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APPLIED RESEARCH

Simulation and Field Trial Results of Reconfigurable Intelligent Surfaces in 5G Networks

RUIQI LIU, (Member, IEEE), JIANWU DOU, PING LI, JIANJUN WU, AND YIJUN CUI
Wireless Research Institute, ZTE Corporation, Shanghai 201203, China
State Key Laboratory of Mobile Network and Mobile Multimedia Technology, Shenzhen 518055, China
Corresponding author: Yijun Cui (cui.yijun@zte.com.cn)

ABSTRACT Recently, reconfigurable intelligent surfaces (RISs) are considered as a strong candidate for next generation wireless technologies, thanks to its advantage of being able to configure the wireless propagation environment in a cost-effective and energy-efficient way. Many literature study the theoretical aspects of RIS-assisted communication while prototyping and field trials are relatively scarce. A key step towards the standardization and commercialization of RISs is to complete comprehensive field trials in cellular networks, such as the 5th generation (5G) network. There are several typical deployment scenarios in 5G networks such as indoors, outdoors and mixed indoors and outdoors, where RISs can provide coverage to weak reception areas, enhance transmission robustness, fix coverage holes and increase the maximum available data rate. In this paper, a variety types of RIS prototypes are fabricated and tested with off-the-shelf 5G user equipments (UEs) in 5G networks to validate the performance gain introduced by RISs to typical deployment scenarios of 5G at different working frequencies. Some system-level simulations are also conducted for several typical scenarios to be used as a baseline to compare to the trial results, where all parameters are selected according to 5G standards. The experimental results confirm the feasibility and effectiveness of RISs to solve coverage issues and improve received signal qualities in 5G networks across different frequency ranges.

INDEX TERMS Reconfigurable intelligent surface, 5G, field trial, test, prototype.

I. INTRODUCTION

Reconfigurable intelligent surfaces (RISs) have been recognized as a strong candidate technology to be integrated into future generation wireless networks, including 5G-Advanced and 6G. In the past decade, there have been extensive research efforts devoted to RISs on RIS modeling, channel modeling, channel estimation techniques, system architecture and hardware implementations [1], [2], [3], [4], [5], [6]. There have also been many funded projects supported by a number of funding agencies and white papers published by different parties, with RISs as a major focus [7]. Besides the significant research and engineering efforts from the academia and the industry, many standard development organizations (SDOs) are also advancing the idea of RIS by starting corresponding study items or work items [8] and the industry players are actively exploring into this field by trying to set out a clear path on how the standardization work of RIS can be continued with the status quo [9].

Based on the theoretical research results, some universities pioneered in building proof-of-concepts of RIS as well as conducting tests in lab or outdoor environments. In [10], the prototype RFocus is demonstrated along with its controller, algorithm and experimental results. The fully passive prototype is tested in a typical indoor environment, achieving a median 9.5 dB improvement in signal strength and twice the original channel capacity. An RIS prototype that can perform amplitude-and-phase-varying modulation to facilitate multiple-input multiple-output (MIMO) transmissions is presented in [11]. The system is evaluated over-the-air (OTA) in real time while taking into account the hardware constraints and their impact on the system.

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The authors of [12] develop a low-cost and high-gain RIS panel that comprises 256 elements, where each element can be configured by 2-bit control signaling. The RIS can provide 21.7 dBi antenna gain at 2.3 GHz and 19.1 dBi antenna gain at 28.5 GHz. The test results on beams are acquired in a radio-frequency (RF) anechoic chamber while the results on system performance are acquired through tests indoors. Orthogonal frequency division multiplexing (OFDM) signals are used in all the tests. In [13], OTA test results are presented for RIS-assisted communication systems operating in both indoor and outdoor scenarios. The RIS comprises 1,100 tunable elements and can provide a 26 dB power gain in indoor scenarios and a 27 dB power gain in short-range outdoor tests. The RIS is able to provide a gain of 14 dB in receiving power when the distance between the transmitter and the receiver is 500 meters. The signals used in the tests are also OFDM, while the transmit power is 13 dBm for 50-meter transmission distance and 23 dBm for 500-meter distance.

The wireless communication industry has also been building different kinds of prototypes and testing them in different environments. The trials started with non-configurable metasurfaces. In November 2018, a communication system in the 28 GHz band using a metasurface reflect-array was demonstrated [14], which achieved a downlink data rate of 560 megabits per second (Mbps) in lieu of 60 Mbps when no reflector is deployed. The metasurface uses very small structures, compared to the free-space wavelength, that are arranged across the array to have different shapes based on their position within the array. The direction of the reflected wave gain and the shape of the beam is determined by the meta-structure of the metasurface, which is not configurable once manufactured. The trial demonstrated the ability of such non-configurable metasurface to increase coverage by reflecting radio waves to users out of sight. In January 2020, the same team conducted a trial of a transparent dynamic metasurface with 5G radio signals in the 28 GHz band [15]. The metasurface appears to be a normal transparent glass but is capable of reflecting radio signals to pre-defined directions with three modes. The designed metasurface can reflect the incident radio signals with full or partial power or can let the signal penetrate with close-to-zero power losses. The portion of the power reflected is manipulated by the separation distance between the metasurface substrate and the movable transparent layer, which can be adjusted from 0 to more than 200 micrometers. The distance between the two substrates was manually controlled in the test, while plans to use piezoelectric actuators were suggested. It's still worth studying the speed of changes between modes such controlling can support and whether it can meet requirements for 5G or next generation networks. The first experiment for backscattering systems empowered by RIS has also been recently conducted [16]. The proposed RIS is able to realize reflected beams, which belong to a codebook, that improve the tag-to-reader bit error rate. The test is conducted in a simple lab environment where the signal source, tag, RIS and the reader are all placed on a table and close to each other. Recently, the design of a liquid crystal based metasurface which works on 28 GHz is revealed [17]. The prototype is designed to solve current problems in 5G networks, such as coverage holes in high frequencies. Reference [18] presents the design of a RIS prototype with 1600 elements operating at around 29.5 GHz. The prototype is tested indoors with horn antennas used as the transmitter and receiver. The transmitter is placed in an office room while the receiver is outside in the corridor such that there is no line-of-sight (LOS) path between them. The results show that the RIS can effectively enhance the constellation diagram of quadrature phase shift keying (QPSK) for the above scenario.

Alongside the testing with RIS prototypes, there are also studies on network planning for RIS-assisted networks, evaluating the performance of RIS with synthetic network deployments. One recent study [19] focuses on an indoor environment and demonstrates that deploying RISs can enhance the performance on top of the existing network infrastructure, solve the dead-zone problem in highly-crowded environments and improve fairness among users.

From the year of 2018, there have been continuous efforts on network planning and optimization through simulations for RIS-assisted wireless networks as well as prototyping and testing to demonstrate the performance enhancement introduced by RISs. Some early tests are done in lab environment or indoors, while some recent tests are conducted in clean outdoor environments. Most tests utilize single frequency signals or signals of simple modulation for performance evaluation, and use tailored transmitters and receivers.

Against this background, we designed and built start-of-the-art RIS prototypes for typical working frequencies of 5G networks, conducted tests in RF anechoic chambers, indoors, outdoors and sophisticated environment such as mixed indoors and outdoors, using 5G networks as signal sources and off-the-shelf 5G user equipments (UEs) as receivers. Trials on different types of RISs, such as single-polarized 1-bit phase quantization and duel-polarized 4-bit phase quantization, are conducted and the comparison is given. In parallel, network planning and optimization is conducted through simulations for some key scenarios and field trial results achieve similar performance as the simulations. It's also worth mentioning that all field trials introduced in this paper are conducted in practical environment, with potential pedestrians and vehicles moving around.

The organization of this paper is as follows. Section II gives the physical model of RIS, which will be used in later simulations and analysis. In Section III, we share our views on the potential use cases and deployment scenarios where RISs can enhance network performance. Section IV provides the experimental results under multiple different test environments, including both simulations and field trials in 5G networks. Finally, Section V concludes the paper.

II. PHYSICAL MODEL OF RIS

In this section, the physical model of RIS elements and the RIS panel are analyzed to be used for later analysis and simulations. To calculate and simulate the effect of RIS to the received signal strength, the physical model of RIS as well as channel models need to be formulated. There are currently many mature channel models adopted by both the academia and the industry, such as the 3rd generation partnership project (3GPP) model [20] and the international telecommunication union (ITU) model [21], while the question for link-level or system-level simulation of RIS-assisted networks is how to integrate these channel models with the physical model of RIS.

There are many possible ways to implement RIS from hardware perspective, such as the PIN diodes, metal-oxide-semiconductor field-effect-transistors (MOSFET) and radio frequency microelectro-mechanical systems (RF-MEMS). A comprehensive comparison among different types is provided in Table 1, by extending the results in [22] and including more types as well as key performance indicators (KPIs) from wireless communication perspective.

As shown in Table 1, different types of hardware implementation are suitable for different deployment scenarios, considering the working frequency, the requirement on the speed to change the codebook applied on all RIS elements, as well as practical considerations including the working voltage, power consumption and deployment costs. There are still a few missing pieces in Table 1 to be further studied, while it can be seen that PIN diodes can be seen as a reasonable choice to implement RIS thanks to the wide range of working frequency, fast speed to change the codebook and low costs. In this paper, different RIS panels designed and fabricated to work on different frequencies are all implemented by PIN diodes.

The RIS panel implemented by PIN diodes can be modeled as a multi-layered surface where each layer is designed to achieve certain functions. An example of a typical design of a three-layered reflective RIS panel is given in Fig. 1. The outer layer comprises of a usually large number of reflecting elements, usually arranged in a form of two-dimensional arrays. The elements are usually made of small squared thin metal plates, and can be controlled to shift the phase of incident electro-magnetic (EM) waves according to the signaling of one or multiple bits. The middle layer is intended to stop the incident radio wave from penetrating the panel, and is usually made of copper. The inner layer is connected to the RIS controller and usually comprises of control circuits, which can take the power level from RIS controller as input, and upon that specific power level equivalently change the response of the circuit so that the corresponding elements on the outer layer will pose a specific change on the incident radio wave.

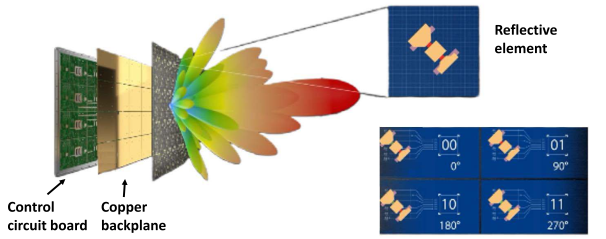


FIGURE 1. Structure of a three-layered PIN diode based 2-bit RIS panel.

The physical model of RIS elements depend on a variety of factors, such as the polarization characteristics, granularity of phase shifting, insertion loss which is frequency dependent, direction of the impinging wave, current codebook applied on RIS and other non-ideal factors. Many of these factors are dependent on the hardware implementation. However, to effectively create a feasible mathematical model for RIS elements, some factors need to be ignored in the trade-off between accuracy and complexity. The model shall also be implementation independent and sufficiently generic to apply to all types of materials and technologies. Thus, in this paper, a simplified model of RIS elements is used, which is based on the following assumptions. Firstly, ideal polarization without polarization leakage is assumed to simplify the model and the simulations. Although insertion loss is generally frequency dependent, for the sake of reducing complexity, a frequency independent insertion loss is considered in the physical model and it's also assumed that RIS elements are perfectly electrically conducting. The codebook applied on RIS is meant to configure the phase shifts on every elements, and ideal phase shifting which is frequency independent is assumed.

There are some key steps when formulating the impact of RIS to wireless transmissions, for instance how to calculate the intensity of the EM field on a single element which has finite surface and how to calculate the received signal strength at the receiver based on the results acquired for every single RIS element. Some of the issues are theoretically well studied, and some existing approaches can be used. To derive the intensity of the local EM field on a single element given the global EM field, the Stratton-Chu diffraction theory [23] can be used.

With the model of a single RIS element and the assumption that all RIS elements have an identical and unified response to impinging waves, the impact of RIS at the receiver side in terms of received signal strength can be calculated readily with existing approaches [24]. The algorithm takes several variables as input, including the intensity of the EM field on every element, the geometrical information of the RIS panel, the insertion loss, the relative phase change due to EM-wave traveling from RIS elements to the receiver and the phase shifting effect by the codebook.

III. RIS EMPOWERED WIRELESS NETWORKS

There are potentially many typical use cases of RISs in future wireless networks, some of them depicted in

TABLE 1. Different hardware implementations of RISs and their comparison over multiple KPIs.

	RF-MEMS	PIN diodes	Varactor diodes	MOSFET	Photo-conductive	Ferro-electric	Liquid crystal
Working frequency (GHz)	< 40	< 110	< 20	< 200	–	–	> 20
Working voltage	High	Medium	High	High	Low	Very high	High
Power consumption	Low	Medium	High	Low	Medium	Low	Low
Time to change codebook	μs	ns	ns	ns	μs	ms	ms
Insertion loss	Low	Medium	High	Medium	Medium	–	High
Digital / analog control	D	D	A	D	D	A	A
Cost	Medium	Low	High	Medium	–	High	–

Fig. 2. Since RIS can effectively manipulate the propagation environment, especially when a line-of-sight (LOS) path doesn't exist between the transmitter and the receiver, it's natural to utilize RIS to assist wireless communication, especially in higher frequency bands such as millimeter waves (mmWave). RIS can also empower device-to-device (D2D) communication, where the coverage of the cluster can be enlarged with the help of RIS and higher signal quality can be expected. RIS can also enhance simultaneous wireless information and power transfer (SWIPT) and unmanned aerial vehicles (UAVs), by providing artificial link to overcome blockage, increase robustness of the transmission and raise the quality of received signals. The studies and trials in this paper focus on RIS-aided wireless communications.

There are also many possible deployment scenarios for the use case of assisting wireless communications, which can be classified into purely indoor environment, purely outdoor environment and mixed indoor and outdoor environment. These cases will be analyzed in detail below.

A. INDOOR SCENARIOS

In an indoor environment, radio waves are vulnerable to blockage of walls and objects. In this scenario, RISs can be deployed to provide signal coverage to corners at the corridor or office rooms, where there is no LOS path from a base station (BS). A typical indoor use case for RIS is depicted by Fig. 3, where there is only one BS in the corridor and there is no BS in the room. For such cases, conventional solutions usually require the network operators to deploy micro BS inside the room to provide proper coverage, otherwise the UEs deep in the room will hardly connect to the network.

With RISs, which are potentially simpler, lighter and cheaper than micro BSs, a new solution emerges for such indoor scenarios which is to deploy a RIS at the door to create a virtual LOS path between the BS and the UE. A simple solution would be to place a static RIS to try to serve all UEs in the room using a wide beam, which can further reduce the deployment cost and power consumption. Alternatively, if the room is quite large and UEs in the room may appear at locations far from each other, the RIS needs to support dynamic beam training and beam tracking to follow the UEs. Either way, RISs can become a powerful tool to combat the blockage in indoor scenarios and provide network coverage with a more affordable cost.

B. OUTDOOR SCENARIOS

Even in well-planned cellular networks, coverage holes still exist in outdoor scenarios due to fading and blockage, especially when higher frequencies (such as mmWave) are used for communications. To better serve the intended area, BSs are usually deployed on the roof top of tall buildings overlooking the city block nearby. However, there are still corners that are challenging to cover, such as the example illustrated in Fig. 4. Since there is a limitation to the maximum elevation of signals transmitted by the BS antennas, the UEs close to the building where a BS is located cannot be served by LOS paths, and the transmission quality decreases. UEs around the building may also be blocked by trees or other buildings, resulting in not sufficient received signal strength to support robust communication.

Instead of deploying another BS or relays, RISs can be deployed in these scenarios to reflect the transmitted signals to the UEs initially in the non-LOS (NLOS) area or coverage holes. If the RIS is capable of joint beam training and optimization with the BSs, the BS and RIS can select the best beamforming and reflecting coefficients jointly to serve UEs based on the channel estimation results.

C. OUTDOOR TO INDOOR COVERAGE

Fig. 5 shows an illustration of a typical outdoor to indoor scenario, where the BS is located at the rooftop of a building, and there is a long corridor in a nearby building. This scenario can be used to approximate railway stations with long platforms or tunnels or shopping complexes with long indoor pathways.

According to the engineering experience from the network planning and optimization, for such indoor environments with a nearby outdoor BS on the rooftop of another building, the UE can still get signals near the entrance. When the UE moves deeper inside the building, the receiving signal strength would drop drastically and indoor micro BSs are needed to provide continuous coverage. RISs now provide an alternative solution to the micro BSs, which has more advantages in terms of deployment costs and energy consumption.

IV. EXPERIMENTAL RESULTS

In this Section, the experimental results of RIS-assisted 5G networks are presented. Specifically, for the scenarios mentioned in Section III, simulations and field trials are

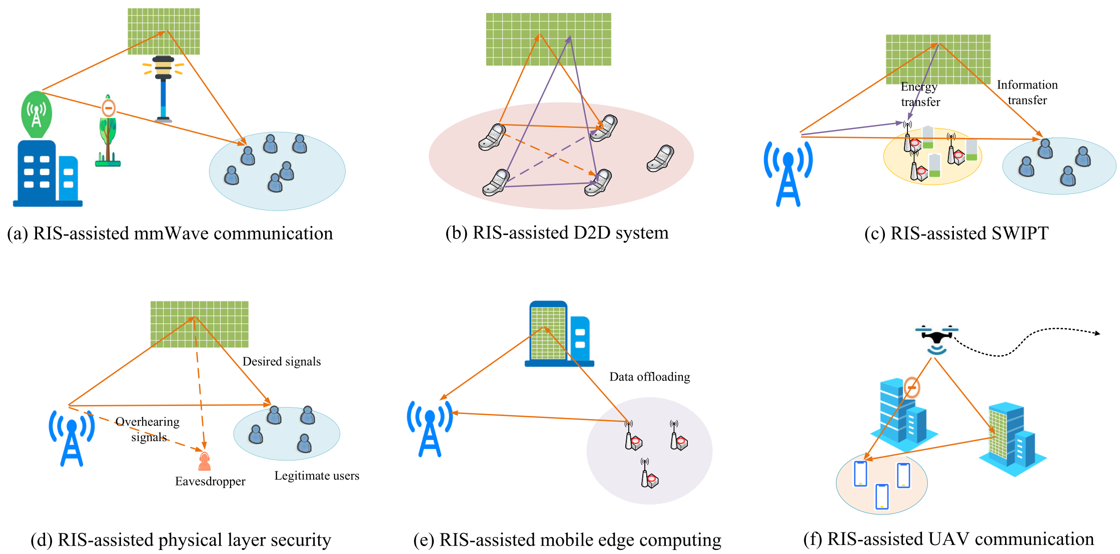


FIGURE 2. Typical use cases of RISs in future wireless networks.

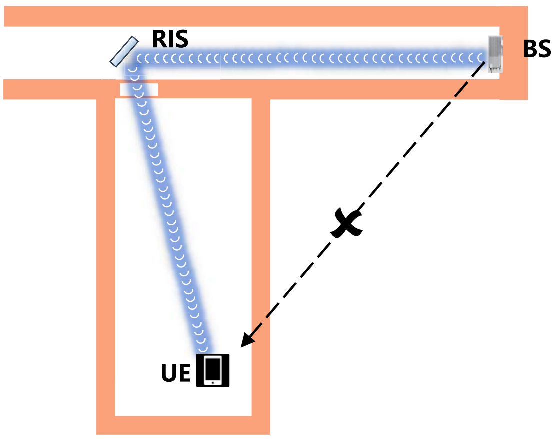


FIGURE 3. Typical indoor environment where RIS can help to provide coverage to a room.

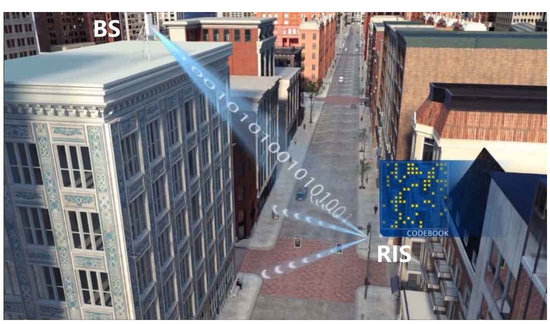


FIGURE 4. Typical outdoor deployment scenario for RIS to fix coverage holes.

conducted to provide comprehensive results on the performance enhancement. In the simulations, the parameters of transmitted signals are chosen according to 5G standards.

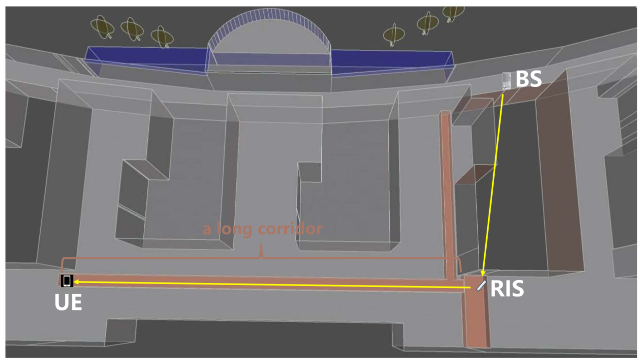


FIGURE 5. Illustration of a deployment scenario where RIS is used to provide coverage to indoor environment using a BS outdoors.

All tests are conducted with off-the-shelf commercial 5G UEs and 5G BSs. The physical layer parameters of the signals transmitted by 5G BSs can be found in [25]. To test and demonstrate the suitable deployment scenarios and corresponding performance of RISs, the tests are conducted in different environments, including indoors, outdoors and outdoors to indoors. The trials are conducted in different locations in China from the year of 2021. Under different tests which are conducted at different frequencies, different RIS panels are fabricated and used. All RISs used in the tests of this paper are square panels as demonstrated in Fig. 6.

The reference signal received power (RSRP) is a commonly used criteria in 5G systems to determine the receiving quality at the receiver side, as defined in [26]. RSRP is defined as the linear average over the power contributions of the resource elements that carry the reference signals, and the synchronization signal block (SSB) is used as the reference signal in the following simulations and tests. The common

FIGURE 6. Two RISs fabricated for test purposes, the right one with a protecting mask.

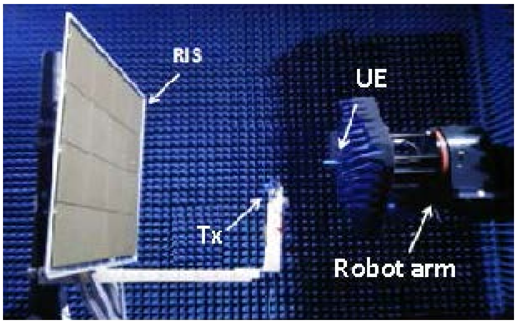


FIGURE 7. Setup for the radiation pattern test in the RF anechoic chamber.

unit for RSRP is dBm per resource element (dBm/RE) and the thermal noise measured at the UE when no intended signal exists is approximately -115 dBm/RE.

A. RADIATION PATTERN TEST

The purpose of this test is to validate that the fabricated RIS prototype is built with satisfying quality and can be used to conduct later trials. The tests are done in an OTA manner by measuring the direction of the main lobe of the beam reflected by the RIS and compared to the theoretical direction as configured by the codebook. As shown in Fig. 7, the transmitter is placed in front of the RIS panel, and a UE is fixed on a robot arm which can move and rotate to measure the radiation pattern of the reflected beam.

The reflection coefficients are adjusted according to pre-defined codebooks to form beams with different azimuth directions from -50° to 50°. The RIS in this test has 1024 elements, is single-polarized and supports 1-bit quantified codebook. As reflected in Table 2, the fabricated prototype along with the designed codebook gives high accuracy in beamforming, with the error between the theoretical and measured direction of the main lobe less than 1° for all the test cases.

B. SIMULATIONS AND TRIALS FOR INDOOR SCENARIOS

Based on the physical model of RIS derived in Section II, simulations are conducted to compare the performance of different RIS panels. Fig. 8 shows the test environment, where the BS is placed at one end of the corridor, the RIS is placed in front of the door of one room and the UE is in that room.

TABLE 2. Test results of different radiation patterns.

Theoretical	Measured (vertical)	Measured (horizontal)
-50°	-49.8°	-49.8°
-30°	-29.6°	-30.4°
0°	0.64°	-0.68°
30°	30.1°	29.7°
50°	49.5°	50.6°

FIGURE 8. Setup for the indoor OTA test.

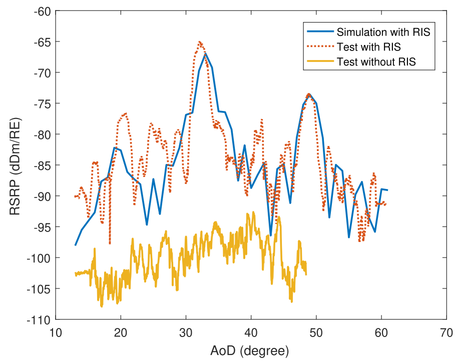


FIGURE 9. Simulation and test results for the 1-bit single-polarized RIS in an indoor environment.

The distance between the BS and the RIS is approximately 20 meters and the distance between the RIS and the UE is around 10 meters. There is no LOS path between the UE and the BS. Such an environment is illustrated in Fig. 3.

The simulation and test results for this scenario are presented in Fig. 9 and Fig. 10, for the 1-bit single-polarized panel and the 4-bit dual-polarized panel respectively. Both panels have 64×64 elements. The working frequency is 26 GHz. The angle of arrival (AoA) of the impinging wave is -32° while the angle of departure (AoD) for the intended reflected beam is 48°.

As shown in both Fig. 9 and Fig. 10, the test results are coherent with the simulations in most AoDs. It is also observed that the 1-bit single-polarized RIS provides around 30 dB gain in RSRP for the target direction, and the gain provided by the 4-bit dual-polarized RIS is around 38 dB for the target beam direction. By comparing Fig. 9 and Fig. 10 it can be seen that the 4-bit dual-polarized panel is able to form one sharp beam directing at the wanted AoD, while the 1-bit single-polarized panel generates one leakage beam at 20° and one mirror beam at 33°. The leakage beam is due to the 1-bit phase ambiguity, and the mirror beam exists because of polarization mismatch. It is also observed that the 4-bit

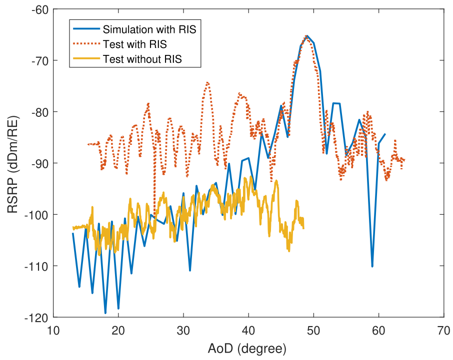


FIGURE 10. Simulation and test results for the 4-bit dual-polarized RIS in an indoor environment.

dual-polarized RIS also forms some weak mirror beams at 33° and 39°, due to potential polarization leakage.

C. SIMULATIONS AND TRIALS FOR OUTDOOR SCENARIOS

To properly validate to which extent RISs can assist wireless communication outdoors and fix coverage holes, both simulations and trials are done using a same outdoor setup. Fig. 11 shows the environment for the simulation and the test. The BS is on the rooftop of a 5-floor building and is able to cover the open area in front of the building. However, for the UE in a small parking lot behind the building, it cannot receive signals from the BS due to lack of propagation paths in between.

In the test, a 1-bit single-polarized RIS with 1024 elements is placed at the crossroad, which allows it to have LOS paths with the BS and the UE in the parking lot simultaneously. The distance from the RIS to the BS and the UE is around 120 meters and 20 meters, respectively. The working frequency of the 5G system is 26 GHz. With the RIS, the reference signal transmitted by the BS is reflected into the parking lot which is blocked by trees nearby. Compared to the case without RIS, the received RSRP of SSBs increases over 30 dB to a level higher than -70 dBm/RE.

Fig. 12 shows that the system-level simulation results match the field test results, confirming that RISs can provide a nearly 30 dB gain in RSRP to the parking lot.

D. TEST OF OUTDOOR TO INDOOR SCENARIO

The results of OTA tests in an outdoor to indoor scenario are presented in this subsection. Providing indoor coverage with outdoor BSs is one of the key use cases for RISs, and trials are conducted with 5G networks working at different center frequencies to validate the performance gain introduced by RIS in different frequency bands. The field trials are completed, at 2.6 GHz, 4.9 GHz and 26 GHz respectively.

1) TRIAL AT 2.6 GHz

The 2.6 GHz band is a commonly used frequency band in the sub-6GHz range as it can provide sufficient coverage to a relatively large area. This advantage means that the BS will not be deployed in a dense manner, potentially resulting in coverage holes in some corner areas.

Fig. 13 shows the environment where RIS for 2.6 GHz 5G network is tested. The height of the BS is 29 meters, while the distance from the RIS to the BS and the test UE is approximately 206 meters and 7 meters, respectively. The BS transmits signals in 60 MHz bandwidth using a transmission power of 120 W. The RIS used in this trial is single-polarized, with a total of 20×20 elements on the surface. The codebook is 1.5-bit, which means there are 3 available phase shifts on every element. The physical size of the RIS panel is 1 m × 1 m.

During the test, the UE is located in the lobby of the building, which is a weak coverage area. Measurement results show that the RSRP increases 15 dB for the UE and the data rate in downlink and uplink increases 275% and 200%, respectively.

2) TRIAL AT 4.9 GHz

In this trial, the BS works at 4.9 GHz and transmits with a power of 200 W in a 100 MHz bandwidth. The distance from the RIS to the BS and the UE is approximately 145 meters and 45 meters, respectively. The RIS is 2-bit dual-polarized, with 32 × 32 reflective elements and the physical size is 1 m × 1 m. The test UE is inside the lobby of the building, which is a typical weak coverage area. The overall setup for the trial is shown in Fig. 14.

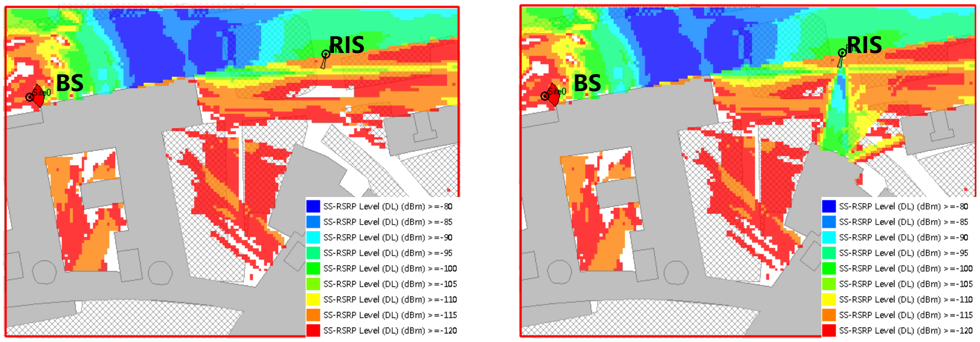
In this trial, both RSRP and data rate are evaluated as KPIs of the network. The RSRP increases 21 dB after the RIS is placed, while the data rate is increased by 442% in both downlink and uplink. In weak coverage areas where the communication is usually power constrained, RISs can configure a virtual LOS path and increase the data rate drastically.

3) TRIAL AT 26 GHz

To test the performance gain of RIS to mmWave systems for outdoor to indoor coverage purposes, another trial is done at 26 GHz. 26 GHz bands belong to the mmWave frequency range, where blockage occurs more frequently since the center frequency is much higher than sub-6GHz bands, and propagation loss is also significantly higher. At this frequency range, RISs are seen as a complimentary technology to help the network to compensate the high losses.

As shown in Fig. 15, the BS is located on the rooftop of a 3-floor building overlooking the site, and there is a long corridor extending from the entrance to the inside of the building. The bandwidth of the transmitted signal is 100 MHz. The distance from the BS to the RIS is around 45 meters, while in Fig. 15 the RIS is not visible since the photo is taken at the location of the RIS. In the trial, a 1-bit dual-polarized RIS with 64 × 64 elements is used to reflect the beam from the BS into the corridor where the test UE is located. The AoA and AoD for the RIS is 35° and −56°, respectively. An illustration of this scenario is given in Fig. 5.

FIGURE 11. Photo of the outdoor environment studied in this paper taken by a wide-angle lens.



(a) Coverage without RIS (b) Coverage with RIS

FIGURE 12. Simulation results for the outdoor scenario where the trials are conducted.

FIGURE 13. Test environment for outdoor to indoor trials at 2.6 GHz.

FIGURE 15. Photo taken at the location of the RIS for the outdoor to indoor coverage test.

FIGURE 14. Test environment for outdoor to indoor trials at 4.9 GHz.

During the test, the UE moves from the entrance all the way into the building along the corridor. When there is no RIS deployed, within 30 meters into the corridor the received signal fades away and the RSRP drops to -105 dBm/RE. Comparatively, when RIS is deployed and a proper codebook is used, even at the end of the corridor, which is 106 meters inside the building, received signal strength is still medium strong with a RSRP of −93 dBm/RE.

V. CONCLUSION

In this paper, a variety of RIS prototypes are designed and fabricated including 1-bit single-polarized, 1-bit dual-polarized, 1.6-bit single-polarized, 2-bit dual-polarized and 4-bit dual-polarized panels with 20×20, 32×32, 64×64 or 128×128 elements, working on 2.6 GHz, 4.9 GHz or 26 GHz. These state-of-the-art prototypes are tested in typical deployment scenarios of 5G networks, with off-the-shelf 5G UEs, 5G BSs and reference signals defined in 3GPP 5G standards. Simulations results corresponding to some of the test cases are also provided to validate that the tests achieve a similar results with theoretical analysis.

As demonstrated by the trial results, RISs can increase the RSRP in different reception scenarios around 15 dB to 35 dB depending on the detail test setup and the implementation of RIS. In all scenarios, RISs successfully demonstrate the capability of assisting a more robust wireless communication in a more cost-effective and energy-efficient way compared to their counterparts such as relays.

The challenges for RIS commercialization include identification of killer applications, technical advancements on critical problems such as channel estimation and feedback, proper standardization through the broad consensus and improvement on the RIS fabrication techniques to make RISs more reliable and affordable.

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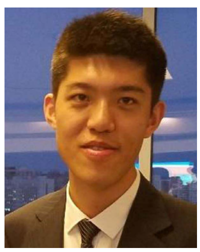
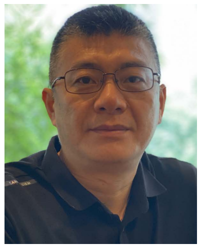


RUIQI (RICHIE) LIU (Member, IEEE) received the B.S. and M.S. degrees (Hons.) in electronic engineering from the Department of Electronic Engineering, Tsinghua University, in 2016 and 2019, respectively. He is currently a Master's Researcher with the Wireless Research Institute, ZTE Corporation, responsible for long-term research as well as standardization. His research interests include reconfigurable intelligent surfaces, wireless positioning, quantum communication, and visible light communication. He is the author or coauthor of several books and book chapters. During his three-year service at 3GPP, from 2019 to 2022, he has authored and submitted more than 500 technical documents with over 100 of them approved, and he served as the co-rapporteur of the work item (WI) on NR RRM enhancement and the feature lead of multiple features. He is the Standardization Officer of IEEE ComSoc ETI on reconfigurable intelligent surfaces (ETI-RIS) and the Standards Liaison Officer of IEEE ComSoc Signal Processing and Computing for Communications Technical Committee (SPCC-TC). He received the Outstanding Service Award from the SPCC-TC in 2022 and two Best Workshop Awards as the Chair. He currently serves as the Vice Chair for ISG RIS, ETSI. He actively participates in organizing committees, technical sessions, workshops, symposia, and industry panels in IEEE conferences as the chair, an organizer, a moderator, a panelist, and an invited speaker. He served as the Lead Guest Editor for the Special Issue on 6G in IEEE Open Journal of the Communications Society. He serves as the Editor for *ITU Journal on Future and Evolving Technologies* (ITU J-FET) and an Associate Editor for *IET Quantum Communication*.

JIANWU DOU was born in Yuci, Shanxi, China, in 1973. He received the Ph.D. degree in robotic mechanism from the Beijing University of Technology, Beijing, China, in July 2001. From 2000 to 2014, he was the Head of the Wireless RRM Team, including 2G/3G/4G/WLAN, and was in charge of developing multi-RAT wireless system simulation platform. From 2005 to 2017, he was the Vice Director with the Wireless Algorithm Department, ZTE. From 2012 to 2014, he was the Product Manager at ZTE iNES, a multi-cell/multi-UE hardware wireless channel emulator. He was in charge of a national major project and participated in two 5G projects sponsored by the Ministry of Industry and Information Technology of China. His current research interests include 5G/B5G channel modeling, new air-interface, unmanned aerial vehicle, non-terrestrial network research, THz, meta-materials, and RIS. He received the Science and Technology Award (first level), in 2014 and 2015, and the Award for Chinese Outstanding Patented Invention from the China Institute of Communications and WIPO-SIPO, in 2011, respectively.

PING LI received the B.S. and M.S. degrees in information and communication engineering from Xi'an Jiaotong University, in 2001 and 2004, respectively. She is currently a Senior System Algorithm Engineer with ZTE Corporation. She has participated in several key state and corporate research projects. She has filed more than 100 patent applications and published more than ten conference and journal papers. Her research interests include signal processing for wireless communication, multiple antennas, performance optimization for wireless systems, reconfigurable intelligent surfaces, and network planning.

JIANJUN WU received the B.S. and M.S. degrees in electronic engineering from Xidian University, in 2002 and 2005, respectively. He is currently a Senior Wireless System Engineer with ZTE Corporation. He has participated in several key state and corporate research projects. He has published many conference and journal articles and holds many granted patents. His research interests include radio frequency technologies for wireless communication, multiple antennas, massive MIMO, reconfigurable intelligent surfaces, and integrated sensing and communications.



YIJUN CUI is currently an Architecture Chief Engineer at New Radio Base Station, ZTE Corporation, and a Shenzhen high-level national talent. His research interests include 5G/6G wireless product architecture, ultra-wideband base station, massive MIMO, and intelligent electromagnetic surface. He took in charge of research and development of Pre5G massive MIMO, which won the Best Mobile Technology Breakthrough Award and the CTO Choice Award in the Global Mobile Awards of MWC Expo. He has participated in and presided over a number of major national science and technology projects. He applied for more than 30 patents as well. He won the Second Prize of Science and Technology Progress Award of Henan Province and the First Prize of Science and Technology Award of China Communication Society.