors of [31] investigated a dual-hop mixed FSO/RF network in which the source message was forwarded to the destination via a RIS on the second hop. The majority of previous studies considered the scenario in which a RIS is utilized to replace relays. Another key situation is that the RIS, in conjunction with the RF signal generator, could be employed as part of the transmitter to assist the source in data transmissions [32]. The idea of employing a RIS as a transmitter was recently tested using a testbed platform [33]. Recently, the performance of a RIS-assisted source mixed radio frequency (RF)/FSO relay network with opportunistic source scheduling was developed and evaluated by the authors in [34].

3.4. RIS-Assisted Visible Light Communication (VLC) System and Hybrid VLC-RF Networks

RIS can transform the physical propagation environment into a fully programmable and configurable area in a low-cost, low-power manner. RIS-assisted VLC has emerged as a viable platform with novel applications in 5G and 6G systems. In highly dynamic situations, such as vehicle application scenarios, VLC performance is dependent on efficiently overcoming line-of-sight blockage, which has a negative impact on wireless reception dependability. Integration of RIS in LiFi-enabled networks helps to mitigate blockages while also allowing for complex interactions between network entities [9]. Moreover, RIS-Assisted Hybrid LiFi-RF Networks demonstrate exceptional capacity, throughput, and coverage enhancement capabilities. This integration can provide considerable solutions for future wireless applications in extremely low-latency, energy efficiency, ultra-reliable, data-driven, and seamless wireless communication [35].

3.4.1. Dynamic Channel Gain Modeling

In RIS-assisted LiFi systems, it would be possible to dynamically change the perceived channel gains at different users by controlling the multi-path channel propagation, and performance can be enhanced in two different ways:

(1) Increased reliability: By introducing and managing channel gains, ideal conditions for effective power allocation and, as a result, successful consecutive interference cancellation can be created.

(2) Improved fairness: NOMA users with lower decoding order, i.e., lower channel gain, must always decode their signals with interference present, which means that their achievable data rates may not be sufficient to meet their QoS needs. Dynamic RIS tuning allows users to adjust their decoding order regardless of their location, resulting in increased fairness.

3.4.2. Physical Layer Security

VLC links are susceptible to eavesdropping by malicious users. Therefore, securing LiFi transmissions in public places like shopping malls, airports, libraries, and outdoor vehicular applications [8]. Incorporating RIS into LiFi systems can result in improved PLS in one of the following ways:

(1) Improved secrecy: Dynamic multi-path tuning maximizes channel gain for legal users while reducing eavesdroppers.

(2) Jamming: Artificial noise created by randomized multi-path reflections directed at the eavesdropper.

Finally, RIS-aided VLC systems can provide increased light-based monitoring as well simultaneous light-wave information and power transfer to extend the lifetime of energy-constrained terminals. Each reflected path in RIS-assisted scenarios has its spatial signature, determined by the locations and EM responses of the objects in the environment [36]. Controlling the EM response of each RIS element can shape the reflections from the elements, allowing for better mapping from the position space to the measurement space. Therefore, an accurate localization can be achieved in outdoor and indoor applications, such as measuring the distances between buildings, vehicles, and people for safety and surveillance, physical rehabilitation, automated manufacturing, and gesture recognition [37].

3.5. RIS as Reconfigurable Reflectors to Deal with Non-LOS Phenomenon

In most wireless communications technologies, the router’s transmitters direct a signal to ensure that it reaches receivers. The larger the size of said receivers, the better the reception. However, connected nodes represent a challenge when it comes to integrating such components. The complexity of a mobile radio environment makes it difficult to predict the propagation in this environment simply. Knowing the signal level at any point of the coverage is essential to assess the quality of coverage in this environment. This quality will sometimes be degraded, even for a good level of the signal received, particularly for the frequency selectivity of the propagation channel. Several models, methods, and commercial tools are offered to model electromagnetic propagation in complex environments and whose improvements are constantly evolving. In an indoor environment, the fundamental phenomena of the propagation of electromagnetic waves depend on the nature and dimensions of the materials encountered (electrical and magnetic properties) and the characteristics of the incident wave (frequency, polarization, angle of incidence).

The presence of other radiant sources may interfere with the useful (transmitted) signal and generate a degradation of the signal received from the electromagnetic waves. These interferences mainly come from other radio equipment. Therefore, it is important to study this parameter to predict the reception quality in terms of signal to interference ratio. One of the most interesting use cases for using RISs in wireless networks is to use them as reconfigurable reflectors when the LOS route is either blocked or not powerful enough to help cell-edge users—solving non-LOS scenarios. RISs, for example, can be easily connected to indoor walls or floors and can be built into outdoor building.

3.6. Solving the Localized Dead Zone Issue

The use of RISs to counteract localized coverage holes in urban scenarios and indoor harsh propagation conditions is another promising case study. Indeed, in many urban and heavily populated cities around the world, there are localized dead zones where the signal strength is not good enough. In indoor settings, including industrial plants and underground metro stations, similar problems exist. Conventional options for overcoming coverage holes in these situations are to deploy more BSs or relays/repeaters. These solutions, unfortunately, are costly and raise the carbon footprint of wireless communications. On the other hand, the introduction of RISs is a cost-effective and environmentally sustainable approach to address the problems of localized gaps in coverage.

3.7. Achieving High Beamforming Gain for IoT Networks

In future wireless networks, the IoT is an important feature. Some IoT devices are, however, limited in scale as well as energy consumption. In the mmWave channels, where highly directional antenna gains are necessary for achieving efficient high-rate communications, future 5G and beyond cellular networks will run. The RISs can be used to provide significant beamforming gains for these devices, far greater than they can afford due to their limited size.

3.8. Energy Harvesting and Decrease in EM Radiation Level

Electromagnetic waves were used for broadcasting as early as 1940, then with the appearance of television, microwave ovens, radars, mobile telephony, and more recently, induction hobs. Even if it arouses a particular fascination and significant concerns, wireless technologies (mobile, Wi-Fi, Bluetooth) in everyday life have constituted a real revolution in modern lifestyles. As a result, the sources of radio frequency electromagnetic fields omnipresent in our environment have been an object of health and environmental concern for several years. The recycling of radio waves referred as energy harvesting in a productive and energy-efficient way is one of the key features of RISs. In reality, multipath propagation is often viewed as uncontrollable and is typically counteracted by increasing the transmitters and receivers complexity. This typically includes an increase in the number of radio waves generated by deploying more BSs or relays that create additional environmental signals. This results in an increase in the emission of EM radiation. On the other hand, the use of RISs does not predict the generation of new signals but enable their intelligent use. Therefore, the principle of RISs is a promising strategy for lowering EM radiation levels, with significant applications in situations such as hospitals and aircraft [38].

3.9. RF Sensing and Localization

RIS-assisted sensing and localization of radio frequency (RF) is another promising direction. The RIS's wide aperture size and its ability to form the propagation environment will boost RF sensing capabilities significantly. To provide favorable conditions for RF sensing, the channel can be altered and then controlled with high precision. Encouraging findings for potential applications in energy-efficient surveillance assisted living and remote health monitoring has been studied in the literature. The question of optimizing the RIS configurations to improve RF-sensing, however, remains to be investigated. Most of the current research on RIS-enabled SREs has relied on communications-related applications. RISs, on the other hand, provide opportunities for research that extends beyond communications. Electrically massive RISs, for example, can be used for high-precision radio localization and mapping because of their excellent focusing capability (i.e., the construction of a model or map of the environment). The potential of RISs for various applications and anticipated performance as a function of their size, sub-wavelength structure, and near-field vs. far-field operation forms an open research question. Furthermore, radio mapping and localization might be considered key enablers for realizing important communication-related activities [39][40][41].

References

1. Hum, S.V.; Perruisseau-Carrier, J. Reconfigurable reflectarrays and array lenses for dynamic antenna beam control: A review. IEEE Trans. Antennas Propag. 2013, 62, 183–198.
2. Özdogan, Ö.; Björnson, E.; Larsson, E.G. Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling. IEEE Wirel. Commun. Lett. 2019, 9, 581–585.
3. Di Renzo, M.; Zappone, A.; Debbah, M.; Alouini, M.S.; Yuen, C.; De Rosny, J.; Tretyakov, S. Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and the Road Ahead. IEEE J. Sel. Areas Commun. 2020, 38, 2450–2525.
4. Basar, E. Reconfigurable intelligent surface-based index modulation: A new beyond MIMO paradigm for 6G. IEEE Trans. Commun. 2020, 68, 3187–3196.
5. Nadeem, Q.-U.-A.; Kammoun, A.; Chaaban, A.; Debbah, M.; Alouini, M.-S. Asymptotic Max-Min SINR Analysis of Reconfigurable Intelligent Surface Assisted MISO Systems. IEEE Trans. Wirel.

Commun. 2020, 19, 7748–7764.

6. Gao, X.; Liu, Y.; Liu, X.; Qin, Z. Resource Allocation In IRSs Aided MISO-NOMA Networks: A Machine Learning Approach. In Proceedings of the GLOBECOM 2020—2020 IEEE Global Communications Conference, Taipei, Taiwan, 7–11 December 2020; pp. 1–6.
7. Huang, C.; Alexandropoulos, G.C.; Yuen, C.; Debbah, M. Indoor signal focusing with deep learning designed reconfigurable intelligent surfaces. In Proceedings of the 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Cannes, France, 2–5 July 2019; pp. 1–5.
8. Abumarshoud, H.; Chen, C.; Islim, M.S.; Haas, H. Optical wireless communications for cyber-secure ubiquitous wireless networks. Proc. R. Soc. A 2020, 476, 20200162.
9. Abumarshoud, H.; Mohjazi, L.; Dobre, O.A.; Di Renzo, M.; Imran, M.A.; Haas, H. LiFi through Reconfigurable Intelligent Surfaces: A New Frontier for 6G? arXiv 2021, arXiv:2104.02390.
10. Long, H.; Chen, M.; Yang, Z.; Li, Z.; Wang, B.; Yun, X.; Shikh-Bahaei, M. Joint Trajectory and Passive Beamforming Design for Secure UAV Networks with RIS. In Proceedings of the 2020 IEEE Globecom Workshops (GC Wkshps), Taipei, Taiwan, 7–11 December 2020; pp. 1–6.
11. Yang, L.; Meng, F.; Zhang, J.; Hasna, M.O.; Di Renzo, M. On the performance of RIS-assisted dual-hop UAV communication systems. IEEE Trans. Veh. Technol. 2020, 69, 10385–10390.
12. Zhang, L.; Wang, Z.X.; Shao, R.W.; Shen, J.L.; Chen, X.Q.; Wan, X.; Cheng, Q.; Cui, T.J. Dynamically realizing arbitrary multi-bit programmable phases using a 2-bit time-domain coding metasurface. IEEE Trans. Antennas Propag. 2019, 68, 2984–2992.
13. Pan, X.; Yang, F.; Xu, S.; Li, M. A 10 240-element reconfigurable reflectarray with fast steerable monopulse patterns. IEEE Trans. Antennas Propag. 2020, 69, 173–181.
14. Liang, Y.-C.; Chen, J.; Long, R.; He, Z.-Q.; Lin, X.; Huang, C.; Liu, S.; Shen, X.S.; Di Renzo, M. Reconfigurable intelligent surfaces for smart wireless environments: Channel estimation, system design and applications in 6G networks. Sci. China Inf. Sci. 2021, 64, 200301.
15. Cui, T.J.; Qi, M.Q.; Wan, X.; Zhao, J.; Cheng, Q. Coding metamaterials, digital metamaterials and programmable metamaterials. Light Sci. Appl. 2014, 3, e218.
16. Wan, X.; Qi, M.Q.; Chen, T.Y.; Cui, T.J. Field-programmable beam reconfiguring based on digitally-controlled coding metasurface. Sci. Rep. 2016, 6, 20663.
17. Yang, H.; Cao, X.; Yang, F.; Gao, J.; Xu, S.; Li, M.; Chen, X.; Zhao, Y.; Zheng, Y.; Li, S. A programmable metasurface with dynamic polarization, scattering and focusing control. Sci. Rep. 2016, 6, 35692.
18. Zhang, L.; Chen, X.Q.; Liu, S.; Zhang, Q.; Zhao, J.; Dai, J.Y.; Bai, G.D.; Wan, X.; Cheng, Q.; Castaldi, G.; et al. Space-time-coding digital metasurfaces. Nat. Commun. 2018, 9, 4334.

19. Zhang, L.; Wu, R.Y.; Bai, G.D.; Wu, H.T.; Ma, Q.; Chen, X.Q.; Cui, T.J. Transmission-reflection-integrated multifunctional coding metasurface for full-space controls of electromagnetic waves. Adv. Funct. Mater. 2018, 28, 1802205.

20. Ojaroudi, M.; Loscri, V.; Vegni, A. Design and analysis of a reconfigurable intelligent meta-surface for vehicular networks. ITU J. Future Evol. Technol. 2020, 1, 79–88.

21. Li, L.; Shuang, Y.; Ma, Q.; Li, H.; Zhao, H.; Wei, M.; Liu, C.; Hao, C.; Qiu, C.-W.; Cui, T.J. Intelligent metasurface imager and recognizer. Light Sci. Appl. 2019, 8, 97.

22. Al-Hilo, A.; Samir, M.; Elhattab, M.; Assi, C.; Sharafeddine, S. RIS-Assisted UAV for Timely Data Collection in IoT Networks. arXiv 2021, arXiv:2103.17162.

23. Liu, X.; Liu, Y.; Chen, Y. Machine learning empowered trajectory and passive beamforming design in UAV-RIS wireless networks. IEEE J. Sel. Areas Commun. 2020, 39, 2042–2055.

24. Yang, X.; Wen, C.K.; Jin, S. MIMO Detection for Reconfigurable Intelligent Surface-Assisted Millimeter Wave Systems. IEEE J. Sel. Areas Commun. 2020, 38, 1777–1792.

25. He, J.; Leinonen, M.; Wymeersch, H.; Juntti, M. Channel estimation for RIS-aided mmWave MIMO channels. arXiv 2020, arXiv:2002.06453.

26. Kishk, M.A.; Alouini, M.-S. Exploiting randomly located blockages for large-scale deployment of intelligent surfaces. IEEE J. Sel. Areas Commun. 2020, 39, 1043–1056.

27. Zhang, S.; Zhang, R. Intelligent reflecting surface aided multiple access: Capacity region and deployment strategy. In Proceedings of the 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Atlanta, GA, USA, 26–29 May 2020; pp. 1–5.

28. Di Renzo, M.; Song, J. Reflection probability in wireless networks with metasurface-coated environmental objects: An approach based on random spatial processes. EURASIP J. Wirel. Commun. Netw. 2019, 2019, 99.

29. Najafi, M.; Schober, R. Intelligent reflecting surfaces for free space optical communications. In Proceedings of the 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 9–13 December 2019; pp. 1–7.

30. Alnwaimi, G.; Boujemaa, H. Hybrid RF/FSO communications through Reconfigurable Intelligent Surfaces in the presence of pointing errors. Telecommun. Syst. 2021, 78, 155–162.

31. Yang, L.; Guo, W.; Ansari, I.S. Mixed Dual-Hop FSO-RF Communication Systems through Reconfigurable Intelligent Surface. IEEE Commun. Lett. 2020, 24, 1558–1562.

32. Bhowal, A.; Aissa, S.; Kshetrimayum, R.S. RIS-Assisted Advanced Spatial Modulation Techniques for Ambient Backscattering Communications. IEEE Trans. Green Commun. Netw. 2021, 5, 1684–1696.

33. Tang, W.; Dai, J.Y.; Chen, M.; Li, X.; Cheng, Q.; Jin, S.; Wong, K.-K.; Cui, T.J. Programmable metasurface-based RF chain-free 8PSK wireless transmitter. Electron. Lett. 2019, 55, 417–420.
34. Salhab, A.M.; Yang, L. Mixing RIS-Assisted Sources with FSO Link. arXiv 2020, arXiv:2011.05612.
35. Cao, B.; Chen, M.; Yang, Z.; Zhang, M.; Zhao, J.; Chen, M. Reflecting the Light: Energy Efficient Visible Light Communication with Reconfigurable Intelligent Surface. In Proceedings of the 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada, 18 November–16 December 2020; pp. 1–5.
36. Abdelhady, A.M.; Salem, A.K.S.; Amin, O.; Shihada, B.; Alouini, M.-S. Visible light communications via intelligent reflecting surfaces: Metasurfaces vs mirror arrays. IEEE Open J. Commun. Soc. 2020, 2, 1–20.
37. Ndjiongue, A.R.; Ngatched, T.M.N.; Dobre, O.A.; Haas, H. Re-configurable intelligent surface-based VLC receivers using tunable liquid-crystals: The concept. J. Light. Technol. 2021, 39, 3193–3200.
38. Yuan, X.; Zhang, Y.-J.A.; Shi, Y.; Yan, W.; Liu, H. Reconfigurable-intelligent-surface empowered wireless communications: Challenges and opportunities. IEEE Wirel. Commun. 2021, 28, 136–143.
39. Chehri, A.; Fortier, P.; Tardif, P.M. On the TOA Estimation for UWB Ranging in Complex Confined Area. In Proceedings of the 2007 International Symposium on Signals, Systems and Electronics, Montreal, QC, Canada, 30 July–2 August 2007; pp. 533–536.
40. Chehri, A.; Fortier, P.; Tardif, P.M. Geo-Location with wireless sensor networks using non-linear optimization. Proc. Int. J. Comput. Sci. Netw. Secur. 2008, 8, 145–154.
41. Slalmi, A.A.; Kharraz, A.; Saadane, R.; Hasna, C.; Chehri, A.; Jeon, G. Energy Efficiency Proposal for IoT Call Admission Control in 5G Network. In Proceedings of the 2019 15th International Conference on Signal-Image Technology & Internet-Based Systems (SITIS), Sorrento, Italy, 26–29 November 2019; pp. 396–403.