

Reconfigurable Intelligent Surfaces vs. Relaying: Differences, Similarities, and Performance Comparison

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ABSTRACT

Reconfigurable intelligent surfaces (RISs) have the potential of realizing the emerging concept of smart radio environments by leveraging the unique properties of meta-surfaces. In this article, we discuss the need and potential applications of RISs in wireless networks that operate at high-frequency bands, e.g., millimeter wave (30-100 GHz) and sub-millimeter wave (greater than 100 GHz) frequencies; we overview the technology enabler of reconfigurable meta-surfaces; we elaborate on the working principle of RISs when used as low-complexity transmitters and anomalous mirrors; and we describe promising use cases that encompass signal, interference, security, and scattering engineering. When used as anomalous mirrors, the RISs resemble multiple-antenna relay stations. Therefore, we elaborate on the key differences and similarities between RISs and relaying, and, notably, illustrate numerical results that highlight the spectral efficiency gains of RISs whose transverse size is large as compared with the wavelength of the radio wave. Finally, we discuss the key open issues that need to be addressed in order to unlock the potential of RISs, and, in particular, to unveil their ultimate performance limits and to optimize their deployment in future wireless networks.

INTRODUCTION

Over the last years, there has been a continuous increase of the demand for higher data rates driven by the proliferation of smartphones and the introduction of broadband services and applications, such as virtual and augmented reality, the Internet of Things, and mobile live streaming. By 2022, it is expected that the global mobile data traffic will reach a monthly run of 77 exabytes, which corresponds to a 7-fold growth compared with the monthly run of 2017. Such demands cannot be accommodated by current cellular standards that utilize sub-6 GHz frequency bands to convey information, e.g., the Long-Term Evolution Advanced (LTE-A) standard that can offer peak data rates up to 1 Gbps. Motivated by these overwhelming demands for ever-increasing data rates, a key feature of future wireless networks is the migration to higher frequencies, e.g., the millimeter (30-100 GHz) and sub-millimeter (above 100 GHz) wave bands [1].

Extensive measurements have been conducted at the millimeter wave band and, more recently, the sub-millimeter wave band. These have demonstrated that the use of highly directional steerable antennas can enable mobile communications at such high frequencies [1]. In particular, early measurement campaigns executed at 28 GHz and conducted in New York City in 2012 revealed that, if directional antennas are used at

the transmit and receive end-points, distances up to 200 meters can be reached. However, millimeter and sub-millimeter wave frequency bands are highly susceptible to blockages from large-size structures, e.g., buildings, on the radio path [1, Tables 4, 5]. Also, millimeter- and sub-millimeter wave signals are severely attenuated by the presence of small-size objects, e.g., human bodies and foliage. For example, due to the human body, penetration losses of around 20-40 dB have been measured at the millimeter wave frequency band. In spite of their high penetration losses, such objects may act as good reflectors and scatterers for the impinging radio waves. Thanks to the resulting secondary paths, the receiver may be able to capture a sufficient signal power. To capitalize on such paths, however, the receiver generally needs to rely upon antennas with a wide beamwidth, which may result in low antenna gains. This inevitably reduces the maximum range of communication under non-line-of-sight (NLOS) conditions.

The problems highlighted above become more pronounced in dense urban environments because of the highly dynamic nature of the radio environment. Many factors, such as moving cars and humans, render, in fact, the establishment of reliable communication links challenging due to the rapidly varying propagation conditions at high frequencies. A major question is, therefore, whether such limitations can be curtailed, enabling high-rate and ultra-reliable wireless access networks at high-frequency bands and in the presence of mobility.

A possible approach for circumventing the unreliability of high-frequency channels is to sense the environment and to identify, on a real-time basis, alternative propagation routes through which the same information-bearing signal can be received. This is a realistic proposition, especially at high frequencies, since the potential interference caused by the presence of multiple propagation paths can be kept under control by the large path-loss of longer propagation routes. An established method to create additional routes for receiving the same information-bearing signal is the deployment of relay stations that capitalize on the concept of (distributed) cooperative diversity [2]. Relay stations can effectively turn a single NLOS link into multiple line-of-sight (LOS) links. This approach necessitates each relay station to be equipped with a dedicated power source and with the necessary front-end circuitry for reception, processing, and re-transmission. Thus, the use of relay stations usually reduces the network energy efficiency and increases the network complexity at run time, while requiring a larger capital expenditure for deployment.

Apart from the cost-related drawbacks highlighted above, the network spectral efficiency or relay-aided systems is reduced if a half-duplex (HD) relaying protocol is employed, since transmitters and relay stations are not allowed to trans-

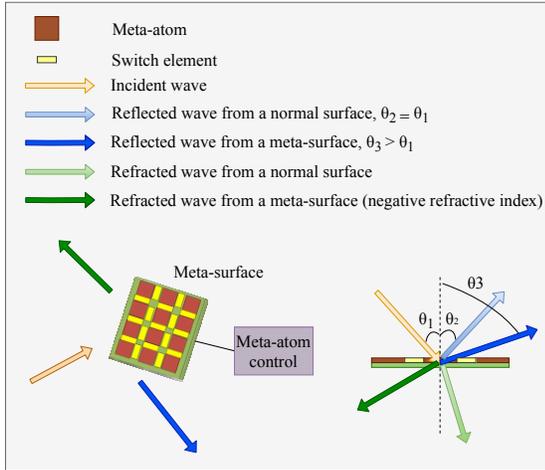


Fig. 1: Working principle of a reconfigurable meta-surface.

mit concurrently on the same physical resource. This issue can be overcome by employing a full-duplex (FD) relaying protocol, but at the cost of: (i) introducing high *loop-back self-interference* at the relay station because of the concurrent transmission and reception of signals; (ii) generating *co-channel interference* at the destination, since relay stations and transmitters emit different information data on the same physical resource; and (iii) increasing the *signal processing complexity* and the *power consumption* of the relay stations.

When the LOS path is of insufficient quality, another approach for establishing alternative routes is through *passive non-reconfigurable specular reflectors*, e.g., dielectric mirrors. This method for coverage enhancement has the potential of being more cost efficient as compared with relaying, especially at high-frequency bands. But a main limitation of non-reconfigurable reflectors is that they cannot enable the dynamic shaping of the impinging waves, since their operation cannot be modified after fabrication, i.e., at the time of deployment and operation. Due to the highly dynamic nature of the wireless environment at high frequencies, it is essential that such reflectors be capable of adaptively shaping the impinging radio waves based on actual blockage and environmental conditions. This would ideally enable the network to maximize the network coverage and throughput on a real-time basis.

Propitiously, electromagnetic-based reconfigurable structures that are capable of applying specified transformations to the impinging radio waves do exist and can operate at different frequency bands [3], [4]. They are referred to as **reconfigurable intelligent surfaces (RISs)**, and, when deployed in wireless networks, have the potential of turning the wireless environment, which is highly probabilistic in nature, into a programmable and partially deterministic space, which is referred to as **smart radio environment** [5]. The aim of this paper is to provide an introduction to this topic, with focus on the differences with relay-aided systems.

WHAT IS A RECONFIGURABLE INTELLIGENT SURFACE?

An RIS is an artificial surface, made of electromagnetic material, that is capable of altering the propagation of the radio waves impinging upon it. An example consists of reflecting surfaces whose constituent (often discrete) elements can be

programmed in order to apply arbitrary phase shifts to the signals [6], [7]. These solutions are referred to as **intelligent reflecting surfaces (IRSs)**. Large-scale testbeds for IRSs have recently been built, and have empirically proved that IRSs can enhance the signal strength by a factor of 10 and can increase the median data rate by a factor of 2 [8], [9].

A conceptually and technologically different solution consists of realizing RISs based on the two-dimensional equivalent of meta-materials, which are referred to as **meta-surfaces**. RISs based on meta-surfaces are very thin – their thickness is much smaller than the wavelength – sheets of electromagnetic material that are engineered to possess peculiar properties that cannot be found in naturally occurring materials [3]-[5]. In contrast to IRSs, RISs based on meta-surfaces are not only capable of modifying the phase of the impinging radio waves, but they can shape their wavefront in more general ways. This can be realized by reflecting and refracting the impinging signals towards anomalous directions not predicted by the Snell's law (see Fig. 1), or by changing their polarization and waveform [5]. RISs based on meta-surfaces are better viewed as continuous surfaces of electromagnetic material that modify the wavefront of the radio waves by introducing an appropriately designed phase gradient that depends on the specific function to be realized. As far as the propagation of the radio waves is concerned, an RIS based on meta-surfaces acts as an abrupt electromagnetic discontinuity that alters the scattered field. Prototypes of meta-surfaces that realize various reconfigurable functions exist [10], and their potential and achievable gains in complex reverberating media, e.g., indoor environments, have been proved since 2014 [11].

As discussed, the key element to realize multi-function RISs is a meta-surface. A meta-surface is a sub-wavelength array formed by sub-wavelength metallic or dielectric scattering particles that are referred to as meta-atoms [3]-[5]. It can be described as an electromagnetic discontinuity that is sub-wavelength in thickness, with typical values ranging from $1/10$ to $1/5$ of the wavelength, and is electrically large in transverse size. Its unique properties lie in its capability of shaping the electromagnetic waves, for reflection and transmission, in very general ways, which overcome the limitations of the phased-array principles of reflection and refraction (also known as the **generalized Snell's laws**) [12]. This is illustrated in Fig. 1, which depicts the expected reflection and refraction response of a normal surface and a meta-surface for a given angle of incidence of the electromagnetic wave.

It should be noted that meta-surfaces can be either reconfigurable or not. As mentioned, the highly dynamic nature of wireless environments requires reconfigurable meta-surfaces. In non-reconfigurable meta-surfaces, the meta-atoms have fixed structural and geometrical arrangements, which result in static interactions with the impinging radio waves that cannot be modified once they are manufactured. In **reconfigurable meta-surfaces**, the arrangements of the meta-atoms can be modified and programmed based on external stimuli. The reconfigurability can be enabled by electronic phase-changing components, such as semiconductors or graphene, which are used as switches or tunable reactive and resistive elements. They can be either inserted between adjacent meta-atoms (see

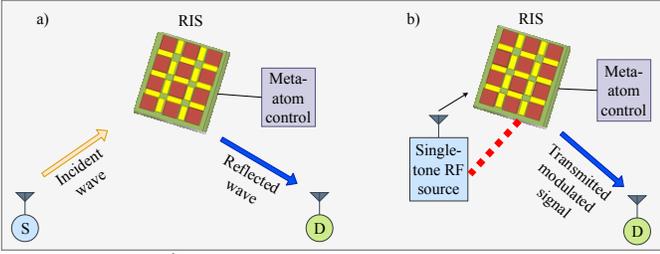


Fig. 2: An RIS operating as a multi-function “anomalous mirror” (a) and as a single-RF transmitter (b).

Fig. 1) or can be used to adjust the properties of individual meta-atoms. This way, the wavefront of the radio waves scattered by a meta-surface is manipulated by controlling the status of the switches, in order for different functions to be realized. The functions can be optimized by a central controller through software-defined networking technologies, as recently demonstrated in [3]. A major difference between static and reconfigurable meta-surfaces lies in their associated power consumption. Static meta-surfaces can be fully passive, since no active electronic circuits are needed. Reconfigurable meta-surfaces can only be **nearly passive**, since some energy is needed to control the switches. No dedicated power supply is, in general, needed for signal transmission.

In summary, based on the mentioned distinctive properties of the meta-surfaces, an RIS can be thought of as a **multi-function “anomalous mirror”**. In this paper, we are primarily interested in this use of the RISs, which is illustrated in Fig. 2(a). Also, we restrict the discussion to planar RISs, called *meta-mirrors*, but we emphasize that the meta-surfaces need not to be planar but can be made conformal to curved surfaces.

We specifically model an RIS as a collection of meta-surfaces that are capable of applying distinct functions to the impinging radio waves, such as reflecting the signals towards different directions, modifying the polarization, and applying different phase shifts. In practice, this is realized via appropriate arrangements of the meta-atoms on the same RIS.

Another promising application of the RISs in wireless systems, not covered in much detail in this paper, is the realization of **single-RF transmitters** [13], which is illustrated in Fig. 2(b). In typical multiple-antenna transmitters, the number of independent information streams that can be transmitted is equal to the number of radio frequency (RF) chains. Each RF chain usually consists of an independent power amplifier, a filter, a digital-to-analog converter (DAC), and a mixer. As a result, the complexity, power consumption, and cost of a multiple-antenna transmitter is larger than for its single-antenna counterpart [4]. Recently, it has been experimentally demonstrated that a multiple-stream transmitter can be realized by using a single-RF feeder and an RIS [13]. As illustrated in Fig. 2(b), a signal generator produces an un-modulated carrier that is radiated through an antenna towards an RIS. The un-modulated signal emitted by the antenna impinges upon the RIS, where it is phase-modulated by appropriately controlling the meta-atoms. For a given un-modulated signal impinging upon the RIS, multiple phase-modulated signals can be reflected off it by appropriately grouping and controlling the meta-atoms. If N is the number of independently controllable

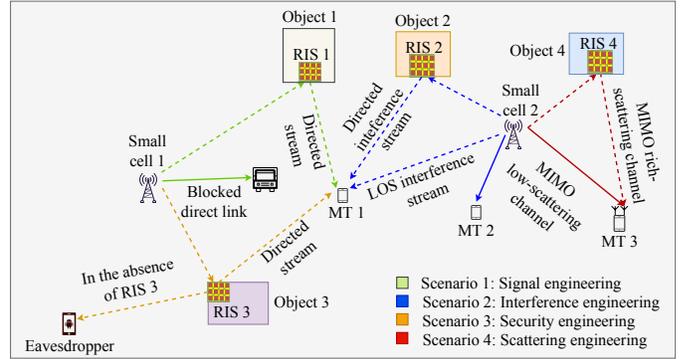


Fig. 3: Example of smart radio environment.

phases, then an N -stream transmitter can be realized with a single-RF chain. As elaborated in [4], this concept is also known as *media-based modulation*. In this implementation, the single-RF feeder and the RIS are viewed as an integral part of the transmitter, and they may be even directly connected with each other, as represented in Fig. 2(b) by the dashed line.

WIRELESS 2.0: SMART RADIO ENVIRONMENTS

From the viewpoint of the communication engineer, the wireless environment is conventionally modeled as an exogenous entity that cannot be controlled, but only adapted to. To this end, communication engineers can only design the transmitters, the receivers, and the transmission protocols in order to achieve the desired performance. Common approaches to capitalize on the properties of the wireless environment and to mitigate its impairments include using multiple antennas, employing complex encoding and decoding algorithms at the end-points of the communication link, and adding additional network infrastructure, e.g., relay stations [2], in an attempt to make the transmission of signals more reliable. These solutions, however, increase the network complexity, the power consumption, and the deployment cost. In deployments such as the Internet of Things, these approaches may not be adopted due to the design constraints at the devices [9].

RISs provide wireless researchers and engineers with a radically **new view of the wireless environment**. Since the RISs are capable of shaping the wavefront of the radio waves throughout the network, the **wireless environment can be in principle customized** to suit the system requirements. The wireless environment is not to be treated as a random uncontrollable entity, but rather as part of the network design parameters that are subject to optimization in order to support diverse performance metrics, such as rate, latency, reliability, energy efficiency, privacy, and massive connectivity.

The overarching vision is that environmental objects and devices are coated with software-controlled RISs, and, through environmental sensing and software-defined networking protocols, they can be programmed for shaping the radio propagation environment and meeting the desired system requirements [3], [5]. An illustrative example of this emerging wireless future is sketched in Fig. 3. Four application scenarios are identified: (i) **signal engineering**; (ii) **interference engineering**; (iii) **security engineering**; and (iv) **scattering engineering**.

Signal engineering: Assume that small cell 1 wishes to communicate with mobile terminal (MT) 1, but the LOS link

is blocked by an object. In this case, small cell 1 redirects the transmitted beam towards RIS 1 that coats object 1, and assists the communication by shaping the incident wave towards MT 1 so that the received signal strength is maximized.

Interference engineering: While small cell 1 communicates with MT 1, small cell 2 communicates with MT 2. Therefore, an interfering signal reaches MT 1 from small cell 2. To suppress it at MT 1, RIS 2 is programmed to shape the impinging radio wave from small cell 2 towards MT 1 in a way that the two signals are destructively combined at MT 1.

Security engineering: In the absence of RIS 3, the signal emitted by small cell 1 and intended to MT 1 is reflected from object 3 towards a malicious user that overhears it. To avoid this, RIS 3 is programmed to shape the reflection towards MT 1 so that it is steered away from the malicious user while being decoded more reliably, via diversity combining, at MT 1.

Scattering engineering: The multiple-antenna small cell 2 wishes to convey information to the multiple-antenna MT 3 with the aid of multiple-input multiple-output transmission. The channel between small cell 2 and MT 3 has, however, a low rank (low scattering environment), which negatively affects the attainable data rate. To avoid this issue, small cell 2 directs the signal intended to MT 3 towards RIS 4, which appropriately shapes it so as to create a rich-scattering environment (high rank channel) for high data rate transmission.

From the analysis of the these four scenarios, it is apparent that, with the aid of RISs, the propagation of radio waves in wireless networks can be engineered and optimized, at a low complexity, in a way that benefits the network.

Let us further analyze the application for **interference engineering**. A widespread approach to deal with the interference from a small cell is to equip it with an adequate number of multiple antennas and corresponding RF chains, so that it can beamform the signal towards the desired direction, and, at the same time, it can suppress the interference towards the unwanted directions. This approach poses size and power consumption issues, since small cells need to be deployed on a wide scale in places that are size-limited, e.g., lampposts. By leveraging RISs, the cost of deploying small cells can be substantially reduced. The RISs, in fact, are nearly passive and can be readily deployed on the facades of buildings and walls.

RECONFIGURABLE INTELLIGENT SURFACES VS. RELAYING

In this section, we elaborate on differences and similarities between RISs that are employed as anomalous mirrors and relays. The comparison is made here on a qualitative basis, and is complemented, in the next section, with results that showcase scenarios in which the RISs constitute a promising alternative to relaying. For ease of description, we focus our attention on two-hop repetition-based relaying, decode-and-forward (DF) and amplify-and-forward (AF) protocols, and HD and FD duplexing methods. For illustrative purposes, the system scenario in Fig. 4 is considered as a reference.

A. Hardware Complexity

Relay stations are active devices that need a dedicated power source for operation. They are equipped with active electronic components, such as DACs and analog-to-digital converters

(ADCs), mixers, power amplifiers for transmission, and low-noise amplifiers for reception. The electronic components that are typically needed for implementing DF and AF relaying are discussed and illustrated in [2, Ch. 5]. The deployment space of relays can, thus, be costly and power-consuming, especially for realizing multiple-antenna designs at millimeter and sub-millimeter wave frequency bands [1]. If, in addition, FD relays are used, the complexity is further increased due to the need of canceling the loop-back self-interference by using tailored antennas, and analog/digital signal processing methods.

In contrast, RISs are meant to be realized with minimal hardware complexity not requiring dedicated power amplifiers, mixers, and DACs/ADCs. As discussed, the operating principle of RISs is based on appropriately designing the distribution of the currents induced by the incident waves on their surface, in order to implement the desired function [10]-[12]. RISs are composite material layers that are made of metallic or dielectric patches printed on a grounded dielectric substrate. Their reconfigurability is ensured through low-power and low-complexity electronic circuits (switches or varactors). As for the hardware complexity, the RISs are aimed to be of much lower complexity than relay stations, especially at mass production and if realized by using inexpensive large-area electronics. An example of large-size RIS made of inexpensive antennas can be found in [9]. In contrast to other implementations, e.g., tunable reflect-arrays, the use of sub-wavelength reconfigurable meta-surfaces ensures a finer-grained control and shaping of the radio waves in both the near and far fields.

B. Noise

The active electronic components used in relay stations are responsible for the presence of additive noise that negatively affects the performance of relaying protocols. In AF relaying, the noise is amplified at the relay stations. The impact of additive noise can be mitigated by employing DF relaying, at the expense of decoding and re-encoding (regeneration) the signal at the relay stations and increasing the signal processing complexity and power consumption. In FD relaying, the impact of residual loop-back self-interference further deteriorates the system performance. The RISs behave, on the other hand, as anomalous mirrors, and, therefore, they are not affected by additive noise. The RISs may, however, be affected by phase noises and they cannot amplify or regenerate the signals [4].

C. Spectral Efficiency

The spectral efficiency of relaying systems depends on the adopted duplexing protocol. Under HD relaying, the achievable rate is generally scaled down by a factor of two since different physical resources are used for the data emitted by the transmitter and by the relay station. The end-to-end signal-to-noise ratio can be increased by optimally combining the direct and relayed signals. Under FD relaying, the achievable rate is not scaled down by a factor of two, but the relay station is affected by the residual loop-back self-interference, and the receiver is impaired by the interference generated by the concurrent transmission of the transmitter. RISs behaving as anomalous mirrors are not subject to the half-duplex constraint and the loop-back self-interference. Also, the phase gradient of the meta-surfaces can be designed for optimally combining the signals received from the transmitter and the RIS.

D. Power Budget

Relay stations need an independent power source for operation, which is used for transmitting the signals (RF power) and for powering up their electronic components. In contrast, the RISs are suitable for nearly passive implementations, since non-reconfigurable meta-surfaces can be realized with fully passive components, and low-power active components (switches or varactors) are needed only for ensuring their reconfigurability. The low-power nature of switches and varactors makes the use of energy harvesting a suitable candidate for realizing close-to-passive implementations. For relaying, it is usually assumed that the total RF power is allocated between the transmitter and the relay, so as to ensure a total power constraint. In RISs, the transmitter uses the total RF power. Also, the power reflected or scattered by the RIS depends on its transmittance, which can be made close to one if the meta-surface is appropriately designed and optimized [14]. In the ideal case, the total power reflected or scattered by the RIS is the same as the total RF power received from the transmitter.

E. Average Signal-to-Noise Ratio vs. Number of Elements

Let us consider a multiple-antenna relay station, as illustrated in Fig. 4, and that it employs maximum ratio weighting for reception and transmission. If N antennas are used at the relay, the average end-to-end signal-to-noise ratio increases *linearly* with N [2]. Recently, it has been analytically proved in [4] and empirically substantiated, for discrete antennas, in [9] that the average end-to-end signal-to-noise ratio of an RIS constituted by N individually reconfigurable elements increases *quadratically* with N , while still being subject to the energy conservation principle. This is due to the fact that, in relay stations, the RF power is allocated among the N antennas so that the total RF power is kept constant. In RISs, in contrast, each constituent meta-surface acts as a separable anomalous mirror, which reflects, after scaling by the transmittance and with no noise addition, the same amount of RF power received from the transmitter. It is worth mentioning, however, that the more favorable scaling law as a function on N does not necessarily imply that the RISs outperform relaying. For a fixed total power constraint, in fact, the path-loss as a function of the transmission distance cannot be overlooked. This is discussed next by considering, for ease of exposition, a free-space propagation model.

F. Average Signal-to-Noise Ratio vs. Transmission Distance

In relay stations with N antenna elements, the distance between adjacent antennas is, usually, of the order of $\lambda/2$, where λ is the wavelength of the radio wave. By optimistically excluding the space needed for accommodating multiple RF chains (amplifiers, ADCs/DACs, mixers), the geometric area occupied by a planar deployment would be of the order of $N\lambda^2/4$. In this case, the end-to-end power received from an AF relay scales with the product of the transmitter-to-relay distance and the relay-to-receiver distance [2], i.e., as $(d_{\text{SR}}^2 d_{\text{RD}}^2)^{-1}$ by using the notation in Fig. 4. When considering the effect of noise, the end-to-end signal-to-noise ratio of both DF and AF relaying scales with the distance of the weakest of the two paths, i.e., as $\min\{d_{\text{SR}}^{-2}, d_{\text{RD}}^{-2}\}$. By

coherently combining the signals from the N antennas at the relay, the scaling law is, therefore, $N \min\{d_{\text{SR}}^{-2}, d_{\text{RD}}^{-2}\}$ [2].

The total power scattered by an RIS, and, therefore, the scaling law of the received power as a function of the distance, depends on the relation between the geometric size of each meta-surface of the RIS and the wavelength of the radio wave. In this paper, two regimes need to be distinguished: (i) **anomalous reflection** and (ii) **diffuse scattering**. In the sequel, these two regimes are also referred to as “**electrically large RISs**” and “**electrically small RISs**”, respectively.

Anomalous reflection: If the geometric size of each constituent meta-surface of the RIS is large enough as compared with the wavelength of the radio wave, e.g., it is ten times (one order of magnitude) larger than λ [3], [4], then each meta-surface behaves, approximately, as an anomalous reflector (mirror). In this case, the power received from each meta-surface and the end-to-end average signal-to-noise ratio scale, as function of the distance, as $(d_{\text{SR}} + d_{\text{RD}})^{-2}$ [14]. This scaling law is employed in state-of-the-art software for ray tracing [1]. Anomalous reflection is, in fact, often referred to as *geometric scattering*, and the laws of geometric optics are sufficient to analyze it. If the meta-surfaces are uniform, i.e., they do not introduce any phase gradients, they behave, approximately, as specular reflectors (i.e., their response adhere to Snell’s law). By combining the signals from the N meta-surfaces of the RIS, the scaling law is $N^2(d_{\text{SR}} + d_{\text{RD}})^{-2}$.

Diffuse scattering: If the size of each meta-surface of the RIS is of the order of the wavelength of the radio wave, then each of them behaves, approximately, as a dipole scatterer, i.e., a diffuser [15]. If the signals from the N meta-surfaces of the RIS are combined together, the received power and the end-to-end average signal-to-noise ratio scale as $N^2(d_{\text{SR}}^2 d_{\text{RD}}^2)^{-1}$ [1], [15]. As a function of the distance, this is the same scaling law as for the received power of AF relaying.

It is worth noting that the behavior of an RIS as an anomalous mirror and as a diffuser has some resemblance, even though the underlying physical phenomena are slightly different, with the propagation mechanisms of specular reflections and diffuse scattering that occur when the radio waves impinge on the surfaces of objects [1, Fig. 2], [2, Fig. 2.2].

Main Takes: For simplicity, let us ignore the direct path in Fig. 4, and assume $d_{\text{SR}} = d_{\text{RD}} = d/2$, i.e., the RIS/relay is located equidistantly from the transmitter and receiver. Then, the average end-to-end signal-to-noise ratio scales as: (i) $4Nd^{-2}$ for a relay station; (ii) $4N^2d^{-2}$ for an electrically large RIS; and (iii) $16N^2d^{-4}$ for an electrically small RIS.

Take 1: From the discussed scaling behavior, it is apparent that an electrically large RIS has the potential of outperforming relaying because of the better scaling law of the received power as a function of N . Even if $N = 1$, an electrically large RIS can potentially outperform a relay due to the absence of noise amplification, loop-back self-interference, and half-duplex constraint. To appreciate the practical value of electrically large RISs, it is sensible to investigate their expected geometric size as compared with relays. As mentioned, the typical size of a relay with N antennas is of the order of $N\lambda^2/4$, and the typical size of an RIS with N reconfigurable meta-surfaces that act as anomalous mirrors is of the order of

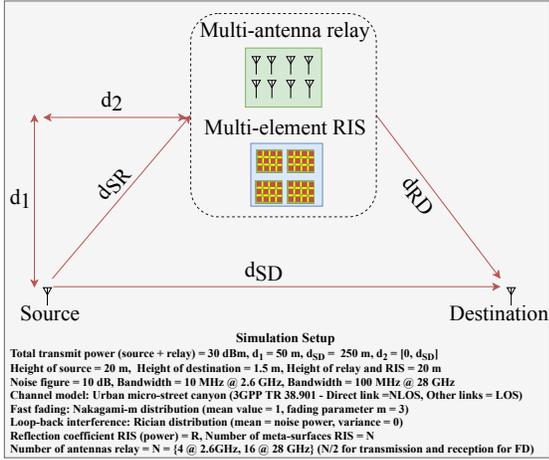


Fig. 4: Simulation scenario and setup.

$N(10\lambda)^2$. Even when the space necessary for the N RF chains, power amplifiers, and associated circuitry of the relays is not taken into account, it is reasonable to argue that the number of meta-surfaces that act as independent anomalous mirrors cannot be too large for practically viable geometric sizes of the RISs. For example, an RIS of 1 m^2 in size can accommodate only one reconfigurable meta-surface if it operates at 3 GHz and 100 reconfigurable meta-surfaces if it operates at 30 GHz.

To sum up, electrically large RISs are a suitable technology for implementing low-complexity anomalous mirrors at millimeter wave and sub-millimeter wave frequency bands.

Take 2: In spite of the quadratic scaling law of the average signal-to-noise ratio as a function of N , electrically small RISs are expected to provide worse performance than relays because of the unfavorable scaling law as a function of the distance. Electrically small RISs are more suitable either for implementing single-RF multi-stream transmitters (see Fig. 2(b)), since the distance from the feeder to the RIS can be ignored, or when they are deployed sufficiently close to the receiver for local coverage enhancement [6], [7]. In the former case, the average signal-to-noise ratio per information stream scales as $d_{RD}^{-2} = 4d^{-2}$. In conventional (equipped with multi-RF chains) transmitters, by contrast, the average signal-to-noise ratio per information stream scales as $d_{RD}^{-2}/N = 4d^{-2}/N$. Electrically small RISs thus have the potential of reducing the implementation complexity and the power consumption, as well as outperforming transmitters with multiple RF chains.

To sum up, electrically small RISs are a suitable technology for implementing low-complexity transmitters at sub-6 GHz, millimeter, and sub-millimeter wave frequency bands.

NUMERICAL RESULTS

In Fig. 5, we compare the performance of RISs and relays based on the simulation setup illustrated in Fig. 4. The results are obtained by employing the analytical formulas of the data rates reported in arXiv:1908.07967. The chosen setup ensures a fair comparison between RISs and relays, since different reflection coefficients for the RISs are analyzed; an optimistic (equal to the noise power) residual loop-back self-interference model is assumed for FD relaying; and, at low frequencies, RISs with a few (even a single) reconfigurable

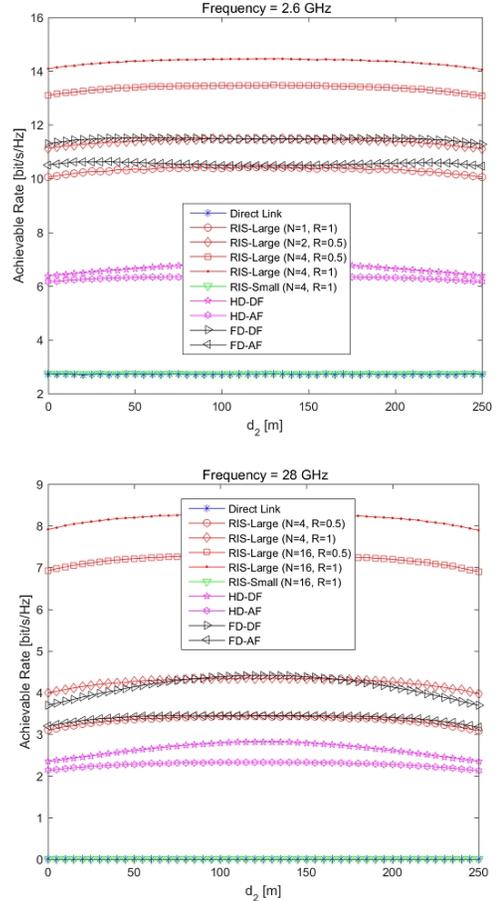


Fig. 5: Achievable data rate (bit/s/Hz) of RISs and relaying versus the distance d_2 for the setup in Fig. 4.

meta-surfaces are considered. For relaying, the transmit powers at the transmitter and relay are optimized to maximize the achievable rate while enforcing a total power constraint. In all cases, perfect channel state information is assumed.

The results unveil the promising performance offered by *electrically large RISs*, even if the reflection coefficient R is small (i.e., $R = 0.5$ so that only 50% of the total impinging power is reflected by the RIS), and $N = 1$ or $N = 2$ reconfigurable meta-surfaces can be accommodated at sub-6 GHz. We highlight three main conclusions from the analysis of Fig. 5: (i) at 2.6 GHz, RISs with $N = 1$, $R = 1$ and $N = 2$, $R = 0.5$ offer rates similar to FD-AF and FD-DF relaying with 4 antennas, optimal power allocation, and optimal transmission/reception vectors, respectively; (ii) at 28 GHz, RISs with $N = 4$, $R = 0.5$ and $N = 4$, $R = 1$ offer rates similar to 16-antenna FD-AF and FD-DF relaying with the same optimal setup as for 2.6 GHz; and (iii) RISs with $N = 4$ at 2.6 GHz and $N = 16$ at 28 GHz, respectively, outperform relaying and double the data rate in the latter case study. It is worth noting that the area occupied by the considered RISs is of the order of 1.33 m^2 for $N = 1$; 2.66 m^2 for $N = 2$; and 5.32 m^2 for $N = 4$ at 2.6 GHz; and only 0.046 m^2 for $N = 4$; and 0.18 m^2 for $N = 16$ at 28 GHz. RISs of 6 m^2 in size have recently been built for operation at 2.45 GHz [9]. These results are encouraging, and highlight the potential benefits of employing RISs in wireless networks.

THE ROAD AHEAD

Theoretical and experimental research on RISs is still at its infancy. Fundamental issues need to be understood to unlock the potential of this emerging technology, to identify the ultimate performance limits, and to optimally design RIS-aided wireless networks. Three fundamental and open research issues deserve, in our opinion, more attention than others.

Physics-Based Modeling. Current research on RISs relies on simplified assumptions and models about the interactions of the radio waves with the meta-surfaces. No equivalent models for the meta-surfaces are available that are suitable for application to wireless networks. Hence, there is a compelling need for developing sufficiently accurate but analytically tractable models for the meta-surfaces whose foundation is to be built on the fundamental laws of electromagnetism and physics.

Experimental Validation. To be accepted by the wireless community, these equivalent models need to be validated through hardware testbeds and empirical measurements. Our analysis reveals that the potential gains and applications of RISs in wireless networks depend on the scaling law of the received power as a function of the distance. There exist, however, no experimental results that allow us to infer, as a function of the wavelength of the radio waves and the geometric size of the meta-surfaces, the most appropriate model for an RIS, i.e., electrically large or electrically small.

Constrained System Design. The potential gains and applications of RISs in wireless networks depend on their nearly passive implementation. This imposes stringent constraints on the development of efficient signal processing algorithms and communication protocols. The absence of power amplifiers and channel estimation units on the RISs implies, for example, that no channel estimation can be performed at the RISs, and new and efficient (low overhead) protocols need to be developed for acquiring the necessary environmental information for optimally programming their operation. The impact of these constraints is exacerbated in high-mobility environments, e.g., in outdoors (see Fig. 3) in contrast to low-mobility environments, e.g., in indoors [11].

CONCLUSIONS

RISs are an emerging and little understood technology with a strong potential for application to wireless networks. The main feature of RISs lies in turning the wireless environment into a customizable space by coating objects and devices with reconfigurable meta-surfaces that are capable of shaping the radio waves impinging upon them. In this article, we have discussed differences and similarities between RISs and relaying, and have provided qualitative and quantitative arguments showing that electrically large RISs can outperform relay-aided communications in terms of data rate, while at the same time reducing the implementation complexity. Electrically large RISs that act as anomalous mirrors can be a suitable technology for wireless communications at high radio frequencies, namely at millimeter and sub-millimeter wave bands. We have briefly discussed the potential applications of electrically small RISs to realize single-RF multi-stream transmitters with low complexity, and have elaborated on their potential for application to sub-6 GHz and higher frequencies.

We believe that the tight collaboration among experts in wireless communications, antennas, electromagnetism, and physics is a compelling need to unlock the potential of RISs in wireless networks. We hope that this article will spur interdisciplinary research to tackle the open research issues.

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