On-Demand (OnD) RIS-Assisted 6G Networks: Concept, Application, and Future Directions

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Abstract

We introduce the concept of on-demand (OnD) reconfigurable intelligent surfaces (RISs), which can provide cost and spectrum resource advantages. In a case study, we demonstrate how the OnD RIS technology can be implemented. In addition, we discuss its impacts on the channel capacity and average received power. Finally, we discuss future research directions.
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Abstract—An evaluation of the infrastructure and operation costs of a communication network can be conducted by scaling up the amounts used in the preceding generation. Thus, development, infrastructure, equipment, and operation costs of the sixth generation (6G) of cellular networks are expected to be higher than those of the fifth generation. To reduce these costs, multiple techniques are proposed. However, operating an infrastructure using these techniques may also be costly. In this article, we introduce the concept of on-demand (OnD) reconfigurable intelligent surfaces (RISs), which can provide cost and spectrum resource advantages. In a case study, we demonstrate how the OnD RIS technology can be implemented. In addition, we discuss its impacts on the channel capacity and average received power. Introducing OnD RIS-assisted links into the 6G infrastructure, the equipment and operation costs can be reduced. Furthermore, when the demand for the RIS technology ceases, the allocated resources can be reassigned to another use.

Index Terms—On-demand (OnD) reconfigurable intelligent surfaces (RISs), RIS-assisted wireless networks, OnD channel capacity, OnD average received power.

I. INTRODUCTION

Research on the sixth generation (6G) of mobile systems is increasing rapidly, with more studies being conducted. These statements can be confirmed by the amount of works recently published by researchers and industry [1]–[7]. The spectrum used in the fifth generation (5G) cellular system and envisaged for 6G is one of the key differences between the two generations. While 5G is allocated frequencies from sub-6 GHz to 71 GHz, 6G is planned to operate with frequencies up to 10 THz [7]. This yields a peak data rate of up to 1000 Gbps with a latency close to 1 µs [1], [7]. As all these preparations continue, the research community wishes to ensure that no area is left uncovered within 6G systems. This explains the widespread research outputs on reconfigurable intelligent surfaces (RISs), which are expected to be part of the 6G ecosystem [2], [3], [3]–[6]. A critical aspect of the 6G preparation that should not be overlooked is the energy consumed by the 6G equipment. In comparison with their 5G predecessors, 6G networks are expected to provide more data bits per kilowatt. It is anticipated that the increase in traffic and density will negate these savings, resulting in an increase in energy consumption. To save energy and provide the required average received power and channel capacity, in this paper we introduce the on-demand (OnD) RIS-assisted 6G concept.

Discussions on major 5G-6G differences and 6G features occupy the front rows of major topics analyzed. For instance, [1] states that the 6G implementation and operation will cost 1000 times less than 5G. It may be due to the fact that part of the 5G infrastructure remains in place, even if the heart of the system changes. It may also be due to the fact that cutting-edge algorithms such as artificial intelligence algorithms will be applied. A factor in this cost reduction is the application of cost-efficient alternative technologies such as visible light communications and light fidelity [2]. It has been demonstrated in [2] that integrating the RIS technology in light fidelity-aided 6G systems spans beyond the line-of-sight (LoS) link blockage. These contributions of the RIS technology are largely demonstrated in the literature [2]–[6], [8]. Additionally, the RIS technology enables the wireless transmission environment to be viewed as a service- and performance-based environment [4]. Beyond shrinking the implementation and operation cost of 6G systems, learning techniques can as well be added to the RIS infrastructure to mitigate the effects of noise and interference on the impinging signal [5]. More applications to 6G include those that enlarge transmission coverage by exploiting simultaneous reflection and refraction by RIS elements [6], [9]. However, adding RIS modules to 6G networks also increases the distance between the transmitter and receiver, resulting in a double fading effect that contributes to weaken the performance of the system. This dilemma has been mitigated in [3], while [10] focused on the deployment of an intelligent, resourceful, and resilient 6G radio access network. This was done to enhance intelligence, autonomy, and openness. Other features of the 6G technology include different transmission frequencies, higher transmission speeds with low-latency, energy efficiency, higher network reliability with a modern network architecture, and enhanced support for machine-to-machine connections.

A few OnD concepts have been proposed for 6G systems, as follows. OnD services related to combined advanced computation, network, and storage resources, OnD wireless resource management, OnD proactive traffic caching over shared spectrum, and OnD cell-free networking for the Internet-of-things have been proposed and discussed in [11]–[14]. Nevertheless, to the best of our knowledge, an OnD RIS-assisted network has not been proposed for an RIS connection within the 6G ecosystem. This is the focus of this paper. We examine the features of 6G networks that may require the RIS technology, particularly the average received power and channel capacity. We present a case study where the free-space optical (FSO) LoS link of an access system is disrupted by a cloud, requiring the use of a RIS module to re-establish the connection between...
the transmitter and receiver. Preliminary results of this study show that the OnD RIS technology has a significant impact on the 6G system performance, with an undeniable repercussion on its resource management and operation costs.

II. DETAILS OF THE NEED OF THE RIS TECHNOLOGY WITHIN 6G

A. Beyond Solving Skip Zones: The Case of Optical Wireless Communication Systems

Due to its advantages, the RIS technology is a largely researched concept. Superseding the relay technology, the RIS technology was initially introduced to address dead zone impediments in telecommunication systems. In addition, the RIS technology enhances the system’s energy efficiency. It further offers a degree of control over the transmission environment. These advantages apply to both radio frequency and optical wireless communications. Its use in optical systems mainly targets visible light and FSO communication systems. An RIS module inserted into an optical wireless communication network helps to re-establish the LoS transmission performance. Indoor optical environments require the RIS technology in multiple scenarios. These are mostly situations where the LoS path of the transmitted signal is lost through a blockage. For example, in indoor visible light communication systems, the LoS signal blockage mainly results from users’ movement, while in terrestrial FSO, satellite-to-ground FSO, and satellite-to-satellite FSO, this happens due to cloud, adverse weather conditions, and any other situations that may lead to received signal outage. These blockage-related problems have found solutions in the implementation of an optical RIS in the environment. Additionally, they have performance-related impacts such as energy efficiency.

B. 5G and 6G Enabling the RIS Technology

The differences between 5G and 6G technologies can be categorized according to spectrum usage, data transmission speed, latency, reliability, security threats, advancements in the Internet-of-things, and incorporation of machine learning. Although 5G has its merits, it also has limitations. 5G has limited coverage, especially in rural areas or remote locations. Users can also experience signal interference and latency issues with 5G networks. Three frequency bands are crucial for 5G: sub-1 GHz, mid-band (3.5 GHz and 6 GHz), and mmWave (26 GHz, 28 GHz, 40 GHz). In addition to 5G features, 6G will also offer exciting improvements [7]. With 6G, the physical and digital worlds will seamlessly merge. Users will experience things in an innovative way through multisensory and immersive communications. With 6G, sensing, positioning, and reliability will be improved. Furthermore, 6G networks will improve sustainability and bridge the digital divide. One significant envisioned 6G frequency range is the mid-band spectrum. This includes frequencies between 7 and 15 GHz. Amongst others, two envisaged 6G frequencies are the centimetre range (7-20 GHz) and the sub-THz range (92-300 GHz), which can be used for high-accuracy sensing and positioning [7].

Some of the most compelling reasons justifying the increasing appeal for the RIS technology in 6G are: (i) 6G’s high frequencies will exhibit short coverage. (ii) The 6G technology will deliver up to 1000 Gbps in terahertz bands. 6G will provide 100 times faster data transfer than 5G, with improved reliability, about $10^{-7}$ packet loss probability, and low-latency, about 1 $\mu$s delay [1], [7]. To maintain this speed and quality of service, signal outages are prohibited. (iii) Developing more efficient transmission systems, algorithms, and network architectures is necessary for 6G. This will reduce backhaul and core network delays in transmission, coding, processing, queuing, and routing. As a result, network interruptions will be a major problem for 6G systems. (iv) Power is one of the most essential resources for transmitting data. Thus, power efficiency is a critical key performance indicator. Since power efficiency improvement is one of the features of the RIS technology, its integration into the 6G infrastructure is necessary. (v) 6G deployment may require learning from network data. Network optimization, user feedback, and application performance can be improved with artificial intelligence and machine learning. In 6G, intelligent algorithms and models will optimize network parameters. These objectives will not be met if the connection is disrupted.

Figure 1 depicts a summary of the envisioned use of the RIS technology in 6G networks. The most investigated topics include: (i) RIS-assisted multicell networks; (ii) RIS-supported mobile edge computing systems; (iii) RIS-aided non-orthogonal multiple access networks; (iv) RIS-assisted cognitive radio networks; (v) RIS-assisted systems with physical layer security; (vi) RIS-aided systems with simultaneous wireless information and power transfer; (vii) RIS-supported systems with unmanned aerial vehicle; and (viii) RIS-assisted intelligent transportation and city.

C. RIS Infrastructure Implementation May Be Costly

Considering that recovering the LoS performance of the system is the main objective of the RIS technology, then, it is evident that it will consume energy since the increase in the transmission distance is traded-off with an integrated amplifier. For this reason, it is critical to evaluate active RISs and discuss the performance-price ratio of the system. For example, in an optical RIS made of liquid crystals, the cost of the overall RIS infrastructure will consist of the liquid crystal substance, the externally applied voltage, which is used to control the system, the dye, which facilitates the signal amplification process, and labor, which may be high due to the requirement for liquid crystals manipulation.

III. THE OND RIS-ASSISTED WIRELESS NETWORKS

A. Concept Introduction

The above description of the 6G features demonstrates that efficiency in network resource management is a significant asset to the 6G technology. This includes power management, infrastructure management, frequency reuse, and resource allocation. As part of the infrastructure, an RIS module may be requested to join the network at specific time slots, when there is a need to improve some of the network parameters like the
average received power and channel capacity. When one of these parameters is lower than the threshold value, the RIS module is engaged to improve the corresponding parameter and the entire system. The OnD RIS module could also be required when the number of users increases and the LoS path is unable to meet all these users requirements. If the module has already been connected to the network, a request to increase the number of active elements can be emitted. If all elements of the RIS module are in operation, a second OnD RIS module can be invited to join the network. Figure 2 depicts a number of application scenarios for the OnD RIS technology in a 6G network.

B. OnD Network Solutions

Figure 2 is an illustration of a city environment with outage scenarios, where the outage is not permanent in some cases. For example, User 1 has poor connection to the roof top base station. With the help of a permanent RIS module located on a wall opposite the shaded area, the user can re-connect to the network. This scenario is well-known and researched. The cases requiring an analysis are Users 2 and 3. While walking, User 2 reaches an area where the transmitted signal is absent, or the received power is not sufficient to properly decode the received bits. A mobile and temporary RIS module is activated to re-connect the user. If the user leaves this zone and moves back to an area where the LoS signal is effective, the temporary RIS module switches off. Note that in this case, the OnD RIS module may follow the user if necessary. In the last case, an obstacle disrupts the connection to User 3. As a result, the corresponding average received power falls below the threshold value. The user is re-connected to the main base station through a fixed and temporary RIS module activated for the circumstance. As soon as the obstacle moves away, the temporary RIS module is switched off.

Algorithm 1: OnD RIS Module Activation.

Input: Set the threshold values for the average received power.
Evaluation: Evaluate the average received power.
Comparison: Compare the measured value of the average received power to its threshold counterpart.

if the average received power is lower than or equal to the threshold power, then
| do: proceed with OnD RIS activation.
end
else
| do: keep the OnD RIS inactive.
end

Algorithm 1 describes the OnD RIS module activation procedure when the average received power is compared with its threshold value. The evaluation requires different algorithms not discussed in this paper; a number of wireless channel characterization algorithms can be found in the literature [8].

IV. Case Study: An OnD RIS-Assisted FSO Systems

A. Transmission Scenarios

Consider the system depicted in Fig. 3, where transmission is done through free space using an optical signal. The top part of the figure shows that transmission is effective between
transmitter and receiver; the average received power if greater than the threshold value. In the bottom part, transmission is disrupted and the system requires an RIS module to meet the LoS objectives. To engage an OnD RIS module, the average received power, measured at the receiver, must be less than or equal to the threshold power. This transmission can be summarized as follows. (i) The average received power is higher than the threshold value: The system operates normally and there is no need to support the LoS link. Therefore, the RIS module remains in hibernation with no power consumption. (ii) The average received power is lower than or equal to the threshold power: The adverse weather conditions or any other obstacles enable the need to support the LoS path to meet the system objectives. This can be implemented through an alternative path that will illuminate the receiver and overcome the consequences of outage on the system performance and quality-of-service. Different solutions can be utilized: (i) Flying and non-flying vehicles that carry one or multiple OnD RIS modules can be used. (ii) A dormant static RIS module located on a building can be switched on. All these alternative paths must compensate for the power loss and channel capacity degradation observed on the LoS link. With this compensation, the average received power and channel capacity will be determined by their LoS and NLoS components. The angle between the transmitter-user and transmitter-RIS links is a critical parameter in this model as it defines the transmitter-RIS and RIS-user distances. Having a lower value of this angle means that the sum of the transmitter-RIS and RIS-user distances is close to the transmitter-user distance. This exposes the transmitter-RIS-user link to the same blockage as the LoS link, especially in clouds or adverse weathers (see Fig. 3). On the other hand, with high values of this angle, the transmitter-RIS-user link is less exposed to the obstacle on the LoS link. However, it yields larger values of transmitter-RIS and RIS-user distances, which are not desirable as they result in an increase in the signal attenuation. Note that an increase in the signal attenuation requires a higher amplification gain at the RIS module to compensate for the signal loss, which has a financial impact. Also note that the atmospheric attenuation, which results from this adverse weather, is due to two main
components, including scattering and absorption [15]. The attenuation coefficient is a combination of both scattering and absorption coefficients. According to the particle size compared to the light wavelength, scattering can be classified into Rayleigh scattering for particle size smaller than the wavelength, Mie scattering for particle of the same size as the wavelength, and geometric scattering for particle much larger than the wavelength. The attenuation regime depends on both the attenuation coefficient and the light wavelength. For example, due to the low scattering coefficients in the Rayleigh regime, the atmospheric attenuation reduces to absorption. In all cases, the attenuation can be expressed based on the Beer-Lambert’s law using the transmission range and the coefficient of attenuation [15].

B. OnD RIS-Assisted Wireless Communication System Design Example

Consider the access system introduced in Fig. 3. The transmission is susceptible to obstacles that may either prevent or degrade it. As a result, the average received power and channel capacity may decline. For the upcoming 6G networks, this option will not be acceptable. A RIS module is inserted into the system to improve the average received power and channel capacity. However, engaging the RIS module requires a number of conditions, to avoid using the RIS module and consuming power when not needed. Depending on the required data rate, threshold values of the average received power and channel capacity are set to serve as triggers for the OnD RIS module. Blockage and signal degradation in this case study are due to cloud or adverse weather. For this reason, the analysis is based on the atmospheric attenuation coefficient, which, at certain values, will result in power loss and channel degradation. We consider cases where the transmitter-user distance is 1 km, 2 km, and 5 km, respectively. The total transmit power is 20 dBm, obtained from a light generated at 1550 nm of wavelength, and the receiver effective diameter is 15 mm. Furthermore, the RIS module consists of square elements with the same area as the receiver. The signal bandwidth is 30 MHz and the power spectral density of the noise is $2 \times 10^{-12}$ WHz$^{-1}$. The transmitter and receiver are characterized by a gain of 0.85 each, while the RIS has a receiving and transmitting gain of 0.95. The transmitter divergence angle is 2 mrad over both transmitter-user and transmitter-RIS directions. It is assumed that at the RIS, the emerging light has the same 2 mrad divergence angle. Depending on the position of the RIS module, the angle $\phi$ between the transmitter-user and transmitter-RIS axes defines whether or not the transmitter-RIS-user is also affected by the obstacle present over the transmitter-user link. In all cases, it is assumed that the RIS module is placed equidistant from the transmitter and user. We consider that if the value of $\phi$ is less than 15°, then the obstacle over the transmitter-user link also affects the transmitter-RIS-user link. By setting this angle to 14.59°, the transmitter-RIS distances are 516.7 m, 1.032 km, and 2.58 km, for the transmitter-user distances of 1 km, 2 km, and 5 km, respectively. We also consider that for values of $\phi$ greater than 15°, the obstacle over the transmitter-user link does not affect the transmitter-RIS-user link. In this case, we consider $\phi = 30°$, which yields equal transmitter-RIS and RIS-user distances of 577.4 m, 1.155 km, and 2.89 km, for the transmitter-user distances of 1 km, 2 km, and 5 km between the transmitter and user, respectively. The threshold values are 0.1102 dBm and 59.71 Mbps for the average received power and channel capacity, respectively. We analyse such a system and provide preliminary results in Figs. 4 and 5.

Figure 4 depicts the average received power with respect to the atmospheric attenuation, showing the impact of using the OnD RIS module in the two aforementioned cases. As the weather condition worsens, the attenuation coefficient increases and the average received power decreases. If this
power is equal to or drops below 0.1102 dBm, as described by the algorithm, the OnD RIS module is inserted into the system. As a consequence, the average received power, obtained from both the transmitter-user and transmitter-RIS-user links, is increased. This is materialized in Fig. 4 by the shift in their respective curves. (i) In the situation where \( \varphi \) is less than 15\(^\circ\), the insertion of the RIS module uplifts the average received power from 0.1102 dBm to 1.24 dBm, 1.02 dBm, and 1.37 dBm for 1 km, 2 km, and 5 km, corresponding to attenuation coefficients of 39 dB.km\(^{-1}\), 17 dB.km\(^{-1}\), and 5 dB.km\(^{-1}\), respectively, and materialized in Fig. 4 by the middle half curves. Since the angle between the transmitter-user and transmitter-RIS axes is not large enough, and considering that the spread of the cloud on the transmitter-user link covers the transmitter-RIS-user link, the newly obtained average received power decreases with the increase of the atmospheric attenuation coefficient (see Fig. 4). If the system contains more than a single OnD RIS module, a second RIS module could also be engaged in the case the updated average received power drops again below the threshold value. The same result may be obtained by switching on more RIS elements if the total number of RIS elements has not been used. (ii) Assuming that the angle \( \varphi = 30^\circ \) and due to the fact that the obstacle over the transmitter-user link does not affect the transmitter-RIS-user link, the attenuation is constant on this link with a lower value. The resulting changes are materialised in Fig. 4 by the shift to the upper half curves exhibiting a slow slope for 1 km, 2 km, and 5 km, respectively.

Figure 5 depicts the plot of the channel capacity with respect to the weather condition through the atmospheric attenuation coefficient. We observe a similar pattern for channel capacity as for the average received power. The OnD RIS module is enabled when the channel capacity equals or drops below 59.71 Mbps. As an OnD RIS module is introduced into the system, the channel capacity shifts to new values depending on \( \varphi \). When \( \varphi = 14.59^\circ \), the channel capacity shifts from 59.71 Mbps to 109.02 Mbps, 109.81 Mbps, and 116.33 Mbps for 1 km, 2 km, and 5 km, respectively. Further, when \( \varphi = 30^\circ \), the channel capacity respectively changes from 59.71 Mbps to 376.31 Mbps, 349.76 Mbps, and 315.28 Mbps, respectively.

It is pertinent to note that if the cause of the power loss and channel capacity degradation disappears, the OnD RIS module hibernates. As a result, the OnD RIS-assisted technology can help managing resources effectively and efficiently in 6G systems.

V. IDEAS FOR FUTURE RESEARCH AND CONCLUSION

As with any new concept, OnD RIS-assisted networks require further analysis, and multiple aspects of the technology need to be further studied. In the following, we discuss ideas for future research directions with regard to the OnD RIS technology.

Implementation delays: On-off switching of fixed RIS modules, or sending a command sequence to bring over the mobile RIS module may take time. Therefore, depending on the application, it is necessary to investigate different types of RIS modules that can be utilized in an OnD way. The aim is to select the most efficient RISs that can work in an OnD RIS-assisted 6G system.

OnD RIS-assisted applications: The applications of the OnD RIS-assisted technology have not been evaluated in this paper. Either through reflection, refraction, or simultaneous reflection and refraction, the OnD RIS-assisted technology may be utilized in a number of applications. The technology may be required in applications where users are mobile, or applications where obstacles over the LoS link are not permanent. This represents a significant area of open research.

Coupling of modulation and coding schemes, and signal processing algorithms for the LoS link and the OnD link: There are several questions to be answered regarding the transmission. For example, will the modulation and coding schemes used for the permanent LoS channel be suitable for the OnD channel? Even if the RIS module is only used for reflection and refraction, and not for signal processing, what will be the effects of inserting the OnD RIS module into a system considering these signal processing algorithms? Adapting these techniques and schemes to an OnD RIS-assisted technology may not be straightforward and represents an area of future investigation.

For a transmission system experiencing signal blockage or severe fading, we proposed and discussed the OnD RIS-assisted technology to mitigate the consequences on the received signal degradation. We introduced and explained the OnD RIS concept and application scenarios. Additionally, we studied an example of an OnD RIS-assisted optical access system. Preliminary results of the average received power and channel capacity highlighted the impact of the OnD RIS technology on the system performance.

References


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