energies

Review

Reconfigurable Intelligent Surfaces for 5G and beyond Wireless Communications: A Comprehensive Survey

Teena Sharma [1,*], Abdellah Chehri [1] and Paul Fortier [2]

[1] Departement des Sciences Appliquées, Université du Québec à Chicoutimi, Chicoutimi, QC G7H 2B1, Canada; achehri@uqac.ca
[2] Department of Electrical and Computer Engineering, Laval University, Québec, QC G1V 0A6, Canada; fortier@gel.ulaval.ca
* Correspondence: teena.sharma1@uqac.ca

Abstract: 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. This paper presents a comprehensive literature review on reconfigurable intelligent surfaces (RISs) and assisted application areas. With the RIS, the network operators can control radio waves' scattering, reflection, and refraction characteristics by resolving the harmful properties of environmental wireless propagation. Further, the RIS can effectively control the wavefront, such as amplitude, phase, frequency, and even polarization, without requiring complex encoding, decoding, or radio wave processing techniques. Motivated by technological advances, the metasurfaces, reflectarrays, phase shift, and liquid crystals are potential candidates for implementing RIS. Thus, they can be considered the front runner for realizing the 5G and beyond network. Furthermore, the current research activities in the evolving field of wireless networks operated by RIS are reviewed and discussed thoroughly. Finally, to fully explore the potential of RISs in wireless networks, the fundamental research issues to be addressed have been discussed.

Keywords: meta-surfaces; 5G; line-of-sight; reconfigurable intelligent surfaces; liquid crystal; field programmable gate arrays; smart reflect-arrays; wireless communications

Citation: Sharma, T.; Chehri, A.; Fortier, P. Reconfigurable Intelligent Surfaces for 5G and beyond Wireless Communications: A Comprehensive Survey. *Energies* **2021**, *14*, 8219. https://doi.org/10.3390/en14248219

Academic Editors: Alberto Geri and Daniele D. Giusto

Received: 12 August 2021
Accepted: 2 December 2021
Published: 7 December 2021

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.

The rest of this paper is organized as follows. Section 2 presents the existing and recent technologies for communication based on Intelligent surfaces with recent state-of-the-art schemes. Section 3 describes the principle of operation of RIS, RIS-assisted smart radio environment, its associated limitations, and RIS performance parameters comparison. The principle and operation of the metamaterials are discussed in Section 4. Performance comparison of passive/phase shifts active/Liquid crystals-based RIS implementation and novel active RIS signal models are discussed in Section 5. RIS-assisted FPGA-based, and its integrated architectures are discussed in Section 6. Section 7 presents the applications and future research directions. Finally, the paper is concluded in Section 8.

2. Research Background

2.1. RIS Relationship with 5G and Internet of Things (IoT)

A RIS-assisted downlink transmission scenario to help multiple users is presented in [12]. However, a high-gain line-of-sight (LOS) link will almost certainly suffer from a spatially sparse low-rank channel, limiting the number of spatial streams and, as a result, the possible rate. Furthermore, there is only one suitable propagation vector in several LOS cases, and spatial multiplexing is not feasible. Therefore, to avoid these drawbacks, the authors focused on the system model in which a multi-antenna BS supports K single-antenna users through intelligent reflections without a direct LOS path between the users and the BS. The fundamental studies and state-of-the-art schemes on intelligent surfaces and initial technologies are summarized in Tables 1 and 2 with their architectures and functionalities, merits, and demerits.

Energy consumption has become a severe concern to 5G and beyond wireless networks to achieve high data rate requirements. To reduce energy consumption, multiple approaches were proposed: renewable energy sources, relevant deployment techniques, energy-efficient hardware components with green resource allocation, and transceiver signal processing algorithms, to name a few, [13,14].

RIS has emerged as a new hardware technology with increased potential for significant energy consumption reductions. RIS technology is advantageous in energy consumption because it allows for the amplification and forwarding of incoming signals without using a power amplifier. Each reflected signal can also be constructively combined by adequately engineering the phase shifts applied by each reflecting element. A RIS consumes significantly less energy because no power amplifier is employed [15,16]. To maximize energy efficiency by using RIS reflectors with finite resolution phases, authors performed computer simulations and showed that even 1-bit phase (0 and π) resolution reflecting elements improved the system's energy efficiency compared to traditional AF relaying systems [17].

In reference [4], researchers proposed the RIS-SM and RIS-SSK schemes to understand the concept of intelligent surfaces-assisted index modulation (IM) techniques. The phase optimization and the principle of index modulation are combined in these schemes to improve spectral performance and signal quality. As a result, RISs are a promising software-defined architecture that can be realized at lower cost, size, weight, and power (C-SWaP design) and are seen as a key enabler for implementing the growing notion smart radio environments (SREs).

Table 1. Technologies for communication based on Intelligent surfaces.

Ref.	Technology	Functionality	Structure
[21–23]	Reconfigurable Intelligent wall	Complete transparent/reflecting base	Frequency selective active base utilizing PIN diodes
[24]	Spatial microwave modulators	Complex microwave fields shaping	Tunable meta-surfaces with binary phase state capabilities
[25]	Coding meta-materials	Scattering patterns (reconfigurable)	Binary elements based Meta-surfaces
[26]	Meta-materials (Programmable)	Reconfigurable polarization, phase and scattering	PIN diode-equipped cells based Meta-surfaces
[27]	Reconfigurable reflect-arrays	Adjustable reflection phase	Reflect-arrays with tunable (varactor-tuned) resonators
[28–31]	Large intelligent surface	Gains compared to massive MIMO	Active contiguous surface for Tx/Rx
[32,33]	Hypersurface (software-controlled)	Wave absorption, steering and polarization	IoT gateways based Meta-surfaces

IoT devices in the future will be compact and have a restricted power supply. Reference [18] proposed the ambient backscattering (ABSc) approach, together with spatial modulation (SM) and space shift keying (SSK) for data transfer supported with RIS, to make these devices spectrally and energy-efficient in accordance with advanced 5G and 6G specifications. In terms of outage probability and bit error rate, performance examination of various schemes revealed that RIS-enabled SM and SSK, along with ABSc, outperform conventional communications. Designing a joint active and passive beamformer is investigated in [1,19]. In a multi-user downlink communication scheme, the authors focused on minimizing total transmit power at the BS by the RIS's phase shifts while placing SINR constraints on the users. Authors in [20] proposed a technique to improve the phase shifts at the RIS and beamformer at the AP while considering the highest possible spectral efficiency.

2.2. Optimization Methods Developed for RIS Analysis

The authors in the study [34] proposed a discrete (finite resolution) RIS process. In addition, the author presented a mathematical method for calculating the average SEP of RIS-assisted systems in [35]. The idea of using a RIS as an AP (transmitter) by using an unmodulated carrier for intelligent reflection is also being investigated. Using computer simulations, it was proved that doubling the number of reflecting elements reduces the SNR by 6 dB while maintaining the same SEP. To put it another way, the average received SNR of RIS-based systems is proportional to the square of the total number of reflecting elements (N).

Further, in [4], the authors proposed the large, intelligent surfaces-spatial modulation (LIS-SM) and LIS-space shift keying (SSK) schemes to understand the concept of intelligent surfaces-assisted index modulation (IM) techniques. The phase optimization of intelligent surfaces and the principle of index modulation are combined in these schemes to improve spectral performance and signal quality. The theoretical average bit error probability is calculated using a unified framework that includes maximum energy-based suboptimal (greedy) and exhaustive search-based optimum (maximum likelihood) detectors. Computer simulations reveal that the resulting bit error probability is much higher than traditional fully digital precoding-based receive SSK methods.

In [36], the authors considered a RIS-assisted large-scale antenna system in which a BS communicates with a single antenna user. Precoding can be implemented, and the system's ergodic capacity is enhanced by optimizing the RIS phases, as in previous works, assuming knowledge of CSI and RIS phases at the BS. The authors also investigated different Rician K factors and discontinuous phase shifts. Computer simulations demonstrate that using 2-bit phase shifts can result in a high capacity. In rank-one or full-rank LOS channels between the BS and the RIS, the authors in [5] evaluated the optimization of the minimal SINR for a RIS-assisted multi-user MISO system.

Furthermore, correlated Rayleigh channels are studied between RIS elements and users, and an algorithm for optimizing RIS phases in the presence of large-scale fading is provided. The authors of [37] suggested a new channel estimation protocol for a single-user MISO system with energy harvesting that uses RIS. The authors take into account the fact that RISs do not have active components in particular. Both active and passive near-optimal beamforming designs are designed to enable effective power transfer.

The authors in [38] proposed a deep learning-based method. The RIS learns how to deal with incoming signals in the most efficient way possible by utilizing the predicted channels at active elements. Two independent strategies for RIS design in the presence of unknown channel information, one based on compressive sensing and the other based on deep learning, to lower the training overhead in the presence of passive RIS elements. A novel RIS design based on sparse channel sensors is proposed, with part of the RIS units being active (connected to a baseband processor). In other words, the RIS uses many active aspects to make the channel estimation process easier.

In [39,40], the physical layer security of RIS-based systems was considered for a downlink MISO broadcast system with numerous legitimate listeners and eavesdroppers. The authors developed a minimum secrecy-rate maximization problem by jointly optimizing the beamformer at the BS and reflecting coefficients (continuous and discrete) at the RIS. The authors present both globally optimum and low-complexity sub-optimal algorithms.

The authors in [39] looked closely at a RIS-assisted secure communication system with a legitimate recipient and an eavesdropper. The secrecy rate is improved by optimizing the beamformer at the BS and the phase shifts at the RIS. In addition, the secrecy rates of massive MIMO and RIS-assisted systems are compared. It is discovered that increasing the number of RIS reflecting elements is more helpful than increasing the number of antenna elements at the BS.

The authors in [41] recently addressed the problem of a more robust eavesdropping channel and improved the legitimate user's secrecy rate by constructing the AP's transmit beamformer and RIS phases together. The authors in [42,43] examined the maximization of the SINR for the multi-user MISO scheme. Furthermore, correlated Rayleigh channels are considered between RIS elements and users, and an algorithm for optimizing the phases of the RIS is suggested. The authors in [44] provided more extensive simulation results on energy efficiency and system sum-rate for a more practical system design and system characteristics. The transmit beamforming with this approach needs complete channel state information (CSI) and knowledge of RIS phase terms at the BS.

Table 2. Recent state of the art for RIS-assisted schemes.

References	Existing RIS-Assisted Schemes
[45–47]	For multi-user downlink transmission, RIS scheme with periodic-aided structure is considered. Maximization of energy efficiency and sum rate is performed with finite resolution reflectors.
[42,43,48,49]	For massive MISO multiuser system design, the joint active and passive beamforming problem is discussed. Using square law scaling in transmitted power and optimization, minimization of base station transmit power is performed.
[4,35,50]	For the estimation of the symbol error probabiity (SEP) of RIS supported systems, a mathematical method is proposed. Further, by considering the RIS as an AP, the concept of RIS (LIS)-assisted IM is developed. For the LIS-SM and LIS-SSK systems, greedy and maximum likelihood detectors are formulated, along with theoretical derivations.
[36]	The capacity is increased by RIS phase optimization, and for massive MIMO is with Rician channel is considered.
[44]	The problem of RIS phase shifter and optimal transmit beamforming is analyzed in order to increase achievable spectral efficiency.
[37]	For an RIS assisted MISO system, a new channel estimation protocol with energy harvesting feature is proposed.
[40]	An RIS assisted secure communication system with legitimate receivers and eavesdropper is concerned.
[39]	Joint optimization using RIS reflecting coefficient and BS beamformer for MISO system.
[51,52]	A sensing system for estimating radio waves impinging on HyperSurfaces is proposed. It is demonstrated that HyperSurfaces may be programmed to detect and manipulate waves at the same time. Further, an approach is suggested based on machine learning for HyperSurfaces-assisted programmable environments in order to configure it adpatively.
[5,53]	The maximization of the minimum SINR is analyzed for RIS -MIMO System. Further, for phase optimization, LOS channels, large scale fading statistics and correlated RIS channels are considered.
[4]	By considering RIS as AP, RIS assisted IM is along with mathematical optimization (such as Greedy Algorithms).
[38]	RIS architecture with sparse channel sensors (few of the existing RIS active units) and the use of Deep learning techniques are presented.

In [51], the authors contributed to the most recent research (HyperSurface design). They proposed a sensing system for estimating radio waves impinging on HyperSurfaces that can work without external or internal hardware, such as field nano-sensors. It is demonstrated that hypersurfaces may be programmed to detect and manipulate waves at the same time. In [52], authors suggested an approach based on machine learning (neural networks) to adaptively configure HyperSurfaces-assisted programmable environments.

The authors in [20] and [43,48] proposed a few techniques to improve the phase shifts at the RIS and beamformer at the AP while considering the highest possible spectral efficiency [48]. Other works related to RIS-based for SIMO, MIMO, were proposed in [54,55].

3. Principle of Operation of RIS

RIS surfaces are flat structures made of metamaterials and electromagnetically discontinuous. They do not adhere to the conventional laws of reflection and diffraction; instead, the phase and wavefront of the radio waves that affect them can be controlled. If deployed to cover building objects, walls, or facades, they could allow real-time personalization of the electromagnetic response of environments. Further, the RISs are reconfigurable EM material sheets that intensely monitor the propagation in the atmosphere to improve the efficiency of the received signal.

The RISs are composed of many low-cost components (such as a PIN Diode capable of manipulating the electromagnetic waves) that influence them in ways that are not capable of naturally occurring materials. In addition, these “intelligent” surfaces can be controlled in phase with complexity and precision while requiring a very low consumption. The objective is to improve communication performance. Moreover, the benefit of RISs compared to traditional reflect array/transmit array antennas is that it is possible to dynamically adjust the parameters of each functionality, such as the direction of reflection/refraction, the location of the focal point, etc.

When integrated into the physical environment (e.g., on walls), these surfaces create reflection anomalies, making it possible to control the radio propagation channel at a lower cost and with a lower energy footprint. By doing so, the RIS will reduce the transmission power required at a constant rate, serve a user located in an uncovered area, limit radio interference, or even reinforce the security of radio links concerning passive eavesdropping. In addition, the RIS was proposed to improve efficiency in terms of link quality and coverage.

The basic principle of RIS is depicted in Figure 1; the EM wave is tuned to any other angle instead of the symmetric reflective wave, based on Snell’s law when the surface is divided into a large number of closely spaced components (supercells of scattering particles). Each metasurface element is rendered to have suitable phase shifts. Ideally, if each metasurface element phase shift can be calibrated to any value, a reflected beam can be generated at any angle [2]. The RIS consists of meta-surfaces due to its huge number of advantages, and it also serves as programmable reflectors. However, the phase shift of the surface element must be set appropriately or smartly to shape the reflected beam with incident EM wave. A signal processing design technique or machine learning-based approaches can be applied, resulting in the so-called reconfigurable intelligent surface. Continuous or analog phase changes can be challenging to accomplish in practice. Recently, as stated in [56], quantized phase shift configurable RISs have been built. When the input or output signal is a plane, the basic features of RIS can be summarized in the following steps:

(1) reflection/refraction, where a plane wave is redirected from its original propagation path to another direction;
(2) absorption, where the amplitude of a plane wave is greatly reduced;
(3) focusing/collimation, where a plane wave is condensed to a single point or a spherical wave is transformed to a single plane wave from a point source;
(4) alteration of polarization, where procedure (1) or (3) often includes modifying the incoming wave polarization from linear polarization to circular polarization. We have presented RIS performance parameters comparison in Table 3.

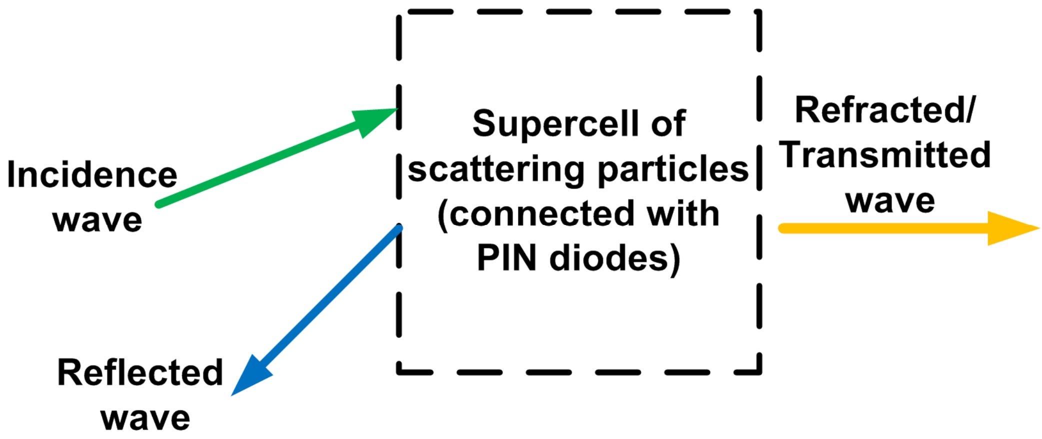

Figure 1. Schematic of RIS system illustrating basic principle [57].

3.1. RIS-Assisted Smart Radio Environment

The RIS-based smart radio environment is discussed in [32]. The advantage of this smart radio solution can be enhanced by utilizing one or more RISs in the case of wireless propagation. For example, to encourage spatial multiplexing by the received power via beamforming or by affecting the channel. In essence, a RIS can be named any passive surface that can be dynamically reconfigured to control electromagnetic incident waves and modify the channel's conditions.

Limited Phase Shifts Problem and RIS Assisted Communication Model

In such a smart environment scenario, sometimes the line of sight (LOS) propagation link may not be stable, or even fall into a complete outage due to the varying wireless environmental circumstances resulting in unexpected fading and possible obstacles. As a result, RIS has gained a great deal of worldwide attention to tackle this problem [58]. RIS is adopted to reflect the signal to enhance the QoS to establish a perfect condition for propagation. For example, a cellular uplink network using M×N electrically controlled RIS elements is shown in Figure 2. There is a deep fading of the direct connection between the base station (BS) and the user. RIS with minimal phase shifts is considered to enhance the QoS at the BS to reflect the signal from the consumer to the BS in the presented scenario.

Table 3. RIS performance parameters comparison.

Ref.	Performance Parameters	Values
[59]	Outage probability	3×10^{-3}, M = 100 3×10^{-1}, M = 1600
[60]	Ergodic rate	3.8, M = 100, K = 5 4.5, M = 1600, K = 20
[61]	Network Spectral efficiency (bps/hz)	85, M = 100 (T = 50 and t = K)
[61]	Ergodic System Spectral efficiency (bps/hz)	65, M = 100 (L = 0.5, K = 20)
[60]	Variance of data rate	0.2, M = 1600 (L = 0.5, K = 20)
[62]	Achievable Data rate (bps/hz)	21, d = 200 m
[16]	Average EE (Kbit/Joule)	130 at Pmax (dBm = 40) M = 32, K = 16, N = 12
[16]	Average SE (bps/hz)	145 at Pmax (dBm = 40) M = 32, K = 16, N = 12
[42]	Received SNR (dB)	17, N = 100
[63]	Secrecy outage probability	10^{-1}, N = 50
[64]	Coverage distance (km)	12, N = 8
[64]	Probability of SNR gain (dB)	0.9, N = 4
[64]	Delay outage rate	10^{-1}, B = 2 MHz

Where, N = Number of LISs, K = Number of LIS units in each LIS (equal to the number of devices) = 0.5, M = Number of antennas on each LIS unit = 100, 1000, L = Half length of each LIS unit = 0.5 m.

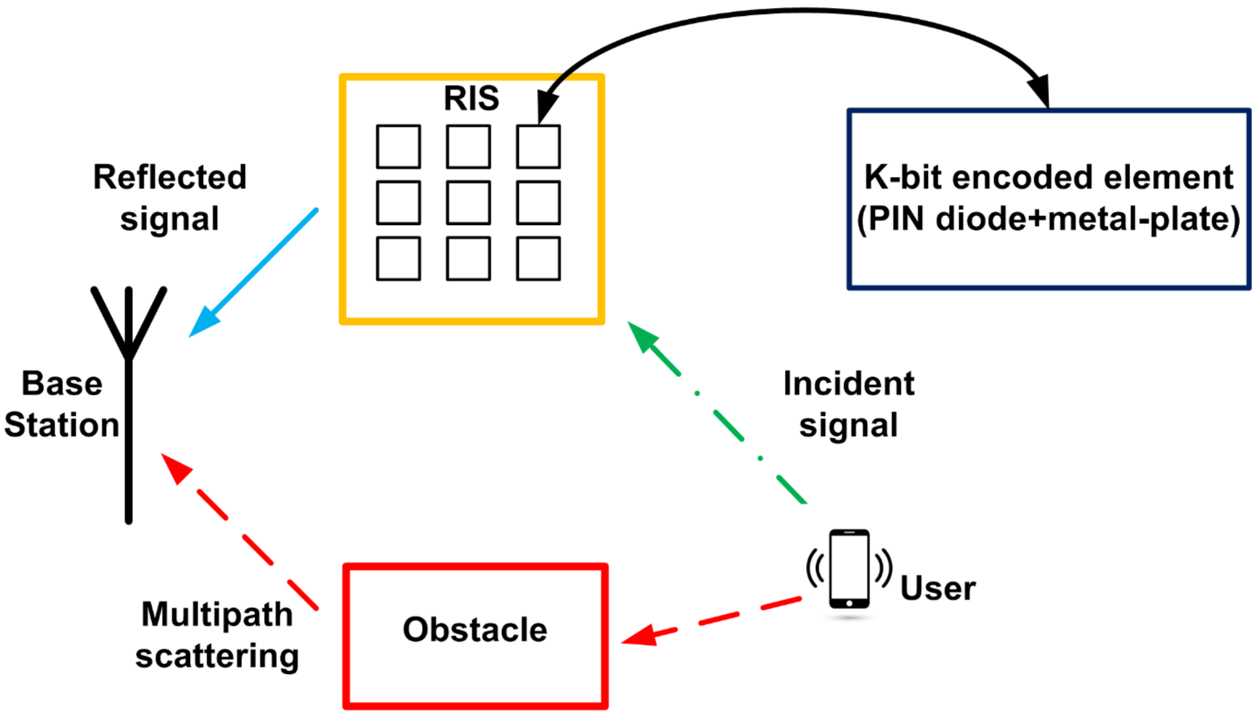

Figure 2. RIS assisted communication model for uplink cellular network.

4. Principle and Operation of the Metamaterials

Artificial bulk and planar materials having subwavelength structural inclusions are known as metamaterials and metasurfaces. Metasurfaces have demonstrated significant powers in achieving various capabilities, such as perfect absorption, anomalous reflection, focusing, imaging, and so on, due to their customized unit cell architectures. The RIS is designed to use small unit cells of metamaterials, referred to as metasurfaces [65]. The idea is to use new materials with controllable electromagnetic properties to manipulate the propagation of radio waves in the environments where we live and work.

Metamaterials have established themselves as a powerful technology with many applications, especially in wireless communications. Metamaterials consist of a class of artificial materials whose physical properties, such as permeability and permittivity, can be varied to desired features [66]. A brief survey of the existing state-of-the-art schemes for metamaterials is compiled in Table 4. In addition, metamaterial structures have recently been anticipated as a novel way to turn any naturally passive wireless transmission environment (the set of items between a transmitter and a receiver makes up the wireless environment) into an active one [32,65,67].

Table 4. State of the art schemes for metamaterials.

References	Histry of Metamaterials
[68]	Concept of left-handed material • $\epsilon < 0$, $\mu < 0$ • Negative refraction
[68]	Concept of left-handed material • $\epsilon < 0$, $\mu < 0$ • Negative refraction
[69]	Proposal of meta-surface • Two-dimensional • Simplify design and manufacturing
[70]	Transformation optics • Design metamaterial with any ϵ and μ • Enabling flexible control of EM wave
[71]	Reconfigurable large reflectarray A reflecting element consisting of a microstrip patch with PIN diodes as a single-bit digital phase shifter was used. • Easy to control • Millimeter wave
[25]	Programmable/digital metasurface A digital metamaterials with unit cells is presented with a unique metamaterial particle with a 0 or 1 responsed • Simplify the design • Digital coding
[72]	Realize -ε and -μ • -ε: periodic array of metallic rods • -μ: periodic array of split ring
[73]	Programmable metasurface A tunable metasurface absorber with an optically programmable capacitor as the tuning element. • Varactor • 360° reflection phase tuning
[65]	Proposal of reconfigurable intelligent surfaces • Focus on reflection • Extensive applications in wireless networks
[74]	Proposal of intelligent omni-surface RIS enabled metasurface provides dual function of transmission and reflection • Enabling dual function of reflection and transmission • Extends the coverage of wireless networks
[75]	Protype of metamaterial reflector • 10× increase in data rate

In the case of planar structures (e.g., metasurfaces), effective parameters of metamaterials can be tuned to achieve the desired transformation on transmitted, received, or impinging electromagnetic waves [76]. They are cost-effective, and their extremely low hardware footprint technology makes them usable in different components of the wireless propagation environment such as room walls/ceilings and building facades. This is beneficial in controlling artificial EM wave propagation and environmental AI. Due to usages of metamaterials, RIS-enabled wireless communications have recently gained a lot of attention in 5G and the forthcoming 6G broadband network applications. Moreover, semiconductors and graphene are two preferred RIS materials. As discussed, metamaterial or patch-array-based technologies can be used to realize RISs structures. Metamaterial-based RISs can be deployed at different locations and can work as reflecting/refracting RIS between the user and base station (BS) or waveguide RIS operating at the BS [77]. A typical geometry layout of the patch-array smart surfaces based on RIS can be represented as a substrate with periodic (or quasi-periodic) unit cells. RISs are based on a local design, in which the cells do not interact with one other for clarity (referred to as a non-local design). Typically, a local design results in the creation of sub-optimal RISs.

Further, 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. However, electrical control is the most suitable way as the electrical voltage is easier to quantize and control with FPGA chips. Metasurfaces based on three important RIS structure working conditions: reflection [78], refraction [79], and waveguide [76] are presented:

(1) Reflecting RIS: A digital coding reflective metasurface design is discussed in [80]. Varactor diodes with a configurable biassing voltage are contained in each element of metasurfaces. Each metasurfaces element can conduct discrete phase shifts and achieve beamforming for the reflected wave by predesigning various digitized biased voltage values.
(2) Refracting RIS: A theoretical design of a perfectly reflecting/refracting metasurface is presented in [80]. An equivalent impedance matrix model is introduced to optimize the tangential field components on the two sides of the metasurface. Self-oscillating teleportation metasurfaces formed entirely of lossless components and nonlocal metasurfaces, the three possible device realizations, are discussed. Additionally, the importance of omega-type bianisotropy in constructing lossless-component implementations of perfectly refractive surfaces is discussed.
(3) Waveguide RIS: A theoretical concept of waveguide-fed metasurfaces is presented in [76]. The metasurface's elements are characterized as uncoupled magnetic dipoles. The product of the reference wave and each element's polarizability measures the magnitude of each dipole element. The metasurface antenna can conduct beamforming by adjusting its polarizability. Each metasurface element functions as a micro-antenna. The small waveguide metasurface takes up less space than traditional antenna arrays and can broadcast a large range of radiation patterns.

4.1. Operting Principle for Metasurface Based RISs from the View of Physics

An EM wave propagating in three-dimensional (3D) space is referred to as a wireless signal. As the electromagnetic wave propagates across space and interacts with scattering objects, it attenuates the signal strength. According to basic electromagnetic principles, the signal power per unit area in a particular medium is proportional to the square of the electric field of the associated wave. This result allows us to analyze the EM wave in order to acquire a better knowledge of the wireless signal and its interaction with reflecting objects for reflective and refractive smart surfaces. The equivalence principle, particularly the surface equivalence principle (SEP), provides the foundation for all of these EM wave manipulation studies. In the context of RIS designs, the Huygens principle and the Love's field equivalence principle can be used. According to the Huygens principle, EM wave manipulation boils down to the controllable change in amplitudes and phases at each spot on the surface wavefront. Another essential viewpoint is Love's field equivalence concept, which can be used to both the external (source-free zone) and internal problems. In this concept, the refracted and reflected EM field can be analyzed by introducing equivalent surface magnetic and electric current [81]. The following is a summary of the operational principle of waveguide-based RISs. The coupling between 3D free space waves and two-dimensional surface waves is performed by the EM wave manipulation of the waveguide metasurface in [32]. As a result, the metasurface can be considered a hologram containing additional information about its radiated signal traveling in three dimensions (3D) space. After being excited by the source, this pre-designed information is launched into the radiated field.

On the other hand, advanced signal processing methods have also been proposed to deal with the multiple radio echoes resulting from reflections and/or diffractions of the waveform transmitted in its environment. These multiple received paths, which depend significantly on the geometry of the radio link, are then treated as a source of valuable information for tracking mobile radio nodes inside buildings, or even for mapping the environment. Unlike other related technologies, such as relays and MIMO beamforming, no power source is needed for RISs. Furthermore, unlike software-defined surfaces (SDSs), RIS software can be programmed to respond to radio waves. When an EM wave reaches the boundary between two isotropic mediums, the relationship between the angle of incidence and angle of reflection and refraction is governed by Snell's law. In particular, for reflection, the angle of incidence for the normal surface of the medium is the same as the angle of reflection. However, the recent advances in research on metasurface and reflectarrays make it possible to adjust the surface impedance and achieve a certain phase shift between the incident and the scattered waves [1].

4.2. Programmable Metasurfaces

Once a unit cell is designed in the early stages of metamaterial and metasurface research, its function is fixed. For example, an absorber functions at a specific frequency where the input impedance is matched to the free space. However, due to the intrinsic structure of the unit cells, re-design and re-fabrication operations are not allowed if there is a change in the working frequency or even the functionality [82]. Adding "tuning" capabilities to the unit cells can alter the properties of metamaterials and metasurfaces. The behavior of their electromagnetic waves can then be modified externally by changing the stimulation. The resonance frequency can be shifted by changing the parameters of the substrate or structural material. For example, the permittivity of the liquid crystal can be modified under different gate voltages [83].

Furthermore, a computer algorithm can control such tuning. For developing programmable metasurfaces, there are a variety of tuning procedures available in the literature [84]. The solutions are classified as global tuning at the metasurface level such as electric, magnetic, light, and thermal tuning and local tuning at unit cell levels such as switch diodes, continuous tuning varactors, and collective tuning varactors. Such metasurfaces are programmable, and they open up more possibilities for dynamical wave applications without the need for re-fabrication or re-design. In this paper, we have directed our research about software-defined metasurfaces, which have the capacity to tune the characteristics of each RIS unit cell separately.

4.3. Future towards Software-Defined Metamaterials/Metasurfaces

Tunability in the alteration of unit cell structural configurations is more challenging for a tunable metasurface. This method involves connecting sections of the unit cell to achieve various structural configurations. A hardware system that applies the software primitives and effectively reconfigures the metasurface is needed to realize a software-defined metasurface. Some researchers propose that a network of microscopic controllers be integrated into the metasurface structure and wirelessly interfaced with an external entity [85]. Each controller can interpret global commands and act locally, for example, by tuning its associated varactors to produce the required impedance configuration. The key problems are constructing an ultra-low-cost network of controllers and connecting it with the metasurface within a single structure [86].

The metasurface profile refers to the systematic registration of functionalities offered by a certain metasurface. This profile is the linchpin between academic knowledge and real-world applications in the software-defined platform. The profile's information enables software developers and engineers to create systems that incorporate object electromagnetic behavior into their control loops without understanding the underlying physics. Software-defined metasurfaces may give the IoT a new application field in the electromagnetic behavior of things in the future. IoT can be extended to the Internet-of-Materials (IoM), providing unparalleled capabilities combined with attempts to enable control over mechanical qualities [87].

5. RIS Implementation Structures

Reconfigurable intelligent surfaces (RISs) have emerged as a candidate technology for future 6G networks as a novel paradigm for regulating wireless channels. In this section, first, various implementations of reconfigurable intelligent surfaces and their differences are discussed. The literature has studied two major implementations based on standards, i.e., reflectarrays or metasurfaces [88]. Following this, a novel in-depth review of passive and phase shift-based active RIS and liquid crystals (LCs) RIS structures is carried out.

5.1. Reflectarray RIS Implementation

Most of the reported RIS work assumes a reflectarray-based implementation, where each part is a configurable load-terminated antenna (Figure 3a,b) [41]. However, this execution would require a great deal of productivity to be successful.

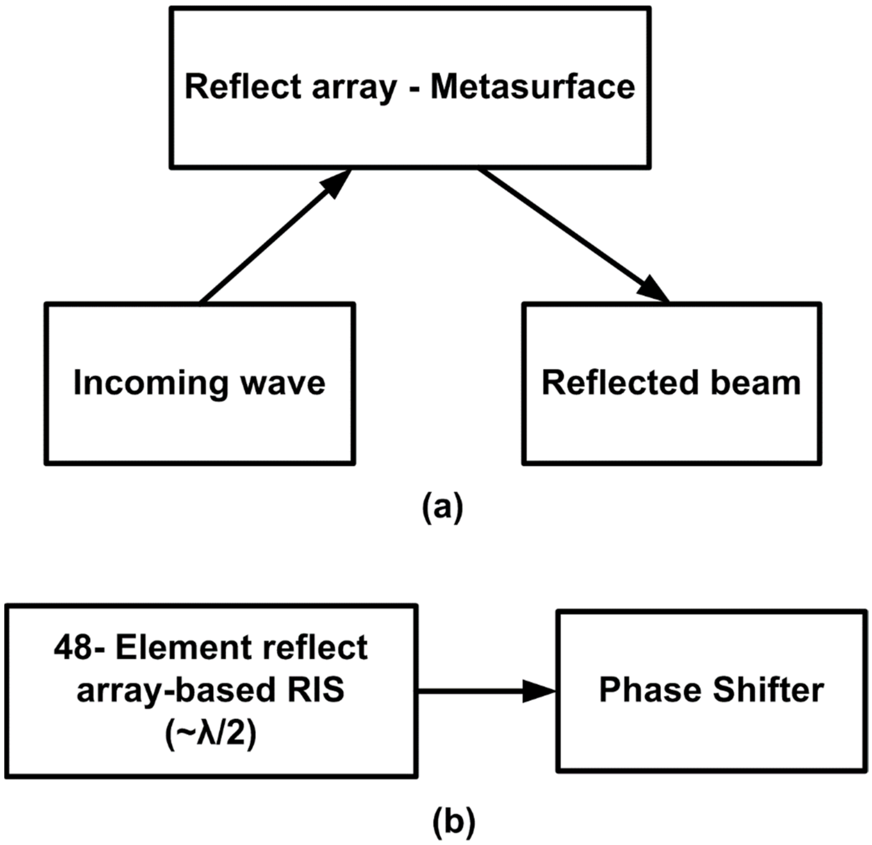

Figure 3. (**a**) Reconfigurable Intelligent Surface (Reflectarray) (**b**) Reflectarray RIS implementations: A 48-element reflect array-based RIS. Each element is a traditional antenna connected to a phase shifter.

5.2. Metasurface-Based Implementation

A metasurface is made up of a large number of deeply subwavelength resonating structures, which are closely spaced. The very small size and large number of these tightly packed atoms give a massive number of degrees of freedom to control the electromagnetic waves, as shown in Figure 4 [19]. Earlier designs of metasurfaces have been based on static preset methods of meta-atoms. As a result, the elements cannot be changed after fabrication. However, this is good enough for optical applications to create custom lenses where the reconfigurability could be accomplished by combining electrical components tuned in two ways: thermally, electrically, or mechanically. In particular, when the antenna size and antenna spacing decrease and the applied amplitude/phase profile becomes roughly continuous along the surface. This allows for a significant degree of versatility in wave-front manipulation of the incident. For instance, in a different direction, each tile may represent the incident wave-front. The increased versatility associated with metasurface-based RIS results in even better results in the literature; however, only real-world experiments could say whether realistic performance gains will result from increased sophistication.

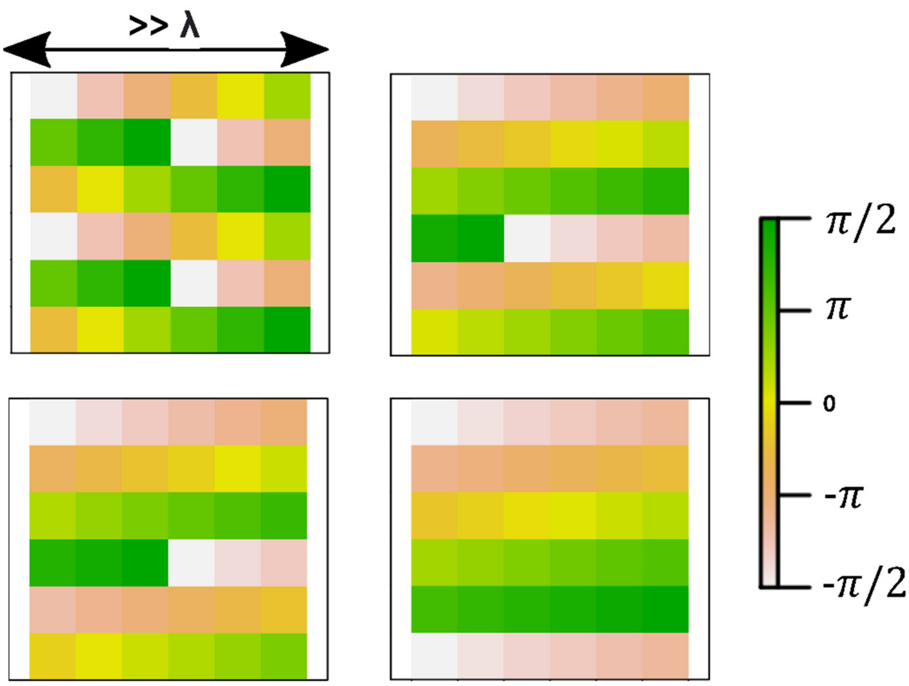

Figure 4. Reconfigurable Intelligent Surface (Metasurface): A 4-element metasurface based RIS (Each element is a dynamic meta-surface with numerous tightly packed meta-atoms and can apply an arbitrary quasi-continuous phase gradient).

5.3. Passive and Active RIS

RISs can be divided as passive-lossy, passive-lossless, or active based on their energy consumption. Their active or passive nature can determine the performance capabilities of RIS. However, RISs cannot be completely passive due to their inherent property of being configurable. A passive RIS is made up of a large number of passive elements, each of which can controllably reflect the incident signal with a phase shift. Each passive RIS element is made up of a reflecting patch connected to a phase-shifting impedance-adjustable circuit. A passive RIS element consumes little direct-current power due to its passive operating mode, and the thermal noise contributed is likewise low. However, passive RISs only yield a minor capacity boost in many circumstances with strong direct links due to the “multiplicative fading” effect. This equivalent path loss of the transmitter-RIS receiver reflection link is the product (instead of the sum) of the path losses of the transmitter-RIS link and RIS-receiver link. Therefore, it is thousands of times larger than that of the unobstructed direct link [89]. Figure 5a,b demonstrates the active and passive RIS structures based on energy consumption.

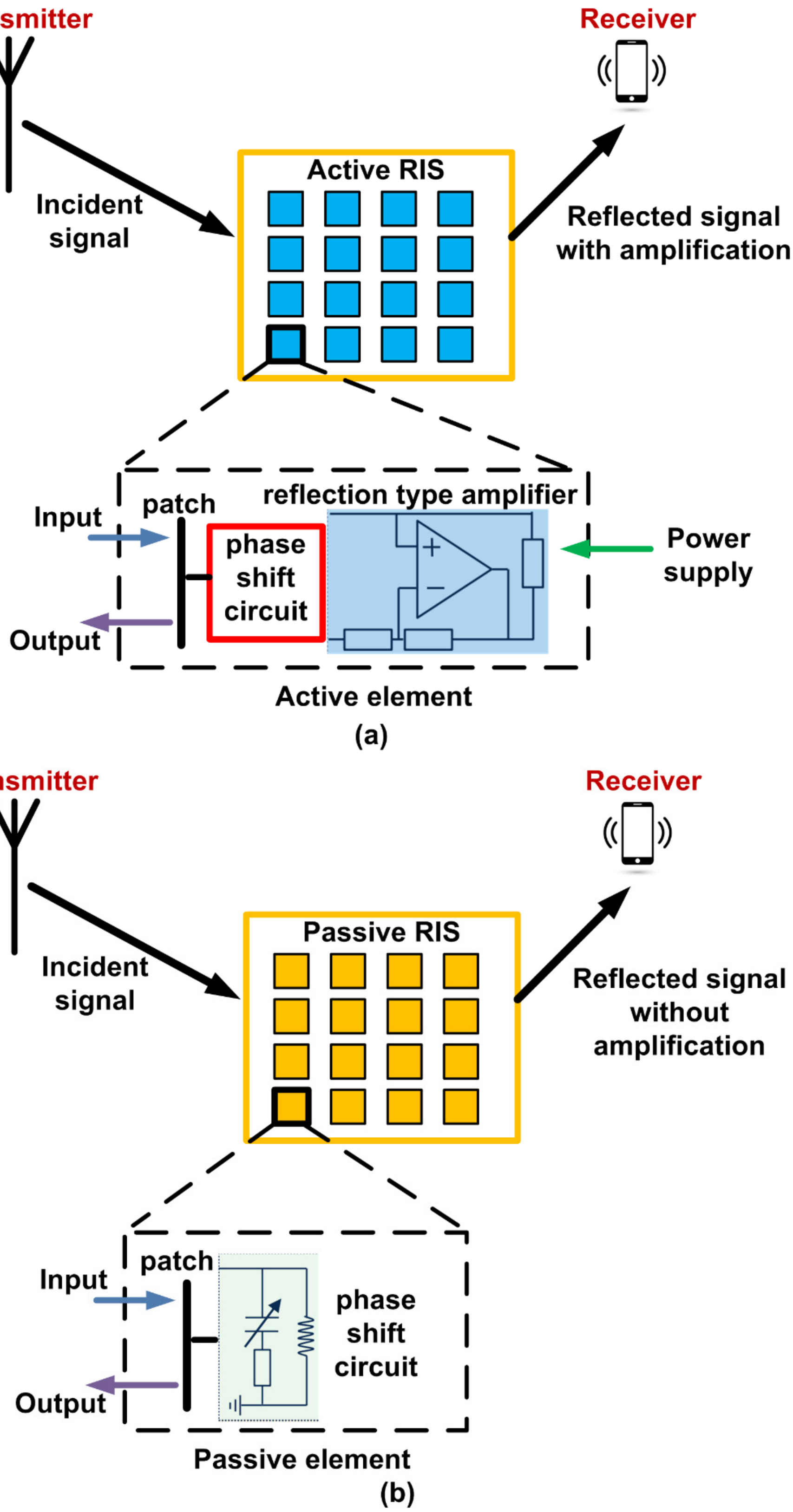

Figure 5. RIS structures based on energy consumption (**a**) An active RIS implementation (**b**) Existing passive RIS impementation.

5.4. Novel Active RIS Structure and Signal Model

Active RISs are considered novel implementation structures due to their numerous benefits and applications in many communication areas. As opposed to passive RISs that reflect signals without amplification, they can further amplify the reflected signals. Active RISs can avoid the drawbacks of passive RIS, especially the multiplicative fading phenomenon, as active RISs can enhance the reflected signals at the expense of extra power consumption, unlike passive RISs that only reflect signals without amplification. In addition, active RISs can also reflect incident signals with adjustable phase shifts, similar to passive RISs. The additionally integrated active reflection-type amplifier, which can be realized by different existing active components, such as current-inverting converters, asymmetric current mirrors, or even some integrated circuits, is the key component of an active RIS element.

The drawback of active RISs is that they consume more power to amplify reflected signals because they utilize active components. The thermal noise created by active RIS elements cannot be ignored as easily as it can be with passive RISs. The authors in [90] developed an active RIS signal model that was validated by experimental measurements. A point-to-point multiple-input single-output (MISO) wireless system in which an Access Point (AP) serves a single-antenna user with M antennas is developed and analyzed. An intelligent reflective surface (IRS) made of N passive elements is mounted on a surrounding wall to aid the AP-user communication/power transfer to improve connection performance. The IRS, equipped with a smart controller, can modify the phase shift of each reflecting element dynamically based on the propagation environment learned through periodic monitoring via the same passive array (when not reflecting). The IRS controller coordinates the transition between two operating modes: receiving mode and environment sensing mode. Finally, the sum-rate maximization problem for active RIS-assisted multiple-input multiple-output (MIMO) systems was framed using this paradigm. A precoding solution was developed and presented a joint transmit beamforming and reflect precoding algorithm that solves this problem. The results demonstrated that existing passive RISs could only achieve a small sum-rate gain of 3% in a typical wireless system. However, the suggested active RISs achieved a considerable sum rate gain of 108 percent, thereby avoiding the "multiplicative fading" phenomenon present in passive RISs [42].

In many industrial internet-of-things (IoT) applications, such a system can be used to facilitate wireless information and/or power transfer. Therefore, the authors also optimized the (active) transmit beamforming at the AP and (passive) reflect beamforming by the phase shifters at the IRS to achieve the maximum signal power received at the user. The authors assumed that the user receives superposed signals from the AP-user (direct) link and the IRS-user (direct) link.

5.5. Toward Liquid Crystal (LCs) Based RIS

Recent developments using liquid-crystal-loaded unit cells demonstrate promising metasurfaces with adjustable reflection phase distribution [91]. The phase tunability of the metasurface reflector is achieved via the dielectric anisotropy of nematic LCs in the reconfigurable metasurface. The effective dielectric constant and, thus, phase differential at various points of a metasurface can be changed by adjusting DC voltages on microstrip patches of liquid-crystal-loaded unit cells. The concept combines aspects of a metasurface with the unique attribute of electronically adjustable LCs. In literature, there are many electrically sensitive materials, but nematic LCs are particularly well-known due to rapid advancement in optical display technology. Nematic LC molecules reorient themselves in response to the bias electric field, resulting in voltage-dependent birefringence. Furthermore, their liquid nature can be infiltrated into various metasurface structures, resulting in substantial refractive index modulation for operation in the microwave, terahertz, and optical regimes. Nematic LCs have been used in multiple prominent metasurface applications, including tunable absorbers and cloaks with real-time invisibility control [92,93].

A large number of metamaterial cells are loaded with a thin layer of LCs in the proposed metasurface. Due to the anisotropic features of the nematic LCs, the effective dielectric constant and resonant frequency of such unit cells can be modified individually by adjusting the external electrostatic field. Because the frequency of the incoming wave in relation to the resonance frequency determines the reflection phase, such a metasurface can be changed in real-time to obtain the desired reflected wave direction by providing a suitable DC voltage distribution across the surface [94]. The metasurface is a multilayered printed circuit board surface with a high impedance. The metasurface's bottom layer is a solid ground plane, while the top layer is a gridded wire mesh utilized for DC grounding of the top microstrip patches. An array of little microstrip patches can be located in the central layers. These microstrip patches are approximately a quarter of a wavelength in size. Between the two microstrip patch layers is an LCs mixture with a tunable dielectric constant. As a result of the anisotropy of the LCs, the dielectric constant between the microstrip patches at each unit cell can be controlled individually by altering the electrostatic field between the patches.

A RIS, in particular, is made up of a large number of low-cost and passive reflecting elements (REs) that are not connected by radio frequency chains. RIS wireless systems can achieve system gain by modifying the phase shifts and amplitudes of the REs so that the desired signals can be combined constructively at the receiver. However, a RIS often has limited signal processing capabilities and cannot do active transmitting/receiving in general, posing significant issues in RIS wireless system physical layer design. From the literature, it is clear that LCs technology has been identified as a potential solution for the improved design of passive and reflectarray-based RIS. Therefore, it plays a significant role in the future RIS structure design. Additionally, a flat reflector made of liquid-crystal-loaded metasurface can be used for beam-steerable antenna applications by utilizing the dielectric anisotropy of LCs. Changing the DC voltages of LC-loaded unit cells in real-time to give the desired phase distribution throughout the metasurface can be used to create a beam steering IoT system. In addition, the proposed unit cell structure can be used in dual linearly polarized applications. In existing research, the dependence of LCs on the voltage applied has been utilized to design efficient RIS with control over a huge range of wavelengths. In the future, investigations related to improving the reflection loss performance and frequency tunability are required, which can be done by a depth study of LCss's material properties. The main limitation of LCs is the time taken by their molecules to change their orientation. This time consumed by the LCs based reflector for achieving frequency tunability needs to be further investigated. The above-stated drawback of LCs based RIS can be overcome by using novel active RIS implementation, as discussed in the next section.

6. 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 6, and its related work is discussed next.

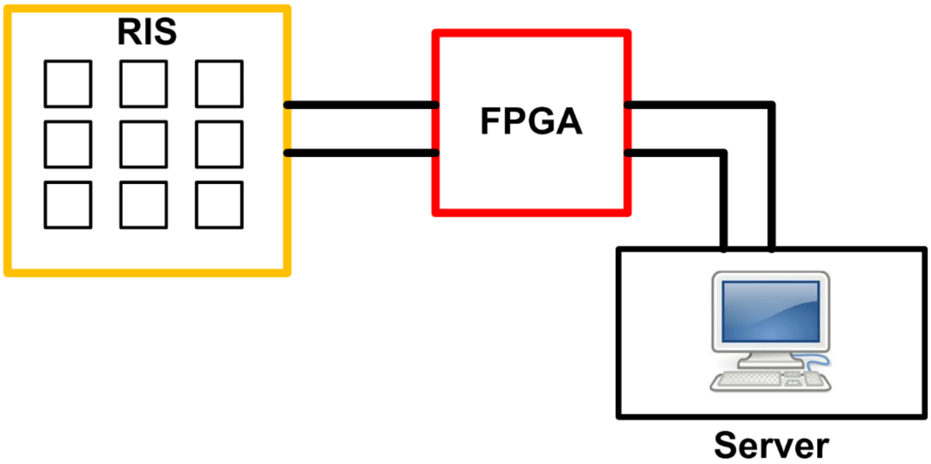

Figure 6. FPGA based dynamically controlled RIS structure.

A system based on a microcontroller unit (MCU), DACs board, and FPGA is commonly used to dynamically control the RIS [95,96]. The RIS in [96] 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 6). The simulated radiation pattern of beam scanning is obtained using this control mechanism [97].

In [25], 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 [98], 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 [99], 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. [26], 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 [100]. 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. [101], 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 [102]. In [96], 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.

7. Applications and Future Research Directions of RIS

7.1. 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 [103], 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 [104], 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.

7.2. 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 [105] 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.

7.2.1. 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 [106] 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.

7.2.2. 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 [107].

(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) [108].

(3) Probability of Reflection: Authors in [109] 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.

7.3. 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 [110]. 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 [111]. 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 [112] 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 [113]. The idea of employing a RIS as a transmitter was recently tested using a testbed platform [114]. 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 [115].

7.4. 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 [116].

7.4.1. 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.

7.4.2. 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 [117]. 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 [118]. Other possible use cases of RIS are discussed in Section 7.5, Section 7.6, Section 7.7, Section 7.8, Section 7.9.

7.5. 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.

7.6. 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.

7.7. 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.

7.8. 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 [119].

7.9. 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 [120–122].

8. Conclusions

To date, all wireless systems have assumed that the radio propagation channel is fixed by nature and cannot be changed. It is only well accounted by increasingly complicated transmission/reception systems. Moving away from this hypothesis could be a significant evolutionary leap for 5G networks and beyond. The innovative idea of developing wireless networks is managed and controlled through RIS-assisted wireless communications.

In this work, we reviewed state-of-the-art research findings in the emerging field of RIS, given its potential for substantial performance improvement by adapting the propagation environment for next-generation wireless communication networks. Further, an in-depth overview of RIS is provided for wireless communications regarding its principle, opportunities, and challenges encountered for metasurfaces and reflect arrays RIS. Further, extensive survey on various candidate implementations such as phase shift and LCs based RIS has been reviewed. We have demonstrated the key differences that distinguish RISs as a modern technology compared to conventional literature technologies. In addition, RIS optimization methods using existing and novel beamforming techniques are discussed. Furthermore, comprehensive summaries are given for practical considerations of RIS hardware design and optimization.

Additionally, a detailed review of existing FPGA-based dynamically controlled RIS structures, and the future opportunities associated with this new technology has been presented. The possible use cases where the RIS could play an important role in various application areas, such as UAV, mmWave, FSO, and VLC communications, have been demonstrated with future challenges. Finally, the fundamental research issues to be addressed have been explored to full determine the potential of these technologies.

Author Contributions: T.S. and A.C., designed the research. T.S. conducted the investigation and literature review, T.S. writing—original draft preparation. T.S., A.C. and P.F. writing—original draft preparation. MITACS and Thales-Quebec provided the research funding to the first author at University of Quebec in Chicoutimi (UQAC), Canada. T.S. was the corresponding author. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by MITACS and Thales-Quebec, grant number UBR 326853.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author T.S., upon reasonable request.

Acknowledgments: The authors thanks to the anonymous reviewer and editors for their constructive comments.

Conflicts of Interest: The authors declare no conflict of interests.

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. [CrossRef]
2. Özdogan, Ö.; Björnson, E.; Larsson, E.G. Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling. *IEEE Wirel. Commun. Lett.* **2019**, *9*, 581–585. [CrossRef]
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. [CrossRef]
4. Basar, E. Reconfigurable intelligent surface-based index modulation: A new beyond MIMO paradigm for 6G. *IEEE Trans. Commun.* **2020**, *68*, 3187–3196. [CrossRef]
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. [CrossRef]

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. [CrossRef] [PubMed]
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. [CrossRef]
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. [CrossRef]
12. Akdeniz, M.R.; Liu, Y.; Samimi, M.K.; Sun, S.; Rangan, S.; Rappaport, T.S.; Erkip, E. Millimeter wave channel modeling and cellular capacity evaluation. *IEEE J. Sel. Areas Commun.* **2014**, *32*, 1164–1179. [CrossRef]
13. Sharma, T.; Chehri, A.; Fortier, P. Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies. *Trans. Emerg. Telecommun. Technol.* **2020**, *32*, e4155. [CrossRef]
14. Ntontin, K.; Di Renzo, M.; Lazarakis, F. On the Rate and Energy Efficiency Comparison of Reconfigurable Intelligent Surfaces with Relays. 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.
15. Jia, S.; Yuan, X.; Liang, Y.-C. Reconfigurable Intelligent Surfaces for Energy Efficiency in D2D Communication Network. *IEEE Wirel. Commun. Lett.* **2021**, *10*, 683–687. [CrossRef]
16. Zappone, A.; Di Renzo, M.; Shams, F.; Qian, X.; Debbah, M. Overhead-aware design of reconfigurable intelligent surfaces in smart radio environments. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 126–141. [CrossRef]
17. Sharma, T.; Chehri, A.; Fortier, P.; Saadane, R. Backhaul Networks and TV White Spaces (TVWS) with Implementation Challenges in 5G: A Review. In *The Proceedings of the Third International Conference on Smart City Applications*; Springer: Cham, Switzerlnad, 2020; Volume 13, pp. 954–965.
18. Bhowal, A.; Aïssa, S.; Kshetrimayum, R.S. RIS-Assisted Spatial Modulation and Space Shift Keying for Ambient Backscattering Communications. In Proceedings of the ICC 2021—IEEE International Conference on Communications, Montreal, QC, Canada, 14–23 June 2021; pp. 1–6.
19. Saber, M.; Chehri, A.; Saadane, R.; El Hafid, Y.; El Rharras, A.; Wahbi, M. Reconfigurable Intelligent Surfaces Supported Wireless Communications. *Procedia Comput. Sci.* **2021**, *192*, 2491–2501.
20. Guo, H.; Liang, Y.-C.; Chen, J.; Larsson, E.G. Weighted sum-rate maximization for intelligent reflecting surface enhanced wireless networks. In Proceedings of the 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 9–13 December 2019; pp. 1–6.
21. Kiani, G.I.; Esselle, K.P.; Weily, A.R.; Ford, K.L. Active frequency selective surface using PIN diodes. In Proceedings of the 2007 IEEE Antennas and Propagation Society International Symposium, Honolulu, HI, USA, 9–15 June 2007; pp. 4525–4528.
22. Chang, K.; Yoon, Y.J. Active frequency selective surfaces using incorporated PIN diodes. *IEICE Trans. Electron.* **2008**, *91*, 1917–1922. [CrossRef]
23. Subrt, L.; Pechac, P. Controlling propagation environments using intelligent walls. In Proceedings of the 2012 6th European Conference on Antennas and Propagation (EUCAP), Prague, Czech Republic, 26–30 March 2012; pp. 1–5.
24. Kaina, N.; Dupré, M.; Lerosey, G.; Fink, M. Shaping complex microwave fields in reverberating media with binary tunable metasurfaces. *Sci. Rep.* **2014**, *4*, 6693. [CrossRef]
25. 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. [CrossRef]
26. 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. [CrossRef]
27. Tan, X.; Sun, Z.; Jornet, J.M.; Pados, D. Increasing indoor spectrum sharing capacity using smart reflect-array. In Proceedings of the 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, 22–27 May 2016; pp. 1–6.
28. Hu, S.; Rusek, F.; Edfors, O. The potential of using large antenna arrays on intelligent surfaces. In Proceedings of the 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, Australia, 4–7 June 2017; pp. 1–6.
29. Long, R.; Liang, Y.-C.; Pei, Y.; Larsson, E.G. Active Reconfigurable Intelligent Surface Aided Wireless Communications. *IEEE Trans. Wirel. Commun.* **2021**, *20*, 4962–4975. [CrossRef]
30. Hu, S.; Rusek, F.; Edfors, O. Beyond massive MIMO: The potential of positioning with large intelligent surfaces. *IEEE Trans. Signal Process.* **2018**, *66*, 1761–1774. [CrossRef]
31. Hu, S.; Rusek, F.; Edfors, O. Beyond massive MIMO: The potential of data transmission with large intelligent surfaces. *IEEE Trans. Signal Process.* **2018**, *66*, 2746–2758. [CrossRef]

32. Liaskos, C.; Nie, S.; Tsioliaridou, A.; Pitsillides, A.; Ioannidis, S.; Akyildiz, I. A new wireless communication paradigm through software-controlled metasurfaces. *IEEE Commun. Mag.* **2018**, *56*, 162–169. [CrossRef]
33. Liaskos, C.; Nie, S.; Tsioliaridou, A.; Pitsillides, A.; Ioannidis, S.; Akyildiz, I. A novel communication paradigm for high capacity and security via programmable indoor wireless environments in next generation wireless systems. *Ad Hoc Netw.* **2019**, *87*, 1–16. [CrossRef]
34. Di, B.; Zhang, H.; Li, L.; Song, L.; Li, Y.; Han, Z. Practical hybrid beamforming with finite-resolution phase shifters for reconfigurable intelligent surface based multi-user communications. *IEEE Trans. Veh. Technol.* **2020**, *69*, 4565–4570. [CrossRef]
35. Basar, E.; Di Renzo, M.; De Rosny, J.; Debbah, M.; Alouini, M.S.; Zhang, R. Wireless communications through reconfigurable intelligent surfaces. *IEEE Access* **2019**, *7*, 116753–116773. [CrossRef]
36. Han, Y.; Tang, W.; Jin, S.; Wen, C.-K.; Ma, X. Large intelligent surface-assisted wireless communication exploiting statistical CSI. *IEEE Trans. Veh. Technol.* **2019**, *68*, 8238–8242. [CrossRef]
37. Mishra, D.; Johansson, H. Channel estimation and low-complexity beamforming design for passive intelligent surface assisted MISO wireless energy transfer. In Proceedings of the ICASSP 2019—2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Brighton, UK, 12–17 May 2019; pp. 4659–4663.
38. Taha, A.; Alrabeiah, M.; Alkhateeb, A. Enabling large intelligent surfaces with compressive sensing and deep learning. *IEEE Access* **2021**, *9*, 44304–44321. [CrossRef]
39. Chen, J.; Liang, Y.-C.; Pei, Y.; Guo, H. Intelligent reflecting surface: A programmable wireless environment for physical layer security. *IEEE Access* **2019**, *7*, 82599–82612. [CrossRef]
40. Yu, X.; Xu, D.; Schober, R. Enabling Secure Wireless Communications via Intelligent Reflecting Surfaces. In Proceedings of the 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 9–13 December 2019; pp. 1–6.
41. Elmossallamy, M.A.; Zhang, H.; Song, L.; Seddik, K.G.; Han, Z.; Li, G.Y. Reconfigurable Intelligent Surfaces for Wireless Communications:Radio-wave propagation for emerging wireless personal-communication systems Principles, Challenges, and Opportunities. *IEEE Trans. Cogn. Commun. Netw.* **2020**, *6*, 990–1002. [CrossRef]
42. Wu, Q.; Zhang, R. Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design. In Proceedings of the 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, United Arab Emirates, 9–13 December 2018; pp. 1–6.
43. Wu, Q.; Zhang, R. Beamforming optimization for intelligent reflecting surface with discrete phase shifts. In Proceedings of the ICASSP 2019—2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Brighton, UK, 12–17 May 2019; pp. 7830–7833.
44. Yu, X.; Xu, D.; Schober, R. MISO wireless communication systems via intelligent reflecting surfaces. In Proceedings of the 2019 IEEE/CIC International Conference on Communications in China (ICCC), Changchun, China, 11–13 August 2019; pp. 735–740.
45. Díaz-Rubio, A.; Asadchy, V.S.; Elsakka, A.; Tretyakov, S.A. From the generalized reflection law to the realization of perfect anomalous reflectors. *Sci. Adv.* **2017**, *3*, e1602714. [CrossRef]
46. Huang, C.; Zappone, A.; Debbah, M.; Yuen, C. Achievable rate maximization by passive intelligent mirrors. In Proceedings of the 2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Calgary, AB, Canada, 15–20 April 2018; pp. 3714–3718.
47. Huang, C.; Alexandropoulos, G.C.; Zappone, A.; Debbah, M.; Yuen, C. Energy efficient multi-user MISO communication using low resolution large intelligent surfaces. In Proceedings of the 2018 IEEE Globecom Workshops (GC Wkshps), Abu Dhabi, United Arab Emirates, 9–13 December 2018; pp. 1–6.
48. Di, B.; Zhang, H.; Song, L.; Li, Y.; Han, Z.; Poor, H.V. Hybrid Beamforming for Reconfigurable Intelligent Surface based Multi-User Communications: Achievable Rates with Limited Discrete Phase Shifts. *IEEE J. Sel. Areas Commun.* **2020**, *38*, 1809–1822. [CrossRef]
49. Wu, Q.; Zhang, R. Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming. *IEEE Trans. Wirel. Commun.* **2019**, *18*, 5394–5409. [CrossRef]
50. Basar, E. Transmission through large intelligent surfaces: A new frontier in wireless communications. In Proceedings of the 2019 European Conference on Networks and Communications, Valencia, Spain, 18–21 June 2019; pp. 112–117.
51. Liaskos, C.; Tsioliaridou, A.; Pitilakis, A.; Pirialakos, G.; Tsilipakos, O.; Tasolamprou, A.; Kantartzis, N.; Ioannidis, S.; Kafesaki, M.; Pitsillides, A.; et al. Joint compressed sensing and manipulation of wireless emissions with intelligent surfaces. In Proceedings of the 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS), Santorini, Greece, 29–31 May 2019; pp. 318–325.
52. Liaskos, C.; Tsioliaridou, A.; Nie, S.; Pitsillides, A.; Ioannidis, S.; Akyildiz, I. An interpretable neural network for configuring programmable wireless environments. 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.
53. Yue, D.-W.; Nguyen, H.H.; Sun, Y. mmWave Doubly-Massive-MIMO Communications Enhanced With an Intelligent Reflecting Surface: Asymptotic Analysis. *IEEE Access* **2020**, *8*, 183774–183786. [CrossRef]
54. Taha, A.; Alrabeiah, M.; Alkhateeb, A. Deep learning for large intelligent surfaces in millimeter wave and massive MIMO systems. In Proceedings of the 2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, 9–13 December 2019; pp. 1–6.
55. Tang, W.; Dai, J.Y.; Chen, M.Z.; Wong, K.-K.; Li, X.; Zhao, X.; Jin, S.; Cheng, Q.; Cui, T.J. MIMO transmission through reconfigurable intelligent surface: System design, analysis, and implementation. *IEEE J. Sel. Areas Commun.* **2020**, *38*, 2683–2699. [CrossRef]

56. Xu, P.; Chen, G.; Yang, Z.; Di Renzo, M. Reconfigurable intelligent surfaces-assisted communications with discrete phase shifts: How many quantization levels are required to achieve full diversity? *IEEE Wirel. Commun. Lett.* **2020**, *10*, 358–362. [CrossRef]
57. Zhang, L.; Wang, Y.; Tao, W.; Jia, Z.; Song, T.; Pan, C. Intelligent Reflecting Surface Aided MIMO Cognitive Radio Systems. *IEEE Trans. Veh. Technol.* **2020**, *69*, 11445–11457. [CrossRef]
58. Du, L.; Huang, C.; Guo, W.; Ma, J.; Ma, X.; Tang, Y. Reconfigurable intelligent surfaces assisted secure multicast communications. *IEEE Wirel. Commun. Lett.* **2020**, *9*, 1673–1676. [CrossRef]
59. Jung, M.; Saad, W.; Jang, Y.; Kong, G.; Choi, S. Reliability analysis of large intelligent surfaces (LISs): Rate distribution and outage probability. *IEEE Wirel. Commun. Lett.* **2019**, *8*, 1662–1666. [CrossRef]
60. Jung, M.; Saad, W.; Jang, Y.; Kong, G.; Choi, S. Performance analysis of large intelligent surfaces (LISs): Asymptotic data rate and channel hardening effects. *IEEE Trans. Wirel. Commun.* **2020**, *19*, 2052–2065. [CrossRef]
61. Jung, M.; Saad, W.; Kong, G. Performance Analysis of Active Large Intelligent Surfaces (LISs): Uplink Spectral Efficiency and Pilot Training. *IEEE Trans. Commun.* **2021**, *69*, 3379–3394. [CrossRef]
62. Di Renzo, M.; Ntontin, K.; Song, J.; Danufane, F.H.; Qian, X.; Lazarakis, F.; De Rosny, J.; Phan-Huy, D.-T.; Simeone, O.; Zhang, R.; et al. Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison. *IEEE Open J. Commun. Soc.* **2020**, *1*, 798–807. [CrossRef]
63. Yang, L.; Yang, J.; Xie, W.; Hasna, M.O.; Tsiftsis, T.; Di Renzo, M. Secrecy performance analysis of RIS-aided wireless communication systems. *IEEE Trans. Veh. Technol.* **2020**, *69*, 12296–12300. [CrossRef]
64. Yang, L.; Yang, Y.; Hasna, M.O.; Alouini, M. Coverage, Probability of SNR Gain, and DOR Analysis of RIS-Aided Communication Systems. *IEEE Wirel. Commun. Lett.* **2020**, *9*, 1268–1272. [CrossRef]
65. Di Renzo, M.; Debbah, M.; Phan-Huy, D.-T.; Zappone, A.; Alouini, M.-S.; Yuen, C.; Sciancalepore, V.; Alexandropoulos, G.C.; Hoydis, J.; Gacanin, H.; et al. Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come. *EURASIP J. Wirel. Commun. Netw.* **2019**, *2019*, 129. [CrossRef]
66. Smith, D.R.; Pendry, J.B.; Wiltshire, M.C.K. Metamaterials and negative refractive index. *Science* **2004**, *305*, 788–792. [CrossRef]
67. Huang, C.; Zappone, A.; Alexandropoulos, G.C.; Debbah, M.; Yuen, C. Reconfigurable intelligent surfaces for energy efficiency in wireless communication. In *Proceedings of the IEEE Transactions on Wireless Communications*; Institute of Electrical and Electronics Engineers Inc.: Manhattan, NY, USA, 2019; Volume 18, pp. 4157–4170.
68. Smith, D.R.; Kroll, N. Negative refractive index in left-handed materials. *Phys. Rev. Lett.* **2000**, *85*, 2933. [CrossRef]
69. Smith, D.R.; Pendry, J.B. Homogenization of metamaterials by field averaging. *JOSA B* **2006**, *23*, 391–403. [CrossRef]
70. Pendry, J.B.; Schurig, D.; Smith, D.R. Controlling electromagnetic fields. *Science* **2006**, *312*, 1780–1782. [CrossRef] [PubMed]
71. Kamoda, H.; Iwasaki, T.; Tsumochi, J.; Kuki, T.; Hashimoto, O. 60-GHz electronically reconfigurable large reflectarray using single-bit phase shifters. *IEEE Trans. Antennas Propag.* **2011**, *59*, 2524–2531. [CrossRef]
72. Armghan, A.; Hu, X.; Yuan, S.; Xia, J. Negative refractive index metamaterial structure using SRR by incidenting the light horizontally. *J. Electromagn. Anal. Appl.* **2015**, *7*, 276. [CrossRef]
73. Kossifos, K.M.; Antoniades, M.A.; Georgiou, J.; Jaafar, A.H.; Kemp, N.T. An optically-programmable absorbing metasurface. In Proceedings of the 2018 IEEE International Symposium on Circuits and Systems (ISCAS), Florence, Italy, 27–30 May 2018; pp. 1–5.
74. Zhang, S.; Zhang, H.; Di, B.; Tan, Y.; Di Renzo, M.; Han, Z.; Poor, H.V.; Song, L. Intelligent omni-surface: Ubiquitous wireless transmission by reflective-transmissive metasurface. *arXiv* **2020**, arXiv:2011.00765.
75. Zhang, H.; Di, B.; Song, L.; Han, Z. *Reconfigurable Intelligent Surface-Empowered 6G*; Springer: Berlin/Heidelberg, Germany, 2021.
76. Smith, D.R.; Yurduseven, O.; Mancera, L.P.; Bowen, P.; Kundtz, N.B. Analysis of a waveguide-fed metasurface antenna. *Phys. Rev. Appl.* **2017**, *8*, 54048. [CrossRef]
77. Molero, C.; Palomares-Caballero, Á.; Alex-Amor, A.; Parellada-Serrano, I.; Gamiz, F.; Padilla, P.; Valenzuela-Valdés, J.F. Metamaterial-Based Reconfigurable Intelligent Surface: 3D Meta-Atoms Controlled by Graphene Structures. *IEEE Commun. Mag.* **2021**, *59*, 42–48. [CrossRef]
78. Dai, J.Y.; Zhao, J.; Cheng, Q.; Cui, T.J. Independent control of harmonic amplitudes and phases via a time-domain digital coding metasurface. *Light Sci. Appl.* **2018**, *7*, 90. [CrossRef]
79. Zhu, B.O.; Chen, K.; Jia, N.; Sun, L.; Zhao, J.; Jiang, T.; Feng, Y. Dynamic control of electromagnetic wave propagation with the equivalent principle inspired tunable metasurface. *Sci. Rep.* **2014**, *4*, 4971. [CrossRef]
80. Asadchy, V.S.; Albooyeh, M.; Tcvetkova, S.N.; Díaz-Rubio, A.; Ra'di, Y.; Tretyakov, S.A. Perfect control of reflection and refraction using spatially dispersive metasurfaces. *Phys. Rev. B* **2016**, *94*, 75142. [CrossRef]
81. Rengarajan, S.R.; Rahmat-Samii, Y. The field equivalence principle: Illustration of the establishment of the non-intuitive null fields. *IEEE Antennas Propag. Mag.* **2000**, *42*, 122–128. [CrossRef]
82. Turpin, J.P.; Bossard, J.A.; Morgan, K.L.; Werner, D.H.; Werner, P.L. Reconfigurable and tunable metamaterials: A review of the theory and applications. *Int. J. Antennas Propag.* **2014**, *2014*, 429837. [CrossRef]
83. Boardman, A.D.; Grimalsky, V.V.; Kivshar, Y.S.; Koshevaya, S.V.; Lapine, M.; Litchinitser, N.M.; Malnev, V.N.; Noginov, M.; Rapoport, Y.G.; Shalaev, V.M. Active and tunable metamaterials. *Laser Photonics Rev.* **2011**, *5*, 287–307. [CrossRef]
84. Liu, F.; Pitilakis, A.; Mirmoosa, M.S.; Tsilipakos, O.; Wang, X.; Tasolamprou, A.C.; Abadal, S.; Cabellos-Aparicio, A.; Alarcón, E.; Liaskos, C.; et al. Programmable metasurfaces: State of the art and prospects. In Proceedings of the 2018 IEEE International Symposium on Circuits and Systems (ISCAS), Florence, Italy, 27–30 May 2018; pp. 1–5.

85. Liaskos, C.; Tsioliaridou, A.; Pitsillides, A.; Akyildiz, I.F.; Kantartzis, N.V.; Lalas, A.X.; Dimitropoulos, X.; Ioannidis, S.; Kafesaki, M.; Soukoulis, C.M. Design and development of software defined metamaterials for nanonetworks. *IEEE Circuits Syst. Mag.* **2015**, *15*, 12–25. [CrossRef]
86. Abadal, S.; Liaskos, C.; Tsioliaridou, A.; Ioannidis, S.; Pitsillides, A.; Solé-Pareta, J.; Alarcón, E.; Cabellos-Aparicio, A. Computing and communications for the software-defined metamaterial paradigm: A context analysis. *IEEE Access* **2017**, *5*, 6225–6235. [CrossRef]
87. Mihovska, A.; Sarkar, M. Smart connectivity for internet of things (IoT) applications. In *New Advances in the Internet of Things*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 105–118.
88. Dajer, M.; Ma, Z.; Piazzi, L.; Prasad, N.; Qi, X.-F.; Sheen, B.; Yang, J.; Yue, G. Reconfigurable Intelligent Surface: Design the Channel—A New Opportunity for Future Wireless Networks. *Digit. Commun. Netw.* **2020**, 1–22. [CrossRef]
89. Wang, P.; Fang, J.; Yuan, X.; Chen, Z.; Li, H. Intelligent reflecting surface-assisted millimeter wave communications: Joint active and passive precoding design. *IEEE Trans. Veh. Technol.* **2020**, *69*, 14960–14973. [CrossRef]
90. Zhang, Z.; Dai, L.; Chen, X.; Liu, C.; Yang, F.; Schober, R.; Poor, H.V. Active RIS vs. passive RIS: Which will prevail in 6G? *arXiv* **2021**, arXiv:2103.15154.
91. Ismail, M.Y.; Inam, M. Liquid crystal based reconfigurable reflectarray antenna design. *Int. J. Electr. Comput. Energ. Electron. Commun. Eng.* **2016**, *10*, 52–56.
92. Zhang, F.; Zhao, Q.; Zhang, W.; Sun, J.; Zhou, J.; Lippens, D. Voltage tunable short wire-pair type of metamaterial infiltrated by nematic liquid crystal. *Appl. Phys. Lett.* **2010**, *97*, 134103. [CrossRef]
93. Zografopoulos, D.C.; Beccherelli, R. Tunable terahertz fishnet metamaterials based on thin nematic liquid crystal layers for fast switching. *Sci. Rep.* **2015**, *5*, 13137. [CrossRef]
94. Foo, S. Liquid-crystal reconfigurable metasurface reflectors. In Proceedings of the 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, USA, 9–14 July 2017; pp. 2069–2070.
95. 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. [CrossRef]
96. 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. [CrossRef]
97. 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. [CrossRef]
98. 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. [CrossRef]
99. 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. [CrossRef] [PubMed]
100. 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. [CrossRef]
101. 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.
102. 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. [CrossRef] [PubMed]
103. 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.
104. 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. [CrossRef]
105. 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. [CrossRef]
106. He, J.; Leinonen, M.; Wymeersch, H.; Juntti, M. Channel estimation for RIS-aided mmWave MIMO channels. *arXiv* **2020**, arXiv:2002.06453.
107. 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. [CrossRef]
108. 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.
109. 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. [CrossRef]
110. 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.
111. Alnwaimi, G.; Boujemaa, H. Hybrid RF/FSO communications through Reconfigurable Intelligent Surfaces in the presence of pointing errors. *Telecommun. Syst.* **2021**, *78*, 155–162. [CrossRef]

112. 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. [CrossRef]
113. 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. [CrossRef]
114. 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. [CrossRef]
115. Salhab, A.M.; Yang, L. Mixing RIS-Assisted Sources with FSO Link. *arXiv* **2020**, arXiv:2011.05612.
116. 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.
117. 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. [CrossRef]
118. 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. [CrossRef]
119. 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. [CrossRef]
120. 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. [CrossRef]
121. 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.
122. 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.