ETSI GR RIS 005 V1.1.1 (2025-02)

Reconfigurable Intelligent Surfaces (RIS); Diversity and Multiplexing of RIS-aided Communications

Disclaimer

Reference

DGR/RIS-005

Keywords

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ETSI

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Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) Reconfigurable Intelligent Surfaces (RIS).

Modal verbs terminology

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Executive summary

The present document focuses on the array technologies for Reconfigurable Intelligent Surface (RIS)-aided communication systems. First, the present document summarizes use cases and deployment scenarios for RIS. Next, the present document introduces different diversity schemes for RIS-aided communication, such as time diversity, frequency diversity, spatial diversity, etc. For each diversity scheme, the present document introduces the corresponding requirement for RIS hardware and operating mode, the channel model, the impact on Tx and Rx devices, and the diversity scheme design. Then the present document introduces different multiplexing schemes in RIS-aided communication. Finally, the present document introduces other techniques related to array technologies in RIS-aided communication, including beamforming, RIS selection, and channel estimation.

Introduction

RIS has been viewed as one of the enabling technologies for the next-generation communication systems due to its capability to adapt the channel conditions. Utilizing an array of radiating elements, RIS can re-direct incident signals to improve the coverage and reliability of communication against channel impairments such as blockage and Outdoor-to-Indoor (O2I) loss.

As one of the most important technologies in Long Term Evolution (LTE) / 5G, array systems and Multiple-Input-and-Multiple-Output (MIMO) provides significant performance gains to the wireless communication system. RIS, which is also an array system consisting of scattering unit-cells by itself, can potentially provide additional degrees of freedom and further increased gains through diversity / multiplexing schemes. Therefore, it is important to build a comprehensive understanding of the array technologies applicable to RIS-aided communication, as well as the benefits and limitations of these technologies for future system design and standardization.

The present document mainly focuses on an introduction of array technologies applicable to RIS-aided communication systems, including diversity schemes, multiplexing schemes, RIS-aided beamforming, RIS selection, channel estimation, etc. The aim of the present document is to provide a comprehensive survey to analyse the feasibility, requirement, performance, and impact of these technologies, contributing to the continuing evolution and practical deployment of RIS-aided communication systems.

1 Scope

The present document focuses on different array technologies applicable to RIS-aided communication, mainly emphasizing diversity and multiplexing schemes. Other technologies such as beamforming, RIS selection, and channel estimation have also been covered in the present document.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI GR RIS 001 (V1.1.1): "Reconfigurable Intelligent Surfaces (RIS); Use Cases, Deployment Scenarios and Requirements".

[i.2] ETSI GR RIS 003 (V1.1.1): "Reconfigurable Intelligent Surfaces (RIS); Communication Models, Channel Models, Channel Estimation and Evaluation Methodology".

[i.3] ETSI TR 138 901 (V18.0.0): "5G; Study on channel model for frequencies from 0.5 to 100 GHz (3GPP TR 38.901 version 18.0.0 Release 18)".

[i.4] Ramaccia Davide, Dimitrios L. Sounas, Andrea Alu, Alessandro Toscano and Filiberto Bilotti: "Phase-induced frequency conversion and Doppler effect with time-modulated metasurfaces", IEEE™ Transactions on Antennas and Propagation 68, no. 3 (2019): pp. 1607-1617.

[i.5] Chian De-Ming, Chao-Kai Wen, Chi-Hung Wu, Fu-Kang Wang and Kai-Kit Wong: "A novel channel model for reconfigurable intelligent surfaces with consideration of polarization and switch impairments", IEEE™ Transactions on Antennas and Propagation (2024).

[i.6] Yuan Jide, Elisabeth De Carvalho, Robin Jess Williams, Emil Björnson and Petar Popovski: "Frequency-mixing intelligent reflecting surfaces for nonlinear wireless propagation", IEEE™ Wireless Communications Letters 10, no. 8 (2021): pp. 1672-1676.

[i.7] Heng Liang and Louay MA Jalloul: "Performance of the 3GPP LTE space–frequency block codes in frequency-selective channels with imperfect channel estimation", IEEE™ Transactions on Vehicular Technology 64, no. 5 (2014): pp. 1848-1855.

[i.8] Alex Sam P. and Louay MA Jalloul: "Performance evaluation of MIMO in IEEE802. 16e/WiMAX", IEEE™ Journal of Selected Topics in Signal Processing 2, no. 2 (2008): pp. 181-190.

[i.9] Wang Bolei, Mengnan Jian, Feifei Gao, Geoffrey Ye Li and Hai Lin: "Beam squint and channel estimation for wideband mmWave massive MIMO-OFDM systems", IEEE™ transactions on signal processing 67, no. 23 (2019): pp. 5893-5908.

[i.10] Chian De-Ming, Chao-Kai Wen, Chi-Hung Wu, Fu-Kang Wang and Kai-Kit Wong: "Joint phase-time arrays: A paradigm for frequency-dependent analog beamforming in 6G", IEEE™ Access, vol. 10, pp. 73364-73377, 2022.

3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AOA	Angle of Arrival
AOD	Angle of Departure
ASK	Amplitude-Shift Keying
BPSK	Binary Phase-Shift Keying
BS	Base Station
CDL	Clustered Delay Line
CP	Cyclic Prefix
CSI-RS	Channel State Information Reference Signal
DFT	Discrete Fourier Transform
ELAA	Extremely Large Antenna Arrays
HPBW	Half Power BeamWidth
IoT	Internet of Things
KPI	Key Performance Indicator
LC	Inductor-Capacitor
LOS	Line of Sight
LTE	Long Term Evolution
MIMO	Multiple-Input and Multiple-Output
mmWave	millimeter Wave
NLOS	Non-Line Of Sight
O2I	Outdoor-to-Indoor
OFDM	Orthogonal Frequency Division Multiplexing
PAM	Pulse-Amplitude Modulation
RC	Resistor–Capacitor
RIS	Reconfigurable Intelligent Surface
RS	Reference Signal
Rx	Receiver
SFBC	Space-Frequency Block Coding
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
STBC	Space-Time Block Coding
THz	TeraHertz
TRP	Transmission Reception Point
Tx	Transmitter
UE	User Equipment
UL	UpLink
UMi	Urban Microcell

4 General aspects of RIS-based diversity and multiplexing schemes

4.0 Motivation of RIS-based diversity and multiplexing

As the most important technologies in LTE / 5G, multi-antenna systems and MIMO have brought significant performance gains to the communication system. Such gains are mainly realized in the form of diversity, multiplexing, beamforming, etc. Introducing RIS into a network generally provides additional paths for links and therefore emphasizes the greater necessity of diversity and multiplexing schemes. Furthermore, as a multi-antenna system by itself, RIS can provide extra degrees of freedom and potentially enable more diversity / multiplexing options to further improve the performance of the communication system. In the following clauses, the present document will discuss diversity / multiplexing analysis for RIS-aided communication and also cover other multi-antenna technologies such as beamforming.

4.1 Overview of RIS-aided multi-antenna systems

A RIS-aided multi-antenna system generally consists of multi-antenna Tx / Rx and RIS arrays, in which RIS configures the electromagnetic environment to enhance the communication performance. A RIS usually consists of a large number of re-radiation elements, each with at least configurable phase controlled by switches, or diodes, etc. Compared to a conventional multi-antenna system that integrates all antenna elements on the same array, RIS-aided communication has better channel conditions for the usage of diversity and multiplexing schemes. Distributed antenna systems may have comparable channel conditions but require more deployment cost. Besides, when a RIS has additional capabilities, such as fast phase adaptation, frequency shifting, polarization manipulation, etc., it can enable additional diversity / multiplexing schemes by itself and reduce the complexity and requirement of Tx / Rx devices.

4.2 Use cases and deployment scenarios

As is discussed in ETSI GR RIS 001 [i.1] and ETSI GR RIS 003 [i.2], RIS can be deployed in many different scenarios and aid communication in different manners. For a Tx-Rx link, one of the most common scenarios is that the direct Tx-Rx path is not available due to, e.g. high pathloss, blockage, O2I loss, antenna limitations, etc. as is shown in ETSI GR RIS 003 [i.2]. Figure 4.2-1 shows one of such scenarios, in which RIS extends the coverage of BS to the indoor region by avoiding the O2I loss. In such scenarios, RIS can enhance the coverage mainly by providing an additional path and large beamforming gain, while the interaction between Tx-Rx path and Tx-RIS-Rx path is negligible.

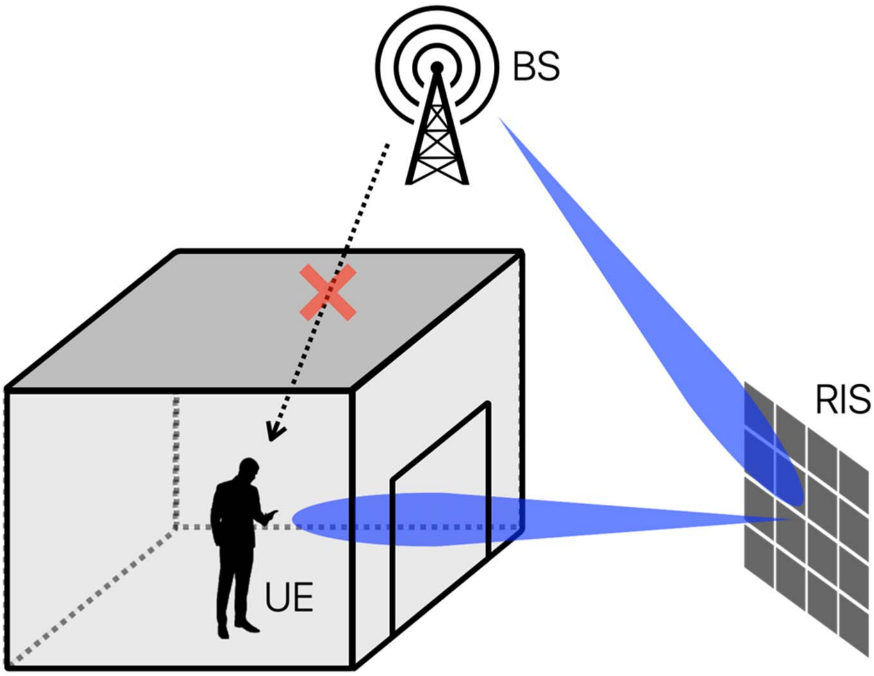


Figure 4.2-1: Illustration of scenarios with only Tx-RIS-Rx paths due to O2I loss

Another scenario is when both Tx-Rx path and Tx-RIS-Rx path are available, while the channel conditions of the two paths are also comparable. A typical use case is shown in figure 4.2-2, in which an indoor RIS is deployed to aid the existing direct link from BS to UE. The interaction between the Tx-Rx and Tx-RIS-Rx paths can influence the composite channel conditions and require adaptation of transmission schemes. Similar use cases can also be deployed in outdoor spaces as is shown in ETSI GR RIS 003 [i.2]. In such scenarios, RIS is usually deployed to improve the link performance (e.g. throughput, outage, etc.) instead of the signal strength. When the channels suffer from uncertainty (e.g. dynamic blockage, high mobility, etc.) and deep fading, diversity schemes can usually be enabled at Tx, Rx, or RIS to enhance the reliability of communication. However, if the channel conditions of both paths are generally good and stable, multiplexing schemes can be used to take the advantage of the additional path and transmit multiple streams simultaneously.

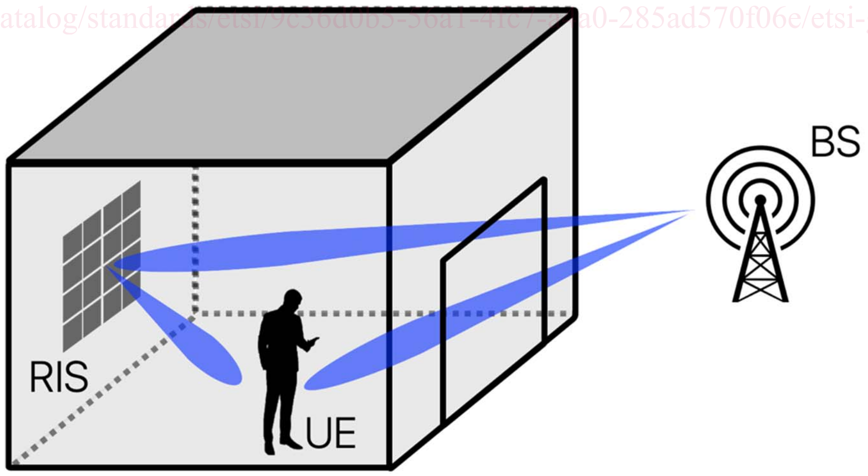


Figure 4.2-2: Illustration of scenarios with coexistence of Tx-Rx and Tx-RIS-Rx paths

In multi-user scenarios, RIS can also be deployed for diversity and multiplexing purposes. A single RIS can be configured to generate multiple beams simultaneously to support transmission from BS to multiple UEs, either in broadcast manner or using different sub-bands for different UEs. Such schemes can also be extended to scenarios with multiple BSs and multiple RIS. In some scenarios, RIS can support the space-division multiplexing of multiple BS-UE pairs if they can utilize the same RIS re-radiation pattern. The deployment of RIS can also diversify the channel conditions and allow the BS to better utilize user diversity and achieve high throughput. These scenarios will be discussed in more details in clauses 5 and 6.

4.3 General characteristics of RIS-aided channels

In most scenarios, RIS aids a link by re-radiating incident signals towards the Rx and redirects the propagation. Therefore, the RIS path can generally be viewed as an additional multipath with path gain enhanced by a configurable phased array. For common reflective RIS, the AOA and AOD of such RIS paths are mostly different from that of LOS paths. Besides, the RIS path can also have its own Tx-RIS multipaths and RIS-Rx multipaths. Therefore, the channel of a RIS-aided link is expected to have rich multipaths and more significant fading effects, especially when the LOS path is available. A detailed modelling of the RIS-aided channel will be discussed in following clauses.

5 Diversity schemes for RIS-aided systems

5.1 Time Diversity

5.1.0 Time Diversity schemes

Time diversity schemes are usually designed for robust communication with time-varying channel conditions. Burst errors can occur when symbols are transmitted in slots with deep fading channels and can cause outage. The channel of RIS-aided communication can be time-varying when mobility and blockage happens. Therefore, time diversity schemes, e.g. repetition coding / interleaving, can also be applied to RIS-aided communication systems to enhance the robustness. Such time diversity schemes are mostly applied on Tx side. In addition, by cooperating with traditional Tx diversity schemes, RIS can also dynamically adapt the channel to further improve the time diversity.

5.1.1 Requirements for RIS hardware

RIS needs to be fabricated and configured to re-radiate signals from Tx to Rx. Besides, to dynamically adapt the channel and further improve time diversity, RIS elements need to be able to change their phases with a high frequency and short delay.

5.1.2 Requirements for RIS operating mode

RIS should be able to work in reflection / refraction mode to re-radiate signals from Tx to Rx.

5.1.3 Characteristics of RIS-aided channels

RIS-aided channels can be time-varying when Tx / Rx is mobile, as is demonstrated in the following example in figure 5.1.3-1. It is assumed that the lengths of BS-UE, BS-RIS, and RIS-UE paths are d_{BU}, d_{BR}, and d_{RU}, respectively. The corresponding path gains are G_{BU}, G_{BR}, and G_{RU}, respectively. The RIS re-radiation gain is represented by $G_R e^{i\phi}$, where ϕ is assumed to be a common base phase applied to all RIS elements and does not affect the re-radiation beam pattern. The sub-band carrier frequency considered in this example is f, and the light speed is c. Then the overall channel from BS to UE is:

$$h = G_{BU} e^{\frac{-i2\pi f d_{BU}}{c}} + G_{BR} G_R G_{RU} e^{i\phi} e^{\frac{-i2\pi f (d_{BR}+d_{RU})}{c}} = e^{\frac{-i2\pi f d_{BU}}{c}} \left[G_{BU} + G_{BR} G_R G_{RU} e^{i\left[\frac{-2\pi f (d_{BR}+d_{RU}-d_{BU})}{c}+\phi\right]} \right] \quad (1)$$

Depending on the term $\frac{-2\pi f (d_{BR}+d_{RU}-d_{BU})}{c} + \phi$, the channel gain ranges from $|G_{BU} - G_{BR} G_R G_{RU}|$ to $G_{BU} + G_{BR} G_R G_{RU}$. When UE is mobile, the channel gain on this sub-band can drop from maximum to minimum within half wavelength of movement, which is a small distance for mmWave band. The channel gain difference in RIS-aided communication can be even larger than that caused by fading, as the RIS provides a much larger re-radiation gain compared to ordinary clusters. Doppler effect can also result in similar time-domain channel variations. Such channel gain variation can result in burst errors and even outage, requiring time diversity schemes to be applied on Tx or RIS side to reduce the outage probability.

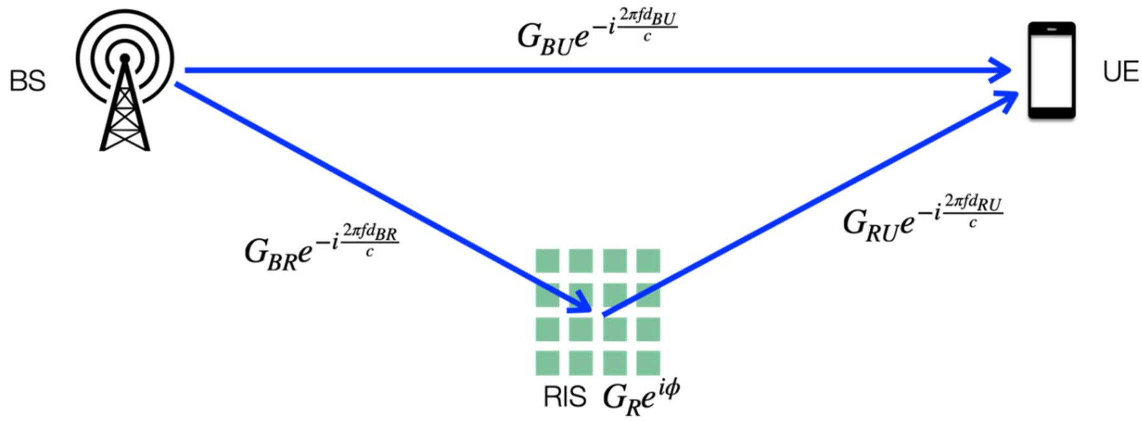
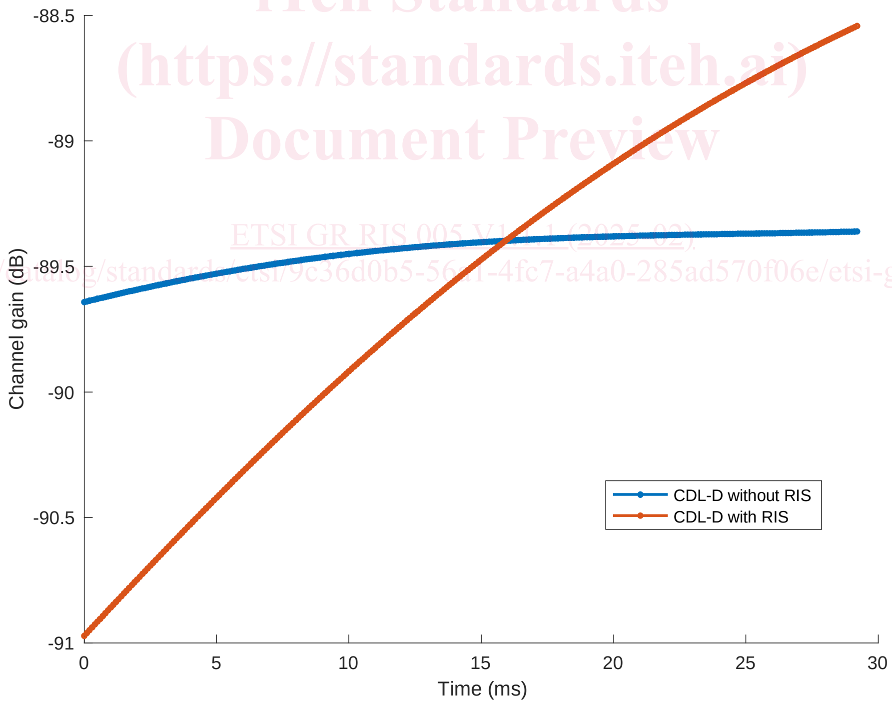


Figure 5.1.3-1: Dependence of RIS-aided channel on path lengths, which leads to time-varying channel when UE is mobile

Figures 5.1.3-2 to 5.1.3-4 illustrate the simulated time-domain channel with / without RIS. At a carrier frequency of 4 GHz, the CDL-D channel model defined in ETSI TR 138 901 [i.3] is used to generate the BS-UE and RIS-UE fading channel with LOS paths. The Doppler effect and the path length change both contribute to the channel variations. Different UE speeds (3 km/h, 30 km/h, and 100 km/h) are considered in this evaluation to better illustrate the time variation of channel. In these simulations with and without RIS, the multi-path component contributed by the surface (e.g. a wall) on which RIS would be mounted is not considered. However, it is expected that the gain provided by such a surface is usually much smaller than the RIS gain due to a lack of beamforming.



NOTE: The UE speed is assumed to be 3 km/h.

Figure 5.1.3-2: Illustration of time-varying channel with / without RIS caused by Doppler effect and path length change