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PERCEPTIVE, RESILIENT, AND EFFICIENT NETWORKS

Programming the Wireless Environment with Reconfigurable Intelligent Surfaces

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Wireless communications are nowadays shifting to higher operation frequencies, with the aim to meet the ever-increasing demand for bandwidth. While reconfigurable intelligent surfaces (RISs) are usually envisioned to restore the line of sight (LOS) of blocked links and to efficiently counteract the increased path loss, their functionalities can extend far beyond these basic operations. Owing to their large surface and the multitude of scatterers, RISs can be exploited to perform advanced wavefront engineering, essentially transforming the incident beam into a nontrivial reflected beam that is able to address the challenges of high frequencies more efficiently than conventional beamforming. In this article, it is demonstrated how advanced wavefront engineering with RISs enables beam profiles that are able to focus, bend, and self-heal, thus offering functionalities beyond the current state of the art. Their potential as enablers of perceptive, resilient, and efficient networks is discussed, and a localization technique based on a hybrid beamforming/beam-focusing scheme is demonstrated.

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Introduction

In recent years, research in industry and academia has been directed toward identifying critical scenarios for future networks and devising the corresponding enablers to address the associated challenges. To take full advantage of the large bandwidth offered by high-frequency bands and to ensure high-quality links, it is necessary to efficiently counteract the sources of blockage and attenuation that lead to signal degradation, and therefore, the necessity for new approaches to address such challenges becomes vital [1]. In this context, the capability to flexibly engineer the wavefront of beams that carry information, taking into consideration environmental parameters and usage scenario characteristics, opens up a new "beyond communications" playground, where communication nodes can be employed to identify the shape of surrounding obstacles, map the environment, detect the presence of objects, focus power, localize, track mobility, and navigate [2].

It is gradually becoming common ground that the sixth generation of networks will be programmable and reconfigurable, with situational awareness that maps the communication landscape, achieving unprecedented quality of service with low latency and high data rates [1]. As a result, the networks are expected to support a multitude of functionalities and, therefore, to bear multiple qualities; they are expected to be perceptive within the communication environment, resilient to communication outages, and power efficient. Specifically, a perceptive network, through a process called sensing, will be able to detect changes in the communication environment. A resilient network will be able to quickly restore connections in cases of outages from power loss or blockage and even avoid blockage. The link restoration will be seamless so as not to affect the user experience. A power-efficient network will function with low energy requirements and with as few corrective measures as possible.

These qualities can be enabled with beam profiles that offer advanced functionalities beyond conventional beamforming. For example, beams that are able to distribute the power into a focused area, or even bend or self-heal, are ideal candidates. They can be produced either directly from a specially designed emitter, e.g., a large antenna array, or a reflecting surface that is able to transform the incoming beam, such as a RIS. Such beams usually involve rapidly varying phase profiles, and therefore, to produce them, it is required that their wavefront be adequately sampled. As a result, many radiating elements are usually necessary, rendering large antenna arrays that require bulky hardware nonpractical and inefficient.

Contrary to large antenna arrays, RISs are nearly passive surfaces; that is, they do not require active power amplifiers, digital signal processing, and multiple radiofrequency chains [3]. Owing to its passivity, the RIS may offer hundreds or thousands of elements at relatively low power consumption levels, making it ideal for advanced wavefront engineering operations that require dense wavefront sampling. Besides promising to restore the LOS of links interrupted by a blocker and to increase the channel gain via beamforming, the potentially large size of RISs enables a number applications, such as cost-efficient redirection of a beam, focusing the power of a beam to a small area with controllable size, and generating beams that can bend to bypass obstacles, enabling them to reach users beyond the LOS of conventional beams. Overall, RISs can adjust the wireless medium, which was previously thought to be uncontrollable, by controlling the scattering, refraction, and reflection characteristics of waves [3]. With RISs, wavefront engineering also becomes programmable [4]. This enables the transmitter to sense the wireless environment and allows for integrated communication and sensing, thus taking full advantage of the high bandwidth offered by high-frequency bands and promising high-quality, perceptive, resilient, and efficient links.

So far, communications have been driven by omnidirectional emitters and directional beamformers, while, in recent years, beam focusing has been gaining ground. Additionally, most applications in wireless communications have been designed for the far field of transmitting antennas. However, with RISs, it is now possible to adjust the near- and far-field regions [5], thus enabling new functionalities. In this article, the potential of RISs for advanced wavefront engineering is investigated. The main contributions of this article are as follows:

- The concept of beamforming, beam focusing, self-accelerating, and self-healing as enablers of perceptive, resilient, and efficient networks is proposed.
- It is demonstrated how beams that are able to focus, bend, and self-heal enable advanced functionalities necessary for 6G networks beyond typical beamforming, and the design specifications to reach the beams' full potential are discussed.
- A hierarchical localization method based on a hybrid beamforming/beam-focusing scheme is proposed.
- A hierarchical ranging method is proposed, based on beam focusing.
- New approaches to counteract the effect of blockage based on self-accelerating and self-healing beams are proposed.
- Methods for achieving energy-efficient networks are demonstrated. The concept of wireless power transfer and how the received power can be maximized with low transmitted power is discussed.

Advanced Wavefront Engineering Capabilities

It is well known that the waves radiated by antennas evolve into the far field roughly at the Fraunhofer distance [6]. For conventional antennas, e.g., phased arrays, the size of the radiating element (or radiating aperture) extends from a fraction of a wavelength up to only a few wavelengths, and therefore, the radiated waves quickly enter the far field. With RISs, though, this intuitive picture can change. Owing to their large surface, usually extending up to several wavelengths, waves reflected by the RIS may evolve under a new aperture, i.e., a new Fraunhofer distance. For example, a pencil beam that partially illuminates a large RIS area is steered with the aperture determined by the size of the beam footprint on the RIS (this is typically referred to as *partial illumination*). On the other hand, a beam impinging on a RIS that illuminates the entire RIS surface is steered under a new aperture determined by the size of the RIS (this is typically referred to as *full illumination*). In the latter case, with increasing RIS size, the Fraunhofer distance increases, pushing the transition from the near to the far field farther than what is intuitively expected, despite the fact that the beam incident on the RIS remains unchanged [5]. This flexibility to adjust the Fraunhofer distance can enable new functionalities, such as focusing and generally advanced beams that require relatively large apertures with a tailored phase response to operate in the near field.

The RIS transforms the incident beam by, first, correcting the tilt of the incident beam and, subsequently, introducing a phase ϕ with a tailored functional form to shape a reflected beam with desired characteristics [4]. In Figure 1, four beam profiles are presented, corresponding to beamforming, beam-focusing, self-healing, and self-accelerating operations. These profiles can be advantageous to a number of applications, including but not limited to beam tracking, blockage avoidance, and power transfer.

Beamforming is the most fundamental of the functionalities of RISs and is typically used to steer the incident beam toward the desired direction. This is achieved by imposing linear phase shifts on the RIS elements; i.e.,

$$\phi = k \sin \theta_r x \tag{1}$$

where k is the free-space wavenumber, θ_r is the angle of reflection on the steering plane, and x is the Cartesian coordinate; in this example, the RIS is on the xy-plane, steering waves on the xz-plane. Beamforming with a RIS

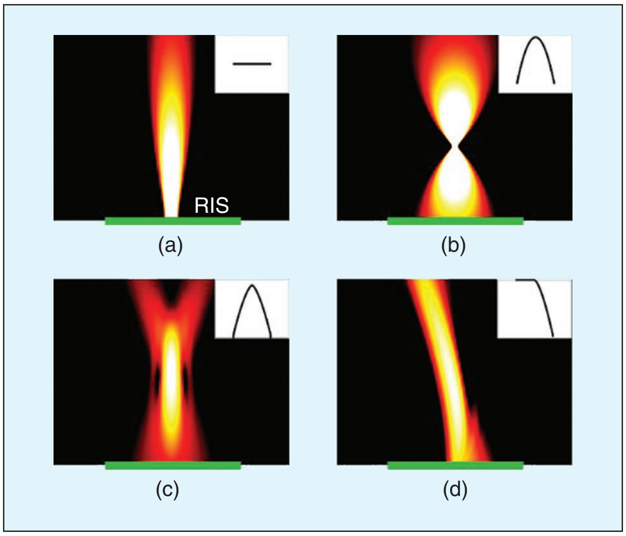

FIGURE 1 Beamforming and other advanced beam profiles. The subfigures show the cross section of the phase profile of the RIS elements that generate each beam. The operation frequency is 150 GHz (λ = 2 mm), and the RIS (marked with the green line) consists of 1,000 × 1,000 elements of size $\lambda/2$. (a) Beamforming, (b) beam focusing, (c) a self-healing beam, and (d) a self-accelerating beam.

can be used to increase the received power at the direction of the user, establish an additional LOS link, or track the user. The width of the reflected beam depends on the size of the footprint of the incident beam on the RIS or the size of the RIS, whichever is smaller. Controlling the near-to-far-field transition distance is fundamental, as the optimization of beamforming in terms of received power depends on it. As shown in [5], maximizing the received power at a certain distance requires a specific RIS size or footprint that sets the Fraunhofer distance at the RIS–user equipment (UE) distance, i.e., that effectively places the UE at the near-to-far-field transition of the RIS. Moreover, under partial illumination (in this case, the near-to-far-field transition is determined by the Rayleigh distance), the beam in its near field undergoes negligible diffraction, essentially propagating with constant peak power, which is ideal for power transfer applications [7].

Beam focusing is the ability of a RIS to focus the power of the reflected beam to a small area, similar to how a lens focuses light onto a focal point. This can be achieved simply by imposing a parabolic phase profile on the RIS elements [8], i.e., of the form

$$\phi = \frac{-kr^2}{2f_0} \tag{2}$$

where f_0 is the focal distance and r is the distance of each element from the center of the RIS. Beam focusing can be used to estimate the location of the UE to maximize the received power as well as for wireless power transfer applications. The power is maximized at the focal point, and the locus of the spatial locations with half-maximum (or 3-dB) power marks an ellipsoid centered at the focal point and oriented with its major axis along the beam propagation direction. Its size depends on the incident beam footprint as well as the RIS–focal point distance (focal distance). In principle, the larger the footprint on the RIS, the smaller the size of the 3-dB ellipsoid and, consequently, the higher the resolution in localization-related applications and the higher the maximum power at the focal point.

Self-healing beams are a type of diffraction-free beams with the ability to reconstruct themselves when faced with an obstacle [9]. This is possible because rays from the edge of the beam replace the blocked rays as the beam propagates. Therefore, self-healing beams are ideal for counteracting the effect of blockage. Such beams require a power law phase profile of the form

$$\phi = -kCr^{\gamma} \tag{3}$$

where γ and C are design parameters (constants) [9]. Theoretically, although such beams require an infinitely large array to be generated properly [10], they can be efficiently generated with finite apertures, as shown in Figure 1. The effectiveness as well as the distance of the beam reconstruction depend on the size of the obstacle relative to the RIS aperture. In principle, the larger the RIS, the faster and better the beam recovers.

Self-accelerating beams are formed using the phase profile in (3), with $r \rightarrow x$. Such beams have the ability to bend with the propagation distance and reconstruct after an obstacle, like all diffraction-free beams [9], and therefore, they are also ideal for counteracting the effect of blockage. With knowledge of the wireless environment, the location of the UE, and the beam propagation, self-accelerating beams can establish a connection between points otherwise inaccessible with conventional beamforming. In principle, sharper bendings can be achieved with larger RISs. The origin of bending can be understood in the equivalent ray picture. While rays travel along straight paths, their envelope (or caustic) may form a bent curve, which depends on the slope of each ray at its starting location. In the wave picture, the slope of the rays is directly associated with the wavefront of the beam [11], and the caustic marks the trajectory of the beam's main lobe. Hence, by engineering the phase of the beam at its starting location, the beam can be designed to bend.

Advanced Wavefront Engineering Techniques

Wireless communications so far have been operating in the far field of the radiating elements. With the incorporation of RISs, though, the near-to-far-field transition can be engineered via the footprint size, and therefore, new techniques that can take advantage of this ability can be implemented. These techniques are designed to enable the three main properties that future networks are expected to have, namely, being perceptive, resilient, and efficient. Table 1 summarizes these properties and the relevant beam profiles to realize them.

Perceptive

Wireless communication environments are highly volatile. This is especially true in dense networks with highly directional antennas operating at high-frequency bands, as future networks are expected to be. As a result, such networks must be perceptive within the wireless environment to be able to adjust to all scenarios.

TABLE 1 ***The capabilities of the four beam profiles.***

Property	*Beam Steering*	*Beam Focusing*	*Self-Healing*	*Self-Accelerating*
Perceptive	✓	✓	—	—
Blockage resilience	—	—	✓	✓
Energy efficiency	✓	✓	—	—

Hierarchical RIS-Assisted Localization

The ability of the RIS to focus the power of the reflected beam to a small area is ideal for localization. Due to the small size of the focal area, searching the entire area of interest with beam focusing alone may require prohibitively large overhead, and therefore, searching can be assisted by hierarchical beam tracking. The whole procedure can be split into two phases, as described in Figure 2.

In phase 1, beam tracking is performed with beamforming through the RIS in order to estimate the direction of the UE with respect to the RIS. In phase 2, ranging is performed with beam focusing through the RIS in order to estimate the distance of the UE from the RIS along the direction identified in phase 1. With information about both the direction and the distance, the location of the UE is fully determined. Both phases follow a hierarchical and binary tree structure. Essentially, the area of interest (e.g., the semi-infinite space in front of the RIS) is represented by a polar grid with the RIS at its origin. In phase 1, the angular sector where the user is located is identified, and in phase 2, the radial distance

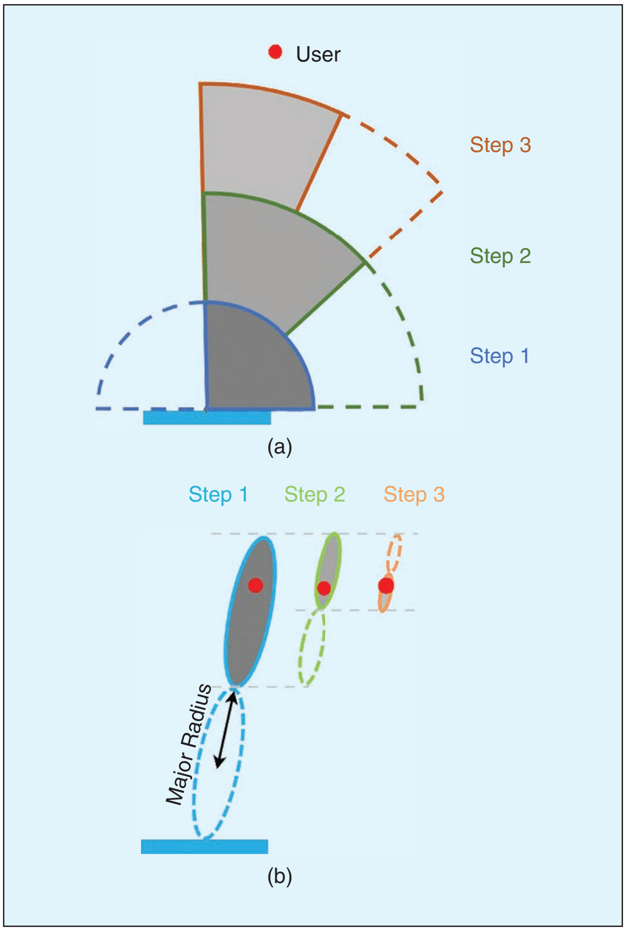

FIGURE 2 Hierarchical RIS-assisted localization. The shaded regions mark the areas where the user location is successfully identified at each hierarchical level. (a) Phase 1 and (b) phase 2.

of the UE is estimated within the available resolution of the focal spot.

Phase 1: Beamforming (Beam Tracking)

Typically, beam tracking is performed in the far field, where the beam spreads as the propagation distance increases [12]. In conventional beam tracking (without a RIS), the access point (AP) scans a number of predefined directions, which depends on the number of antenna elements. The number of directions to scan can be reduced significantly using a hierarchical codebook that follows the binary tree structure [12]. The hierarchical codebook consists of $\log_2 N$ levels, where N is the number of antenna elements. In the first level, the AP divides the area into two sectors and finds the UE in one of them. In each subsequent level, the AP divides the previous sector, where the UE was found, into two more sectors. This continues until the highest level, where the narrowest beam is reached. With this method, the number of directions to scan with exhaustive search changes from N to $2\log_2(N)$, and this difference becomes more significant with increasing N. Because a larger antenna aperture pushes the Fraunhofer distance farther, the choice for the maximum N also defines the minimum distance from the antenna where this technique can be successfully applied.

In the proposed beam-tracking framework, the same beam-tracking method is applied by the AP, where a RIS is used to steer the beam while the signal processing remains at the AP. Unlike antenna arrays, where the antenna elements are directly fed by currents, the RIS elements are excited by the incident wave of the AP. By controlling the properties of the incident wave, the excitation conditions of the RIS elements can be tuned. Therefore, the adjustment of the number of RIS elements is mainly performed by controlling the AP antenna gain and, as a result, the beam footprint on the RIS.

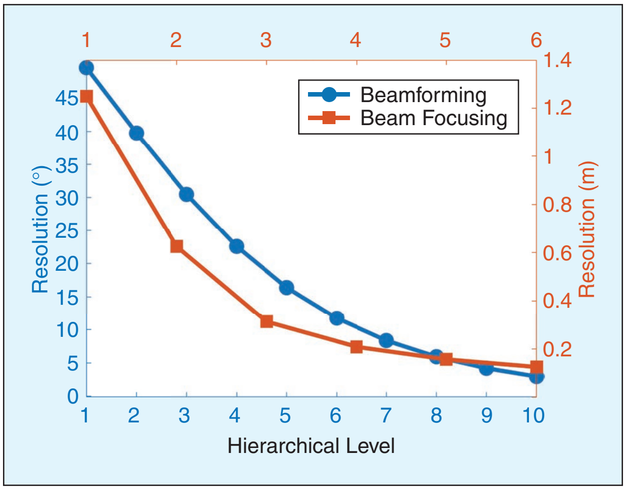

FIGURE 3 The resolution versus the hierarchical level for the two phases of the hierarchical RIS-assisted localization scheme. For beam focusing in phase 2, the maximum distance is 5 m.

Phase 2: Beam Focusing (Ranging)

With beam focusing, most of the power is concentrated along the direction of the reflected beam. With knowledge from phase 1 of the angular sector where the UE is located, the elliptical shape and controllable size of the focal area make beam focusing ideal for hierarchical localization. This approach can be implemented as follows. The AP through the RIS divides the angular sector from phase 1 into two distance-based sectors with beam focusing at two large focal areas that cover more than half of the maximum distance each. The maximum distance is chosen at will, and the focal areas can be chosen to overlap, to avoid blind spots. After the user is found in one of those areas, the RIS divides that area into two smaller ones by adjusting the footprint size and focal distance. This process is repeated until the desired accuracy of the localization is achieved, as in Figure 2.

In phase 1, the resolution at each level depends on the 3-dB (angular) width of the beam that is formed using a certain codebook. For example, the beams provided by the codebook in [13] were used to fill the levels of a new hierarchical codebook. The maximum number of hierarchical levels depends on the maximum desired angular resolution. The resulting resolution at each level of phase 1 is presented in Figure 3. In phase 2, the resolution at each level depends on the size of the focal area and, more specifically, the major radius (since it has an elliptical shape). The maximum number of hierarchical levels depends on the maximum desired radial resolution (or major radius) as well as on the maximum distance that is to be scanned. For example, in the first level, the area is divided into two areas distance-wise. Assuming that the maximum distance is 5 m, the two new areas cover a 2.5-m distance each. The major radius of each area is half of the distance each area covers (see Figure 2), meaning 1.25 m each. For each subsequent level, the number of focal areas is doubled, and the major radius of each area is halved. If the maximum distance is doubled, the major radius at each level is doubled, and one more codebook level is required to reach the same resolution as previously. The resolution at each level of phase 2 is provided in Figure 3.

The highest hierarchical level defines the maximum number of areas (direction-wise or distance-wise) that are scanned to find the user with the desired resolution. As the approach is binary-tree structured, in each hierarchical level, two areas are scanned. Therefore, Figure 3 implies that there is a tradeoff between how fast the UE location is to be determined and with what accuracy; finer resolution requires higher hierarchical levels, i.e., additional steps in the binary search procedure.

The search can be accelerated with prediction. In the absence of prediction, all levels are utilized to find the user, although the starting level may be different in each phase. However, with enough samples about the location of the UE, the AP can start predicting the next location of the user in relation to the location of the RIS and scan a small area around the predicted location using both phases but with fewer hierarchical levels. Prediction of the user's location in the next time slot enables the AP to start the search from a higher hierarchical level in both phases, resulting in reduced overhead and required time to find the UE location.

The size of the focal area and, hence, the highest achievable resolution in phase 2 depend on the size of the beam footprint on the RIS. Overall, the larger the footprint on the RIS, the higher the achievable resolution. Figure 4 displays the required footprint radius to achieve a fixed focal area size of major radius 0.1, 0.2, 0.5, and 1 m at a focal distance from 2 to 10 m. As the focal distance increases, the footprint radius of the beam on the RIS must increase as well to ensure that the size of the focal area stays the same [8]. Otherwise, the focal area is elongated along the direction of the reflected beam.

Resilient

In recent years, more and more real-time applications have emerged, such as video conferences and live streaming. As a result, resilience to outage is becoming increasingly more significant, calling for networks that can avoid outages and quickly restore links.

In high frequencies, one significant cause of outage is blockage. For example, at 73.5 GHz, the power losses can reach 40 dB [14]. At higher frequencies, the losses are higher. To this end, the use of RISs has been proposed in order to offer an additional LOS link and avoid obstacles entirely, with low power requirements and without extra additive white Gaussian noise. However, in environments with many obstacles (humans, furniture, and so on), adding more RISs does not necessarily increase the LOS probability. Therefore, new ways to resist blockage are required.

Resilience Against Blockage

Nondiffracting beams, such as self-healing and self-accelerating beams, can reconstruct behind obstacles, making them resilient to blocked links as long as the size of the obstacle is smaller than the beam and a part of the energy is not blocked, as in Figure 5. Such beams are ideal candidates for resilience against blockage.

Blockage Avoidance

Self-accelerating beams have the ability to "bend" with the propagation distance and possibly restore the LOS when the LOS of the AP–UE and AP–RIS–UE links are blocked. This ability offers a way to avoid obstacles without additional APs, relays, or RISs. It can be especially useful in cases with static obstacles in indoor scenarios or obstacles that unexpectedly interrupt the LOS of the RIS–UE link in outdoor scenarios. This possibility is demonstrated in Figure 6, where a self-accelerating beam is used to avoid two large obstacles and reach UE at a position beyond the RIS–UE LOS, i.e., not accessible with conventional beamforming.

Efficient

The main reasoning behind the expected low energy consumption of dense networks is that as each AP covers a small area, less power will be required overall. However, depending on the density of the networks, the

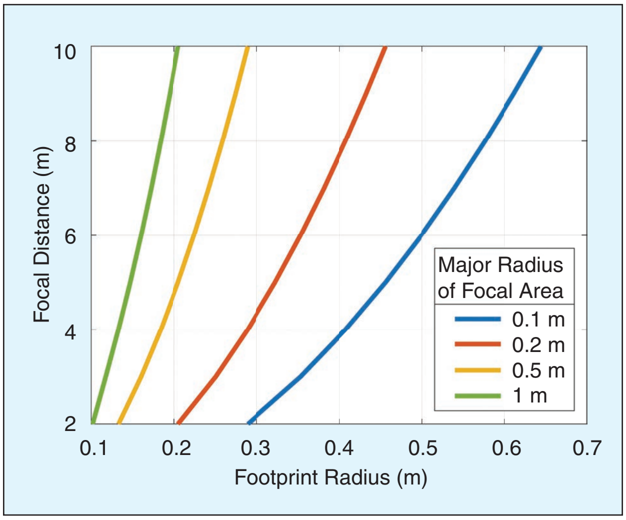

FIGURE 4 The focal distance versus the RIS footprint size for achieving the focal area sizes shown in the inset.

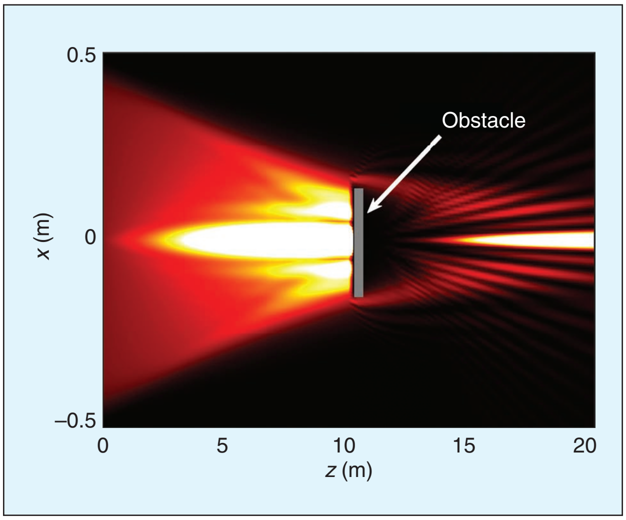

FIGURE 5 A self-healing beam reconstructs after encountering an obstacle.

energy consumption can still be quite high. For that reason, the energy efficiency must be further improved. This can be achieved directly by reducing the energy consumption of the networks, at the expense of reduced transmitted power and, hence, a reduced signal-to-noise ratio (SNR). To maintain high SNRs with reduced power consumption, new functionalities, such as power transfer or sensing (e.g., localization), can be incorporated with communications.

Energy-Efficient Communications

RISs are nearly passive surfaces and, therefore, give promise for energy-efficient communications, as opposed to power-hungry relays or the deployment of additional APs. In view of their potential to be exploited for advanced wavefront engineering, their efficiency can be further boosted with different beam profiles serving different scenarios. For example, beamforming with high gain concentrates the power to a desired direction. Self-healing and self-accelerating beams suppress or even eliminate the effect of blockage, reducing the need for different routes, more hops, and more APs, RISs, or relays, all of which increase the energy consumption. Beam focusing concentrates the power of the reflected beam at a small area with controllable size. The size of the focal area depends on the beam footprint size on the RIS, with two important implications: 1) the power at the focal point can be significantly increased by enlarging the incident beam's footprint on the RIS while keeping the power of the incident beam constant, and 2) the same power at the focal point can be achieved with beams of lower power and a larger footprint on the RIS. Therefore, focused beams are ideal for energy-efficient applications, as they can either amplify the received power with no additional power needed or they can offer the same received power with significantly reduced power consumption. Importantly, due to the relatively small size of the focal area, the interference with other focal areas is practically negligible. Therefore, beam focusing is ideal for a high signal-to-interference ratio at the receiver with low transmitted power.

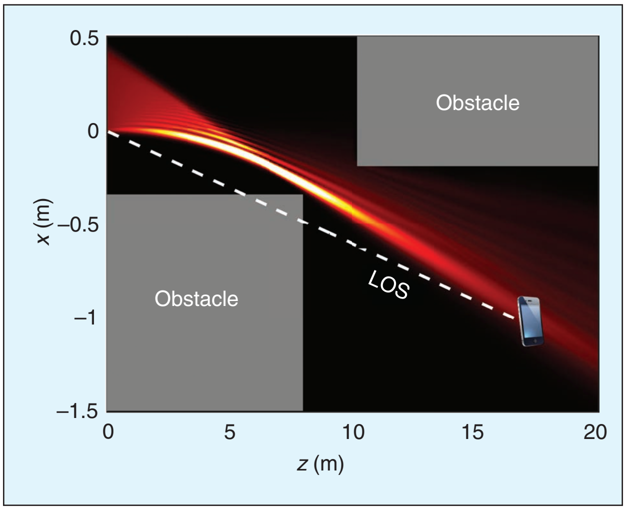

Figure 6 A self-accelerating beam avoids obstacles, reaching the UE beyond the LOS.

Power Transfer

Wireless power transfer is an application that has rapidly gained ground in recent years. Although it can be performed with all beam profiles, some are better-suited for this application than the others. Beamforming with partially illuminated RISs offers uniform beams from the near field to the far field, without near-field oscillations (as would occur with fully illuminated RISs). Importantly, at distances shorter than the Fraunhofer distance, the beam hardly diffracts. Hence, such beams can provide almost constant power along their propagation direction for areas of interest within such distances [15]. Finally, the ability of beam focusing to concentrate the reflected beam power at a desired area with adjustable size is ideal for power transfer applications.

Conclusions

To this day, communication networks are designed to operate in the far field. The need for agility, programmability, and reconfigurability pushes the operating frequency to higher bands and imposes the need for large antenna arrays and RISs, consequently bringing communications in the near field. The large area of the RIS and the multitude of scatterers it offers render the RIS ideal for advanced wavefront engineering, where the incident beam is transformed into a nontrivial reflected beam that is able to address the challenges of high frequencies more efficiently than conventional beamforming. In this article, the potential of advanced wavefront engineering was investigated for RIS-assisted networks, with the purpose of making the networks perceptive to changes in the wireless communication environment, resilient to outages, and energy efficient. Three advanced wavefront engineering beam profiles were demonstrated along with RIS-assisted beamforming, the beam focusing that concentrates the power at a small area, the self-healing beam profile that is resilient to obstacles, and the self-accelerating beam profile that can avoid obstacles. The design specifications to reach their full potential were discussed, and some techniques were demonstrated in an effort to make wireless communications networks perceptive, resilient, and efficient.

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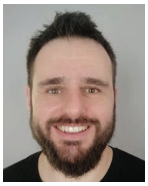

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