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Reconfigurable Intelligent Surfaces for Enhanced Wireless Communication

Abstract:

The future of mobile communications seems promising, with possible new applications and demanding needs for forthcoming sixth-generation (6G) and subsequent wireless networks. Since the advent of modern wireless communications, the propagation medium has been regarded as a stochastic entity between the transmitter and receiver, which diminishes the quality of the received signal due to the unpredictable interactions of transmitted radio waves with surrounding objects. The recent emergence of reconfigurable intelligent surfaces in wireless communications allows network operators to manipulate the scattering, reflection, and refraction properties of radiowaves, therefore mitigating the adverse impacts of natural wireless propagation. Recent findings indicate that reconfigurable intelligent surfaces may proficiently manipulate the wavefront, including phase, amplitude, frequency, and polarization of incoming signals, without necessitating intricate decoding, encoding, or radio frequency processing procedures. This article aims to furnish readers with a comprehensive overview and historical context of cutting-edge solutions, elucidate the fundamental distinctions from other technologies, identify critical open research challenges, and explain why the implementation of reconfigurable intelligent surfaces requires a reevaluation of the communication-theoretic models currently utilized in wireless networks. This paper examines the theoretical performance limitations of reconfigurable intelligent surface-assisted communication systems via mathematical methodologies and discusses possible applications of intelligent surfaces in 6G and future wireless networks.

Introduction

Cisco's February 2019 estimate indicates that by 2022, the number of networked devices and connections would reach 28.5 billion, with 12.3 billion including mobile-ready devices and connections. The assistant editor responsible for the paper assessment and its publication approval was Feng Li. Moreover, the total mobile data traffic is projected to reach 77 exabytes per month by 2022, representing a seven-fold increase from 2017. In June 2018, following years of research and development, the first commercial 5th generation (5G) mobile communication standard (3GPP Release 15) was finalized. By mid-2019, 5G wireless networks had been implemented in select nations, and the first 5G-compatible mobile devices were being launched in the market. The emergence of 5G has introduced a new paradigm in mobile communications, including three distinct use cases with varying requirements: increased mobile broadband, ultra-reliable low-latency communications, and enormous machine-type communications. Nonetheless, it has become evident throughout the standardization of 5G wireless networks that no one enabling technology can fulfill all 5G application needs. From this vantage

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point, researchers have started investigations into beyond 5G and even sixth generation (6G) technology, moving beyond the confines of 5G-centric solutions. Although prospective 6G technologies currently appear to be an extension of existing 5G technologies, akin to the perception of 5G a decade ago, emerging user demands, novel applications and use cases, and evolving networking trends will introduce more complex communication engineering challenges, thereby requiring fundamentally new communication paradigms, particularly at the physical layer.

Microwave modulators may efficiently modify complicated existing microwave fields in echoing settings using passive means with non-coherent energy feedback. The authors demonstrated that binary-only phase state adjustable meta-surfaces provide effective control of waves, due to the stochastic characteristics of the electromagnetic fields in complex media. Subsequent studies by the same group of researchers are located in [43], [44].

An alternative method for acquiring reconfigurable and intelligent reflect-arrays is the use of varactor-tuned resonators [45], as seen in Fig. 4. This approach aims to modify the resonant frequency of the existing patches using electrical tuning, rather than altering the size of the resonators as is done in non-reconfigurable reflect arrays. In this configuration, a tunable capacitor (varactor) is used in each reflector unit, and a tunable phase shift is achieved by modifying the bias voltage given to the varactor to alter its capacitance. A smart reflector of 48 patch components is made using this methodology in [46]. The electromagnetic response of the patch components may be modified by the use of microcontrollers, which provide input signals to adjust the varactors and vary the phase of the reflected signal. An improved reflect-array including 224 reconfigurable patches is proposed in [47] for application to 60 GHz WiFi signals, using electronically-controlled relay switches.

In this system, each reflector may be activated or deactivated based on the condition of its switch. A beam searching-based reflect-array control technique is shown, wherein the access point (AP) and the reflect-array engage in beam searching to optimize signal quality for the intended user. However, because to hardware constraints, binary phase control (two potential phases) is used, resulting in a deterioration of the received signal-to-noise ratio (SNR).

The idea of HyperSurfaces involves applying small layers of electromagnetic (EM) material to things, such as walls or furniture, to manipulate the electromagnetic characteristics of a wireless environment by software [22]. The HyperSurfaces are part of the category of software-controlled meta-surfaces.

The states of electronic switches implanted in the meta-surface govern the current distribution, allowing the meta-surface to adjust its reaction based on the incident radio wave and the intended outcome. From this viewpoint, one may readily see the conceptual resemblance between This

FIGURE 5. Reflection from a Reconfigurable Intelligent Surface (RIS) in a dual-hop communication situation without a direct line-of-sight link between the source (S) and destination (D).

Implementation of a metasurface with reconfigurable antennas, whereby the resultant radiation pattern is modified by altering the current distribution. In [22], the component meta-surfaces seen in Fig. 2 are designated as "tiles," which are rectangular structures capable of executing operations such as wave steering, wave polarization, and wave absorption in a software-defined manner. A Hyper-Surface tile facilitates many software-defined electromagnetic functions, which may be programmed by configuring the direction of the incoming wave, the desired reflection direction, and the relevant frequency range, among other parameters. Liquid-crystal reconfigurable metasurface-based reflectors are suggested in [48], using electrically adjustable liquid crystals to provide the real-time reconfigurability of the metasurfaces for beam steering. By altering DC voltages on microstrip patches of liquid crystal-loaded unit cells, the effective dielectric constant of each unit may be modified. Thus, the phase changes at different positions of a meta-surface may be regulated in real-time, allowing for the manipulation of the reflected wave.

Controlling The Multipath Through Reconfigurable Intelligent Surfaces

This section delineates the system model of a generic RIS-based single-input single-output (SISO) scheme and establishes a unified framework for calculating the symbol error probability (SEP) by deriving the distribution of the received SNR. The block diagram of the analyzed RIS-based transmission scheme is illustrated in Fig. 5, where hi and gi represent the fading channels between the single-antenna source (S) and the RIS, and between the RIS and the single-antenna destination (D) for the ith reflecting meta-surface (i = 1, 2, ..., N), with N denoting the total number of reflecting meta-surfaces of the RIS. Assuming Rayleigh fading channels, we obtain hi; gi ~ CN(0, 1), where CN(0, _2) denotes a complex Gaussian distribution with zero mean and _2 variance. For clarity, we note that, as is customary, the path loss is not included in the fading coefficients hi and gi, since it is implicitly accounted for in the (receiver) SNR defined in the subsequent section. Consequently, the configuration of the RIS resembles that shown in Fig. 2, and we posit that it offers configurable phase shifts managed and programmed by communication-centric software. In our study, we assume complete knowledge of the channel phases of hi. DO THEY FUNCTION?

The RISs are reconfigurable sheets of electromagnetic material designed to deliberately manage propagation in the environment to improve signal quality at the receiver. The RISs include of several inexpensive and passive components that may alter the incident radio waves in ways that naturally existing materials cannot. simple scenario in which the RIS comprises meta-surfaces functioning as programmable reflectors.

In contrast to other analogous technologies, such as relays and MIMO beamforming, the RISs do not need any power supply or intricate processing, encoding, and decoding methods.

It is noteworthy that RISs are sometimes termed software-defined surfaces (SDSs), drawing a parallel to the notion of software-defined radio (SDR), which is defined as "a radio in which some or all physical layer functions are software-defined."

In this context, a RIS might be seen as an SDS with a software-programmed reaction to radio waves. This section elucidates the operational concept of RISs in a straightforward but comprehensive manner.

In [41], the authors presented intelligent walls integrated with frequency-selective surfaces. The surfaces possess a planar configuration, with PIN diodes integrated into the metallic connecting components of each surface element. The PIN diodes are activated and deactivated by an external bias, offering two distinct states for the intelligent wall. In the first condition (when the PIN diodes are deactivated), a nearly transparent surface is achieved, permitting the passage of incoming energy. Conversely, when the PIN diodes transition to the second state, the predominant portion of the incident energy is reflected. In other terms, two significant electromagnetic functions (the waves either transmit through or are reflected off the surface) are manifested by an intelligent wall. Figure 3 depicts the configuration of this intelligent wall.

In [42], the authors constructed a 0.4 m² spatial microwave modulator with 102 adjustable electromagnetic reflectors, functioning at a frequency of 2.47 GHz. These 102 reflectors are managed by two Arduino 54-channel digital controllers. The authors demonstrated that spatial and gi for i = 1, 2, ..., N at the RIS is the optimal situation for system functionality and establishes a performance baseline for actual implementations.

Reconfigurable Intelligent Surface As A Low-Complexity And Energy-Efficient Transmitter

This section examines the possibilities of using RISs as a technology that facilitates low-complexity and energy-efficient implementations of MIMO transmitters. The fundamental concept involves lighting a reconfigurable intelligent surface (RIS) with a feeder antenna and encoding the data for transmission onto the phases of the signals reflected off the several reconfigurable meta-surfaces that constitute the RIS. If the RIS has N reconfigurable meta-surfaces, each capable of independent optimization of its reflection phase, then a virtual MIMO system with N streams may be achieved with a single RF active chain [1].

A comparable technique, however not reliant on reconfigurable meta-surfaces, is the notion of symbiotic radio, whereby a backscatter device encodes its information onto an incoming signal from a transmitter by altering its reflection coefficient [51]. This technique resembles distributed SM used in relay-assisted systems [52]. The concept of using a Reconfigurable Intelligent Surface (RIS) as a transmitter has recently been proven via a testbed platform. In [53], the authors have developed an 8-PSK transmitter that employs a programmable surface including 256 reconfigurable components. Altering the bias voltage of varactor diodes achieves a great resolution in phase modulation. The scientists demonstrated that an unmodulated carrier may be modulated by the reconfigurable metasurface using a set of digital-to-analog converters that regulate bias voltages. In [54], the same authors developed a virtual quadrature phase shift keying (QPSK) constellation using the same idea and employing a smaller reconfigurable meta-surface composed of 128 reconfigurable pieces. Reference [55] examines the concept of simultaneous passive beamforming and data transfer within the framework of a RIS-assisted uplink transmission method. In this situation, the authors examined the connection between a multi-antenna base station (BS) and a single-antenna user, whereby the on/off states of the RIS components transmit supplementary data.

These findings validate the capability of RISs to provide low-complexity MIMO transmitters with several comparable radiating parts, using little, maybe a single, RF chain.

This section examines the error performance of RISs when used as transmitters. For the sake of simplicity, a single-stream transmitter is assumed. Figure 8 illustrates the block diagram of the examined RIS-based approach. The RIS is lighted by a proximate RF signal generator or incorporates an attachment that sends an unmodulated carrier signal cos(2πfct) at a certain carrier frequency fc towards the RIS. The unmodulated carrier is produced by an RF DAC equipped with internal memory and a power amplifier, while information bits are sent only via the reflection-induced phases of the RIS. We assume that the RF source is sufficiently proximate to the RIS such that its transmission is unaffected by fading. Conversely, the channel between the ith reflector of the RIS and D is represented

In the examined communication context, RIS-induced phases provide information while also executing clever reflections that enhance the received SNR. The RIS modifies the phases of its reflecting components to optimize the reflected phases that enhance the received SNR while simultaneously aligning the reflected signals to form a virtual two-dimensional M-ary signal constellation diagram.

Potential Use Cases

This section briefly examines many application situations where RISs may significantly contribute to improving coverage probability, spectrum efficiency, and energy efficiency, or to diminishing implementation complexity and power consumption in wireless networks. Five possible use cases are briefly examined. Addressing Non-LOS Scenarios A prospective use of RISs in wireless networks is their utilization as reconfigurable reflectors in situations when the line-of-sight route is obstructed or insufficiently robust to accommodate cell-edge users. For instance, RISs may be readily affixed to walls or ceilings inside and can be incorporated into the exterior of buildings outside.

This application scenario seems pertinent in the high-frequency transmission range, namely inside the millimeter-wave spectrum, the D-band spectrum (exceeding 100 GHz), and the visible light spectrum. In such instances, the line of sight (LOS) path is frequently impeded, making the establishment of robust and reconfigurable non-LOS links a compelling application, particularly due to the favorable scaling laws related to distance and the quantity of reflecting meta-surfaces discussed in Section II. Recent field testing conducted by researchers from NTT Docomo and Metawave Corporation have validated the applicability and potential benefits of this case study for automotive networks .

Addressing Localized Coverage Gaps _ An other intriguing case study is using RISs to mitigate localized coverage gaps in urban settings and challenging indoor propagation circumstances. In several large and heavily populated locations globally, there are isolated dead zones where signal quality is inadequate.

Comparable challenges arise in enclosed settings, such as industrial plants and subterranean metro stations. In these situations, traditional methods to address coverage gaps include the deployment of additional base stations or relays/repeaters. Regrettably, these solutions are costly and augment the carbon footprint of wireless communications. The use of RISs is, conversely, a cost-efficient and environmentally sustainable way to address the issues of localized coverage gaps.

Mitigating Electromagnetic Pollution Unlike other communication technologies, a primary characteristic of RISs is their ability to recycle radio waves in a constructive and energy-efficient way. Multipath propagation is often seen as uncontrollable and is typically mitigated by increasing the complexity of transmitters and receivers. This often involves augmenting the quantity of radio waves transmitted, for instance, by installing extra base stations or relays, which generate supplementary signals in the surroundings. This leads to an escalation in the output of electromagnetic radiation. The implementation of RISs, meanwhile, does not anticipate the creation of new signals, but rather their astute use. The notion of RISs presents a viable approach for reducing EM radiation levels, particularly in environments such as hospitals and airlines.

Energy-Free Internet of Things The Internet of Things is considered a crucial element of 5G and 6G wireless networks.

The potential for gathering data from several sensors distributed throughout the network has a multitude of uses. These devices are anticipated to transmit the detected data to fusion centers, which are responsible for the further processing and analysis. The overall energy need for these devices to transmit sensed data is significant and represents a critical limitation to the widespread adoption of IoT technology. The integration of Reconfigurable Intelligent Surfaces (RISs) with backscatter communications is a viable option for enabling Internet of Things (IoT) devices to transmit sensed data in an energy-efficient way. Envision the creation of garments and IoT devices using reconfigurable meta-surfaces that can alter reflected waveforms based on detected data. Utilizing the backscatter communications technique, the detected data may be included into the reflected signals without incurring overhead or energy expenditure .

Low-Complexity and Energy-Efficient Massive Transmitters The benefits of using MIMO, and more recently, huge MIMO, are indisputable. Nonetheless, these advantages are not acquired without cost. The advantages of MIMO are often accompanied by the need for a number of RF chains that matches the quantity of radiating devices. The complexity and power consumption involved with using several antennas cannot be underestimated. The use of RISs as transmitters presents a unique possibility to implement extensive antenna arrays with minimal, maybe a single, RF chain. The newly established testbed in and exemplifies the feasibility of achieving low-complexity massive MIMO via the use of SM, MBM, and, more broadly, IM concepts.

Conclusion

This article summarizes recent research activity in the growing field of RIS-empowered wireless networks. We have delineated the primary distinctions that classify RISs as a novel technology in contrast to ostensibly analogous technologies, such as relaying and backscatter communications.

We have delineated two potential applications to exploit the capabilities of RISs in wireless networks: to manipulate radio waves to deterministically govern multipath propagation, such as directing signals reflected from walls towards specified orientations, and to develop low-complexity, energy-efficient transmitters that necessitate only a minimal, ideally singular, active RF chain. The error probability of both implementations has been analyzed using the Central Limit Theorem (CLT), demonstrating that the error probability displays a waterfall pattern in relation to the number of reconfigurable components of the Reconfigurable Intelligent Surfaces (RISs) and the Signal-to-Noise Ratio (SNR). Regarding the link budget analysis, we have emphasized that the concept of Reconfigurable Intelligent Surfaces (RISs) differs from relaying and backscatter communications. If their geometric dimensions are sufficiently larger than the wavelength, they can be regarded as specular reflectors, with the received power as a function of distance primarily dictated by Fermat's principle. We have delineated prospective use cases in which the RIS may assume a pivotal role and have examined essential research challenges that must be addressed to fully harness the capabilities of RISs in wireless networks.

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