Cable-aided Distributed Reconfigurable Intelligent Surface (CRIS): New Paradigm for Wireless Communication Networks

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***Abstract*—Reconfigurable intelligent surfaces (RISs) have been introduced to improve the coverage of wireless systems and make the communication environment controllable. The functionality of RIS is based on signal manipulation, in particular reflection, which can be used to steer the electromagnetic waves in the preferred directions. Accordingly, the spatial diversity and signal quality can be enhanced via nearly passive beamforming. Nevertheless, wireless propagation of the signals from the transmitter to the RIS and then to the receiver can still experience a substantial path loss and delay.**

In this work, we introduce a novel concept of cable-aided distributed RIS (CRIS), which seamlessly connects two distant locations and thus enables superior signal propagation conditions compared to state-of-art technologies. In combination with the techniques known in the context of RIS, such as beamforming, spatial diversity enhancement, etc., this technology can provide unprecedented improvements for the coverage and energy efficiency of future wireless networks. Furthermore, the communication environment is expected to become not just controllable, but partially transparent. The obtained numerical results indicate that CRIS outperforms both the traditional RISs and the recently proposed STAR-RISs with simultaneous transmission and reflection capabilities, while the operation requirements and complexity for CRIS are much lower compared to the latter.

***Index Terms*—Reconfigurable intelligent surfaces, relaying, research challenges.**

I. Introduction

Recently, the idea of controllable environment has been proposed [1]. This idea is aligned with the recent advances in the design of reconfigurable intelligent surfaces (RISs), which are planar structures with the capability to manipulate the impinging electromagnetic waves and thus steer them in preferred directions [2]. This is especially beneficial in case of signal blockage, such that a controlled reflection would create an additional signal path and improve the connectivity, see Fig. 1. Typically, RIS is implemented based on metamaterials and either tiny antenna elements or patch patterns [2]. RIS technology has been suggested for a variety of applications, e.g. smart cities [3], internet of things [4], etc. The main benefit of this technology is the nearly passive operation, i.e. only the impedances of the RIS elements need to be updated. Through this, the power consumption is lower than with active relays since it does not scale with the signal magnitude. Furthermore, beamforming can be employed in order to enhance the signal quality, enable spatial decorrelation, reduce the fading effects, increase the efficiency of wireless power transfer, etc. For more information on RIS technology, please refer to [2].

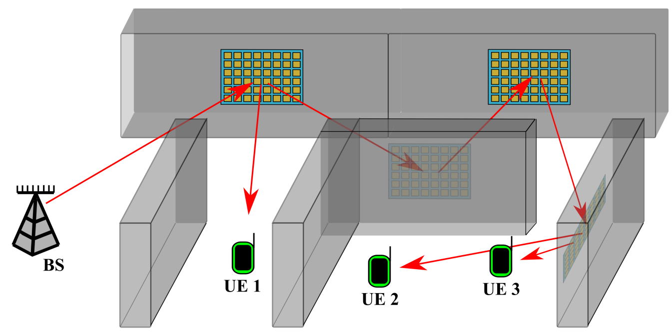

Fig. 1: Multihop RIS-assisted communication with obscured users. High path losses of the cascaded channels render the signal quality insufficient.

In order to study the benefits of RIS, various network configurations have been considered. In some cases, multihop RIS-aided communication has been proposed to improve the coverage of wireless networks [5]. Specifically, the signals are reflected from one RIS to another in a ping-pong fashion

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until they reach the destination, see Fig. 1. However, the resulting signal path can be very long, which typically leads to heavy losses, which scale with the product of the distances of all sub-links. In addition, some of the receivers may still be unreachable due to obstacles, e.g. walls. In such cases, the signal quality may be very low. In particular, in urban areas the attenuation can be very high, if the signal path is not aligned with the geometry of the streets [6]. Correspondingly, it may not be possible to get the signal from one street to another without sacrificing a big part of the link budget. It is worth noting that a novel RIS configuration referred to as simultaneous transmission and reflection (STAR)-RIS has been proposed to enable the penetration of walls [7]. However, if STAR-RIS is employed, it is only possible to improve the coverage directly behind the RIS, e.g. inside the building. If the receiver is outside the building, the signal needs to be guided through the rooms and transmitted through the second STAR-RIS.

In this paper, we introduce a novel paradigm of Cable-aided distributed RIS (CRIS). This concept provides an alternative way of communication with remote locations. CRIS represents a combination of RISs and wired connections, which can be implemented on the basis of powerline communication (PLC) or radio-over-fiber (RoF) technology. As the propagation losses in cables and fibers are often substantially lower than the losses of an equivalent (in terms of transmission distance) wireless propagation, the blockages can become almost transparent to the communication signals. To this end, the use of RIS as part of CRIS ensures that the spatial diversity of the two environments interconnected via CRIS is preserved and can be exploited e.g. for beamforming, multi-user communication or security. Furthermore, various independent communication systems can simultaneously take advantage of the same CRIS including cellular, IoT, device-to-device communication, etc.

The remainder of the paper is organized as follows. In Section II, the concept of CRIS is explained. In Section III, important aspects of signal modeling for CRIS are discussed. In Section IV, we present the most relevant use cases of CRIS. In Section V, the performance of CRIS against the existing benchmarks is numerically evaluated for the magnetic transparency use case. Section VI discusses future challenges and research opportunities.

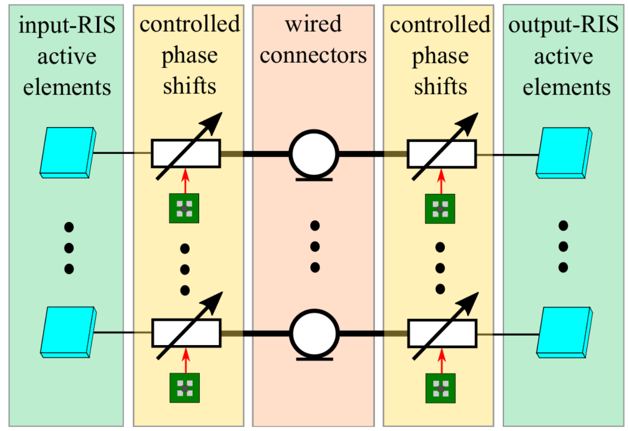


Fig. 2: Passive CRIS based on multiple RISs.

Subsequently, the paper is concluded in Section VII.

II. Cable-aided distributed RIS

CRIS consists of two RISs and utilizes a wired connection between them in order to reduce the path loss and thus facilitate the signal propagation. One part of the CRIS with the input-RIS is visible to the transmitter, e.g. base station (BS). Another part, i.e. output-RIS, is visible to the receiver, e.g. user equipment (UE), see Fig. 2. Of course, the transmitter and the receiver can be other devices, but we follow this network structure for the sake of simplicity. The signal absorption by the RIS has been recently studied in the context of self-sustainable RIS [8], where the impinging electromagnetic waves have been absorbed by the individual RIS elements and used for battery charging. Similarly, the input signals from the BS are received by the input-RIS and guided to the output-RIS instead of a battery. The output-RIS is used to re-emit the signals. The emission of the signal by RIS has been recently proposed in the context of active RIS, i.e. RIS with active signal amplification [9], which is performed prior to signal re-emission. The re-emitted signal is then wirelessly received by the UE. Due to much lower path losses in the cable compared to the wireless propagation, substantial performance gains compared to conventional RIS schemes can be expected. Furthermore, depending on the length of the cable connection and its implementation the latency can be reduced as well, which is especially promising for the future ultra low-latency communication systems.

The connection between the two RISs can be implemented in different ways depending on the type of CRIS. If we assume that the CRIS should have a functionality similar to a classical active relay (received signal is amplified/processed by the relay and forwarded), then the connection between the two parts may contain a cable, a signal processor (digital or analog), a power supply, etc. A more advanced architecture may include the second and third layer communication protocols to assist the packet transmission from one RIS to another. Note that active CRIS can be also implemented using traditional antenna arrays instead of RISs since the phase shifts can be adjusted via signal processing and active beamforming of CRIS.

The interconnection of RISs can be implemented using the well-known PLC technology [10]. Instead of a coaxial cable, optical fibers can be employed for a faster and low-attenuation signal propagation between the two antennas. In this case, the mapping of the RF signal onto optical carriers and back can be done using the RoF technology [11].

Both PLC and RoF technologies require additional power supply for the operation of the respective active components, such as converters and decoders, which may render CRIS inefficient. However, a fully passive CRIS can be realized, if analog-digital converters, amplifiers, filters and decoders are omitted leaving only a simple coaxial cable or fiber in addition to the phase shifters, see Fig. 2.

In order to enable the beamforming functionality of CRIS the phase shifting components of RISs can be optimized. As the reconfiguration of the phase shifts can be performed dynamically, the reconfigurability of RIS is inherited by CRIS. Through this, the performance of CRIS can be adapted to the time-varying environment and scenarios.

Interestingly, each input element of CRIS can be potentially connected to multiple output elements. Accordingly, not only the direction of signal reflection can be manipulated using CRIS, but the beam pattern at both front-ends. In particular, the receive beamforming at the input of CRIS and the transmit beamforming at its output can be optimized to reduce interference and increase the security. This feature is not present in the conventional RIS technology, where each RIS element is typically assumed to reflect all incoming signals equally well. Accordingly, the spatial diversity of CRIS-assisted communication networks may be higher compared to a single conventional RIS. The splitting of the signal can be realized e.g. using power splitters, which are often employed in receivers of simultaneous information and power transmission (SWIPT).

Another interesting aspect is related to the channel estimation complexity. In fact, all traditional double-hop RIS or STAR-RIS-aided communication schemes require the channel estimation for three sub-links. In contrast, CRIS requires the channel estimation only for two sub-links since the sub-link connecting the two RISs is replaced by a stationary cable connection. Similarly, no online time or frequency synchronization is required between the input- and the output-RIS, such that the complexity of operation is also lower than that of the double-hop RIS or STAR-RIS-aided communication.

One potential drawback of the proposed technology is related to the deployment costs, which depend on the length of the cable connection and may be higher than with the stand-alone RISs and STAR-RISs. The trade-off between these costs, the number of CRIS front-ends and the overall system performance is beyond the scope of this work.

III. System model

In this section, we describe the properties of passive CRIS-assisted signal propagation, i.e. modeling aspects, losses and impairments.

A. Signal propagation model

The CRIS-aided signal propagation can be modeled using a channel cascade that comprises a wireless link between the transmitter and the input-RIS elements, cable attenuation, phase shifts, and a wireless link between the ouput-RIS elements and the receiver. The two wireless links contribute to the overall path losses in terms of double fading, similar to RIS. The mapping of the input signals of CRIS onto the output signals is linear and can be described using a diagonal phase shift matrix. Additionally, the magnitude of each diagonal element scales according to the total power drained from the respective input-RIS element and the attenuation of the cable connection.

Typically, RIS-aided signal propagation is modeled using a diagonal phase shift matrix with zero off-diagonal elements. In contrast, CRIS can be realized with a phase shift matrix that has no zero elements. Accordingly, much more flexibility for the optimization can be expected. In particular, the beam pattern of CRIS can be manipulated to select the direction of signal arrival and transmission.

In addition, if advanced CRIS with multiple input- or output-RISs is employed, the phase shift matrix of CRIS can be rectangular. Accordingly, the signal model and the design methods for CRIS are also different than those of RIS.

B. Losses

Depending on the implementation, the path losses in CRIS can substantially vary.

1) Coaxial cable: The signal propagating through the CRIS cable is subject to attenuation loss. The attenuation of commercial coaxial cables varies depending on the operating frequency, the cable length and the cable manufacturing. For instance, at a carrier frequency of 2.7 GHz the attenuation of commercial cables can be as low as around 4.4 dB/100 m [12]. In addition, the insertion losses in connectors are close to 0.1 dB at high frequencies according to [13].

2) Optical fibers: The use of optical fibers requires an electrical-to-optical and an optical-to-electrical conversion of the signal via optical modulators at the respective ends of the cable. Typical attenuation values of a fiber cable are in the order of 5 dB/km [14], which is much lower than with the coaxial cable. However, the insertion losses of the optical modulators and photodetectors are typically rather high, i.e. in the order of 5-8 dB [15].

Accordingly, for short transmission distances, i.e. below 250 m, the coaxial cables might be preferred.

Additional losses may occur by splitting or combining the input signals in CRIS. Such losses usually scale with the number of combination/splitting stages. Depending on the implementation they can be kept sufficiently low.

C. Major signal impairments

1) Cross-talk: Mutual coupling of coaxial cables due to insufficient insulation can lead to interference between signals associated with adjacent reflective elements. Through this, each element of the output-RIS would receive a mixture of signals coming from multiple elements of the input-RIS. Due to the advanced signal processing capabilities of CRIS, this effect can be pre-compensated by applying a (fully passive) spatial equalization inside CRIS.

2) Phase noise: Phase noise is a typical impairment related to the finite precision of phase shift adjustment. This additional phase rotation may influence the beam pattern of CRIS, thus leading to performance degradation. The degradation can be, however, reduced by taking into account this impairment in the phase shift optimization.

IV. Use cases

A. Electromagnetic transparency

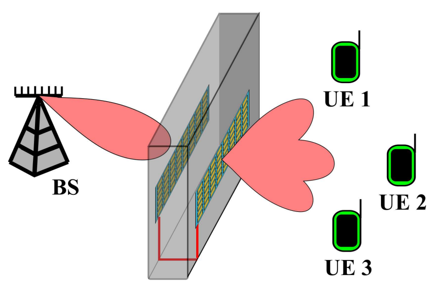
Fig. 3a illustrates, how an obstacle can be made transparent for the electromagnetic radiation using CRIS technology. This specific implementation of the CRIS comprises two RISs connected via cable. The power splitting elements are omitted in the figure. The BS transmits a signal to the input-RIS. The signal is mostly absorbed and guided to the output-RIS behind the wall. The different received copies of the input signal can be passively processed, i.e. attenuated and phase-rotated, in such a way that the signals are precoded and beamed towards the users behind the obstacle. Through this, the obstacle does not significantly affect the signal propagation anymore, which leads to its electromagnetic transparency. Note that a similar effect is observed with the STAR-RIS, which, however, requires the replacement of the wall by a metasurface.

In contrast, using conventional RIS technology, the signals may need to be guided wirelessly over long distances in order to reach the users. Accordingly, the path loss of RIS-aided signal propagation is likely substantially higher than the path loss of CRIS-aided signal propagation.

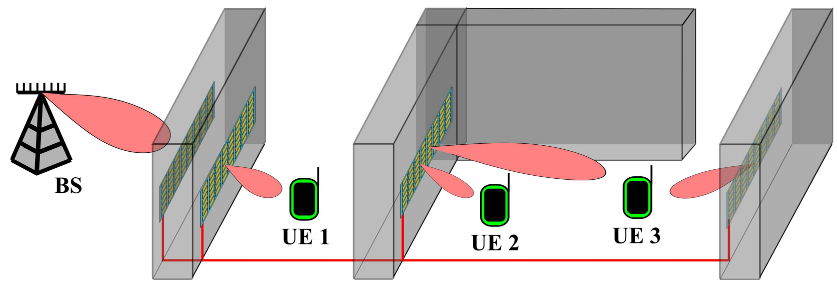
B. Distributed beamforming

More advanced CRIS implementions may include multiple input- and output-RISs, which would enable more sophisticated signal processing, such as distributed transmit and receive beamforming from multiple output-RISs. As an example, using a CRIS with multiple output-RISs we can directly serve all users in different rooms, see Fig. 3b. Here, the signal path is reduced compared to the conventional RIS (see for a similar scenario Fig. 1), since we inject the signals into the target rooms directly, i.e. without guiding them wirelessly through multiple locations via reflections from the walls.

The main benefit of CRIS in this configuration arises from the splitting of the connection. For



(a) Electromagnetic transparency.



(b) Distributed beamforming.

Fig. 3: Use cases of CRIS.

this, CRIS may include multiple power splitters, which produce attenuated copies of the received signals that are guided to different output-RISs. Through this, the beamforming capabilities of CRIS can be substantially enhanced by exploiting the spatial diversity of multiple distributed RISs. In fact, the distributed beamforming from multiple output-RISs can be used to create small high-performance bubbles around the UE (e.g., UE 3 in Fig. 3b) with low co-channel interference and high security.

Apparently, such a CRIS represents a special case of a distributed multi-antenna system with multiple access points. Typical drawbacks of this implementation are therefore related to throughput limitations and power consumption. Clearly, passive CRIS is more advantageous in this scenario since it does not have such drawbacks.

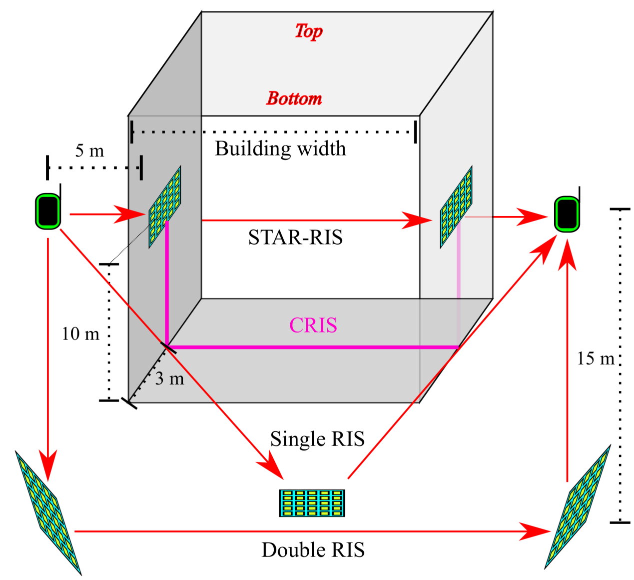


Fig. 4: Evaluated scenario.

V. Numerical Evaluation

We consider a scenario as described in Fig. 4. We assume that the walls cannot be penetrated by electromagnetic radiation and that no sufficiently strong non-LoS propagation path exists, such that the system relies on the signal reflections from the RISs or on the CRIS. As benchmark schemes, we consider a conventional single RIS, double RIS and double STAR-RIS approach. The CRIS consists of two RISs connected via coaxial cable. For a fair comparison, we assume that all involved RISs have the same number of elements. The transmitter and the receiver are equipped with single antennas and placed at 1.5 m height above ground and 5 m away from the opposite walls of a building. The STAR-RISs (and the RISs of CRIS) are deployed in front of the transceivers at 3 m height. The positions of conventional RISs in double-RIS setting are shifted relative to the transceivers by 15 m away from the axis of signal transmission. The conventional single RIS is deployed at the closest position to the building, which has a LoS both with the transmitter and the receiver. We assume a path loss exponent of 2.3 outdoors and 3.7 indoors due to potentially many reflections from multiple walls inside the building. Furthermore, we assume Rician fading channels with a Rician factor of 0 dB that are perfectly known to all devices. All RISs are optimized to maximize the signal strength at the receiver. Furthermore, we employ a passive CRIS with 4.4 dB/100 m cable loss (cable length depends on the building width) and 0.1 dB insertion loss. The path loss is obtained from 1000 Monte Carlo runs.

The resulting average path loss obtained for different building widths and numbers of RIS elements is depicted in Fig. 5. We observe that single RIS-based signal transmission substantially outperforms the double RIS-based system, especially with a low number of reflective elements and low building width. With respect to CRIS, single RIS- and double

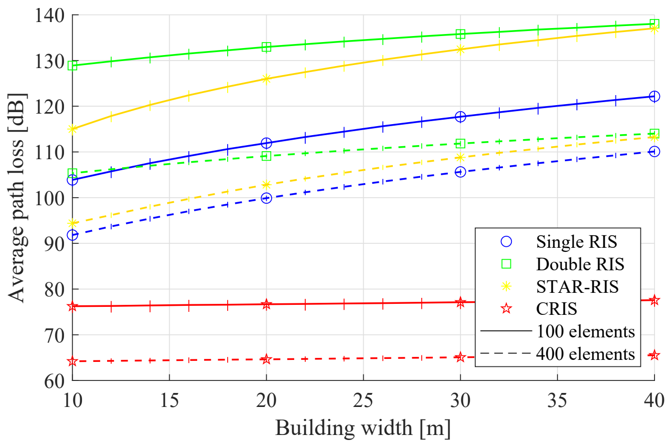


Fig. 5: Average path loss vs. building width for different numbers of RIS elements. Vertical lines indicate 95%-confidence intervals.

RIS-based signal transmissions with 400 elements suffer at least 27.6 dB and 41.1 dB higher average path loss, respectively. In addition, we observe that the path loss using STAR-RISs is larger than that of single RIS, which is due to a larger number of sub-links in the cascaded channel. With respect to CRIS, STAR-RISs have at least 30.2 dB higher path loss. With a small number of elements and a large building width, the gain using CRIS can reach 44.6 dB, 60.4 dB and 59.5 dB with respect to single RIS, double RIS and STAR-RISs, respectively. These large gains support the claim that CRIS is a new paradigm capable of revolutionizing the design of future wireless networks.

VI. Research Challenges and Opportunities

In this section, some of the future research challenges and opportunities using the CRIS technology are discussed. Note that the well-known research challenges of RIS-assisted communications, such as channel estimation and control signaling [2], are inherited by CRIS-aided networks as well and therefore omitted here.

A. *Bi-directional communication*

As mentioned earlier, an advanced CRIS may contain additional power splitters and combiners in order to enable advanced spatial filtering and shape the beam pattern in the desired way. These components define the direction of signal propagation since their functionality cannot be reverted. Hence, one of the main challenges is to design CRIS which operates simultaneously in both directions with reasonable complexity and accuracy.

B. *Network design*

One of the fundamental issues for the network design is related to the channel modeling. The signal propagation is typically described using the well-known models for the fading statistics. These models predict a certain distance-dependent attenuation and channel fluctuations. However, with the proposed CRIS, the signals can be transmitted to very distant locations with rather small path losses. Hence, the signal attenuation relative to the traveled distance is much lower than using classical propagation models, i.e. the path loss exponent is dramatically lower than predicted. Accordingly, the channel statistics may depend on the signal routing and vice versa. As a result, the network design is very challenging with CRIS.

C. *Hybrid CRIS*

The input- and output-RISs of CRIS can be also used to reflect the signals in the preferred direction, i.e. similar to the conventional RIS and STAR-RIS. While this CRIS configuration is even more complicated than individual CRIS and RIS, such a scheme is very promising due to the created additional signal paths.

D. *Massive connectivity*

In order to cope with a large number of simultaneous connections, e.g. from massive IoT networks, the corresponding signals need to be made sufficiently separable. This can be achieved by exploiting signal diversity in time/frequency/space and employing sophisticated detection methods at the receiver. By using an advanced CRIS, the spatial diversity can be increased to accommodate many orthogonal channels, such that the receiver design can be relaxed. Moreover, the path loss is substantially reduced, which allows for more accurate detection.

E. *Wireless power transfer*

The main challenge for the wireless power transfer (WPT) is the path loss, which prohibits efficient wireless charging of distant devices. However, with the proposed CRIS, it is possible to transmit signals over larger distances with reduced path loss. Correspondingly, the harvested energy can be dramatically increased, especially if the user is located close to CRIS. Note that an energy harvester can be also connected to CRIS in order to drain electromagnetic radiation from the environment and use it e.g. for signal amplification. Hence, WPT for CRIS might become a promising research direction in future.

VII. Conclusion

In this paper, a novel concept of cable-aided distributed RIS has been proposed. This concept makes use of a wired connection between the two front-ends implemented on the basis of RIS technology. A signal model has been provided and evaluated for a practical scenario. Potential challenges and promising research directions related to the design of CRIS-assisted networks have been introduced.

The obtained numerical results have demonstrated the superiority of the proposed concept in terms of substantially reduced total path loss compared to the existing technologies. As such, we anticipate that CRIS would become one of the key enablers for future wireless communication systems.

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