Metamaterials

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1. Introduction

The title of this paper is a strange word for most of my readers, but is also an amazing technology that will facilitate fast and secure communication among tomorrow's energy systems. In case you don't think that communication is that important for energy systems, you haven't had my involvement in the intersection between these two technologies in the last three or four decades. Everything from supervisory control systems for electric transmission, distribution and gas pipelines to advanced metering infrastructure and the internet of things touch various energy systems and require ubiquitous communication.

The problem is there are an increasing number of other applications that require fast and secure communication, as well as more and more bandwidth, and we are starting to have a "laws of physics" problem.

For all the tumultuous revolution in wireless technology over the past several decades, there have been a couple of constants. One is the overcrowding of radio bands, and the other is the move to escape that congestion by exploiting higher and higher frequencies. And today, as engineers roll out 5G and plan for 6G wireless, they find themselves at a crossroads: After years of designing superefficient transmitters and receivers, and of compensating for the signal losses at the end points of a radio channel, they're beginning to realize that they are approaching the practical limits of transmitter and receiver efficiency. From now on, to get high performance as we go to higher frequencies, we will need to engineer the wireless channel itself. But how can we possibly engineer and control a wireless environment, which is determined by a host of factors, many of them random and therefore unpredictable?[1]

Although this is an important subject for utility engineers as suggested above, even 3g communication used highly advanced communication and information processing technologies. I remember when I taught 3g courses to utility engineers shortly after Y2K, I started discussions with "…it seems like magic." In 4g and 5g, we have moved much further into this strange new world. Now we need to plan 6g. For that reason, I have divided the discussions below into two phases. Sections 2 & 3 are the basic (but still complex) discussion of how we will use this new technology. In section 4 we move to the deep end – how metamaterials and thus reconfigurable intelligent surfaces (RIS) will interact with advanced 6G communication technologies (feel free to bail-out).

2. Metasurfaces

The global mobile traffic volume is anticipated to reach 5,016 exabytes (EB) per month (EB/mo.) in 2030, which was 7.462 EB/mo. in 2010.[2] *This clearly depicts the importance of the evolution and advancement of mobile communication technologies. To date, fifth-generation (5G) communication, which is expected to realize the targeted 1000x*

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[1] Marios Poulakis, IEEE Spectrum, "Metamaterials Could Solve One of 6g's Big Problems," Sep 3, 2022, https://spectrum.ieee.org/metamaterials-could-solve-one-of-6gs-big-problems

[2] One exabyte is one quintillion bytes = 1 billion gigabytes.

increase in network capacity with new and advanced services, is being rolled out in the world. However, 5G systems will not be able to fully support the growing demand for wireless communication in 2030. The core 5G technologies include massive multiple-input multiple-output (mMIMO) and millimeter-wave (mmWave) communications. The mMIMO technology exploits the spatial domain by deploying numerous antennas to enable parallel transmission to multiple users using the same frequency-time resource block. The mmWaves, on the other hand, offers abundant spare spectrum in high frequency bands, thus resolving spectrum scarcity issues at microwave frequencies. Although mMIMO and mmWaves significantly improve spectral efficiency (SE), high hardware cost and complexity are major hurdles in their practical implementation. Moreover, mmWaves are highly vulnerable to signal blockage and attenuation. Therefore, reliable and efficient communication is still not guaranteed.[3]

Author's comment: mmWaves are primary used in high-density urban environments. But even given their use, as pointed out above, there will not be enough bandwidth for all applications in this environment by 2030, forcing the drive for even higher frequencies.

Perhaps the most promising solution, right now, is to use reconfigurable intelligent surfaces. These are planar structures typically ranging in size from about 100 square centimeters to about 5 square meters or more, depending on the frequency and other factors. These surfaces use advanced substances called metamaterials to reflect and refract electromagnetic waves. Thin two-dimensional metamaterials, known as metasurfaces, can be designed to sense the local electromagnetic environment and tune the wave's key properties, such as its amplitude, phase, and polarization, as the wave is reflected or refracted by the surface. So as the waves fall on such a surface, it can alter the incident waves' direction so as to strengthen the channel. In fact, these metasurfaces can be programmed to make these changes dynamically, reconfiguring the signal in real time in response to changes in the wireless channel. Think of reconfigurable intelligent surfaces as the next evolution of the repeater concept.[1]

That's important, because as we move to higher frequencies, the propagation characteristics become more "hostile" to the signal. The wireless channel varies constantly depending on surrounding objects. At 5G and 6G frequencies, the wavelength is vanishingly small compared to the size of buildings, vehicles, hills, trees, and rain. Lower-frequency waves diffract around or through such obstacles, but higher-frequency signals are absorbed, reflected, or scattered. Basically, at these frequencies, the line-of-sight signal is about all you can count on.

Such problems help explain why the topic of reconfigurable intelligent surfaces (RIS) is one of the hottest in wireless research. The hype is justified. A landslide of R&D activity and results has gathered momentum over the last several years, set in motion by the development of the first digitally controlled metamaterials almost 10 years ago.

RIS prototypes are showing great promise at scores of laboratories around the world. And yet one of the first major projects, the European-funded Visorsurf, began just five years ago and ran until 2020. The first public demonstrations of the technology occurred in late 2018, by NTT Docomo in Japan and Metawave, of Carlsbad, Calif…

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[3] Sarah Basharat, Syed Ali Hassan, Haris Pervaiz, Aamir Mahmood, Zhiguo Ding, and Mikael Gidlund, DeepAI, July, 2021, https://deepai.org/publication/reconfigurable-intelligent-surfaces-potentials-applications-and-challenges-for-6g-wireless-networks

3. How Reconfigurable Intelligent Surfaces (RIS) Strengthen a Wireless Signal

To understand how RIS improves a signal, consider the electromagnetic environment. Traditional cellular networks consist of scattered base stations that are deployed on masts or towers, and on top of buildings and utility poles in urban areas. Objects in the path of a signal can block it, a problem that becomes especially bad at 5G's higher frequencies, such as the millimeter-wave bands between 24.25 and 52.6 gigahertz. And it will only get worse if communication companies go ahead with plans to exploit subterahertz bands, between 90 and 300 GHz, in 6G networks. Here's why. With 4G and similar lower-frequency bands, reflections from surfaces can actually strengthen the received signal, as reflected signals combine. However, as we move higher in frequencies, such multipath effects become much weaker or disappear entirely. The reason is that surfaces that appear smooth to a longer-wavelength signal are relatively rough to a shorter-wavelength signal. So rather than reflecting off such a surface, the signal simply scatters.

One solution is to use more powerful base stations or to install more of them throughout an area. But that strategy can double costs, or worse. Repeaters or relays can also improve coverage but here, too, the costs can be prohibitive. Reconfigurable intelligent surfaces (RIS), on the other hand, promises greatly improved coverage at just marginally higher cost…

The key feature of RIS that makes it attractive in comparison with these alternatives is its nearly passive nature. The absence of amplifiers to boost the signal means that an RIS node can be powered with just a battery and a small solar panel.

RIS functions like a very sophisticated mirror, whose orientation and curvature can be adjusted in order to focus and redirect a signal in a specific direction. But rather than physically moving or reshaping the mirror, you electronically alter its surface so that it changes key properties of the incoming electromagnetic wave, such as the phase.

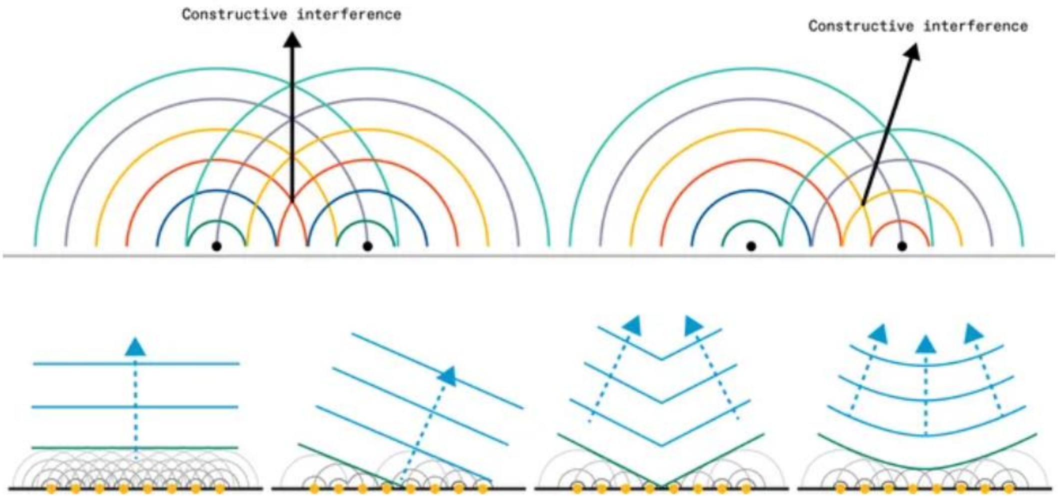
That's what the metamaterials do. This emerging class of materials exhibits properties beyond (from the Greek meta) those of natural materials, such as anomalous reflection or refraction. The materials are fabricated using ordinary metals and electrical insulators, or dielectrics. As an electromagnetic wave impinges on a metamaterial, a predetermined gradient in the material alters the phase and other characteristics of the wave, making it possible to bend the wave front and redirect the beam as desired.

An RIS node is made up of hundreds or thousands of metamaterial elements called unit cells. Each cell consists of metallic and dielectric layers along with one or more switches or other tunable components. A typical structure includes an upper metallic patch with switches, a biasing layer, and a metallic ground layer separated by dielectric substrates. By controlling the biasing—the voltage between the metallic patch and the ground layer—you can switch each unit cell on or off and thus control how each cell alters the phase and other characteristics of an incident wave.

To control the direction of the larger wave reflecting off the entire RIS, you synchronize all the unit cells to create patterns of constructive and destructive interference in the larger reflected waves [see illustration below]. This interference pattern reforms the *incident beam and sends it in a particular direction determined by the pattern. This basic operating principle, by the way, is the same as that of a phased-array radar.*

An RIS has other useful features. Even without an amplifier, an RIS manages to provide substantial gain—about 30 to 40 decibels relative to isotropic (dBi)—depending on the size of the surface and the frequency. That's because the gain of an antenna is proportional to the antenna's aperture area. An RIS has the equivalent of many antenna elements covering a large aperture area, so it has higher gain than a conventional antenna does.

Beamforming by constructive and destructive interference



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A reconfigurable intelligent surface comprises an array of unit cells. In each unit cell, a metamaterial alters the phase of an incoming radio wave, so that the resulting waves interfere with one another [above, top]. Precisely controlling the patterns of this constructive and destructive interference allows the reflected wave to be redirected [bottom], improving signal coverage.

All the many unit cells in an RIS are controlled by a logic chip, such as a field-programmable gate array with a microcontroller, which also stores the many coding sequences needed to dynamically tune the RIS. The controller gives the appropriate instructions to the individual unit cells, setting their state. The most common coding scheme is simple binary coding, in which the controller toggles the switches of each unit cell on and off. The unit-cell switches are usually semiconductor devices, such as PIN diodes or field-effect transistors.

The important factors here are power consumption, speed, and flexibility, with the control circuit usually being one of the most power-hungry parts of an RIS. Reasonably efficient RIS implementations today have a total power consumption of around a few watts to a dozen watts during the switching state of reconfiguration, and much less in the idle state.

3.1. Simulations Used to Define Wireless Channels

To deploy RIS nodes in a real-world network, researchers must first answer three questions: How many RIS nodes are needed? Where should they be placed? And how big should the surfaces be? As you might expect, there are complicated calculations and trade-offs.

Engineers can identify the best RIS positions by planning for them when the base station is designed. Or it can be done afterward by identifying, in the coverage map, the areas of poor signal strength. As for the size of the surfaces, that will depend on the frequencies (lower frequencies require larger surfaces) as well as the number of surfaces being deployed.

To optimize the network's performance, researchers rely on simulations and measurements. At Huawei Sweden, where I work, we've had a lot of discussions about the best placement of RIS units in urban environments. We're using a proprietary platform, called the Coffee Grinder Simulator, to simulate an RIS installation prior to its construction and deployment. We're partnering with CNRS Research and CentraleSupélec, both in France, among others.

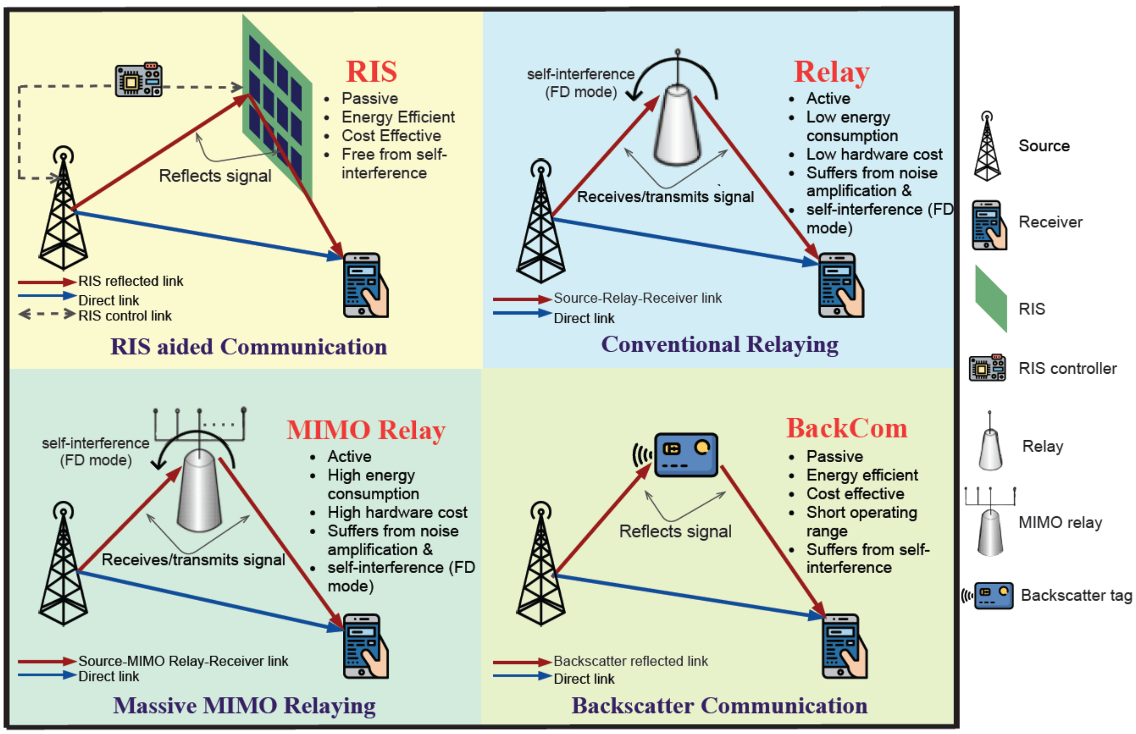
In a recent project, we used simulations to quantify the performance improvement gained when multiple RIS were deployed in a typical urban 5G network. As far as we know, this was the first large-scale, system-level attempt to gauge RIS performance in that setting. We optimized the RIS-augmented wireless coverage through the use of efficient deployment algorithms that we developed. Given the locations of the base stations and the users, the algorithms were designed to help us select the optimal three-dimensional locations and sizes of the RIS nodes from among thousands of possible positions on walls, roofs, corners, and so on. The output of the software is an RIS deployment map that maximizes the number of users able to receive a target signal…

4. Other 6G Methods and Compatibility with RIS

While 5G is yet to be realized fully, the researchers have already started looking for energy and spectral-efficient solution for sixth-generation (6G) systems. In addition to the energy and spectral efficiency, the new paradigm is smart and reconfigurable wireless environments. Recently, a cost-effective and energy-efficient technology, reconfigurable intelligent surface (RIS), also called intelligent reflecting surface (IRS), or passive holographic multiple-input multiple-output (MIMO) surface (HMIMOS), has been proposed in this regard. RIS empowers the smart wireless environments by overcoming the stochastic nature of the propagation channel, thereby improving quality-of-service (QoS) and connectivity. The wireless environment that used to be a dynamic uncontrollable factor is now considered to be a part of the network design parameter.

Author's comment: In the discussion of the subject of this section, I will mainly use a more advanced text (reference 3). I will try to keep the discussion reasonable for readers without communication engineering experience.

As illustrated in the figure below, RIS concept can be viewed to operate similarly as other related wireless technologies such as, conventional relaying, backscatter communication (BackCom), and massive multiple-input multiple-output (mMIMO) relaying. We now present the major differences and competitive strengths of RIS that make it stand out among these technologies. First, compared to conventional relaying that requires additional power for signal transmission, amplification, and regeneration, RIS passively reflects the impinging signal by inducing intelligent phase-shifts, without the need for an additional radio frequency (RF) source. Moreover, RIS operates in full-duplex (FD) mode, free from noise amplification and self-interference. Secondly, compared to traditional BackCom such as radio frequency identification (RFID) tag that loads its own information on the incident signal and then backscatters the modulated signal to the receiver, RIS reflects the incident signal to assist the communication between the source and the receiver without sending any information of its own. BackCom also requires sophisticated signal processing for self-interference cancellation in order to decode the tag message. Finally, unlike mMIMO relaying, RIS can be implemented at a much low hardware cost and power consumption. Although signal-to-noise ratio (SNR) achieved through RIS is less than the equal-sized mMIMO counterpart, however, the SNR of RIS-assisted system can be improved by increasing the reflecting elements, since the cost per reflecting element of RIS is much less than the cost per antenna element in mMIMO relaying. Architecturally, RIS is lightweight with conformal geometry and can be easily mounted on the ceilings, walls, and building facades.



Inspired by the RIS potential to realize smart wireless environments and its compatibility with other technologies, the main contributions of this study can be summarized as follows.

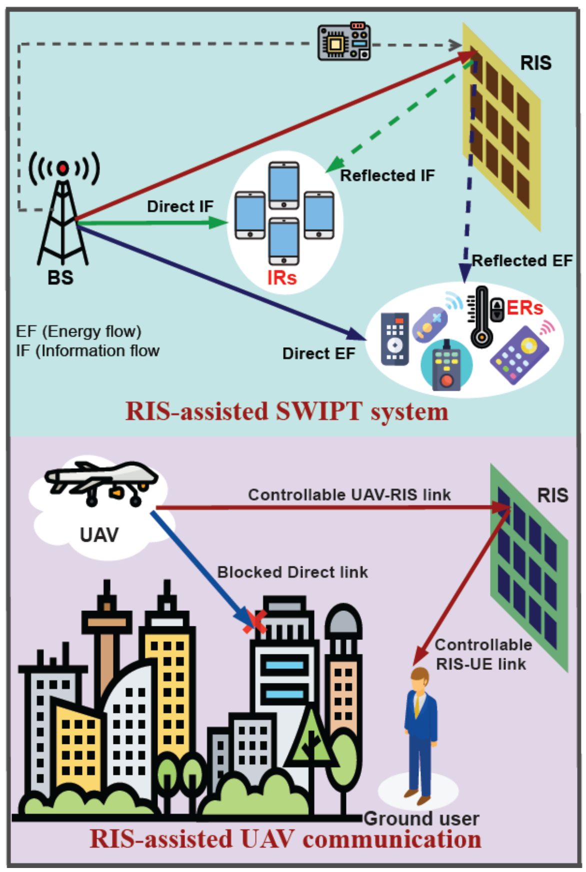
- We provide a comprehensive discussion on integrating RIS with emerging communication technologies for realizing 6G wireless networks, namely, non-orthogonal multiple access (NOMA), simultaneous wireless information and power transfer (SWIPT), unmanned aerial vehicles (UAVs), BackCom, mmWaves, and multi-antenna systems.

- *For practical implementation of RIS-assisted networks, we identify three crucial challenges, including RIS reconfiguration for controllable reflections, deployment and size optimization, and channel estimation.*
- *We present a novel case study for RIS-assisted NOMA network with imperfect channel state information (CSI) to highlight the impact of channel estimation errors on the performance of RIS-assisted NOMA networks. We further determine the various factors that affect the size of RIS, i.e., the number of RIS elements.*
- *To provide effective guidance for future research, we introduce five promising research directions for realizing RIS-assisted networks.*

Current research contributions have revealed RIS to be a cutting-edge technology, opening new promising research opportunities on the road towards 6G. In this section, we elaborate on the performance gains that can be achieved by integrating RIS with emerging communication technologies.

4.1. RIS and NOMA

Non-orthogonal multiple access (NOMA) has emerged as a promising technology for future generation networks to support massive connectivity. Power domain NOMA (PD-NOMA) enables multiple users to share the same resource block (e.g., time, frequency, code), hence improves both spectral and energy efficiency. In a downlink NOMA system, superposition coding (SC) is used at the base station (BS) to multiplex the data of the users with different channel gains, and successive interference cancellation (SIC) is employed at the receiver to decode the message signals. Although NOMA provides sufficient performance gains over OMA, the stringent demands on data rate and connectivity for B5G/6G systems compel to shift to smart and reconfigurable wireless networks; hence, the RIS-assisted NOMA system has been proposed by the research community…



4.2. RIS and SWIPT

Simultaneous wireless information and power transfer (SWIPT) is an effective solution to power massive devices in a wireless-powered Internet-of-things (IoT) network. In practice, the significant power loss over long distances reduces the energy harvested at the energy receiver, which degrades the performance of SWIPT systems. However, the limitations of practical SWIPT systems can be compensated via RIS, as illustrated in In the figure to the right Through intelligent signal reflections, RIS boosts the signal strength both at the *information receiver (IR) and the energy receiver (ER), thereby improving the energy efficiency of SWIPT system…*

4.3. RIS and UAVs

RIS can even be applied to unmanned aerial vehicle (UAV)-enabled communication systems to improve propagation environment and enhance communication quality, as shown in above figure. In a dense urban environment, the line-of- sight (LoS) links between the UAV and the ground users may be blocked, which deteriorates the channel gains. However, the RIS-assisted UAV system can enable virtual LoS paths by reflecting the signal received from UAV to the ground users. The received signal power at the ground user can be significantly enhanced by the joint optimization of RIS beamforming and UAV trajectory. In this regard, Li et al.[4] proposed an iterative algorithm for achievable rate maximization under UAV mobility and the RIS's phase-shift constraints, with the results confirming significant improvement in achievable rate with the aid of RIS.

RIS can also enhance the cellular communication of UAVs[5], which suffers from down-tilted BS antennas, i.e., the main lobes of antennas are optimized to serve the ground users, while UAVs communication is supported by side lobes only. Through intelligent and optimized signal reflections, controlled via cellular BS, RIS can direct the impinging BS signal towards a specific UAV. The RIS reflected signal combines coherently with the direct BS-UAV signal, thus improves the received signal strength at the UAV. Even a small-sized RIS, deployed on a building facade, can improve the cellular communication of the UAV flying substantially above the BS. Moreover, RIS location, i.e., RIS distance from BS distance and RIS deployment height, is a critical factor in such applications as performance gain reached through RIS is maximized if RIS location is selected ideally.

4.4. RIS and BackCom

Backscatter Communication (BackCom) (as used in radio frequency identification (RFID) tags) is a promising solution towards an energy-efficient and sustainable IoT network. Despite the extensive research on the improvement of reliability and throughput of a BackCom system, its short operation range remains a key barrier towards the large-scale deployment that needs to be addressed.

Recently, in the paper referenced at the end of this paragraph, the authors elaborated on the potentials of RIS-assisted monostatic and bistatic BackCom systems, where the RIS is employed to assist the communication between the tag and the reader. The authors proposed a joint optimization framework, under transmit power minimization, to optimize RIS phase-shifts and the source transmit beamforming. The application of RIS to

[4] Sixian Li, Bin Duo, Xiaojun Yuan, Ying-Chang Liang, and Marco Di Renzo, "Reconfigurable Intelligent Surface Assisted UAV Communication: Joint Trajectory Design and Passive Beamforming," IEEE Wireless Commun. Lett., vol. 9, no. 5, pp. 716–720, 2020, https://www.academia.edu/75875550/Reconfigurable_Intelligent_Surface_Assisted_UAV_Communication_Joint_Trajectory_Design_and_Passive_Beamforming

[5] Dong Ma, Ming Ding and Mahbub Hassan, UNSW Sydney "Enhancing Cellular Communications for UAVs via Intelligent Reflective Surface," in IEEE WCNC, 2020, pp. 1–6, https://www.researchgate.net/publication/342325675_Enhancing_Cellular_Communications_for_UAVs_via_Intelligent_Reflective_Surface

BackCom can significantly reduce the transmit power, which can be mapped to improve the operational range...[6]

4.5. RIS and mmWave Communication

Millimeter-wave (mmWave) communication, with the capability to support multi-gigabits of data rate, is perceived as a potential solution for the looming capacity crunch. However, high directivity of mmWaves makes it vulnerable to blockage instants, especially in indoor and dense urban environments. As RIS has the capability to introduce effective additional paths, an RIS-enhanced mmWave system can overcome the limitations of a conventional mmWave system. When the direct links from the BS to users are severely blocked, optimizing the system parameters can provide satisfactory performance gains…

4.6. RIS and Multi-Antenna Systems

The multi-antenna systems aim at actively improving the signal quality by employing a large number of antennas and exploiting the spatial domain for transmit beamforming. However, the conventional multiple-input single-output (MISO) systems suffer from wireless channel randomness, limiting their performance. Therefore, for an energy-efficient solution, RIS can be applied to MISO systems to improve the network performance at significantly low hardware cost and energy consumption. Different from the conventional systems, an RIS-aided MISO system can guarantee the users' quality of service, with less number of base station (BS) antennas, by utilizing the smart passive reflections of RIS…

Author's final comment: Although the authors of reference 3 provide much additional information, figures and references, I believe that this is beyond my scope in this post. If you wish to dig deeper, go through the link in reference 3, go to page 4, and start reading.

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[6] X Xiaolun Jia, Jun Zhao, Xiangyun Zhou, and Dusit Niyato, "Intelligent Reflecting Surface-Aided Backscatter Communications," arXiv preprint arXiv:2004.09059, 2020, https://deepai.org/publication/intelligent-reflecting-surface-aided-backscatter-communications