UNIVERSITÀ DEGLI STUDI DI PADOVA

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"Reconfigurable Intelligent Surfaces: possible applications and benefits"

Relatore: Zanella Andrea

Laureanda: Kosiakov Arina

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Abstract

In recent years, Reconfigurable Intelligent Surfaces (RIS) have received significant attention for their possible use and benefits in the wireless networks. This is one of the most promising technologies for next generation communication networks. RIS potential consists in its structure which makes it possible to reconfigure the wireless propagation environment making it less unpredictable. In this paper an overview of these surfaces is provided, starting with the description of the meta-surfaces as RIS are categorically designed using meta-surfaces. Their operating principles and the comparison of RIS with MIMO technologies, as well as different possible applications for the wireless networks, are going to be explained.

Negli ultimi anni le Superfici Intelligenti e Riconfigurabili (RIS) sono stati al centro di molti studi per motivi legati al loro possibile utilizzo e i diversi benefici che questo comporta per le reti wireless. Questa è considerata una delle tecnologie più promettenti per la prossima generazione delle comunicazioni wireless. Il potenziale delle RIS è legato soprattutto alla loro struttura che permette di riconfigurare l'ambiente di propagazione rendendolo meno imprevedibile e quindi più controllato. In questo documento viene presentata una visione panoramica di questa tecnologia. Innanzitutto, il focus è posto sulle meta-superfici, uno degli elementi alla base della costruzione delle RIS e del loro design fisico, i principi operazionali delle RIS, il confronto delle RIS con le tecnologie MIMO e le diverse possibili applicazioni delle RIS alle reti wireless.

Introduction

Wireless systems are evolving continuously but, the main challenges that are still prevalent are power consumption for communication and unpredictable wireless environment. In fact, the inability to control the wireless environment has always been one of the biggest problems for both indoor and outdoor environments. The solution for such an everlasting problem involves managing the interaction between electromagnetic waves and the surrounding objects in order to reduce some of the negative effects such as uncontrollable interference due to reflections and refractions, path-loss and fading phenomena.

In recent years, a new technology named Reconfigurable Intelligent Surfaces (RIS) is under research to potentially address the unpredictability of the wireless environment. These surfaces are made of low power integrated electronic circuits, that allow these surfaces to control the wireless environment and enhance the capacity and coverage of wireless networks. RIS can be easily integrated with different technologies starting from current wireless, potentially enhancing the performance of the same.

The aim of the current paper is to describe how RIS can be applied to other technologies, and which are its benefits. Chapter I denotes the concept of meta-surface and the definition of RIS be discussed as well as its limits, benefits, and the main differences between RIS and MIMO technologies. The Chapter II illustrates the physical design of the RIS. In the Chapter III different RIS applications are described, such as RIS-assisted UAV communications and RIS for mapping and localization.

Chapter 1

Introduction to Reconfigurable Intelligent Surfaces

The wireless environment is unpredictable by nature, and the presence of the objects in it affects communication quality. Outdoor space is characterized by the presence of structures which are typical in urban areas, while in the indoor environment multiple communicating devices can cause interferences. In addition to that, at lower frequencies (sub-6 GHz) the surrounding structures act as electromagnetic (EM) wave scatterers and with higher frequencies (millimeter wave or terahertz and above) even smaller objects can behave as substantial scatterers.

1.1. Meta-surfaces

In recent years, the conceptual design of RIS have been defined based on an older concept of meta-surfaces. Meta-surfaces are planar structures which can manipulate EM waves and thereby create a controllable wireless system such as reconfigurable intelligent surfaces (RIS). Meta-surfaces are made of smaller repeated conductive elements called meta-atom which are usually placed on a dielectric substrate, as shown in Figure 1. The meta-atoms, and their interconnected switch elements in the dynamic case, act as control factors over the surface currents flowing over the meta-surface and put together, these elements allow to control total EM response of the surface calculated as the total emitted field by all surface currents [1].

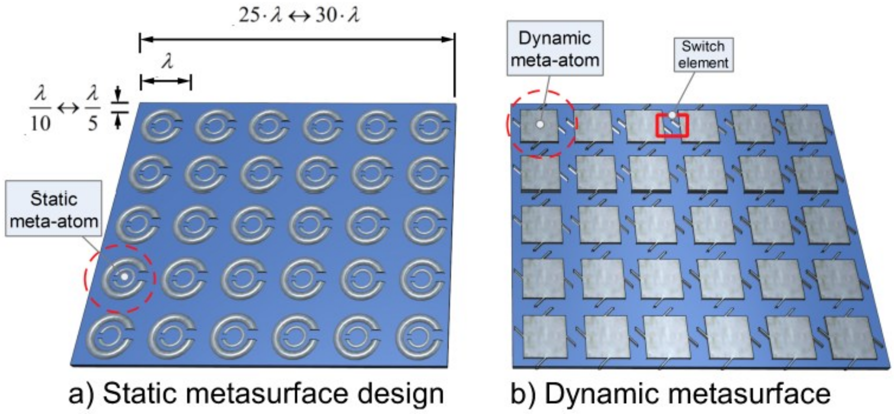

Figure 1: Example of static and dynamic meta-surfaces made of meta-atoms [1].

One of the main features of meta-surfaces is the wide amount of EM functionalities, it can support. Some common functions, briefly described as follows, are [2]:

- **Reflection:** This function defines the reflection of an impinging wave, with a given direction of arrival, towards a custom direction.
- **Refraction:** This function defines the refraction of an impinging radio wave towards a specified direction that may not necessarily coincide with the direction of incidence.
- **Absorption:** This function ensures minimal reflected and/or refracted power for impinging waves.
- **Polarization.** This function changes the oscillation orientation of the wave's electric and magnetic field.

Meta-surfaces also support more advanced functionalities such as focusing an impinging wave towards a specified direction (beamforming), collimation i.e. redirecting a diverging wave in the same direction, splitting which consists of creating multiple reflected or refracted radio waves for a given incident radio wave and analog processing, which involves the realization of mathematical operations directly at the EM level. For example, the radio wave refracted by a smart surface may be the first-order derivative or the integral of the impinging radio wave.

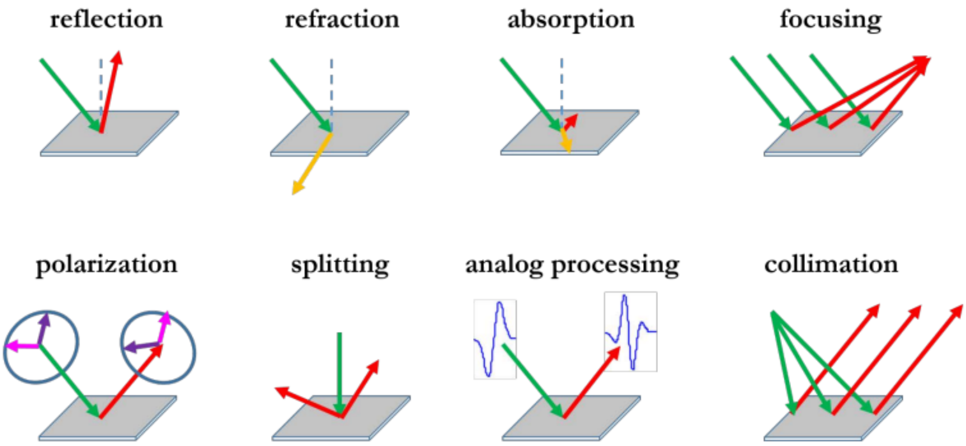

Figure 2: Representation of elementary functions supported by meta-surfaces [2].

1.2. Reconfigurable Intelligent Surfaces

In recent years, the focus of research for Beyond 5G networks has been to devise technologies and to make the wireless environment programmable and controllable, i.e., designing smart radio environment (SRE) or intelligent radio environment (IRE). One of the prominent technologies in such design of SREs is RIS. This kind of surfaces can be also referred to as follows:

• **Large Intelligent Surfaces (LIS):** The term LIS is referred to surfaces that are viewed as the next step beyond massive multiple-input-multiple-output (MIMO) technology.

• **Intelligent reflecting surfaces (IRS):** The term IRS is typically referred to surfaces that operate as reflectors and that are made of individually tunable unit elements whose phase response can be individually adjusted and optimized for beam steering, focusing, and other similar functions

• **Digitally Controllable Scatterers (DCS):** The term DCS is the most similar to RIS, and it is typically employed to emphasize the possibility of controlling, in a digital manner, the behavior of objects and devices coated or made of smart surfaces.

Reconfigurable intelligent surfaces are meta-surfaces and are primarily designed as an adaptive thin combined material sheet which can manipulate the radio waves as desired. Currently, there are two main designs for the realization of these surfaces: a programmable thin wallpaper and a programmable thin glass.

Both these structures operate in a nearly-passive and dynamic way i.e., the surface does not emit new radio waves. Also, it has the following characteristics:

- No power amplification for normal operation phase.
- Minimal digital signal processing capabilities are needed to configure the surface.
- Minimal power consumption for configuration and operation of the surface.

Hence, the RIS is made of low power electronic circuits and can be configured in order to control the departing directions of the impinging waves.

One of the early practical implementations of RIS is an artificially engineered layer which is transparent and thereby suitable for unobtrusive use. As shown in the Figure 3, the smart glass is made of a large number of sub-wavelength elements (i.e., the size of each unit cell is much smaller than the wavelength), placed on a planar surface covered with a glass substrate.

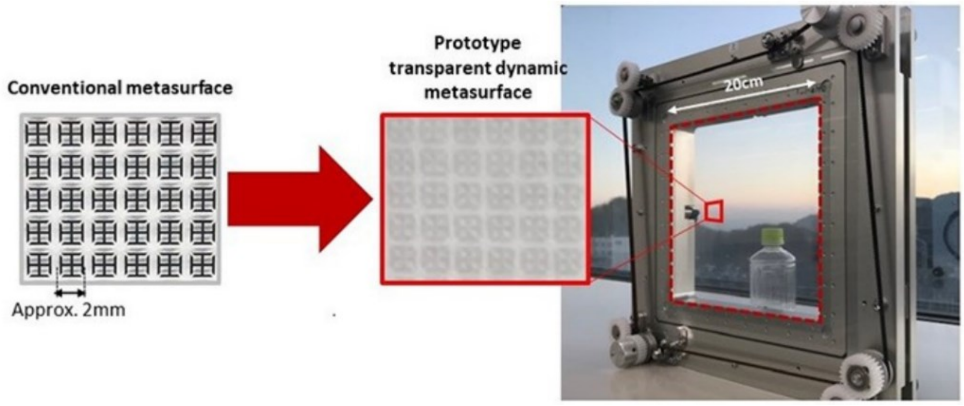

Figure 3: NTT DOCOMO's prototype, example of a programmable glass [2].

1.2.1. MIMO technologies and RIS

Intelligent Surfaces are also considered as natural evolution of Multiple-Input Multiple-Output (MIMO) technology.

An improvement which can be highlighted by going from 5G MIMO technologies to RIS ones is the possibility of increasing even more the Signal-to-Noise-Ratio (SNR) at the receiver by using a larger number of elements. The use of large antenna arrays has been shown to provide a considerable improvement in SNR as the SNR grows linearly with the number of elements N [3]. However, it is possible to improve the SNR even more by using the Intelligent Surfaces. For intelligent surfaces, the SNR improvement theoretically is proportional to N^2 [3]. This assumption, however, is valid when considering the propagation in far-field, where the directions and channel gain are approximately the same from all the elements in the array. The situation is different for the near-field (defined when the width/height of the array is comparable to the distance from the transmitter/receiver), where the EM waves impinge on the elements from different directions.

Figure 4 shows the different communication setups for massive MIMO (mMIMO) antennas and RIS in the near-field used to derive the relations above. Through the analysis of the setups, it is proven that an RIS cannot achieve a higher SNR than any of the mMIMO setups when the array sizes are equal, despite the fact that the SNR in the RIS setup grows as N^2 in the far-field. The total channel gains in the two mMIMO setups grow as N in the far field, while it grows as N^2 in the RIS setup.

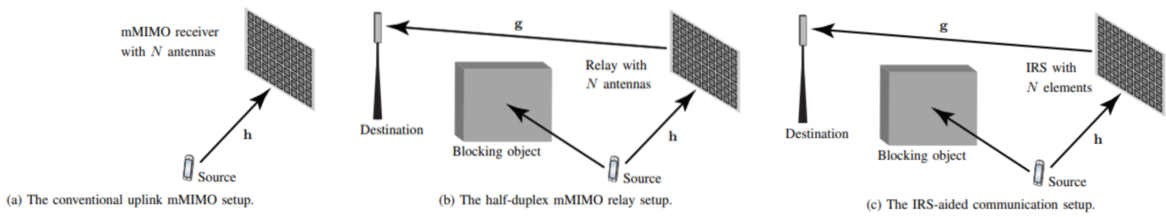

Figure 4: The three setups taken in exam [3].

1.2.2. Benefits of RIS

The integration of the reconfigurable surfaces has shown a significant performance improvement in both indoor and outdoor wireless environments. The main characteristics that make RIS an attractive concept include a reduced cost of the materials, low power usage and easy deployment on different structures including, indoor walls, aerial platforms, roadside billboards, highway polls, vehicle windows, as well as pedestrians' clothes [4]. Moreover, this technology is environment friendly and considerably different from conventional relaying systems due to its passive nature.

1.2.3. Applications of RIS

As mentioned in the previous subsection, the RIS can be easily integrated in the current wireless environment, there are potentially, a large number of applications where RIS can be beneficial.

a) Outdoor environment

• **Smart cities.** RIS can be installed on the buildings in order to enhance the coverage, increase the spectral efficiency, and reduce the exposure to the EM radiation in outdoor environments, since the deployment of RISs may reduce the amount of network infrastructure needed [2].

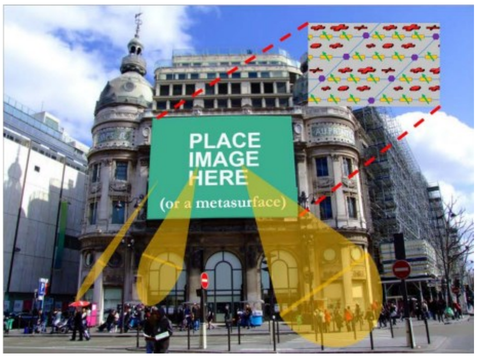

Figure 5: General use of RIS in outdoor environment [2].

• **Smart buildings.** In buildings, large windows can be made of special glasses that can selectively enable indoor to-outdoor and outdoor-to-indoor connectivity.

Figure 6: General use of RIS in outdoor environment [2].

• **Smart vehicles.** RIS can be installed on cars, trains, and airplanes. For example, the glasses and the roof of cars may be coated with RISs and can serve as moving nearly-passive relays for enhancing vehicle-to-vehicle and vehicle-to-infrastructure communications. The trains can have the interior being coated with RISs in order to provide a better signal coverage and to reduce the explosion of the passengers to EM fields. Finally, the airplanes can have the overhead bins coated with RISs that may provide high-speed Internet to passengers and again reduce their EM field exposure [2].

Figure 7: Usage of RIS for vehicular communication in urban areas [2].

b) Indoor environment

• **Smart homes.** The RIS can installed on the inside walls of the houses in order to improve the connectivity of the devices. The houses may also have the smart glasses as shown in Figure 7 which can help enhance the local connectivity.

Figure 8: Usage of RIS in indoor environment [2].

• **Smart clothing.** Clothing can be realized with metamaterials and several embedded smart sensors in order to create wearable body networks for monitoring the health of people.

Hence, RIS can be considered one of the most promising technologies for the new generation of communications and still is a hot topic for current research. The unique characteristics of RIS are:

- The nearly-passive nature of the RIS makes it possible to use eco-friendly materials in order to build sustainable wireless networks.
- Deployment of scatterers is the key concept that makes RIS a distinctive technology. Additionally, the usage of sub-wavelength scattering elements is extremely uncommon in wireless communication.
- RIS can be deployed for usage in near-field by concentrating the EM power in small spot regions. For example, RIS can be used to obtain a precise radio localization or to implement a wireless power transfer to recharge batteries of low power devices.
- RIS can increase the channel capacity if configured in a proper way if the channel matrix has a high rank, while it can also deteriorate the signal using destructive interference in order to protect the information from unauthorized users.

Chapter 2

Physical design of Intelligent Surfaces

RIS is a really promising technology, but there are still different challenges to overcome. One of the most challenging problems of the intelligent surfaces is their physical design.

2.1. Physical design

Intelligent surfaces are made of meta-atoms repeated in a sequence over a substrate. Metasurfaces usually comprise several hundreds of meta-atoms a minimum size of approximately 30×30 meta-atoms are required [15]. A metasurface design can rely on static meta-atoms or dynamic ones. Dynamic meta-atoms incorporate phase switching components which can alter the structure of the meta-atom. There are different types of intelligent surfaces, and even if they are all based on metamaterials each of these types requires a different design solution.

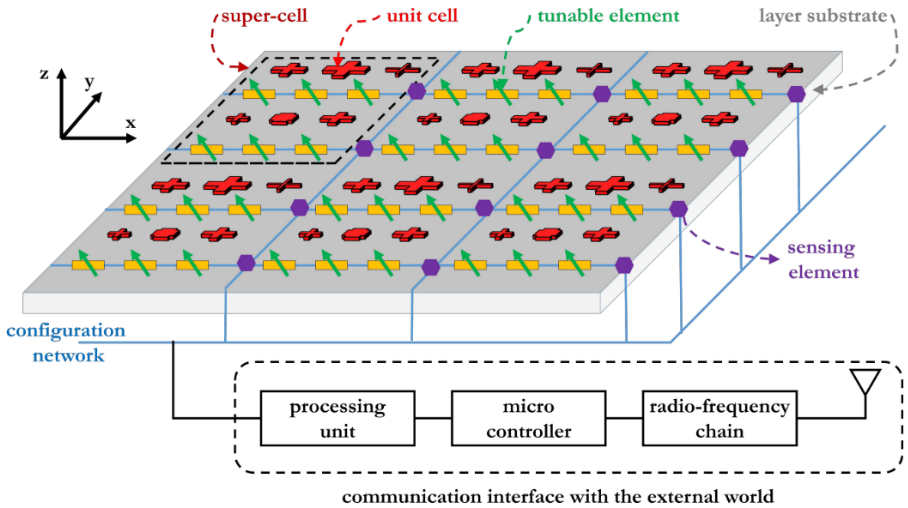

Figure 9: Conceptual structure of a reconfigurable intelligent surface [2].

RIS design is based mainly on three factors. The first factor is the two-dimensional structure of RIS, this means that the transverse size of the model is much larger than its thickness. The second factor is the composite layers based on meta-atoms. The Figure 9 shows that the RIS is constituted be composite material layer made of patches printed on dielectric substrate. These patches are responsible for the macroscopic behavior of the surface and the outcome can be different based on the material with which the unit cells are made of, their size, and the interdistance among them. Last element is the phase reconfiguration controller. RIS can operate dynamically, and it is possible by using low power electronic circuits such as Positive Intrinsic Negative (PIN) diodes.

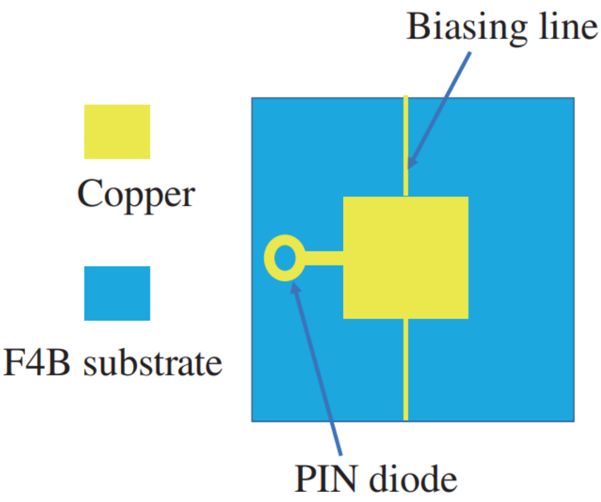

Figure 9: Representation of the PIN diode [17].

Another example is the LIS design. As other intelligent surfaces, LIS are based on the meta-materials, and in particular on the concept of dynamic meta-surfaces (DMA). This type of surfaces can transform the transmitted, received or reflected waves to achieve the desired result. A meta-surface antenna consists of microstrips made of a multitude of sub-wavelength elements. These microstrips are tilted together to create a larger antenna array as shown in the Figure 11.

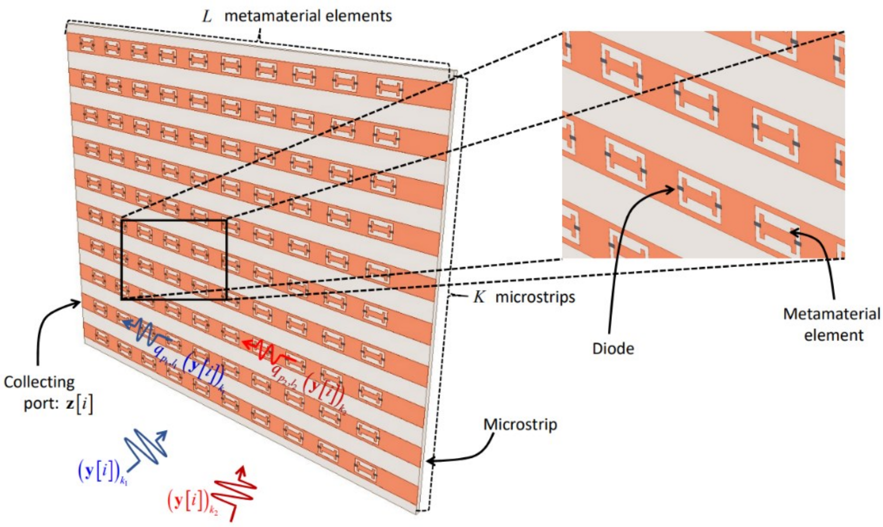

Figure 10: Representation of metasurface antenna [18].

The difference in the physical design is also connected to the aesthetic aspect of this technology. Two prototypes were released which should behave as programmable thin wallpaper and programmable glass. The first one is the prototype from Massachusetts Institute of Technology (MIT), USA, and it is called RFocus. It is made of 3,720 antennas arranged on a six square meter surface and it operates in a nearly-passive mode. This surface can also be configured by means of low power electronic circuits in order to beamform and to focus the radio waves in a specific direction. The second prototype was designed by researchers of NTT DOCOMO, Japan. This prototype is made of a large number of sub-wavelength unit elements, placed in a specific arrangement and covered with a glass substrate. The glass can be moved in order to dynamically control the response of the impinging waves. The smart glass is highly transparent and is a good solution for locations where it is not possible to install base stations (i.e., built-up areas). Another positive aspect of this technology is the fact that it doesn't interfere aesthetically or physically with the surrounding environment.

Chapter 3

RIS for Wireless communication

In recent years, the application of RIS in different communication environments has garnered a lot of interest in research and industry. Their numerous benefits, simple design and possibility to apply them to different technologies makes them one of the key technologies for the 6G wireless networks. Comparing the common antenna array in 5G and one of the key technologies for 6G, the RIS, a major difference is that the RIS is a controllable part of the wireless environment, i.e., it is neither a part of the transmitter nor the receiver [6].

3.1. RIS based communications

RIS can be used for improved communication, by enhancing the signal reception at the desired destinations and improving the SNR at the receiver. Additionally, it can also be used for localization, sensing, and physical layer security by sending artificial noise (AN) to unintended receivers. Moreover, it can be used to assist the existing communication systems serving as a reflector by reforming the reflected signal in a customized way [7].

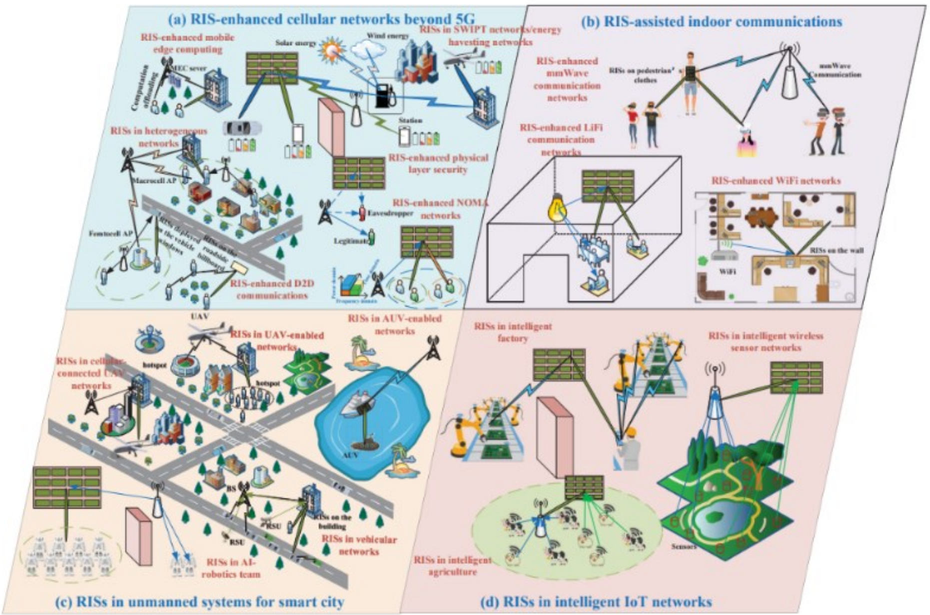

Figure 11: Examples of application of RIS [4].

Another interesting application is Ambient Backscattering. Ambient Backscatter communication is a technique which uses ambient signals in radio frequency (RF) range to enable communication between devices and powering these without using batteries. Due to the nearly-passive nature of the RIS and the ability to manipulate the impinging waves, it may be possible to recycle the existing waves. This may reduce the EM pollution, especially in EM-sensitive environments, such as hospitals.

3.2. RIS-assisted UAV communications

One of the most important improvements for the next generation communications is the use of the unmanned aerial vehicle (UAV). This type of vehicles has several useful features such as higher degrees of freedom regarding positioning and trajectory, low deployment and maintenance costs, and the ability to establish clear line of-sight (LoS) links with other nodes [9].

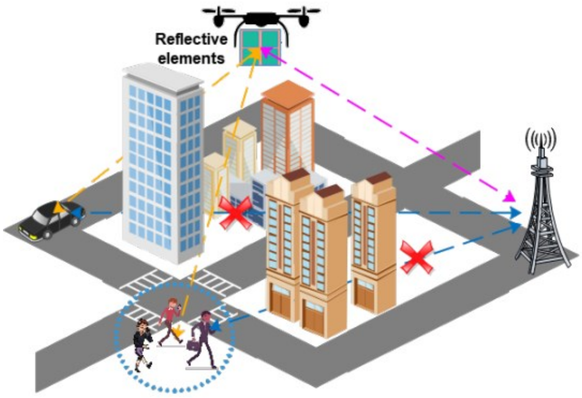

Figure 12: RIS-assisted UAV-aided communications [9].

There are several ways UAV assisted RIS can be implemented to improve the communication systems. Those are:

- Extended coverage:
  In this case a special type of intelligent surface, called omni-surface (IOS), is used. It has antennas on both sides and is able to reflect incident signals coming from the opposite directions. The main characteristic of IOS is its capability to reflect the incident signals on both sides to provide a 360-degree coverage and higher spectral efficiency. It is possible to control the direction of the departure signal from the RIS to the potential receivers without any blind spots.

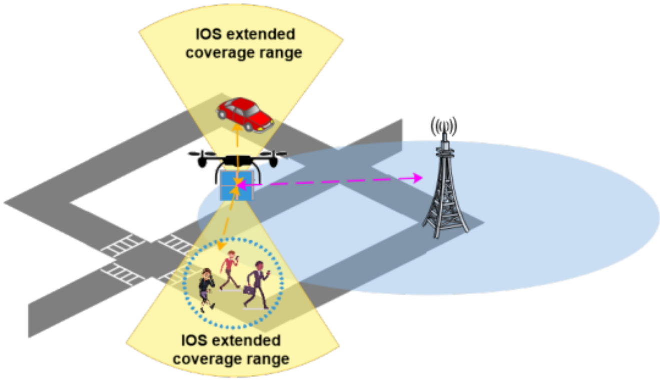

Figure 13: RIS-assisted UAV for extended coverage [9].

- Spectrum sharing:

  RIS can be employed to enable spectrum sharing. Spectrum sharing is a way to optimize the use of the airwaves, or wireless communications channels, by enabling multiple categories of users to safely share the same frequency bands. Hence, RIS can reduce the interference between devices which are simultaneously transmitting in the same frequency band. Moreover, RIS-assisted UAV systems can improve the system capacity with the help of the spectrum sharing [10]. Due to the passive nature of the RIS, this type of systems has a lower energy consumption compared to the traditional spectrum sharing techniques.

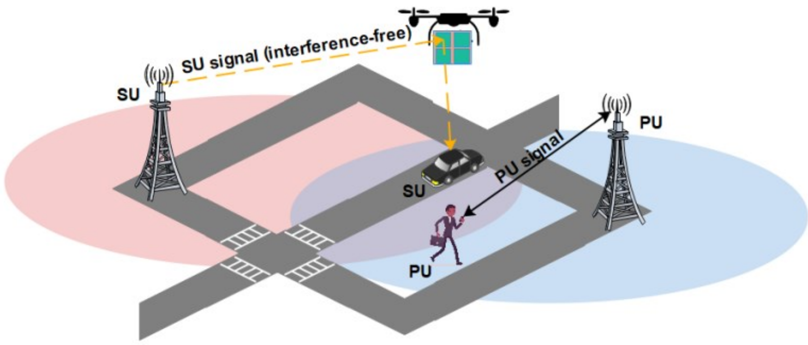

Figure 14: RIS-UAV for spectrum sharing [9].

- Increased capacity:

  Usage of RIS-UAV is most widely used to enhance capacity and throughput. The passive nature of the RIS makes its relaying strategy overcome any antenna noise amplification and self-interference, which translates in less computation and lower power consumption than for active full duplex (FD) relays [9]. Moreover, the combination of RIS with UAV optimizes the phase shifts of the antenna elements introducing rich scattering of line-of-sight (LoS) links.

- RIS-Assisted UAV Communications for physical layer security (PLS):
  RIS-assisted UAV can offer different types of PLS. For instance, it can be used to create an artificial noise to deceive potential attackers and protect users' privacy and data. Moreover, it can be employed as an aerial relay between legitimate and illegitimate users by optimizing the transmit power. Additionally, RIS-assisted UAV can also be used to lower the data rate for eavesdroppers and to tackle smart attackers [9]. In particular, it was proved that the secrecy rate of legitimate users increases as the distance between the communications peers decreases. Therefore, due to the free movement of UAVs, it is possible to decrease the distance between the transmission source and a specific user.

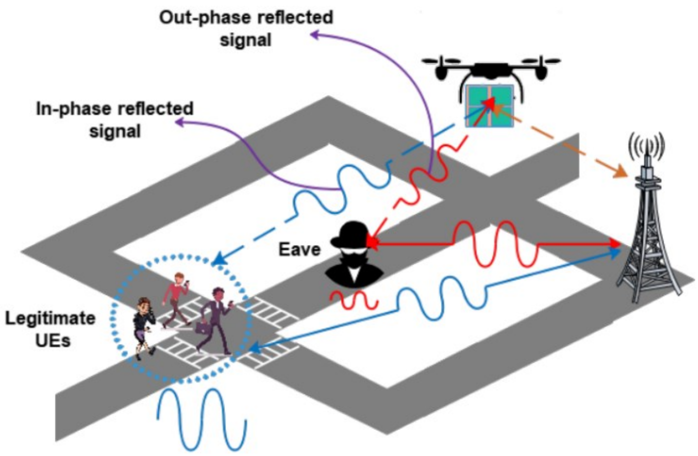

Figure 15: RIS-UAV for physical layer security [9].

3.2.1. Application of UAV assisted RIS

Currently new technologies are studied to meet the requirements of the emerging 6G wireless networks. There are different ways the RIS-assisted UAV can be integrated with these technologies for the 6G networks.
One of the main ideas for the future networks is the RIS-UAV communication system using the machine learning techniques (ML) and artificial intelligence. This type of improvement will provide the UAVs with autonomous decision-making, knowledge extraction and prediction. ML algorithms can be used for enhancing the RIS channel estimation, spectral efficiency, balancing different tradeoffs and extending the scope of current optimization techniques.

Another feature of the future 6G networks is the use of frequency bands, above 100 GHz. The mm-Wave and Terahertz (THz) communications will be affected by the increased blockage rate of the transmitted signals and by the reliability and availability of wireless communications services due to a higher frequency band. The usage of the RIS-assisted UAV can be a valid solution to these problems.

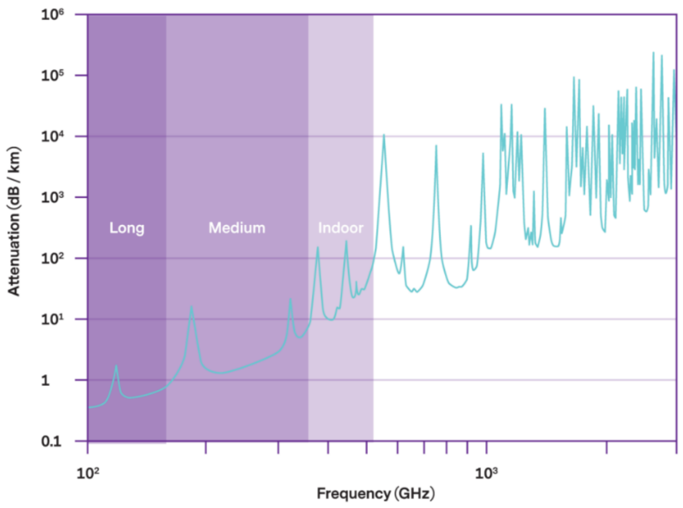

Figure 16: Illustration of the relation between frequency range and radio channel propagation effects [17].

3.3. Wireless power transfer

In the near future, the amount of IoT devices is projected to grow till tens of billions by 2030 [11]. To power this number of devices traditional methods with power cords and batteries are not suitable anymore. The main idea to overcome this issue is the Radio Frequency (RF) wireless power transfer (WPT). Wireless power transfer consists of the transmission of electrical energy without using physical link. RF WPT has the advantage of long charging distance, but the transfer efficiency degrades as the distance increase. RIS is a promising and energy sustainable solution to this problem as it is capable of beamforming and beam focusing without using active components [12]. RIS can be easily deployed in the walls of a building or a room to increase the power transfer efficiency as it is shown in the Figure 15.

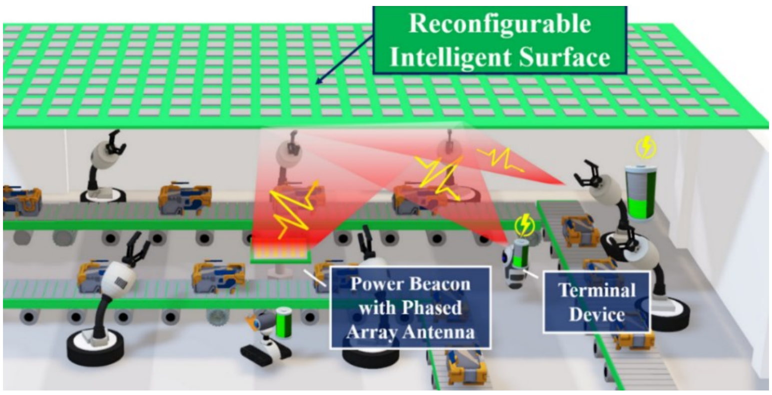

Figure 17: RIS-aided WPT system conceptual application scenario [12].

In this scenario, the RIS is installed in the ceiling of an automated factory for assisting the WPT system. The RIS reflects the EM beam from a power beacon, then it focuses the reflected wave at the devices on the ground.
RIS can be exploited in the simultaneous wireless information and power transfer (SWIPT). In this type of systems, the signal is used to convey both energy and information. There are two possible schemes for SWIPT:

- Power splitting: received signal is partitioned in the power domain, one part for energy harvesting and the other for the information transfer.
- Time switching: switches between the energy harvesting and information transfer in different time slots.

It is also possible to use UAV technology to assist the SWIPT, due to its unique mobility, ease of deployment and low cost.

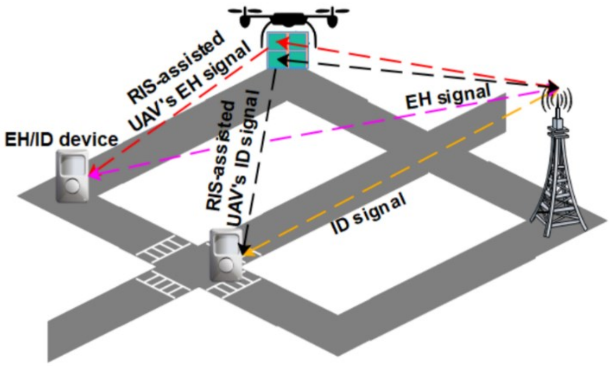

Figure 18: RIS-assisted UAV for SWIPT [9].

3.4. Localization and mapping

Localization can be described as the ability of a device to determine its own location or the location of other devices in the operating environment. There are different technologies applied to this research field and in particular the radio-based ones, such as radar, WiFi, satellite positioning and cellular localization [11]. Radio based technologies are preferred as they're less affected by the environmental factors, have sensing and communication capabilities.
Starting from the 4G, the signals dedicated to localization have been able to achieve location accuracy levels on the order of 10 m. Later, with the use of larger bandwidths and higher carrier frequencies of 5G technologies the location accuracy can be reached up to 1 m. With the next generation systems, it might be possible to improve the accuracy even more [13]. But the propagation at higher frequencies is highly affected by the objects on the path connecting the transmitter and the receiver, i.e., path loss is high for higher frequencies.

Hence, the three basic principles behind the radio localization and mapping are the measurements, the reference system and the inference algorithms. They are as follows:

- Measurements: The measurements directly from the channel estimation routine, from the radio signals between a transmitter and a receiver. The two factors that characterize these measurements are resolution and accuracy. The resolution refers to the ability to distinguish two signals based on their measurements and depends on the signal bandwidth and duration, carrier frequency, the number of antennas, and coherent integration time. The accuracy, on the other hand, to the extent to which we can determine the parameter of interest.

- Reference system: The reference system is necessary to be constant as all the measurements need to be made in relation to points with known states, also called as anchor points. The right geometric placement of the reference is also fundamental, especially for the accuracy of a localization system.

- Inference algorithms: Localization algorithms, differently from the communication algorithms, do not use multipath signals, but the LoS signals as the measurements associated with LOS signals are directly related to the location of the user.

3.4.1. Application of RIS for localization

The use of RIS for localization affects all three the principles described above. The measurements depend on the geometric model of the channel, i.e., that there is a possibility to obtain a mapping from the position space to the measurement space using the locations and EM properties of the environment. The references can be obtained from the interaction between BS/RIS, considered as anchor points, and the users or passive objects which usually have unknown location and orientation information.

The use of RIS for localization has gained a lot of attention in research. Some of the challenges in incorporating RIS in radio localization are summarized below:

- Near-field propagation: The propagation of the signals depends on the RF region the users are located. Localization algorithms can be easily applied using RIS in case of far field scenarios but, in near field cases, the propagation is affected by the wavefront curvature. This means that new signal design is required in order to harness the near-field properties.

- Channel modeling: Channel modelling for RIS is a challenging task especially due to the RIS dependence on operational frequencies. Models are likely to differ, depending on the frequency band, but multi-band operation can benefit from models that are consistent across a very wide frequency range.

- Localization and mapping algorithms. The use of RIS can be clearly useful for localization and mapping algorithms, as their location and orientation are known. This can help with the recovery of the user's position, in fact, as the state of the user contains both the 3D position and 3D orientation, as well as a clock bias, a sufficient number of resolvable signal paths must be available. RIS can be helpful if properly controlled and may lead to reduced number of data association.

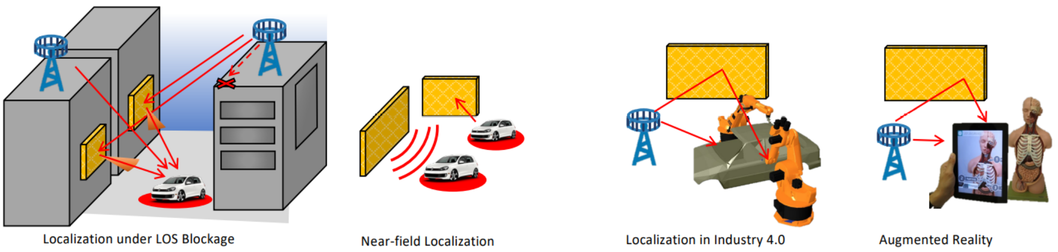

Figure 20: Application examples of RIS-based localization and mapping services [14].

Conclusion

In this paper main characteristics of RIS have been discussed. An introduction to meta-surfaces as well as their usage for design of RIS. Additionally, RIS is shown to provide significant improvements for the challenging requirements in future wireless networks due to its inherent physical characteristics such as nearly passive nature. One of the most relevant aspects of the RIS are the multiple possible implementations. It has been shown that the RIS can be used as covering materials to create smart cities, vehicles, and clothing, but the main idea is to use the RIS to improve communication. One of the ideas to accomplish this task is to assist UAVs with RIS. Another possible implementation of RIS is the Wireless Power Transfer (WPT) which can be used to help deliver energy into difficult territories. This technology can also be extended to incorporate information transfer to help power devices deployed in difficult territories. Lastly, RIS, with its various different applications, can be considered to comparably inexpensive to be deployed in the current wireless environment with less complexity and more sustainability.

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