

Reconfigurable Intelligent Surfaces in Challenging Environments

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Reconfigurable intelligent surfaces (RISs) have been introduced to improve the signal propagation characteristics by focusing the signal power in the preferred direction, thus making the communication environment 'smart'. The typical use cases and applications for the 'smart' environment include beyond 5G communication networks, smart cities, etc. The main advantage of employing RISs in such networks is a more efficient exploitation of spatial degrees of freedom. This advantage manifests in better interference mitigation as well as increased spectral and energy efficiency due to passive beam steering.

Challenging environments (CEs) comprise a range of scenarios, which share the fact that it is extremely difficult to establish a communication link using conventional technology due to many impairments typically associated with the propagation medium and increased signal scattering. Although the challenges for the design of communication networks in such environments are known, there is no common enabler or solution for all these applications. Interestingly, the use of RISs in such scenarios can become such an enabler and a game changer technology. Surprisingly, the benefits of RIS for wireless networking in underwater and underground medium as well as in industrial and disaster environments have not been addressed yet. This paper aims at filling this gap by providing a motivation for the application of RISs in CEs. In addition, novel research challenges to be addressed in this context are discussed.

Index Terms—Reconfigurable intelligent surfaces, challenging environments, underground, underwater, industrial, emergency networks, Internet of Things

I. INTRODUCTION

RECONFIGURABLE intelligent surfaces (RISs) is a promising technology, which has been motivated by the increasing demands of wireless networks beyond 5G [1]. RISs are intelligently designed artificial planar structures with reconfigurable properties enabled via integrated electronic circuits. These electronic circuits can be programmed to reflect an impinging electromagnetic (EM) wave in a controlled manner, thus making the communication environment controllable and smart. RISs are manufactured with low-profile and light weight using inexpensive materials and can be deployed on a variety of surfaces, such as facades of buildings, walls, ceilings, etc. [2]. The signal propagation from transmitters to receivers can therefore be assisted by steering the RIS-reflected signals in directions that enhance the signal quality, suppress co-channel interference and consequently improve the spectral efficiency. The corresponding performance gains of RIS-assisted networks compared to current wireless systems are well-known from the previous works in this domain [3]. Furthermore, co-channel interference can be reduced or avoided by choosing different propagation paths for the interfering signals. This is important in urban environments with dense deployment of terminals, cf. [4].

Challenging environment (CE) refers to a communication environment, in which the signal propagation and connectivity using traditional signaling technologies are heavily impaired, so that a stable, reliable and secure communication link is very difficult to establish. Unlike in the so-called extreme environments, the challenges in CEs are mostly related to wireless communication rather than to the operability of sensor nodes under extreme conditions, cf. [5]. Depending on the actual environment, the reasons for the impaired connectivity

can be very different. One of the typical problems is the increased signal scattering and absorption. Through this, the path loss increases with transmission distance much faster compared to traditional communication environments, i.e. path loss exponent higher than 4. Another problem is related to the accessibility of the network nodes and security of the links. In this context, it is important to find either the shortest or the least impaired path to the intended receiver.

Among various challenging and extreme communication environments, in this work, we focus on four use cases: underwater, underground, industrial, and disaster environments. These environments have very different characteristics and challenges. These problems of the CEs typically motivated the researchers to look for alternative communication-enabling technologies which are very different as well. As an example, magnetic induction has been proposed for the signaling in the underground medium, since it is less prone to scattering and absorption than the traditional EM waves. For the same reason, acoustic signaling has been selected for the underwater communication. Correspondingly, each use case has evolved into an individual research field with specific system design methods and limited generalization potential. Moreover, the interconnection of various networks, such as disaster and industrial environments or underground and underwater, is hardly possible due to the divergent design guidelines and techniques, which prohibit joint optimization. Similarly, it is very challenging to incorporate these networks into terrestrial networks and to achieve homogeneity in their design.

To solve this issue, RIS can be proposed in nearly all possible CEs in order to improve the connectivity. Using the additional degrees of freedom associated with RISs, it is therefore possible to determine the optimal signal path and reduce the impact of the environment on signal propagation. Hence, RIS has the potential of becoming the key enabler for the future wireless systems in CEs. It might be even possible to unify the design methods for the wireless systems in various CEs based on this common enabler. This might be possible

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via conversion of the individual challenges into common challenges for all environments. In this context, future research on RIS-assisted CEs becomes very promising and interesting.

In this work, we aim at providing our vision on the application of RIS in CEs in order to open the discussion on the evolution of RIS-assisted CEs and pave a way to their systematic design.

A. Contributions

Throughout the open literature, the research challenges of integrating RISs into wireless networks are solely discussed within the existing network architectures and the traditional urban ecology. These challenges differ from the ones discussed in the context of CEs, which motivates us to fill this gap by providing a vision of RIS-assisted CE networks along with the proposal of some relevant research challenges. Specifically, the contributions of this work provide a basis for the future investigations in this field as it points in the direction of the most relevant research problems to be addressed in the near future. The main contributions are as follows:

- A brief review of the RIS technology is provided including the application of RISs with unconventional signaling techniques;
- An overview of the peculiarities and features of each considered use case is provided in order to identify the main challenges for the wireless networking without RIS;
- Benefits from the deployment of RIS in the individual use case are discussed, which provides a specific motivation for the research on advanced RIS-assisted communications in the considered scenarios;
- Research challenges for the design and implementation of the RIS-assisted wireless networks in each use case are explained;
- Future research challenges for the unified RIS-based technology in CEs are revealed.

This paper is organized as follows. Prior works and recent advances of the RIS technology are discussed in Section II. Section III provides an overview of the relevant scenarios. Then, the most beneficial strategies for the RIS deployment in these scenarios and the respective challenges for the signal propagation and system design are explained in Section IV. Future challenges and research opportunities are outlined in Section V. Finally, the paper is concluded in Section VI.

II. ADVANCES OF RIS TECHNOLOGY

Communication channels have been traditionally considered as an uncontrollable entity. Hence, most of the conventional wireless communication techniques attempt to adapt the system parameters to the peculiarities of the uncontrolled channel. However, substantial performance gains can be achieved, if the communication channel becomes reconfigurable and correlates with the signaling. This idea has been realized using RIS, which can be used to enhance the performance of communication systems by controlling the reflections of the impinging signals.

RIS has been named a new paradigm in wireless communications in [1]. The authors proposed RIS as one of the key

enablers for the 5G and beyond systems. In particular, research challenges and directions for the design and deployment of RIS based on the prior work [6] have been addressed. Furthermore, the idea of controllable communication environment has been proposed in various works under different names, such as Intelligent Reflective Surface (IRS), Large Intelligent Surface (LIS), Intelligent Mirrors, Intelligent Metasurfaces [7]–[9].

A. Promising research directions

Since RIS represents a fundamentally new concept of signal propagation, channel modeling and acquisition are of utmost importance for the system design. Hence, multiple works have been dedicated to these topics, e.g. [10]–[16]. Since RIS can actively modify the communication environment, the proposed channel estimation methods depend on the individual scenarios, number of RISs, users, etc. [12], [14].

Furthermore, advanced techniques of multi-antenna transmissions need to be developed. Specifically, novel precoding and beamforming methods have been proposed for RIS-assisted multiuser networks [17]–[23]. In this context, joint passive and active beamforming have been investigated for various system configurations. It has been shown that optimized reflective coefficients provide substantial performance gains in terms of spatial diversity and quality of service.

An additional motivation for the theoretical investigations in this area has been provided in [24], [25], where the first experimental results for RIS-assisted signal propagation have been presented. Recently, more thorough practical design aspects and experimental studies have been published, cf. [26]–[28].

Most of the relevant works in the research field of RIS focus on indoor scenarios, where the reflections from the walls can be potentially very harmful without RIS. Using RIS, the number of connected devices in such scenarios can be increased without causing a performance degradation for the network due to harmful co-channel interference signals. Note that the indoor deployment of RIS provides the biggest advantage and diversity gain due to relatively short transmission distances, such that the attenuation of the reflection-based signal paths is not significantly higher than the direct path.

Outdoors, the main target application will be Smart Cities, cf. [4]. So far, however, not many works have investigated RIS-assisted outdoor scenarios. The main innovation addressed in these works is the use of unmanned aerial vehicles (UAVs) [29]–[33]. In such scenarios, UAVs can act not only as receivers, but also as mobile relays to serve as access points for multiple network nodes. As an example, the beamforming towards UAVs and the tracking of the UAV position by the BS has been investigated in [30].

Recently, several surveys on the advances in RIS technology and the creation of a smart environment have been published. For further details on RIS, we refer the reader to [9], [34], where all relevant studies have been described and future challenges in a general context have been addressed.

B. Alternative signaling technologies

In this work, we consider some of the most challenging environments for the wireless communication, where the tra-

ditional EM waves in the moderate frequency range may not provide a sufficient signal quality. In such environments, alternative signaling technologies have been proposed to overcome the drawbacks of the EM waves, such as absorption and scattering. Hence, it is worth looking into the advances of RIS specifically designed with respect to these technologies in order to understand their benefits and practical limitations.

1) *Millimeter-Wave, Terahertz and optical communications*

High signal frequencies are very attractive for the wireless communication systems due to a large frequency band and thus high symbol rate. For Millimeter-Wave (mmWave), Terahertz (THz) and optical signaling, the frequency ranges are up to 300 GHz, 3 THz and several hundreds of THz, respectively. Correspondingly, the signal carriers are characterized by a very small wavelength, which leads to rather small transmit antennas and increased reflection of the impinging waves from the surface compared to the moderate carrier frequencies, e.g. traditional WLAN frequencies of 2.4 GHz. Hence, the application of RIS is very promising with this type of signaling. Most of the existing works focus on THz and mmWave based technologies, cf. [35]–[37]. However, recent studies have been conducted to introduce RIS in optical communication networks, cf. [38], [39]. Here, the weak absorption of light can be exploited in order to guide the signal to the destination with a very little path loss.

2) *Magnetic induction/resonance*

Magnetic induction (MI) or magnetic resonance refers to non-propagating quasi-static magnetic fields using induction coils as part of respective resonance circuit instead of traditional EM antennas. Typically, MI is used with very low signal frequencies, i.e. between few kHz (in conductive media) and 13.56 MHz (according to Near-Field Communications standard), which results in very narrow frequency band. Due to the low frequency, the signal wavelength is very large and does not suffer from reflections or scattering. Interestingly, this fact prevents from directly utilizing the RIS technology with MI. Nevertheless, a similar effect can be achieved via passive relaying of magnetic fields using the so-called MI waveguides, cf. [40]. Specifically, passive MI coils aligned in a waveguide structure generate secondary magnetic fields without explicit power consumption, which can be viewed as pseudo-reflections. These pseudo-reflections can be made reconfigurable by modifying the resonance circuit impedance of each MI relay [41]. However, it is arguable whether or not this concept can be viewed as magnetic RIS.

3) *Acoustic communications*

Depending on the application, acoustic signals are typically generated in the frequency range between few Hz (infrasound) and few MHz (ultrasound). Due to the different type of signal carrier (pressure rather than EM fields), the signals are transmitted using speakers and received using a microphone (or hydrophone in the water medium). Although the conventional RIS technology has been proposed for EM waves, recently acoustic RISs have been introduced, cf. [42], [43]. The primary scope of these works was the cloaking of uneven surfaces to avoid the scattering and improve the ambient sound. However, the use of such acoustic RIS devices for communications has been recognized in [44], where space-time coding using

acoustic RIS has been proposed. Furthermore, the application of RISs for the underwater communication has been demonstrated in [45] using experimental setup. Unlike EM and MI based wireless systems, the passive signal steering or beamforming are not achieved via circuit impedance reconfiguration, but via actual mechanical manipulation of the surface elements [42].

III. TARGET SCENARIOS

In this section, we discuss four most relevant scenarios associated with CEs. The importance of some of these scenarios and their characteristics have been discussed in [5], [46]. We start with the underwater and underground communications, where the propagation medium is the main challenge for the system design. Then we move on to the industrial and disaster environments, where the large number of obstacles impacts the signal propagation. Note that we do not address higher-layer challenges for the network design such as routing and topology control, which depend on the actual applications and system configuration. Instead, we focus on the challenges associated with the connectivity and digital signal transmission.

A. *Internet of Underwater Things (IoUwT)*

Underwater communication networks have been analyzed in a plethora of works for various applications. The research in this area can be traced back to the early days of wireless communications, cf. [47].

The main difference between underwater networks and the terrestrial networks lies in the propagation medium, which dramatically affects the path loss. Among the main relevant properties of the water medium, its conductivity is by far the most important one. The conductivity of water depends on its salinity, temperature and pressure, such that it has values of around 0.01 S/m in sweet water and up to 4-5 S/m in sea water, cf. [48]. These high conductivity levels lead to absorption of the EM fields and very high path loss. Thus, data rates above 8 kbit/s are prohibited over distances beyond 10 m in the sea water [49].

For this reason, underwater communications have been traditionally designed using acoustic waves, which do not suffer from absorption as much as the other signaling techniques. Acoustic signaling relies on the propagation of pressure variations, which can reach up to tens of kilometers in the open water. However, the issues with the acoustic signaling are related to the typical maritime objects, such as ground/shore or fish, to the interference from dolphins/whales, and to the signal scattering/reflections in the acoustically heterogeneous medium, i.e. water streams with different pressure and temperature levels. All these issues impact the communication channels by means of multipath propagation, time-variant impulse responses and interference.

Alternative solutions based on extremely low signal frequencies using MI or based on optical communication have been introduced as well [50], [51]. However, these technologies are much less common due to the path loss, which is not necessarily lower than the traditional EM waves, cf. [49].

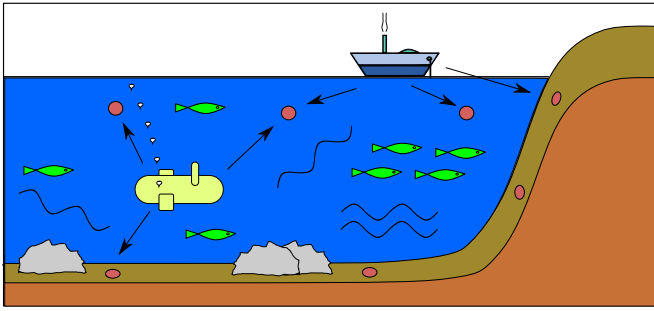


Fig. 1: Example of the IoUwT. Connectivity between networks nodes, i.e. submarine, ship and sensors, is impaired by scattering from the typical maritime obstacles like fish, water streams and rocks.

Recently, the idea of establishing a large wireless network similar to the upcoming Internet of Things (IoT) has been introduced. It has been named the Internet of Underwater Things¹ (IoUwT) and should connect various devices deployed under the water surface, e.g. submarines, autonomous underwater vehicles (AUVs), deployed sensors and ships, see Fig. 1. Here, the goal is to provide sufficient connectivity for the wireless network in the underwater medium. Nevertheless, the mentioned issues of time-variant multipath channels (when using acoustic waves) seem to be the main challenge in this context.

IoUwT is a promising research area, which has seen a lot of advances in the recent years. For more information on underwater communications and IoUwT we refer to [52], [53].

B. Internet of Underground Things (IoUgT)

The research on communications in the underground medium is nearly as old as that of the underwater communications. Similarly, the main challenge of this environment is related to conductive propagation medium, although the conductivity is typically much lower compared to the water medium, below 0.01 S/m. The soil conductivity and correspondingly the absorption rate for the EM radiation depend on the so-called volumetric water content (VWC), i.e. the relative amount of water in soil, as well as on the soil content, such as sand, clay, etc. [54]. Furthermore, variations of the soil content can lead to signal reflections and scattering. These effects lead to a severe multipath and very high path loss. Besides, signal reflection at the ground surface due to the abrupt change of the EM properties contributes to the multipath propagation as explained in [54].

Due to much lower average soil conductivity, most of the works on underground communications are based on traditional EM waves despite the high path loss. However, it is still extremely difficult to reach transmission distances above 50 m. Moreover, low frequency MI solutions have been

¹The usual abbreviation of the Internet of Underwater Things is IoUT, which is commonly used in the literature. However, in this work, we consider also the Internet of Underground Things, which would have the same abbreviation. Hence, in order to distinguish between the two types of network, we utilize IoUwT for the underwater networks and IoUgT for the underground networks.

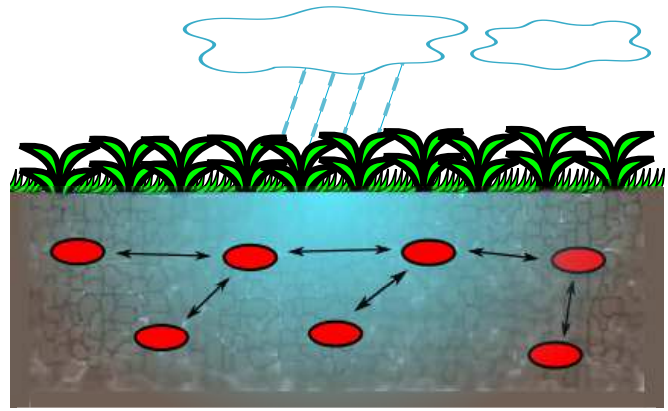


Fig. 2: Example of the IoUgT for smart agriculture applications. The sensors are deployed below the ground surface and monitor the water content in the soil.

proposed to overcome the issues related to the low coverage, cf. [55]. The drawback of the latter is however due to a very narrow bandwidth (centered around the resonance frequency) and relatively large transceivers.

In the context of both EM waves and MI, there has been much progress in the design of wireless networks lately. In particular, wireless underground sensor networks (WUSNs) have been proposed [56], which evolved into a concept of the Internet of Underground Things (IoUgT) in the recent years [57]. Here, the goal is to establish wireless connectivity between distributed sensor nodes in order to monitor seismic activity, structural health of buildings as well as soil quality for the smart agriculture and clever irrigation, see Fig. 2. Furthermore, such wireless networks can be used to provide a communication infrastructure to hardly accessible areas like mines and tunnels.

The main challenge for this type of wireless networks remains the medium-dependent path loss, which leads to a low coverage area and low signal quality. For more information on IoUgT, we refer to [57], [58].

C. Industry 4.0

Industrial applications of wireless communications have gained an increased attention by the research community in the context of the initiative named Industry 4.0. Similarly to the IoT, the concept of Industry 4.0 relies on massive connectivity provided by densely deployed small sensor devices, which are installed in factories and production lines. These sensors are supposed to monitor the accuracy of the manufacturing process and possibly influence this process by providing their feedback to the central processing unit. Through this, the operation of large factories can become fully automated, which may reduce the manufacture and maintenance costs, cf. [59].

Unlike the previously discussed CEs, the propagation medium in the industrial environment has typically almost no influence on the system performance. Instead, the main challenge for the signal propagation in industrial wireless networks is related to a strong wideband interference generated by the production processes. In addition, a large number of

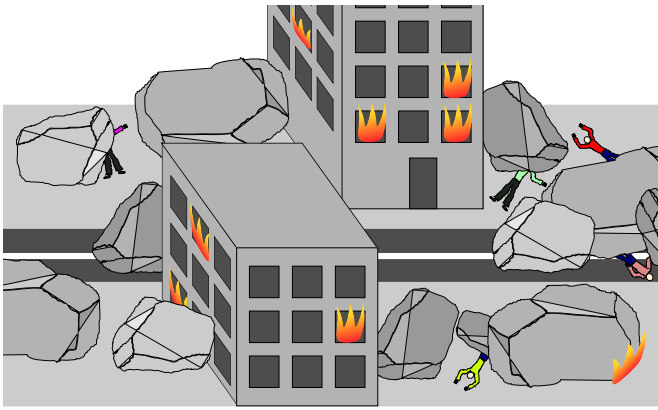


Fig. 3: Collapsed buildings and humans trapped under rocks.

metallic objects as parts of the factory equipment may disturb the transmission. For the massive connectivity of the Industry 4.0, the resulting signal scattering poses a burden, since signal transmissions are impaired by time-variant channels as well as fading effects and multipath. This effect is especially crucial due to the low signal quality from the aforementioned interference.

Further challenge for the design of the industrial wireless networks is related to very strict requirements regarding point-to-point latency and reliability, since potential malfunction of an industrial process needs to be detected and corrected as fast as possible. Otherwise, the efficiency of production may substantially decrease, cf. [60].

In addition, industrial processes belonging to the same production line or task can be spatially distributed over large areas within the same factory, such that multiple connected sub-processes can be located far away from each other. In order to maintain the connectivity of the wireless network or its subset belonging to the same process, the signal path may need to be optimized, which can involve the deployment of multiple relays or similar devices.

Industry 4.0 and related advances for the wireless communications is an active research area. More information about it can be found in [59]–[61].

D. Emergency networks in disaster areas

Disasters related to earth quake, tsunami, landslide, etc. bring about the destruction of the human habitat. Specifically, the infrastructure of whole cities can be destroyed by such natural causes. On the other hand, human activities like gas explosions can lead to similar results leaving behind collapsed buildings and human bodies trapped inside, see Fig. 3.

The search and rescue (SAR) of humans is the first and most important task to be performed after the disaster. In this context, the destroyed infrastructure is one of the main challenges for the SAR, since it is difficult to search for people underneath. Furthermore, the coordination of the rescue teams and potential application of steerable rescue tools like robots, UAVs, etc. depend on connectivity between the network participants and on reliable signal transmission, cf. [62]–[64]. However, the communication infrastructure is likely to

be destroyed in the disaster event as well, which substantially impacts the connectivity and operability of the dedicated wireless network.

Another challenge for the operation of the wireless network (even if the infrastructure is operational) is the large amount of obstacles, i.e. pieces of the destroyed homes, trees, etc. These obstacles provide a high degree of scattering, such that the resulting interference among the adjacent network links can render the communication unfeasible and unreliable.

Various types of emergency networks to be used in case of disaster have been proposed in the recent years. However, many of the proposed solutions assume that parts of the infrastructure remain whole and capable of assisting the rescue operations. Even though such assumptions are not always valid, the challenge related to the signal scattering is very difficult to assess without these assumptions. For more information on the design of emergency networks in disaster areas, we refer to [65], [66].

IV. RIS IN CHALLENGING ENVIRONMENTS

The research challenges can be split in two categories:

- general RIS-related challenges,
- specific RIS-related challenges associated with the deployment in the challenging environments.

At first, we briefly review the general challenges associated with RIS and then we discuss the specific challenges for the respective use cases specified in the previous section.

A. General challenges for RIS operation

Like in the terrestrial RIS-assisted communication networks, the main challenges can be outlined as

- channel estimation/pilot decontamination,
- precoding/beamforming,
- control signaling.

Channel estimation is one of the biggest challenges for RIS-assisted wireless networks, since RISs are typically passive² and cannot perform channel estimation by themselves. Hence, the channel between the network nodes and RIS is difficult to obtain in practice. This problem becomes even tougher with increasing number of RIS elements, for which the estimation needs to be performed, and with increasing number of RIS devices. In addition, similarly to the Massive Multiple-Input Multiple-Output (MIMO) systems, the channel estimation is impacted by the correlation between training sequences in terms of pilot contamination. However, the methods of pilot decontamination may not be entirely applicable due to the problematic channel estimation with passive RISs.

Precoding and beamforming are considered the key functionality of RIS. Despite a large number of research works dedicated to this system aspect, the design rules for the precoding/beamforming in wireless networks with multiple RISs is not yet fully understood. In fact, passive beamforming using

²‘Smart’ RIS can be produced by connecting it to a wireless sensor node, which can perform some signal processing and computation. However, this functionality is viewed as a long-term evolution of RIS and discussed as one of the future challenges in Section V.D.

multiple RISs with ping-pong multihop signaling seems very challenging. Furthermore, the use of symbol-level precoding for large RIS-assisted networks has only been briefly addressed in few works so far.

Control signaling is important for the operability of RIS. In order to update the phase shifts of the RIS elements, the connectivity between RIS and its parental node (e.g. base station) has to be very reliable and fast. This becomes a burden in case of a large number of elements, since the corresponding large amount of data may require a very high data rate to ensure that the update frequency satisfies the system requirements.

Since these challenges are common for all target scenarios as well, similar concepts as already proposed in the literature (and mentioned in Section II) for the respective terrestrial networks can be applied in the challenging environments. The traditional challenges for the design and use of RIS technology in future wireless networks have been well described in the previous works and surveys. Hence, we refer to [4], [9], [34] for more information.

B. RIS in Underwater medium

While EM, MI and even optical signal propagation in the water medium (especially in clean sweet water) are possible over short distances, transmissions over larger distances using acoustic signaling are preferred in the context of the IoUwT. Hence, we focus on acoustic signaling³.

As mentioned earlier, acoustic signal propagation in the underwater medium suffers most from scattering at uneven surfaces, water streams and fish. This leads to a high path loss and extreme frequency selectivity of the communication channel due to the multipath, such that only very narrow signal bandwidths are tolerated. Correspondingly, the effective data rate is very low. Hence, these weaknesses need to be mitigated using RIS.

1) General approach

The steering of the signals in the preferred direction would help constructively align the interference and reduce the multipath. Of course, it may not be possible to completely remove the multipath due to a large number of possible reflections in the water. However, the orientation of RIS elements can be optimized to reduce the frequency selectivity and thus increase the effective signal bandwidth. In this context, the design problem can be formulated as a maximization of the signal quality measured after the applied practical equalization filter in the receiver. Since this signal quality is typically related to the discrete length of the equivalent impulse response (which is associated with the maximum delay spread according to the multipath), an alternative objective can be formulated as a minimization of the delay spread. The solution to this optimization problem needs to be updated very quickly due to the typically short coherence time in the water medium. Hence, the corresponding computational complexity needs to be very low in this scenario.

³It is worth mentioning that the main challenge for the EM signaling is the signal absorption, as mentioned earlier, which can hardly be combated using RIS technology.

The deployment of RIS in the underwater medium can have various configurations depending on its location:

- attached to the ground or to the shore;
- attached to autonomous underwater vehicles.

Note that RIS can be also made floating freely in the water, which requires a very little effort. However, such a floating RIS may disturb other underwater objects. Thus, we do not address this option in our investigations. Nevertheless, for completeness, we note that the challenges and solutions in the considered underwater scenarios are applicable for such floating RIS devices as well.

Next, we would like to discuss some of the challenges related to the operation of the RISs in two underwater scenarios mentioned above.

2) Stationary deployment

The first option, i.e. stationary deployment of RIS, is the simplest and the most beneficial option, since it does not pose too many new challenges for the system design. Hence, RIS can be readily integrated into the IoUwT.

The main benefit of the stationary deployment is that the geometrical configuration does not change over time. In principle, this should lead to more or less stationary communication channels, which is however only valid for relatively short distances. For large distances, e.g. above 100 m, due to the fast time-varying channels in the underwater medium, it might be difficult to reach a sufficiently high level of synchronization and channel estimation accuracy in order to fully benefit from the capabilities of RIS. Hence, robust optimization of the orientation of RIS elements seems to be the key solution that helps to mitigate the impact of the time-varying multipath channels (to some degree) at least on average.

3) Autonomous underwater vehicles (AUVs)

AUVs are expected to serve the deployed nodes of the IoUwT by moving from one node to another, which resembles the traditional mobile relaying. While the main task is to ensure a better connectivity and to recharge the batteries of the distant nodes, AUVs are well suited for carrying RIS. Through this, they can contribute to the smart underwater environment. This type of mobility is therefore steerable and can be adjusted to improve the signal propagation using phase shifting capabilities of RIS in addition to the mobility of the vehicles. In this context, the trajectory of the AUVs is of special interest.

One of the challenges related to the mobility scenarios is the channel prediction. Unlike with stationary deployment, the geometry of the system configuration is not fixed, but changing. Correspondingly, the communication channels may become time-varying. However, the motion of the AUVs may be relatively slow, which leads to a rather long motion-related coherence time. Hence, the motion is not crucial for the system assisted by RIS-equipped AUVs.

One the other hand, the surface of the AUVs will be probably designed to reduce the friction in water, which may otherwise become the main problem for the steering of the vehicle. Hence, only relatively small areas should be covered by RISs in order to reduce this harmful effect while preserving the control over the smart environment.

C. RIS in Underground medium

For the underground communications, we focus on signaling using traditional EM waves in the moderate frequency range. Here, acoustic signaling is not possible due to severe scattering effects inside the acoustically heterogeneous soil medium.

The signal propagation in the underground is very vulnerable to the heterogeneous conductive medium of soil and in particular to the VWC as pointed out earlier. Additional effects like scattering and reflections are related to the soil composition. Similarly to the underwater communication, these effects lead to a very high EM path loss even at short transmission distances. Furthermore, multipath propagation results directly from the signal reflections and can be very harmful for the receive signal quality. Hence, the main challenge that motivates the application of RIS in this context is to reduce the multipath and the path loss by avoiding the signal scattering and by steering the signal through the soil layers with low VWC.

1) General approach

Similarly to the application of RIS in the underwater medium, the phase shifters of RIS can be optimized to reduce the frequency selectivity and increase the effective signal bandwidth. Correspondingly, a practical design problem would aim at minimizing the delay spread and signal quality after the equalization filter. Furthermore, the general challenges associated with RIS remain mostly the same as with underwater communications. However, the main difference lies in the substantially longer coherence time in the underground medium. While the time-varying channels in the underwater medium are much more dynamic due to the water streams, fish, etc., the underground medium can remain constant for a very long period of time, e.g. between two rain periods. Even during the rainy weather, the VWC in soil does not change abruptly, but requires several minutes to provide a measurable change in the signal propagation characteristics. Correspondingly, the complexity of the optimization problems does not need to be as low as in the underwater medium. Specifically, most of the challenges associated with RIS may need to be executed only a few times in the entire lifetime of the designed IoUgT, since the transmission channels remain mostly unchanged, such that the solution remains unchanged as well.

2) Deployment in tunnels and mines

One of the main application scenarios for the IoUgT is the deployment of sensor nodes in mines and tunnels. The main challenge for the EM signal propagation is related to the uncoordinated reflections from the walls of the tunnel or mine as well as scattering at the edges of the walls. This leads to the performance degradation for the signal quality and connectivity of the network. To address this issue, RISs can be installed in the walls and the ceiling of the tunnel in order to improve the directivity of signal propagation by steering the signal according to the direction of the passage, see Fig. 4.

Furthermore, as mentioned earlier, soil may partially absorb the signal, such that each reflection potentially contributes to the overall path loss. On the other hand, RISs are typically designed with the maximized reflection coefficient in order to avoid additional losses, which would otherwise render the use

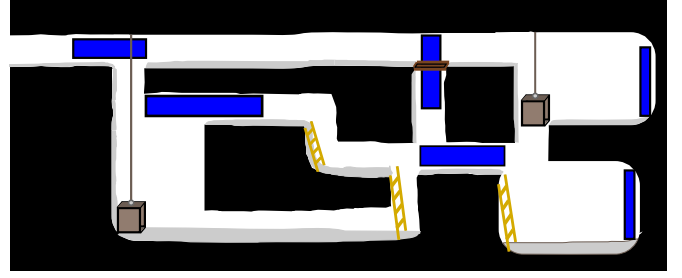


Fig. 4: Mines and tunnels scenario. RISs (blue rectangles) are deployed in the walls to improve the directivity of signal propagation.

of RIS inefficient. Hence, the main challenge for the design of RIS-assisted communication in tunnels and mines is to determine the optimal strategic placement of the RISs and their phase shifts, which would guide the signal in a ping-pong manner through the passage. Due to the stationary deployment of the IoUgT, the optimal position and phase shifts can be determined very accurately offline using just the map of the passage.

3) Other scenarios

In other scenarios of the underground communication networks, such as soil monitoring, the nodes are typically embedded in the soil medium, such that the communication between them is established directly through the ground. In this context, the use of large RISs may not always be feasible due to a high deployment effort. On the other hand, the effectiveness of RIS deployment increases with increasing RIS size, since it is proportional to the number of RIS elements⁴. Hence, it is important to investigate a potential tradeoff between the performance gain and the deployment costs needs with respect to the number of RIS elements and deployment strategies. In some cases, a large set of small RISs may be preferable compared to a single large RIS, leading to a distributed RIS operation.

In practice, the soil medium is typically heterogeneous due to the variations of its content, e.g. amount of sand and water. Hence, the signal propagation may vary as well. In many cases, the ground medium is layered, i.e. neighboring areas along a certain direction or a plane show similar content and therefore similar signal propagation characteristics. This property can be exploited for the design of RIS-assisted underground networks, if the signal is focused in the most suitable layer for the communication. However, since the distribution of the soil layers and their individual properties are unknown in general, this task is very challenging and should be tackled via adaptive beamforming.

D. RIS in Industrial Environments

Industrial environment is best characterized by a large number of obstacles as parts of the infrastructure. These obstacles are responsible for a high degree of signal scattering, which leads to a high path loss as well as severe multipath

⁴Here, we can assume that larger number of RIS elements enables a higher spatial diversity.

propagation. Furthermore, some of the target receivers may be blocked from the signal reception and have only a very little field of view for the communication. These challenges need to be tackled using RISs.

In this environment, we focus on traditional EM signaling in the moderate and high frequency ranges as well as on optical communications. Alternative signaling techniques, i.e. MI or acoustic seem to be less efficient due to shorter transmission distances.

1) General approach

Apparently, this scenario has some similarities with the underground communications and specifically with the communication in tunnels and mines, where the scattering is as severe as in the industrial environment. Hence, a similar approach for the signal steering can be selected in this case. The reflective elements of the RISs need to be optimized in order to steer the signal on the shortest path around the obstacles towards the target node. However, in case of industrial environment, the nodes may be deployed in inaccessible areas, such that it might be extremely difficult to find the right phase shift in order to properly navigate the signal. This problem is even more challenging, if discrete phase shifts are used, which substantially reduces the degree of freedom for the optimization.

Additionally, strong interference from some of the production processes should be reduced by destructively aligning the interference signal paths at the receiver. This is especially challenging, since no channel estimation can be performed for the interfering signals, such that only iterative adaptation methods can be designed.

Furthermore, some parts of the infrastructure can be mobile according to the respective automated process. The implications of such moving objects are discussed in the following.

2) Moving industrial infrastructure

Industrial processes usually have a property of repetitive execution of the same actions in order to produce multiple copies of the same product. This can be exploited for the design of RIS-assisted communication networks even in presence of mobile infrastructure. In particular, the repetition of the infrastructural motion manifests as correlated (in time) and deterministic communication channels due to the repetitive positions of the obstacles. The same holds for the positions of mobile RISs, if they are attached to the mobile infrastructure.

This property is very relevant for the design of RIS-assisted networks in this environment, since it substantially eases the synchronization and control of RIS. Specifically, the channels can be described via Hidden Markov Models (HMMs), such that the well-known methods of signal detection and synchronization for HMMs can be directly employed here. Alternatively, communication channels can be learned using the well-known methods of artificial intelligence and machine learning. Furthermore, the scheduling of transmissions can be adapted to the repetitions of the channel, which pertain to a high signal quality. Through this, the performance compared to other scheduling methods would significantly improve.

E. RIS in Disaster Environments

Disaster environments are related to the situations, where parts of the city infrastructure have been destroyed. The broken infrastructure, i.e. pieces of buildings, trees, etc., poses a burden for the communication due to a large number of reflective obstacles and the resulting scattering of signals. Furthermore, specialized rescue forces, which are supposed to uncover trapped humans underneath collapsed buildings and broken trees, need to be supported by wireless connectivity, e.g. for the steering of drones and robots as well as for their own coordination. Hence, the reduced signal quality may impact the functionality of such wireless networks. Reliable communication in presence of a large number of obstacles has to be established while the supporting infrastructure may be partially or completely broken. This is extremely challenging for the traditional communication as well as for RIS-assisted networks.

Note that the disaster can occur in any medium including underwater and underground. However, the impact of the disaster on the existing infrastructure is higher on the earth surface, since dense medium can partially absorb the energy from the disaster and reduce the force applied to the infrastructure. Correspondingly, the infrastructure deployed in dense media is typically less deformed by possible disasters or may even partially remain unchanged.

Hence, we focus on disasters on the ground surface, where the traditional EM signaling in the moderate frequency range is the most promising technique, since it can provide connectivity over large distances (unlike acoustic and MI-based signaling) and penetrate many types of obstacles (unlike optical signaling).

1) General approach

In order to improve the performance of the mentioned wireless networks supporting the rescue operations in disaster environments, RIS can be deployed as part of the original infrastructure, where the future rescue operations would potentially take place. An example of this infrastructure is the mentioned concept of Smart Cities, where most of the buildings are covered by the reflective surfaces in order to facilitate the massive wireless connectivity. This approach is very beneficial also with respect to the potential danger of a disaster, since parts of the surfaces may still be operational and thus help improving the signal quality of the wireless network established specifically for the SAR operations.

During the disaster, the infrastructure, e.g. smart buildings, may break in pieces. This includes also the RIS as part of this infrastructure. After the disaster, the separated parts of RISs are no longer functional with existing RIS technology. However, an innovative concept for the RIS design may be developed in future in order to account for possible scenarios, where parts of RIS can be easily detached from the main surface.

Such separated RIS parts are expected to have sufficient intelligence to provide a basic RIS functionality for a small set of corresponding RIS elements. During the main RIS operation, the parts of RIS are combined to one surface. On the other hand, the parts should be easily detachable in a

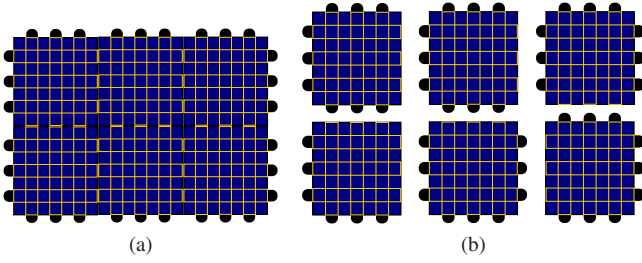


Fig. 5: Separable RIS: parts of the RIS can easily detach in order to avoid damage and preserve the functionality of the individual parts. a) Co-located operation, b) separated operation.

controlled manner in order to not damage the main processors or the steering mechanisms. One possibility to achieve this is using magnetic connectors. The main benefit of these connectors is the ease of deployment and their robustness.

Specifically, there are two modes of RIS operation, which are separated in time by the disaster event: co-located operation and separated operation. These modes are illustrated in Fig. 5. In the following, we discuss the potential research challenges for each mode.

2) Co-located operation

We consider a large RIS, which consists of multiple smaller RIS patches connected to each other. The large RIS should be able to exploit the processing capabilities, memory and stored energy of all its parts to provide the best possible performance. In order to enable its operation, a new architecture is needed, which will supposedly employ distributed computation algorithms via fixed wired or wireless connectivity between the individual parts.

For the RIS optimization, the objective in this mode is mostly related to the beam steering in order to maximize the receive signal power or enhance the secrecy. Hence, the traditional challenges mentioned in Section IV.A apply.

3) Separated operation

After the separation, the distances between the patches of RIS may be substantially larger, such that it probably does not make sense to consider them as parts of the same entity. Instead, each RIS part can be assumed to have only very limited number of reflective elements and shall be responsible only for its own operation.

In this mode, i.e. after the disaster event, the objective for the phase shift optimization of each individual RIS part is related to the reduction of the scattering effect and the resulting multipath. Hence, the individual RIS parts should act as ad hoc nodes and collaborate with other RIS parts in order to solve this task cooperatively. A similar challenge for the ad hoc networking of RIS relays has already been identified in [4]. Here, the difficulty is even higher due to the reduced memory, energy and processing capabilities of the small RIS parts.

V. FUTURE CHALLENGES

In addition to the specific challenges identified for each use case in the previous section, we consider the most promising future research challenges:

- reliable channel modeling,
- deployment planning and automation,
- power of RIS-equipped nodes and
- distributed operation.

These open problems are discussed in the following.

A. Reliable channel modeling

The scenarios described above are extremely challenging for the signal propagation for various reasons. One of the main reasons is the lack of accurate channel models applicable in each scenario, which would take into account all relevant effects, such as: the water flow dynamics in underwater scenario, partial absorption and scattering in the underground, etc. Of course, some approximate models exist in the literature and some of them even have been partially validated by lab experiments. However, the application of RISs in the considered scenarios has never been included in such experiments. Correspondingly, it is unclear, whether or not the existing models can still be employed for the future research in this area. Specifically, in the underwater and underground media, the transition of acoustic and EM waves from the medium to the reflective surface and back is not described by the existing models. In this context, a thorough theoretical description is needed, which is the main challenge for the adequate research in the area of RIS-assisted communications in challenging environments.

B. Deployment planning and automation

The strategic RIS deployment has been considered in some works so far in the context of future wireless networks. Furthermore, the RIS-equipped UAVs have been introduced in order to find the optimal position for the RIS. This optimal position may depend on the scenario as well as on the time-varying channel conditions and available power resources.

In the context of challenging environments, the strategic deployment of RISs is of paramount importance for the effectiveness of RIS due to the high complexity and spatial selectivity of the communication channels.

Specifically, the transmission distances in underwater environment are rather large, which leads to a large path loss both for the main signal tap and for the signal reflections. Correspondingly, by placing RISs in certain areas, the signals reflected from the RIS may be impaired by higher pathloss than the signals reflected from other obstacles. In this case, RIS would not be able to compensate the multipath components.

For the deployment in the tunnels and mines, we expect a large number of reflections for the signal steering. However, each reflection may contribute a higher pathloss. Hence, the strategic deployment of RISs is needed in order to reduce the number of reflections. This would lead to a better overall signal quality.

In disaster environments, the strategic deployment should be performed based on careful modeling of the possible infrastructure impacts. Through this, it might be possible to predict the distribution of RIS parts in the target area and avoid large fluctuations in their concentration, which may impact the

effectiveness of the RIS in the areas with the low concentration of RIS parts.

In general, the path finding optimization for the signal propagation is required in order to identify the best possible locations for the RIS deployment.

Challenging environments are additionally characterized by the difficulties associated with the deployment of the network nodes. The reason is that it might be difficult for the humans to reach the deployment location and perform the deployment work. Hence, this process needs to be automated.

Specifically, the deployment procedure in the underground and underwater media as well as crowded factories will make use of robots to carry RISs and attach them to the dedicated surfaces. In this context, the automation problems related to the design of such robots are of interest. For the disaster environments, the deployment automation is less important, since it is similar to the traditional deployment strategies for the smart cities.

C. Distributed operation

As mentioned in the previous works, distributed operation of RIS can be very beneficial, especially with respect to the discussed application in disaster environments. Distributed RIS operation requires that each RIS or its part should be attached to a sensor node with respective capabilities, i.e. memory, signal processor, battery, etc. Correspondingly, the entire set of wirelessly connected RIS needs to be arranged in wireless sensor/actuator network. Subsequently, the wireless networking aspects need to be investigated, in particular the higher layers, such as network and transport layers.

In this context, routing and topology control for the RIS network (not to confuse with the target network, for which the smart environment is created) are of special interest. These aspects are difficult to optimize due to a very complex dependency between the communication environment and the results of the optimization. Hence, it seems that the most promising optimization methods in this context will be based either on metaheuristics or on game theory. The latter seems promising due to the ad hoc behavior of RIS-equipped nodes.

D. Powering of RIS

One of the main open problems for the distributed operation of RIS is the recharging of its battery. This problem has been identified in the previous works, but in the context of challenging environments, it will become even more tough. The reason is that the channels to be used for wireless powering may be time-variant with a very short coherence time or extremely dispersive, such that the wireless power signals would suffer a very high path loss, which can reduce the transfer efficiency to a minimum. Furthermore, in some applications like disaster environments, there is no common energy source for the wireless powering of small sensor devices. Hence, the battery recharging can be done only using one of the following alternative approaches:

- each RIS may not only reflect the signals, but also partially absorb their energy and use it for the own recharging. A distinct advantage of this strategy is that

RIS would drain the EM radiation from the medium and thus make the environment more green;

- RIS should be able to generate power from any type of received signaling, e.g. EM and acoustic radiation, vibration, x-ray, etc.

The first strategy implies that the signal routing and the optimization of the reflective elements need to be adapted in order to account for the charging of the RIS batteries. The second strategy implies that various types of sensors need to be attached to each RIS in order to be able to harvest energy from the respective sources. While the first strategy is challenging with respect to the online operation, the second strategy is challenging for the initial RIS design.

VI. CONCLUSION

In this paper, we presented our vision and potential research challenges for the deployment of RIS in challenging environments. Specifically, the benefits for the signal propagation in large wireless networks have been highlighted. Regarding the target scenarios, four most challenging use cases have been investigated, i.e. underwater, underground, industrial and disaster environments. These use cases have been unified under the umbrella of a single enabler, i.e. RIS-assisted networking. In this context, the enabling properties of RIS have been discussed. Specifically, for the underwater and underground media, RIS can be used to reduce the impact of the harmful multipath propagation. In industrial environment, RIS can be used to redirect the signals in order to avoid absorption and reflection by metallic objects. In disaster environment, future RIS can be employed to preserve connectivity and thus assist the SAR operations even after a possible infrastructure damage.

Furthermore, open research directions for the near future and for the long-term evolution have been presented. Correspondingly, this paper is expected to contribute to the rapid advancement of the research field both for the challenging environments and for the RIS technology.

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