Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions

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Abstract—The search for physical-layer technologies that can play a key role in beyond-5G systems has started. One option is reconfigurable intelligent surfaces (RIS), which can collect wireless signals from a transmitter and passively beamform them towards the desired receiver. Despite the massive attention RIS is currently receiving from the communication community, we have witnessed how several misconceptions are spreading, as epitomized by following (fictional) abstract:

“While current wireless technologies treat the propagation channels as uncontrollable and given by nature, RIS constitutes a paradigm shift by enabling control of the channels. An RIS behaves as a mirror with the key difference that the reflection angle can be controlled, thus the path-loss is identical to that of a line-of-sight path having the same total length. The RIS achieves array gains both in reception and reflection, which makes RIS more spectrally efficient than using conventional active antenna arrays that only benefit from one array gain.”

Most of these statements are incorrect. In this article, we first review the fundamentals of RIS and then debunk three specific myths. To inspire further research, we conclude by identifying two critical questions that must be answered for RIS to become a successful technology.

INTRODUCTION

The electromagnetic waves that carry information in wireless communications interact with objects and surfaces on their way from the transmitter to the receiver. Although the superposition of many propagation paths gives rise to random-like fading phenomena, every propagation path has a constant behavior. However, there exist engineered materials whose interactions with electromagnetic waves are not constant but reconfigurable. These materials are not naturally occurring but can be manufactured and deployed to shape the propagation environment. The prospects of including such reconfigurable intelligent surfaces (RIS) as a part of beyond-5G network architectures have recently attracted much attention [1], [2]. RIS have also been called software-controlled metasurfaces [3] and intelligent reflecting surfaces [4].

A basic use case of RIS is illustrated in Fig. 1 where a rooftop-mounted base station is transmitting to an indoor user. There is a thick wall between them causing massive propagation losses, however, the signal can pass through the window with only minor losses. Inside the window, an RIS is deployed to capture signal energy proportional to its area and re- radiate it in the shape of a beam towards the receiver. To ensure the beam is focused towards the user device, wherever it is in the room, the RIS must be reconfigurable. By using an RIS in this setup, the signal-to-noise ratio (SNR) can be improved.

An RIS is a thin surface composed of $N$ elements, each being a reconfigurable scatterer: a small antenna that receives and re-radiates without amplification, but with a configurable time-delay [5]. For narrowband signals, this delay corresponds to a phase-shift. Assuming the phase-shifts are properly adjusted, the $N$ scattered waves will add constructively at the receiver. This principle resembles that of traditional beamforming: each element has a fixed radiation pattern but the collection of phase-shifts determines where constructive interference among the scattered waves occurs. The color pattern at the RIS in Fig. 1 represents the phase-shifts necessary to steer a beam towards the receiver. Each element is substantially smaller than the wavelength (e.g., a fifth of the wavelength in each direction [5]) so it scatters signals almost uniformly, giving the surface the ability to form equally strong beams in any direction.

The propagation analysis of an RIS essentially entails (i) finding the Green’s function of the signal source (a sum of spherical waves if close, or a plane wave if far away), (ii) computing the impinging field at each RIS element, (iii) integrating this field over the surface of each element to find the current density, (iv) computing the radiated field from each element, and (v) applying the superposition principle to find the field at the receiver. Since the elements are small, one can approximate the re-radiated field by pretending each element is a point source and then the received signal is a superposition of phase-shifted, amplitude-scaled source signals [6].

There are many prospective use cases for RIS-aided wireless communications, in addition to improving the SNR as in Fig. 1. The RIS can also mitigate interference between users that are spatially multiplexed or limit the signal-leakage outside the intended coverage area, to mitigate eavesdropping [2–4]. Support for wireless power transfer, backscattering, and spatial modulation is also conceivable; in principle, most things that can be implemented using traditional beamforming can also be carried out by an RIS.

The definition of an RIS is a surface with real-time reconfigurable scattering properties (e.g., amplitude, delay, and polarization) that is controlled to improve the communication performance. The concept is often connected with metasurfaces, which are two-dimensional surfaces consisting of arrays of reconfigurable elements of metamaterial. However, there are other potential ways of implementing RIS [2]. One example is using small patch antennas terminated with an adjustable impedance. In any case, the reconfigurability will likely be
limited to a finite set of states per element (with given delays and amplitudes) and mutual coupling between adjacent elements is another limitation. There are many decades of research on reflectarrays and array lenses [7], which are architectures for building transmitters consisting of a feed antenna that sends the signal via a reconfigurable surface capable of electronically tunable beamforming. The key difference is that an RIS is co-located with neither the transmitter nor the receiver, but can be arbitrarily deployed in the propagation environment to aid the communication.

**Myths and Misconceptions About RIS**

The interest in the RIS technology has grown tremendously but, unfortunately, several misconceptions around its fundamental properties are flourishing. We will debunk three such myths.

*Myth 1: Current network technology cannot control or optimize the propagation environment*

A key characteristic of RIS is the ability to alter how wireless signals propagate between the transmitter and receiver. It is a technology for creating controllable/smart/programmable radio environments, which are defined as environments that can customize how waves emitted by the transmitter are propagating on their way to the receiver [2]. This feature enables joint optimization of the transmitter/receiver and the controllable entities in the environment, using channel state information (CSI). The 5G network technology is often described as unable to control the environment, thus making RIS the first step towards realizing controllable radio environments [2–4, 6]. Most wireless systems indeed consist of a transmitter that communicates with a receiver without the involvement of other entities. In such cases, the radio environment is uncontrollable according to the above definition; the transmitter and receiver must conform to it by adaptive modulation/coding, beamforming, and power control. However, this is a design choice motivated by the limited need for controlling the environment because the technology for controlling it has existed all along.

The wireless repeater was invented by Guarini-Foresio in 1899 and advanced relaying technology, capable of improving the conditions of radio environments, has been included in cellular standards since 3G [9]. The term *cooperative communications* is broadly used to refer to network architectures containing entities between the transmitter and receiver that enhance the physical channel, by exploiting diversity, beamforming, and/or multiplexing gains. These entities are co-optimized with the transmitter and receiver, thus satisfying the definition of controllable radio environments. Two main categories are *transparent relaying* and *regenerative relaying*. In the former category, each relay is an entity that receives a signal from the transmitter and processes it in analog (or digitally) before re-radiating it towards the receiver. Amplify-and-forward is a classic protocol for creating additional signal paths by re-radiating an amplified signal in a way that can be
Myth 2: An RIS achieves a better asymptotic array gain than conventional beamforming

Beamforming is the transmission of delayed copies of the same signal from multiple antennas. This gives rise to constructive interference at spatial locations where the copies are received synchronously and destructive interference elsewhere. The more antennas are used, the more spatially focused the transmitted signal becomes. If the time-delays at $N$ antennas are tuned to achieve constructive interference at the receiver, it will receive $N$ times more power than if the same total power was transmitted from a single antenna. This is the conventional array gain of beamforming.

When an RIS is used, it will receive a signal power from the transmitter proportional to the surface area, which in turn is proportional to the number of elements, $N$. When the RIS re-radiates the signal, with time-delays selected to beamform at the receiver, an array gain of $N$ is obtained just as with conventional beamforming. The combination of these two effects, both being proportional to $N$, leads to an SNR at the receiver proportional to $N^2$. This has been called the “square law” and described as an asymptotic scaling law; that is, as the number of elements goes to infinity, the SNR grows unboundedly at the order of $N^2$. It has also been implied the quadratic array gain is preferred over the linear array gain of conventional beamforming. These are two misconceptions.

The first issue is that array gains of the type described above only appear when the surface area (of the RIS or antenna array) is small compared to the propagation distances. The transmitter/receiver must be in the geometric far-field of the surface so that the path-loss is approximately the same to all parts of the surface. Since the surface area grows with $N$, the far-field approximation eventually breaks down as $N$ increases and then the growth in array gain tapers off. Neither linear nor quadratic asymptotic power scaling laws exist in practice but the law of conservation of energy dictates that we can never receive more power than was transmitted.

Although asymptotic power scaling laws are physically impossible, the SNR achieved with an RIS actually grows quadratically with the number of elements for many practically-sized surfaces. Hence, it might seem possible that a better SNR can be achieved compared to having an equal-sized antenna array on the same place that transmits directly to the receiver, an array gain of $N$. This is the conventional array gain. However, the second misconception is the premise that the quadratic power scaling is advantageous. When we say that the received power at the RIS is proportional to $N$, this means that only a tiny fraction of the transmitted power reaches the RIS but that fraction grows with $N$. It is more appropriate to say that the power loss between the transmitter and RIS reduces as $1/N$.

Myths 1 and 2 are shown in Fig. 2. This figure revisits the setup in Fig. 1 and compares the use of an RIS with the use of a DF relay deployed at the same place. The direct path is assumed non-existing, while there are pure line-of-sight paths via the RIS/relay. The transmitter is 300 m from the RIS/relay, while the user is 10 m from it. Typical transmit powers, antenna gains, and penetration losses for the 3 GHz band are used. The figure compares the surface area of an RIS and the area of a multi-antenna relay required to achieve the same SE. The DF relay can generally be substantially smaller, while the advantage of the RIS is the lack of power amplifiers and full-duplex mode.

In summary, current networks already support relaying technology capable of controlling the propagation environment. An RIS is a full-duplex relay that forwards the signal without amplification. It constitutes one of a plethora of relaying protocols, all having their pros and cons.

![Graph](image-url)
with the RIS and DF relay for different surface areas. Since we use logarithmic scales, the quadratic array gain is observed from the steeper slope of the RIS curve. However, this curve begins at a much smaller value and when it approaches the DF relay curve, the steeper slope has tapers off. Both curves will eventually converge to a finite number [10]. The reason that the RIS became preferable for very high SEs in Fig. 2 is that the SNR gap eventually becomes so small that the half-duplex operation of the DF relay becomes the bottleneck.

Myth 3: An RIS is an anomalous mirror

A mirror is a surface that reflects an impinging plane wave as an outgoing plane wave, also known as specular reflection [11]. A conventional mirror satisfies the law of reflection: the angles of the incident and reflected waves to the surface normal are the same but on opposite sides, as illustrated by the blue ribbons in Fig. 4. The term anomalous mirror/reflector is used to describe a surface that reflects impinging plane waves as outgoing plane waves with a different “unnatural” angle to the surface normal [2]. A conventional mirror is an infinitely large homogeneous surface and approximations thereof appear naturally (e.g., a metal plate or water surface). In contrast, an anomalous mirror is not naturally appearing but is an inhomogeneous surface with such unusual properties that it must be engineered. A key property of mirrors is that the receiver observes the transmitting source as if it were behind the mirror. One can analyze the wave propagation as if the transmitter is moved to the location of the mirror image, as illustrated in Fig. 2. It has been stated that an RIS can generally be viewed as an anomalous mirror if it has a width and length larger than ten wavelengths [8]. If that is the case, the path-loss in Fig. 4 can be computed based on the sum of the distance from the transmitter to the RIS and from the RIS to the receiver, because this is the distance from the mirror image to the receiver. However, an RIS is not an anomalous mirror because it can both affect the direction and the shape of the reflected signal [10], [11], as illustrated by the red ribbons in Fig. 4 where the signal is focused at the receiver. We will explain the intuition and consequences below.

Mirrors and plane waves are theoretical idealizations that are common in textbooks but only appear approximately in practice. They can be fairly accurate approximations when considering visible light and are, thus, used in geometrical optics to analyze imaging. The situation is rather different in the radio spectrum used for communications, thus Fig. 2 does not provide an exact but idealized illustration of mirrors and finite-sized RIS that interact with radio waves. A surface that our eyes perceive as a mirror might be far from mirror-like for radio signals. Since the wavelength is roughly 100000 times larger in radio spectrum than in visible light (e.g., comparing green light at 600 THz with a radio signal at 6 GHz), a surface must be 100000 times larger in each dimension to identically reflect signals. Moreover, the transmitter must be 100000 times further away if its emitted spherical waves should be approximated as planar. The receiver must also be 100000 times further away to perceive the reflected signals as plane waves. None of these conditions are guaranteed to hold in practice and a ten-wavelength-sized RIS is generally too small to be approximated as a mirror.

Recall that each element of the RIS is a scatterer with a fixed radiation pattern. A more subtle point is that the entire RIS, being an array of scatterers with varying delays, is itself also a scatterer but with a reconfigurable radiation pattern. If a plane wave is impinging on a finite-sized RIS that is configured to focus the signal towards a receiver located in the far-field, then the radiated field will be strongest in the angular direction of the receiver but it will not be a plane wave. It is only in the limit of an infinitely large surface that a wave can be reflected without changing the shape of the wavefront. The half-power beamwidth of the reflected signal is inversely proportional to the size of the RIS (measured in wavelengths) and becomes $6\degree$ for a surface that is ten wavelengths in each dimension [6]. If multiple surfaces of that size are deployed next to each other, they cannot be viewed as separate anomalous mirrors, as in [8], but the combined surface becomes closer to approximate a single mirror since the beamwidth shrinks. Since the beamwidth is fairly narrow, accurate CSI is required to operate the RIS, which we will return to later. The beamwidth of an RIS is the same as for beamforming from an equal-sized transmitter array; any waveform that can be reflected off an RIS can be synthesized by connecting every element to a signal generator. The beam pattern of the reflected signal will resemble the one shown in Fig. 1. The SNR is proportional to $N^2$ and is inversely proportional to the product of the squared distances to the RIS [6], [11], rather than inversely proportional to the squared sum of the distances as with a mirror.

Fig. 5 continues the example from Figs. 2 and 3 by showing how the end-to-end path-loss depends on how far the receiver is from the RIS (the distance between the transmitter and RIS is as before). The solid curve is for an RIS that is optimized to achieve the highest SNR, while the dashed curve represents an anomalous mirror. We notice that a mirror is a poor approximation of an RIS at most distances. When the
Fig. 4. A mirror reflects an incident plane wave as a plane wave in an angular direction determined by the law of reflection, so the receiver perceives the transmitter as being located at the mirror image location. An RIS can both configure the angle of the reflected beam and its shape, thus it should not be interpreted as an anomalous mirror. The figure illustrates how the RIS focuses the signal at the receiver to maximize the SNR.

Fig. 5. This figure revisits the setup from the previous figures and considers an RIS that is 2 m times 2 m, which represents 20 times 20 wavelengths at a 3 GHz frequency. The figure shows the end-to-end path-loss as a function of the distance between the RIS and the receiver. An optimally configured RIS is compared with an RIS that is configured to mimic a mirror and the path-loss obtained if it was an ideal mirror. It is clear that an RIS can generally not been interpreted as a mirror.

receiver is far from the RIS, the path-loss is worse than with a mirror since the RIS is too small to emit approximately plane waves. When the receiver is close to the RIS, the path-loss is instead much better than with a mirror. This is like when you look into a large mirror and your reflection only appears in a small part of it; the rest of the mirror is not needed. A well-configured RIS makes use of the entire surface by focusing the signal at the receiver in the way illustrated in Fig. 4. The dash-dotted curve in Fig. 5 represents a mirror-mimicking RIS that is configured to delay the signals as a cutout from an infinitely large anomalous mirror would do. This curve is close to the optimized RIS when the receiver is far from the surface, while it begins to oscillate in the vicinity of the mirror approximation at shorter distances. This indicates one thing that the mirror analogy can be used for: identifying suitable time-delays when the receiver is far away. It can also be used as an approximation when only the direction but not the distance to the receiver is known.

In summary, an RIS can generally not be interpreted as an anomalous mirror. When the receiver is far from the surface, it is too small to behave like a mirror. When the receiver is close to the surface, the RIS can approximate the mirror behavior but it is generally suboptimal to do so. One way to describe the capabilities of an RIS is as a parabolic reflector (as in a satellite dish receiver) with curvature and direction that can be electronically steered, but that is also a simplification since an RIS is capable of mimicking the scattering off arbitrarily-shaped objects having the same size.

**Critical Question 1: What is a convincing use case for RIS?**

An immense amount of time and resources are required to bring a new technology concept, such as RIS, from theory to practice. Very convincing benefits compared to existing technologies must be established to motivate such an investment; we essentially need to demonstrate 10 times improvements with respect to a practically important performance metric, not just 20% gains that might disappear in an imperfect implementation. Massive MIMO (multiple-input multiple-output) and mmWave communications passed this test in the 5G development since the former can increase the number simultaneously served users by ten times while the latter can increase the data rate per user by ten times using much wider bandwidths. Several other “5G-branded” technologies failed the test because the gains were too limited.

RIS technology has many technical features beyond current mainstream technology. However, to motivate the practical
development of RIS technology, the critical question is: what is a convincing use case? The question is open: RIS is a hammer looking for a nail. There is no doubt that RIS can be used for many different things [3] but will it excel at anything? Coverage extension is one option but Fig. 2 showed that conventional half-duplex relaying is a competitive solution, and full-duplex regenerative relays are emerging. Since each RIS element must be identically configured over the entire frequency band, the RIS technology has a further competitive disadvantage over wideband channels. Improved spatial multiplexing and interference mitigation is another potential use case, but then it needs to beat Cell-free Massive MIMO, which is the emerging deployment of distributed jointly-operating antennas. Perhaps it is in terahertz bands, where the implementation of coherent transceivers is truly challenging and the sparse channels make additional propagation paths useful even if they are weak, that the RIS technology will be most beneficial. These are just speculations since there is no hard evidence yet.

**Critical Question 2: How can we estimate channels and control an RIS in real time?**

The envisioned use cases of RIS critically depend on a proper configuration of the elements based on CSI. There are two reasons why channel acquisition is particularly complicated with RIS. Firstly, unlike conventional transceiver architectures, an RIS is not inherently equipped with transceiver chains. It lacks sensing capabilities but simply “reflects” the incoming signals. Therefore, conventional channel estimation methods cannot be utilized. Secondly, introducing an RIS into an existing setup will increase the number of channel coefficients proportionally to the number of elements $N$. As shown earlier, a large $N$ is needed for RIS to be competitive, thus the estimation overhead might be huge. A key question is: can an RIS be real-time reconfigured to manage user mobility?

The literature contains initial approaches to tackle the problem. One approach is to transmit a pilot sequence repeatedly and measure the received signal when using different RIS configurations. For example, the elements can be turned on/off according to a pattern or the array geometry can be used to sweep through changes of the main reflection angle. At least $N$ reconfigurations must be tested in different time slots to excite all the channel dimensions. Only a concatenation of the channels to/from the RIS are observed and mutual coupling between RIS elements complicates the estimation. This approach is illustrated in Fig. 6 and requires a wireless control loop between the receiver and the RIS controller circuit with a capacity proportional to $N$. Even when CSI has been acquired, it is computationally complex to select appropriate time-delays, particularly in wideband channels [12]. To reduce complexity, adjacent RIS elements can be grouped to have the same configuration [12], at the cost of a performance loss.

Another approach is to alter the passive nature of the RIS by having a few elements with receiver chains [4], which enables sensing and channel estimation directly at the RIS. The ability to extrapolate a few measurements to estimate the entire wideband channel requires spatially sparse channels with a known parametrization. This might be reasonable in mmWave or terahertz bands but further work on channel and hardware modeling is required. Sparsity-based estimation algorithms were considered in [13]. Even if the RIS has sensing capabilities, a control loop is needed to jointly select the RIS configuration and the beamforming at the transmitter/receiver.

Estimation algorithms can leverage special channel characteristics to reduce the pilot overhead. For instance, the channel between the base station (BS) and RIS is semi-static, which makes the end-to-end channels correlated between users. An estimation algorithm exploiting this correlation is proposed in [14]. It is pointed out in [15] that the BS-to-RIS channel can contain many coefficients if the BS has many antennas but since this channel is semi-static, it can be estimated less frequently than the RIS-to-user channel, which typically contains fewer coefficients since users have fewer antennas.

There is no doubt that RIS can be used for fixed communication links, but mobile operation requires real-time channel estimation and reconfiguration, even in indoor use cases. A few millimeters of movement will change the channels in mmWave bands and above. It remains to be demonstrated if any estimation protocol can enable real-time reconfigurability and under what mobility conditions. There is a hope that the RIS technology will be energy-efficient since the array is passive [8] but this remains to be demonstrated quantitatively. The RIS will require a power source for reconfigurability and wireless control channels. It is likely that the control interface will consume most of the power at the RIS, so one cannot predict the total power consumption of the technology before the channel estimation and reconfigurability have been solved and validated.

**Summary**

An RIS is a full-duplex transparent relay that does not amplify signals but can synthesize the scattering behavior of an arbitrarily shaped object. It cannot beat an active array of the same size but if a larger surface is used than in...
conventional relays or multi-antenna transceivers, it can deliver a comparable SNR. RIS-aided communication is an exciting research topic but we need to identify convincing use cases, as well as practical protocols for reconfigurability.

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