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GROUP REPORT

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

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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

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

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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.

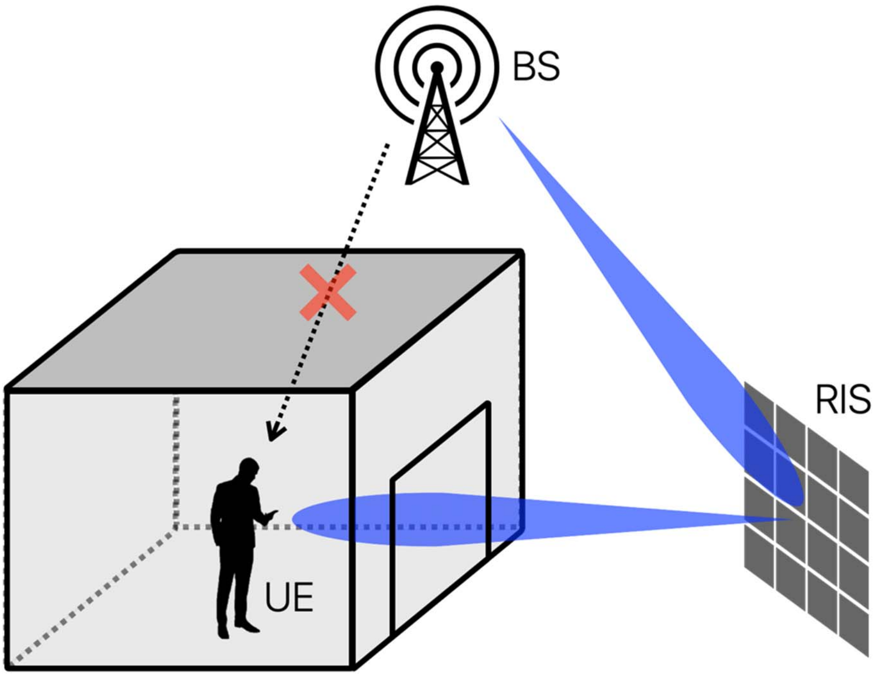


Figure 4.2-1: Illustration of scenarios with only Tx-RIS-Rx paths due to O2I loss

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.

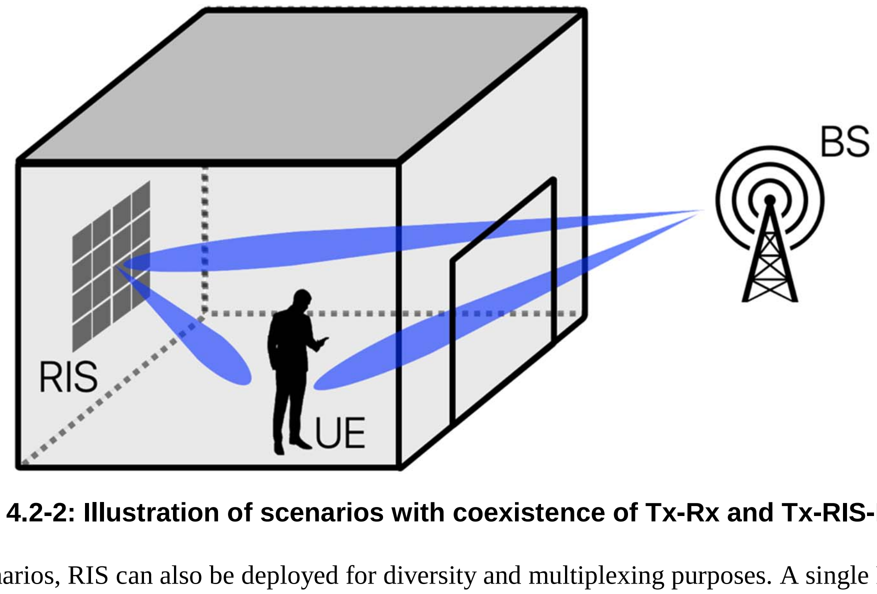


Figure 4.2-2: Illustration of scenarios with coexistence of Tx-Rx and Tx-RIS-Rx paths

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.

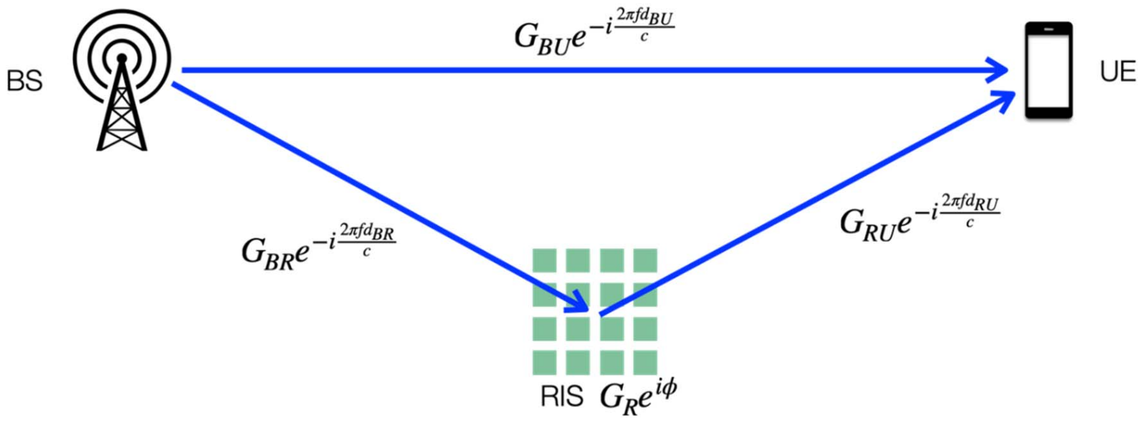
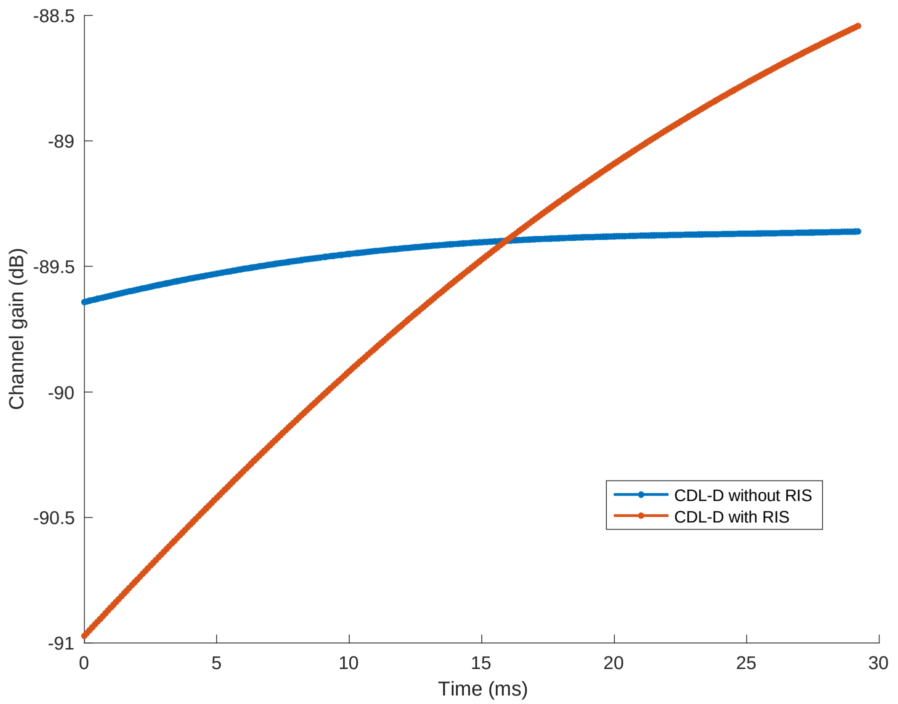


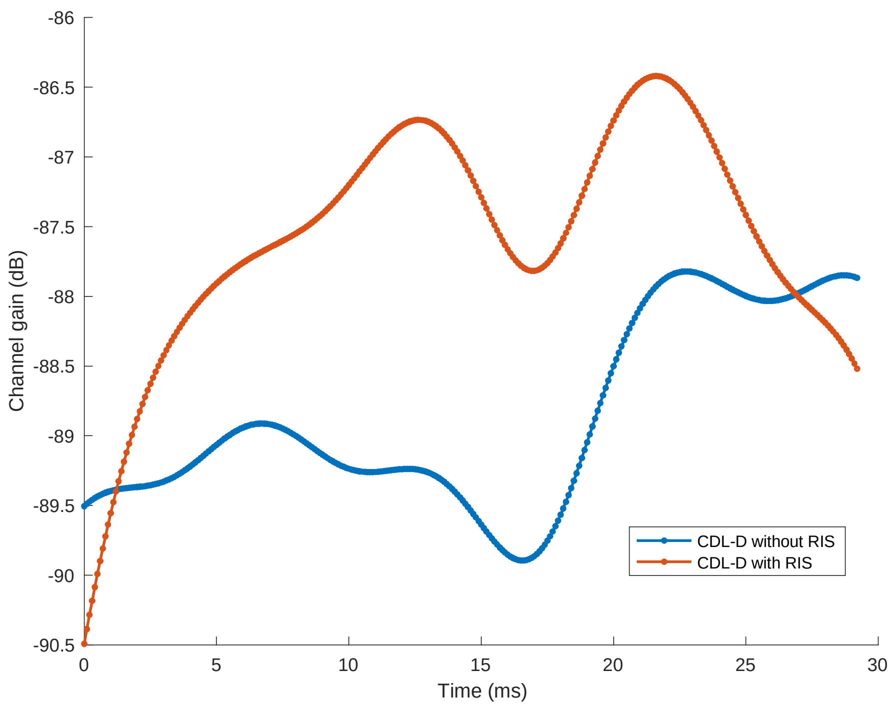
Figure 5.1.3-1: Dependence of RIS-aided channel on path lengths, which leads to time-varying channel when UE is mobile

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.



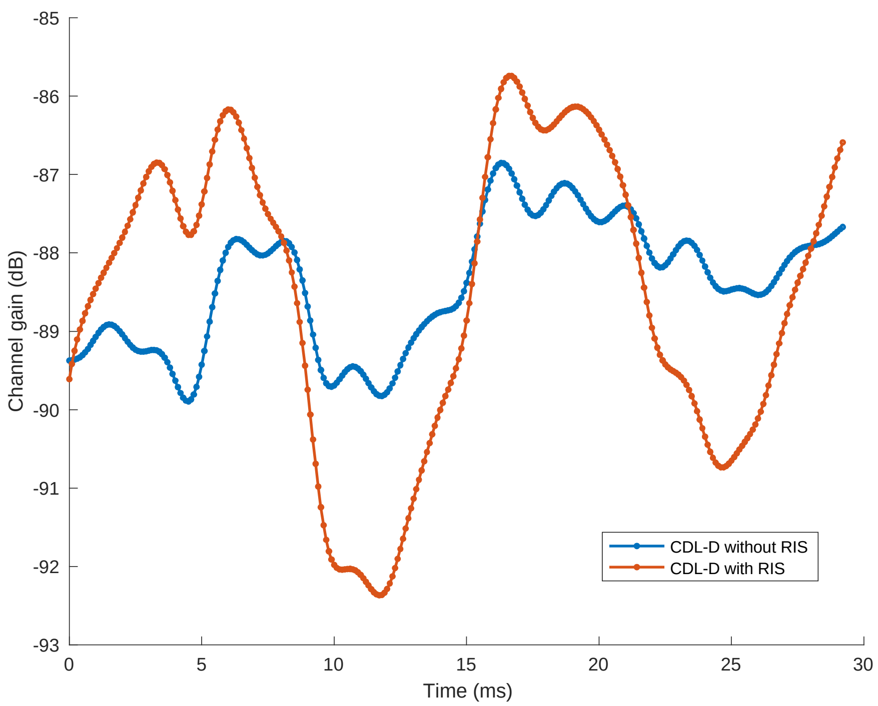
NOTE: The UE speed is assumed to be 3 km/h.

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



NOTE: The UE speed is assumed to be 30 km/h.

Figure 5.1.3-3: Illustration of time-varying channel with / without RIS caused by Doppler effect and path length change



NOTE: The UE speed is assumed to be 100 km/h.

Figure 5.1.3-4: Illustration of time-varying channel with / without RIS caused by Doppler effect and path length change

It is clear from figures 5.1.3-2 to 5.1.3-4 that the time selectivity of channel with RIS is more significant than the channel without RIS, since the gain of RIS path can be much closer to the gain of the main BS-UE path compared to those via scattering clusters. The channel also changes much faster when the UE speed increases in the three figures.

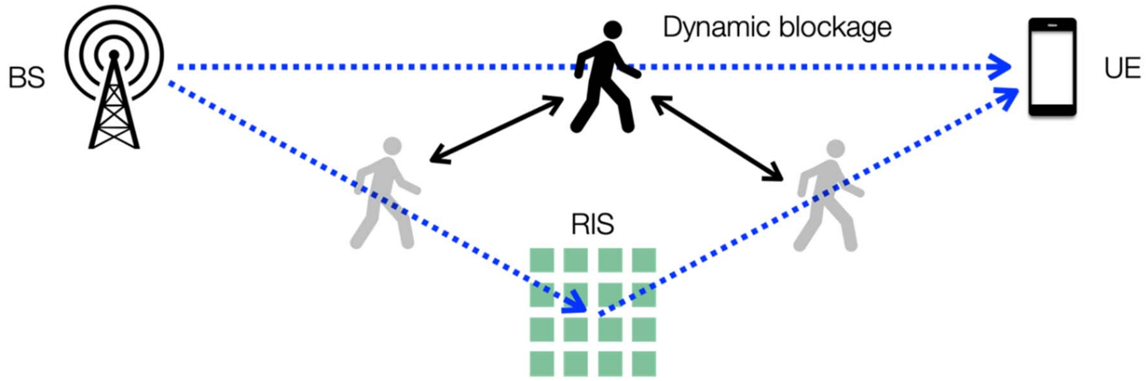
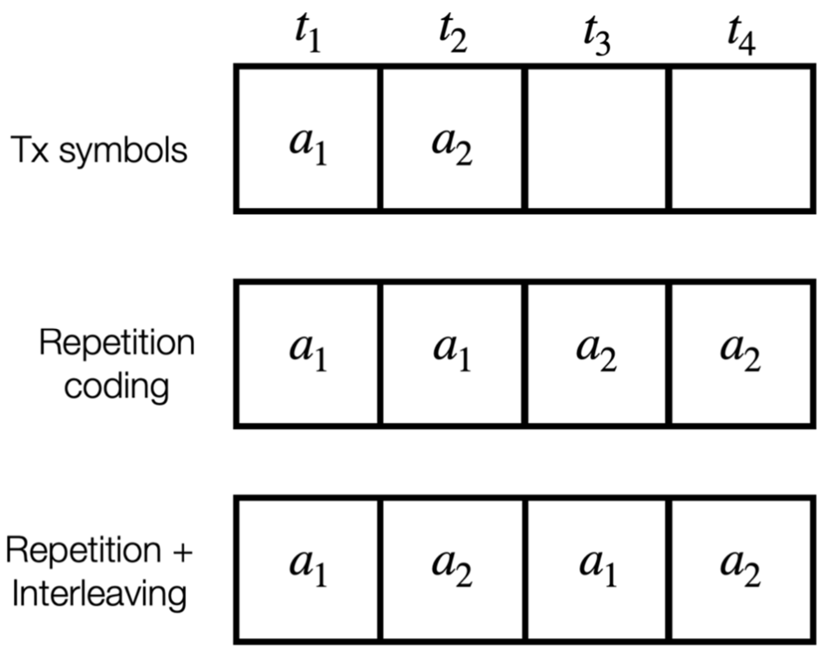


Figure 5.1.3-5: Time-varying channel caused by dynamic blockage

RIS-aided channel can also be time-varying when blockage status dynamically changes, as is shown in figure 5.1.3-5. Although RIS can provide an alternative path for the link and reduce the probability of complete outage, the SNR of the link can still change significantly when a blocker appears / disappears. Time diversity schemes can also be enabled in this scenario to further improve the robustness of communication.

5.1.4 Diversity scheme design

Conventional time diversity schemes, based on the combination of adding redundancy via coding and interleaving, can be applied to RIS-aided systems. Tx can repeat or encode the information bits, and interleave the coded bits in the time domain before transmission, as is shown in figure 5.1.4-1. When the number of diversity branch is sufficiently large, all information bits experience similar channel gains regardless of mobility / dynamic blockage, which alleviates burst errors and improves link robustness. Such time diversity schemes can be applied to counter the time-varying channel caused by both mobility and blockage.



NOTE: Coding schemes other than repetition can also exploit time diversity in RIS-aided communication systems.

Figure 5.1.4-1: Example time diversity schemes that can be used by Tx

When mobility results in the time-varying channel, a new diversity scheme can be enabled by RIS to replace the interleaving function at Tx and cooperate with Tx coding schemes to further enhance the robustness of communication. As is illustrated in figure 5.1.3-1, the fast fading mainly results from the phase difference between BS-UE path and BS-RIS-UE path. Interleaving takes advantage of phase difference changes over time and allows adjacent coded bits to be transmitted with different channel conditions. RIS, however, can adapt its phase ϕ actively (e.g. randomly) to change channel conditions faster so that adjacent coded bits do not need to be transmitted after the channel evolves. This function of RIS can be enabled together with coding schemes at Tx to better enhance the time diversity of the transmission.

In addition, if the transmission happens on a very narrow band, RIS can also adapt it phase so that the waveforms via both BS-UE channel and BS-RIS-UE channel can always be constructively combined at Rx. This method requires BS / RIS to have the knowledge of locations and UE mobility in order to compensate for the phase difference caused by path length difference and Doppler effect.

5.1.5 Impact on transmitter and receiver complexity

Applying time diversity schemes for RIS-aided communication systems can effectively reduce error bursts and simplify the error correction on Rx side. When RIS is used to implement time diversity methods, Tx complexity can be reduced, since coding and interleaving functions can be simplified. If RIS is able to adapt its phase by tracking the movement of UE, both BS-UE and BS-RIS-UE transmissions will always combine constructively, and time diversity schemes at Tx can be minimally enabled.

5.2 Frequency Diversity

5.2.0 Frequency Diversity schemes

Multipath effect is very common in wireless communications, causing signals on different carrier frequencies to experience selective fading conditions. Frequency diversity schemes are usually designed for robust communication with such frequency selective channel conditions. RIS-aided communication has inherent frequency selectivity, i.e. the frequency domain channel is not flat even if both paths with / without RIS have frequency-flat channels, and the frequency selectivity is more significant than multipath channels due to the high re-radiation gain. Therefore, frequency diversity schemes, e.g. coding / frequency hopping, can also be applied to RIS-aided communication systems to enhance the performance. Such frequency diversity schemes are mostly applied on Tx side. However, by cooperating with traditional Tx diversity schemes, RIS can also dynamically adapt the channel to further improve the frequency diversity.

5.2.1 Requirements for RIS hardware

Basic RIS needs to be fabricated and configured to re-radiate signals from Tx to Rx. Besides, to dynamically adapt the channel and further improve frequency diversity, RIS elements can be designed to modulate the incident signals and shift the frequency of incident waveforms (e.g. as is demonstrated in [i.4]), which requires RIS to be able to change their phases with a high frequency and short delay.

A basic architecture of RIS supporting frequency-shifting is demonstrated in figure 5.2.1-1. At each RIS element, the incident signal is re-radiated after traveling through a time-varying phase shifter $e^{j\delta}g(t)$. The term $e^{j\delta}$ corresponds to the beamforming capability of RIS, while $g(t)$ shifts the frequency of incident signals. The simplest realization of $g(t)$ can be a square wave, implying that the phase shift at this element oscillates between δ and $-\delta$. In this case, the RIS does not need any active signal processing components to shift the carriers and can operate in a relatively passive manner. Advanced options for $g(t)$ include, e.g. sinusoidal waves.

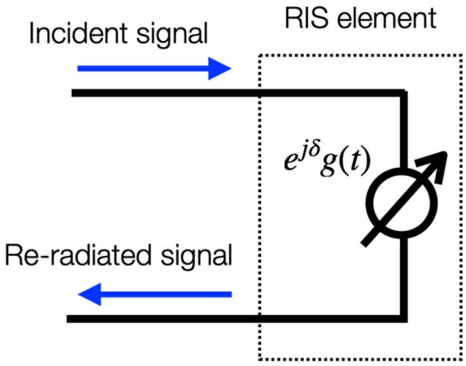


Figure 5.2.1-1: General architecture of RIS element supporting frequency-shifting

5.2.2 Requirements for RIS operating mode

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

5.2.3 Characteristics of RIS-aided channels

Frequency selectivity is an inherent property of RIS-aided communication. As is demonstrated in clause 5.1.3, when BS-UE, BS-RIS and RIS-UE channels are all LOS, the gain of the composite channel from Tx to Rx aided by RIS still depends on constructive / destructive superposition of BS-UE and BS-RIS-UE channels. The phase difference between the BS-UE path and BS-RIS-UE path is $\frac{-2\pi f(d_{BR}+d_{RU}-d_{BU})}{c}+\phi$, which changes with respect to the subcarrier frequency f and determines the frequency selectivity of RIS-aided channels. When multipath effect is considered, the frequency selectivity of a RIS-aided channel is generally more significant than that of a channel without RIS, as the RIS provides a much larger re-radiation gain compared to ordinary clusters. Figure 5.2.3-1 illustrates the simulated frequency-domain channel with / without RIS given simulation setups in table 5.2.3-1. 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 BS-RIS-UE fading channel with LOS paths (note that the composite BS-RIS-UE path is modelled as a single CDL-D channel without losing generality). In these simulations 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. It is clear in figure 5.2.3-1 that the frequency selectivity of RIS-aided channel is indeed more significant than that without RIS.

Table 5.2.3-1: Simulation Assumptions

Simulation parameters	Values / setups
BS-UE distance (m)	About 40
BS-RIS distance (m)	About 20
Carrier frequency (GHz)	4
BS-UE Path loss model	UMi NLOS model
BS-RIS / RIS-UE path loss model	UMi LOS model
BS antenna	1 omni-directional antenna
UE antenna	1 omni-directional antenna
RIS	576 omni-directional elements
Fading channel model	CDL-D
Delay spread (ns)	100
Tx power (dBm)	23
Noise density (dBm / Hz)	-167 (including noise figure)
Bandwidth (MHz)	100

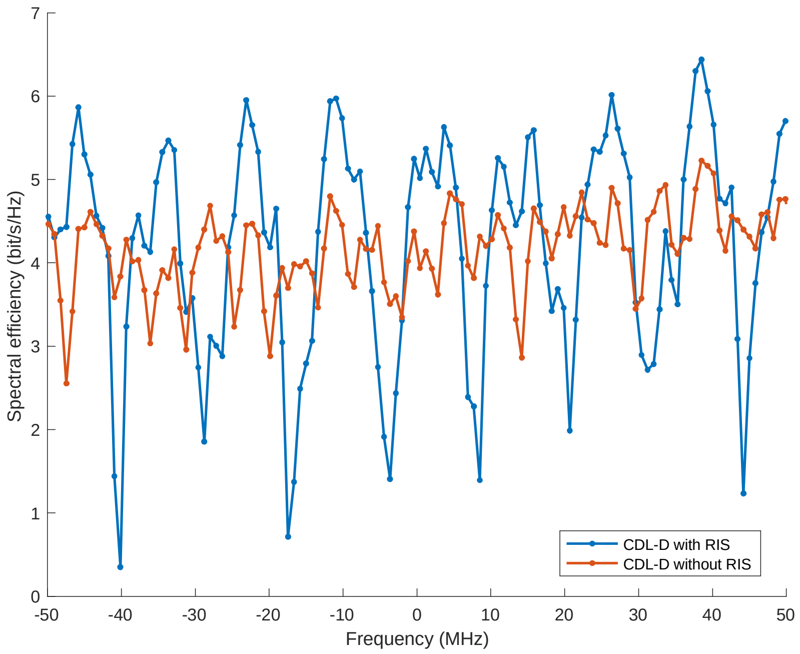


Figure 5.2.3-1: Illustration of spectral efficiency of frequency selective channel with / without RIS considering multipath effect

The frequency selectivity of RIS-aided channel can partially cancel the potential performance gain or result in performance degradation in some scenarios. E.g. even though the SNR of BS-RIS-UE path is comparable to the SNR of BS-UE path in figure 5.2.3-1, the mean spectral efficiency gain of the composite channel is only about 0,055 bit/s/Hz. As the communication may suffer from deep fading in some subcarriers, the power gain contributed by the RIS cannot be fully converted to throughput improvement. Frequency diversity schemes are hence necessary to be applied on Tx or RIS side to maximize the benefit of RIS-aided communication.

5.2.4 Diversity scheme design

Conventional frequency diversity schemes can generally be applied to RIS-aided systems to mitigate the impact of frequency selectivity. E.g. Tx can repeat / encode the information bits with redundancy, and interleave the coded bits on different OFDM subcarriers (also applicable to other waveforms in frequency domain) before transmission. When the number of diversity branch is sufficiently large, all information bits experience similar channel gains regardless of deep fading. In addition, traditional spread spectrum technologies such as frequency hopping can also be used to prevent the communication from experiencing continuous deep fading.

When multiple antennae are available, joint space frequency diversity schemes can be implemented to mitigate the frequency selectivity effect, as is demonstrated in the following simple analysis. For a RIS-aided link between a pair of BS and UE, it can be assumed that the LOS channels of BS-UE path and BS-RIS-UE path are represented by h_1 and $h_2 e^{i\theta(f)}$, respectively. Here $\theta(f)$ represents the frequency-dependent phase difference between two paths. Then the composite channel can be represented by $h_1 + h_2 e^{i\theta(f)}$, and the corresponding channel capacity can be calculated using Shannon's equation:

$$C(f) = \log_2(1 + \left|h_1 + h_2 e^{i\theta(f)}\right|^2) = \log_2(1 + |h_1|^2 + |h_2|^2 + 2Re\{h_1 \overline{h_2 e^{\iota\theta(f)}}\}) \quad (2)$$

On the other hand, when h_1 and h_2 are locally flat, utilizing space frequency diversity schemes allow for a channel capacity as follows:

$$C_{div}(f) = \log_2(1 + |h_1|^2 + |h_2|^2) \quad (3)$$

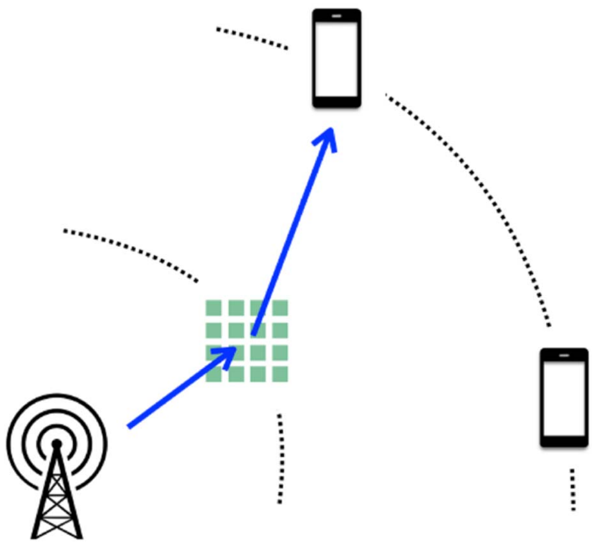
When the band width is large enough, the mean value of $Re\{h_1 \overline{h_2 e^{\iota\theta(f)}}\}$ over the band is approximately 0. Therefore, according to Jensen's inequality:

$$Mean\{C(f)\} \leq= \log_2(1 + Mean\{|h_1|^2 + |h_2|^2 + 2Re\{h_1 \overline{h_2 e^{\iota\theta(f)}}\}\}) \approx C_{div}(f) \quad (4)$$

Therefore, even though such diversity schemes cannot enhance the average SNR, the channel capacity can still be improved when the channel is frequency selective.

Apart from traditional frequency diversity schemes that are implemented by Tx, RIS can also enable frequency diversity schemes to improve the channel. E.g. by changing the RIS phase ϕ (e.g. randomly) in figure 5.1.3-1, RIS can change the channel conditions on different subcarriers, which has a similar function to interleaving and can jointly work with coding schemes to enhance the frequency diversity. In addition, RIS can also be fabricated to modulate the incident waves and shift the carrier frequency of incident waveforms, which can enable space frequency block coding schemes to improve the communication.

Besides, although such frequency selectivity can be harmful for a single link, multi-user scheduling can benefit from this phenomenon. The BS can allocate a subcarrier to another user if one user suffers from deep fading at this subcarrier. Figure 5.2.4-1 evaluates a system composed of 1 BS and different numbers of UEs, each UE aided by a RIS. The simulation setup is generally the same as shown in table 5.2.3-1. All UEs are assumed to have similar distances to the BS to reduce the impact of path loss in scheduling, while RIS are also assumed to have similar distances to BS. Note that different UEs can be served by either different or the same RIS. Direct BS-UE paths are assumed to have NLOS path loss, while BS-RIS-UE paths have LOS path loss. Either BS or each UE is assumed to have a single isotropic antenna. The RIS size is assumed to be 24 × 24, which is approximately 0,9 m × 0,9 m. The carrier frequency is set to 4 GHz. BS allocates each subcarrier in a 100 MHz band separately to the UE with better channel conditions. The spectral efficiency gain of RIS-aided communication in percentage is shown in figure 5.2.4-2.



NOTE: 1 BS serves multiple UEs with similar distances (around 40 m) via frequency multiplexing. Each UE's link is aided by a RIS. Different UEs can use either different or the same RIS. The distances between different RIS and BS are also similar (around 20 m).

Figure 5.2.4-1: Illustration of multi-user system aided by RIS

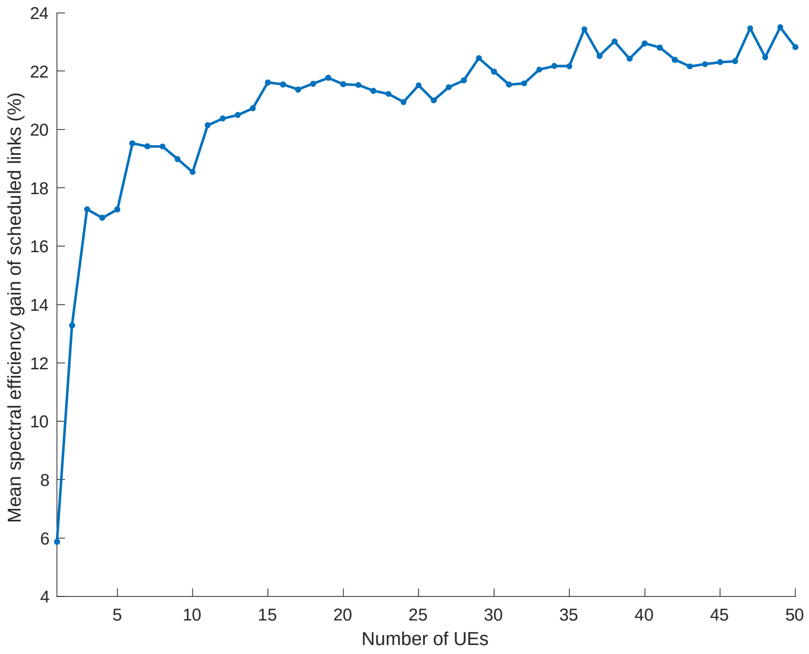


Figure 5.2.4-2: Illustration of mean spectral efficiency gain in percentage with respect to the number of UEs served by the BS

As is shown in the simulation, the spectral efficiency on each subcarrier is always better with RIS when there are enough UEs. Frequency selectivity demonstrated in figure 5.2.3-1 benefits the system performance instead. Besides, it has also been shown that the mean spectral efficiency increases with the number of UEs both with and without RIS. The improvement of spectral efficiency brought by RIS also increases with the number UEs in the system. In single-user scenario, such improvement is only about 0,28 bit/s/Hz, whereas around 1 bit/s/Hz improvement can be expected when there are at least 5 UEs in the system. As is shown in figure 5.2.4-2, in single-user scenario, the gain is only about 5,9 %, while the gain reaches 17,3% when there are at least 5 UEs in the system.

5.2.5 Impact on transmitter and receiver complexity

Applying frequency diversity schemes for RIS-aided communication systems can effectively enhance the minimal SNR of signals on Rx side and simplify the error correction accordingly. When RIS is used to implement frequency diversity methods, including frequency shifting or dynamic phase tuning, the interleaving function at Tx can be partially / completely replaced by RIS as elaborated in clause 5.2.4, resulting in a reduction of Tx complexity. Besides, although Tx still needs to encode the information bits, the coding rate used in each code block can be increased due to the improved minimal SNR, which can lead to reduced computational complexity for encoding the same amount of data.

5.3 Tx and Rx Antenna Diversity

5.3.0 Tx and Rx Antenna Diversity schemes

Antenna diversity has been viewed as one of the most important technologies in current wireless communication systems for quality and reliability enhancement. The diverse channel conditions associated with different Tx / Rx antenna elements allow Tx / Rx to mitigate potential channel impairment, such as deep fading and blockage, by antenna switching / selection / combining, etc. Such channel diversity can also impact RIS-aided communication, and as an antenna array system, a RIS can also be used to enable antenna diversity schemes to further enhance the communication performance.

5.3.1 Requirements for RIS hardware

RIS needs to be fabricated and configured to re-radiate signals from Tx to Rx, which usually involves a beamforming capability that combines the re-radiation via all RIS elements. Besides, to enable antenna diversity schemes such as antenna switching / selection based on RIS array elements, the RIS should be able to activate / deactivate a subset of its re-radiating elements given its own channel estimation or external signalling. The near-field effect of RIS can only be exploited for antenna diversity when the size of RIS is sufficiently large.

5.3.2 Requirements for RIS operating mode

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

5.3.3 Characteristics of RIS-aided channels

The diversity of channel conditions at Tx / Rx antenna elements has been numerically evaluated in RIS-aided communication. As is shown in a general RIS-aided wireless link in figure 5.1.3-1 in clause 5.1.3, the composite channel between Tx and Rx is usually a superposition of the direct path and the RIS path. Due to the difference of antenna locations and the path lengths, such channel superposition can exhibit spatial selectivity as is illustrated in preliminary evaluations. Figures 5.3.3-1 and 5.3.3-2 show the simulated composite channel of a direct BS-UE path and BS-RIS-UE path at each BS / UE element with / without RIS given simulation setups in table 5.3.3-1. The channel of the direct path between BS and UE uses the CDL-E fading channel model defined in ETSI TR 138 901 [i.3] and a free-space path loss model. On the other hand, the BS-RIS-UE path only considers the free-space path loss without fading effects.

Figure 5.3.3-1 considers the channel SNR from the centre element of UE array to each BS antenna element. It can be observed that the spatial selectivity of the channel is more significant in RIS-aided communication (with an SNR range of more than 10 dB at different antenna elements). A similar spatial selectivity analysis has been conducted for UE antenna array in figure 5.3.3-2. The SNR with RIS can also have more than 10 dB variation at different elements, while the channel SNR without RIS is much less variant. These results demonstrate that the composite channels in RIS-aided communication can be more spatially selective compared to the scenario without RIS.

Table 5.3.3-1: Simulation Assumptions

Simulation parameters	Values / setups
BS-UE distance (m)	60
BS-RIS distance (m)	57,08
RIS-UE distance (m)	4,24
Carrier frequency (GHz)	28
BS antenna	Uniform linear array with 64 omni-directional elements
UE antenna	Uniform linear array with 8 omni-directional elements
RIS	1 600 omni-directional elements
BS-UE channel model	CDL-E multipath channel with free-space path loss
BS-RIS-UE channel model	Free-space path loss model
Delay spread (ns)	100
Tx power (dBm)	23
Noise density (dBm / Hz)	-174
Bandwidth (MHz)	100

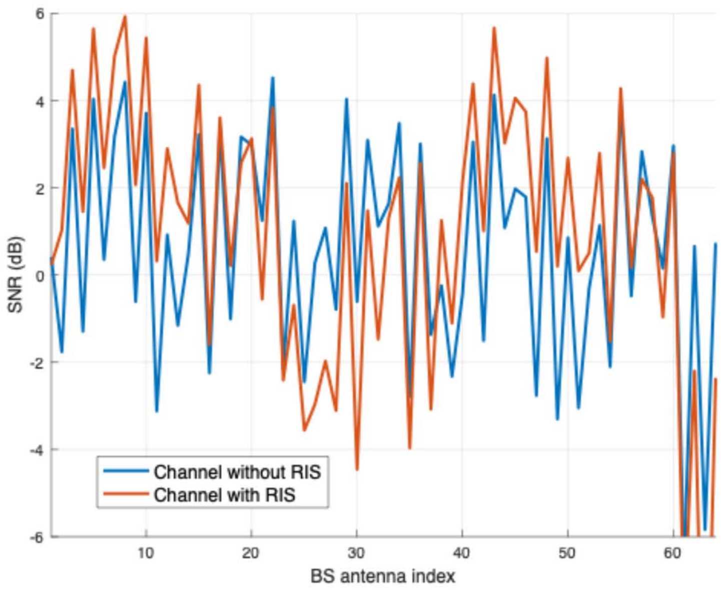


Figure 5.3.3-1: Illustration of SNR of spatial selective channel between each BS antenna element and the centre element of UE antenna array with / without RIS considering multipath effect

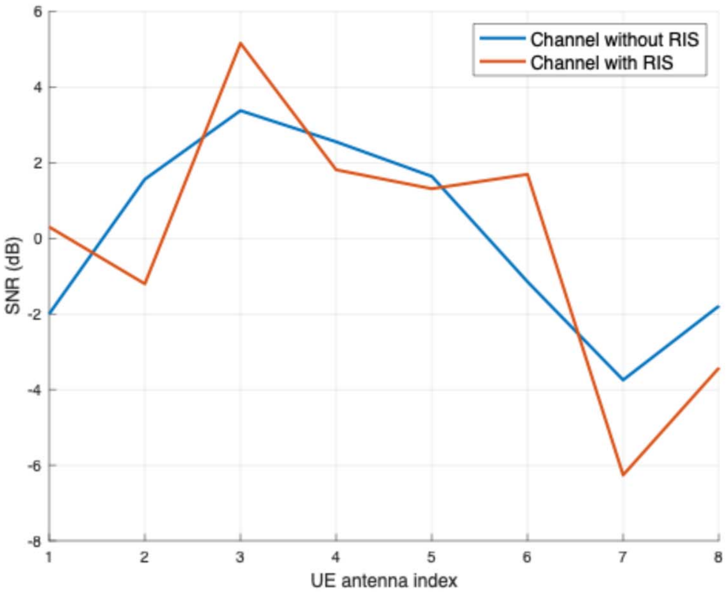


Figure 5.3.3-2: Illustration of SNR of spatial selective channel between each UE antenna element and the centre element of BS antenna array with / without RIS considering multipath effect

The analysis above has assumed far-field communication and planar wave model for both BS-UE path and BS-RIS-UE path. Due to the simple structure and low fabrication cost of RIS, the array size of RIS can be much larger than that of conventional communication devices. In this scenario, the near-field effect of RIS needs to be taken into account, and the spherical wave model is necessary for channel modelling, leading to more significant spatial selectivity of channels between Tx/Rx antenna element pairs.

5.3.4 Diversity scheme design

Conventional Tx / Rx antenna diversity schemes mainly select the best antenna for transmission or combine the signals transmitted / received by different antenna elements. These methods can still be used in RIS-aided communication. In addition, a RIS can also enable similar antenna diversity schemes by either selecting / switching a set of sub-arrays of RIS to aid communication or combining the re-radiation via different subarrays using beamforming. In multi-user scenarios, such diversity schemes can be extended to optimize the allocation of RIS sub-arrays to aid different users simultaneously, exploiting multi-user diversity and improving the utilization of wireless networks.

5.3.5 Impact on transmitter and receiver complexity

As conventional antenna diversity schemes enabled at Tx / Rx can also be used in RIS-aided communication, the required complexity of Tx / Rx will not increase. Besides, when RIS can implement diversity schemes, Tx / Rx may need much fewer antenna elements and the complexity of Tx and Rx can be significantly reduced.

5.4 Polarization Diversity

5.4.0 Polarization Diversity schemes

Antennae with orthogonal polarizations have been widely applied in wireless communication systems to enhance the diversity. While a single polarized antenna cannot guarantee the detection of signals with random polarizations, dual polarized antenna can detect any polarized incoming signals. The channels between different polarizations are generally uncorrelated in a rich-multipath channel, allowing diversity schemes to enhance the reliability of communication. However, in suburban areas with fewer multipaths, such diversity gain could degrade significantly. RIS can provide additional paths between Tx and Rx and can hence minimize the degradation. Besides, as is discussed in ETSI GR RIS 003 [i.2], RIS can also have dual polarized unit-cell elements and manipulate the channels between polarizations given the desired channel properties to enable high throughput / diversity gains.

5.4.1 Requirements for RIS hardware

Basic RIS needs to be fabricated and configured to re-radiate signals from Tx to Rx with orthogonal polarizations, i.e. RIS needs to have dual polarized unit-cell elements. Besides, RIS elements can also be designed to manipulate the polarization of incident waveforms and re-radiation channels in order to support advanced polarization diversity schemes. Such a design requires different polarizations (H / V) of RIS unit-cells to be controlled (or even connected and controlled) using different switches / diodes etc.

5.4.2 Requirements for RIS operating mode

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

5.4.3 Characteristics of RIS-aided channels

When BS, UE, and RIS are all equipped with dual polarized unit-cell elements, the MIMO channel between both polarizations of BS and UE can be represented by $C = C_{RU}(H_p + H_{ps})C_{BR}$, where C_{BR} represents the cross-polarization matrix between BS and RIS; C_{RU} represents the cross-polarization matrix between RIS and UE; H_p represents the transformation of polarization at RIS, which can be dynamically configured given the corresponding RIS capabilities. When polarizations of RIS elements are not connected, H_p is a diagonal matrix; otherwise H_p can be any matrix with normalized rows. Besides, according to [i.5], H_{ps} is the contribution of spontaneous re-radiation from RIS elements, which can only be managed through hardware design. This channel model depicts the BS-RIS-UE path, and the corresponding channel capacity depends on the singular values of C.

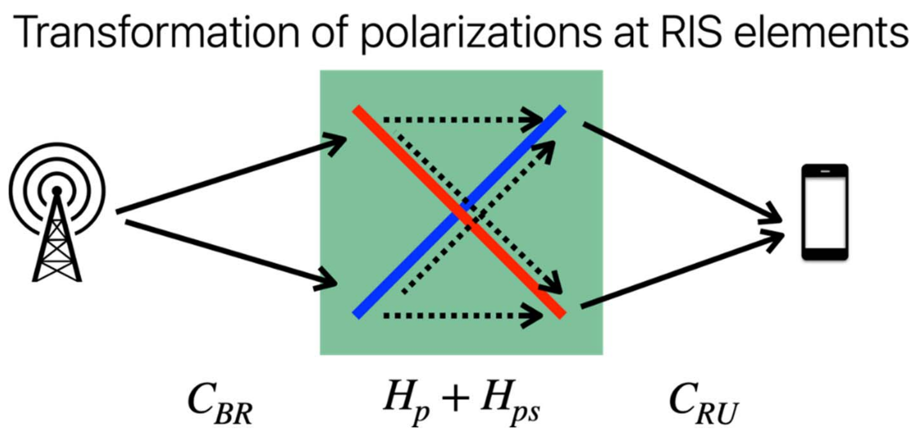


Figure 5.4.3-1: Illustration of polarized channel model in RIS-aided MIMO

5.4.4 Diversity Scheme Design

Conventional Tx polarization diversity schemes can still be used in RIS-aided communications to enhance the reliability, e.g. transmitting the same data on both polarizations. In a rich-multipath environment, channels between different polarizations can be highly uncorrelated, leading to reduced outage probability when there is deep fading on one polarized channel.

When RIS has the capability of polarization manipulating, such diversity schemes can be enabled / enhanced by RIS. According to the channel equation in clause 5.4.3, the MIMO throughput of each polarized channel is:

$$S_i = \log_2(1 + \frac{P_i \sigma_i^2}{N}) \quad (5)$$

Where P_i is the Tx power allocated using the water-filling algorithm, σ_i is the singular value of C, and N is the noise power. The throughput substantially depends on the singular values of the channel, which can be optimized by tuning H_p. E.g. when outage is not desired on either polarized channel, the minimum capacity of both polarized channels can be significantly improved by about 1,5 times in conducted simulations by carefully selecting H_p to reduce the difference between singular values. Similarly, the sum throughput can also be a little improved when H_p is carefully selected.

In addition, RIS can enable polarization diversity jointly with time diversity by dynamically configure its transformation matrix H_p so that Rx gets data on different polarizations in different slots. This scheme can jointly work with coding schemes to enhance both time and polarization diversities.

5.5 Spatial Diversity

5.5.1 Requirements for RIS hardware

A RIS needs to be fabricated and configured to re-radiate signals from Tx to Rx to support general spatial diversity schemes. To enable RIS-aided Space-Frequency Block Coding (SFBC), the RIS needs to have the capability of frequency manipulation as is explained in clause 5.2.1, which utilizes a time-varying driving function to control the RIS re-radiation coefficients. One preferred driving function for RIS units to support RIS-aided SFBC is the sine wave. A RIS controller can be optionally used to get configurations from Tx / Rx if the SFBC scheme needs to be customized.

To enable RIS-aided Space-Time Block Coding (STBC), the RIS needs to be equipped with digital circuits to receive and buffer symbols sent by Tx. Depending on the detailed STBC scheme, RIS may need to estimate the phase of received symbols. In re-radiation, RIS needs to modulate the received symbols, and also needs to re-radiate signals either with or without short delays (e.g. re-radiate the last received symbol instead of the current one). To coordinate the re-radiation of RIS with the transmission at Tx, a RIS controller is necessary to get configurations from Tx. Depending on the detailed STBC scheme, the RIS controller may need to establish a data channel from Tx so that RIS can modulate received symbols as Tx requires.

5.5.2 Requirements for RIS operating mode

RIS should be able to work in reflection / refraction mode to re-radiate signals from Tx to Rx. Besides, to enable RIS-aided STBC that may involve delaying / changing the order of received symbols, RIS also needs to work in receiving mode as is defined in ETSI GR RIS 001 [i.1].

5.5.3 Diversity scheme design

5.5.3.1 RIS-Aided Space-Frequency Block Coding (SFBC)

Traditional SFBC coding schemes such as Alamouti coding requires repetitions of multiple symbols to be transmitted via different channels, while different repetition of the same symbol needs to use different time / frequency resources. Therefore, SFBC can be enabled by adding a RIS path when the direct path between Tx and Rx is available. In addition, when RIS has the capability of frequency manipulation as is described in clauses 5.2.1 and 5.5.1, SFBC can be supported even if Tx does not have such capability.

A brief introduction of RIS-aided SFBC strategy is shown in the following example. It is assumed that Tx sends two symbols, a_1 and a_2, to Rx using two subcarriers f_1 and f_2, as is shown in figure 5.5.3.1-1. A RIS with frequency manipulation capability is used to aid the link, applying a universal time-varying coefficient $R(t) = A\,cos(2\pi\Delta f t + \psi)$ to all RIS elements before applying beamforming coefficients [i.6]. Rx receives these two symbols on corresponding subcarriers via both Tx-Rx path and Tx-RIS-Rx path. The Tx-Rx, Tx-RIS, and RIS-Rx channels are $h_0(f)$, $h_T(f)$, and $h_R(f)$, respectively. The beamforming amplitude gain of RIS is assumed to be G.

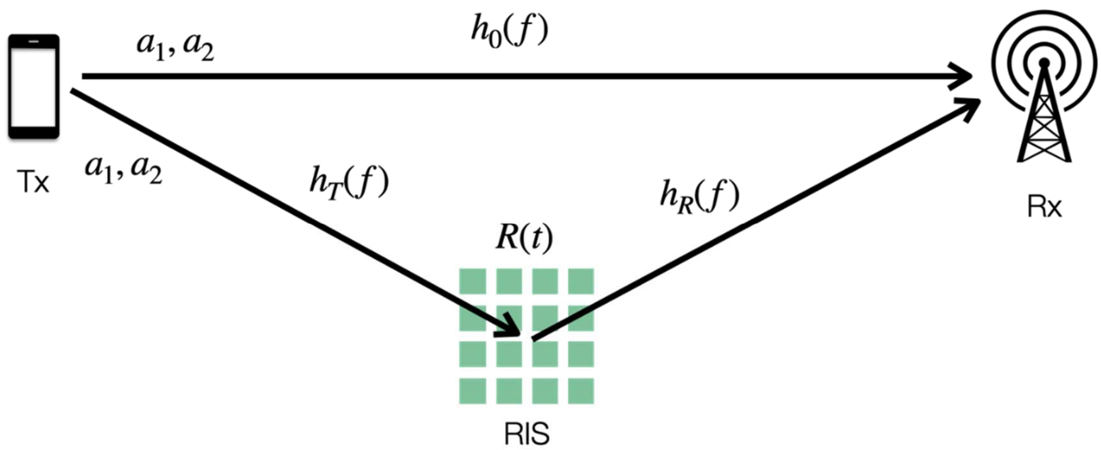


Figure 5.5.3.1-1: SFBC aided by RIS with frequency manipulation capability

When the incident wave carrying symbol a_1 is $s_1 = a_1 e^{j2\pi f_1 t}$, the re-radiated waveform becomes the following:

$$s_1^R = a_1 e^{j2\pi f_1 t}\mathrm{R}(t) = \frac{A}{2} a_1 e^{-j\psi} e^{j2\pi(f_1-\Delta f)t} + \frac{A}{2} a_1 e^{j\psi} e^{j2\pi(f_1+\Delta f)t} \quad (6)$$

Therefore, after re-radiation, the transmitted symbol a_1 on subcarrier f_1 has been migrated to two new subcarriers: $f_1 - \Delta f$ and $f_1 + \Delta f$. The migrated symbols now have their amplitudes scaled and phase rotations of $\pm\psi$. When any real modulation (e.g. BPSK, ASK, PAM, etc.) has been applied to transmitted symbols and $\psi = -\frac{\pi}{2}$, the re-radiated symbols on subcarriers $f_1 - \Delta f$ and $f_1 + \Delta f$ are $-a_1^* e^{j\psi}$ and $a_1^* e^{j\psi}$, respectively, where a_1^* denotes the conjugate of a_1. Similarly, the symbol a_2 will also be migrated to $f_2 - \Delta f$ and $f_2 + \Delta f$ accordingly. If RIS is configured such that $\Delta f = |f_2 - f_1|$, then Rx receives the symbols on different subcarriers as is shown in figure 5.5.3.1-2.

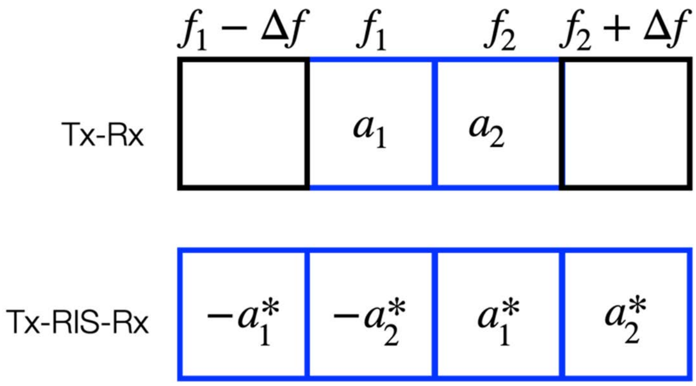


Figure 5.5.3.1-2: Received symbols at Rx side on different subcarriers via different paths

The received signals on the subcarriers f_1 and f_2 in figure 5.5.3.1-2 form an Alamouti coding block and can be jointly decoded using the Alamouti decoding scheme. When f_1 and f_2 are adjacent subcarriers and channels are locally flat, the channel gain of each symbol can be shown to be $|h_0|^2 + 0{,}25A^2|Gh_T h_R|^2$. When received signals on subcarriers $f_1 - \Delta f$ and $f_2 + \Delta f$ are also used for joint decoding, the channel gain is $|h_0|^2 + 0{,}5A^2|Gh_T h_R|^2$.

The proposed RIS-aided SFBC scheme can improve the reliability of communication, especially for UL transmissions which are usually power limited rather than resource limited. The same RIS configuration can be used to serve multiple UEs in the same beam coverage simultaneously. Besides, RIS can be easily configured for this scheme and the required control information for RIS is very limited. One limitation of the proposed scheme is that it requires more advanced Rx processing compared to communications without SFBC coding. Also, the performance of SFBC may degrade when the channel estimation is not accurate at Rx side or when the channel is highly frequency-selective (i.e. even the channels of adjacent subcarriers are significantly different) [i.7].

5.5.3.2 RIS-Aided Space-Time Block Coding (STBC)

When RIS could buffer symbols in the incident waves, STBC can be enabled without corresponding Tx capability. Such RIS can receive a symbol, estimate its phase, and re-radiate a modulated symbol after a very short delay, as is specified in clause 5.5.1. A proposed RIS-aided STBC method is demonstrated in figure 5.5.3.2-1. It is assumed that Tx sends two symbols s_1 and s_2 to RIS and Rx in three symbol durations t_1, t_2, and t_3. The Tx-Rx, Tx-RIS, and RIS-Rx channels are assumed to be h_0, g_1', and h_1'. Then the transmission and re-radiation strategy in table 5.5.3.2-1 enables RIS-aided STBC.

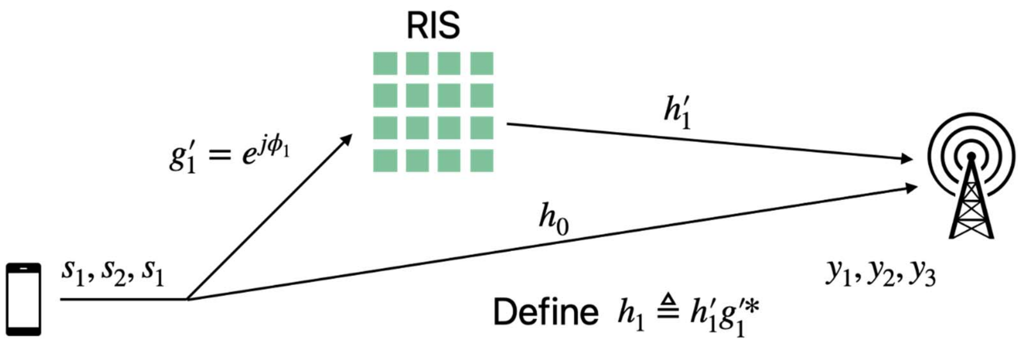


Figure 5.5.3.2-1: RIS-aided STBC

Table 5.5.3.2-1: Tx and Rx symbols in RIS-aided STBC method

Time	UE (Tx)	RIS		BS (Rx)
	Tx	Rx	Tx	Rx
t_1	s_1	$g_1' s_1$	$g_1' s_1$	$y_1 = (h_1' g_1' + h_0) s_1 + n_1$
t_2	s_2	$g_1' s_2$	$e^{-j2\psi_1} g_1' s_1$	$y_2 = h_0 s_2 + h_1' e^{-j2\psi_1}(g_1' s_1) + n_2 = h_0 s_2 + h_1 s_1^* + n_2$
t_3	s_1	$g_1' s_1$	$e^{j(\pi-2\psi_2)} g_1' s_2$	$y_3 = h_0 s_1 + h_1' e^{j(\pi-2\psi_2)}(g_1' s_2) + n_3 = h_0 s_1 - h_1 s_2^* + n_3$

At time t_1, Tx transmits s_1 to RIS and Rx. RIS re-radiates the symbol without any further modulation and buffers the symbol at the same time. At time t_2, Tx transmits s_2 to RIS and Rx. Although RIS receives s_2 at this moment, it re-radiates the buffered symbol containing s_1 with a phase modulation $-2\psi_1$, where ψ_1 is the phase of $g_1' s_1$ estimated by the RIS. Then the received signal at Rx side is $y_2 = h_0 s_2 + h_1 s_1^* + n_2$. At time t_3, Tx retransmits s_1 to RIS and Rx. Although RIS receives s_1 at this moment, it re-radiates the buffered symbol containing s_2 with a phase modulation $\pi - 2\psi_2$, where ψ_2 is the phase of $g_1' s_2$. Then the received signal at Rx side is $y_3 = h_0 s_1 - h_1 s_2^* + n_3$. It can be observed that y_2 and y_3 form a Alamouti coding block and can be decoded jointly. The SNR can be further improved if y_1 is also considered in joint decoding.

The proposed RIS-aided STBC can also be applied to scenarios with multiple RIS using modified symbol transmission / re-radiation schemes. In addition, the phase modulation ψ_1 and ψ_2 can also be the phase of s_1 and s_2 provided by Tx via a control link, when modified symbol transmission / re-radiation schemes are used and different RIS capabilities are supported as mentioned in clause 5.5.1. One limitation of STBC is that the performance can degrade with high Doppler in high-mobility scenarios [i.8].

5.5.4 Impact on transmitter and receiver complexity

Applying spatial diversity schemes such as RIS-aided SFBC / STBC can effectively enhance the SNR of signals on Rx side with mitigated fading effects, simplifying the error correction accordingly. Compared to other diversity schemes that require Tx coding / interleaving, RIS-aided SFBC / STBC only requires the minimal transmission capability of Tx and relies on RIS to enable the diversity schemes. Therefore, such diversity schemes are very suitable in scenarios where a small number of RIS aids the UL transmission from a large number of reduced capability devices for, e.g. sensor data collection. Control information for the configuration of such diversity schemes, especially RIS-aided SFBC, can be very simple, which further reduces the required complexity of Tx hardware. For Rx, however, the complexity can be minorly increased since more advanced processing capability is necessary for STBC / SFBC decoding.

5.6 Diversity Scheme Comparisons

The RIS-aided communication usually suffers from much more significant fading effects compared to conventional links. Therefore, diversity schemes introduced in this clause are mostly designed to enhance the reliability and capacity of RIS-aided communication by mitigating the fading effect and flattening the channel SNR over time / frequency / antenna resources, including coding / interleaving based time / frequency diversity schemes, polarization diversity, antenna switching, etc. Although the overall channel SNR cannot be improved with these methods, the throughput and outage performance can be significantly enhanced by avoiding deep fading in transmission. Some other diversity schemes for RIS-aided communication are not limited to channel flattening and can bring additional gain to communication systems. In clause 5.2.4, it has been shown that RIS-aided communication can achieve higher multi-user diversity gain due to the frequency selectivity.

Most of the introduced diversity schemes, e.g. coding / interleaving, completely or partially rely on Tx to configure its transmission. However, methods like polarization diversity in clause 5.4.4 and RIS-aided SFBC introduced in clause 5.5.3.1 do not require Tx to implement any complicated transmission schemes and only rely on RIS to implement diversity. These methods are most suitable for serving reduced-capability devices such as IoT sensors.

6 Multiplexing schemes for RIS-aided systems

6.1 Space-Division Multiplexing

6.1.1 Space-Division Multiplexing based on Superposition Method and Multi-Tiles RIS

To support space-division multiplexing, the RIS should be able to generate multiple beams simultaneously each in a distinct direction. Different techniques can be used to realize such a RIS. One of the well-known techniques is the superposition method [i.2]. Given a RIS of $M \times N$ elements, the complex reflection coefficient for steering a beam towards k^{th} user can be expressed as:

$$\boldsymbol{\Gamma}_k = \left[\left|\gamma_{m,n}\right| e^{j\angle\gamma_{m,n}}\right]_k \in \mathbb{C}^{M\times N} \tag{7}$$

Subsequently, the required reflection coefficient to serve all users K simultaneously can be obtained by summing these individual reflection coefficients as follows:

$$\boldsymbol{\Gamma} = \frac{1}{K}\sum_{k=1}^{K} e^{j\varphi_k}\boldsymbol{\Gamma}_k = \frac{1}{K}\sum_{k=1}^{K} e^{j\varphi_k}\left[\left|\gamma_{m,n}\right| e^{j\angle\gamma_{m,n}}\right]_k \tag{8}$$

where φ_k is a phase added collectively to the phase set for forming the beam k to form a null or improve the gain in a specific direction.

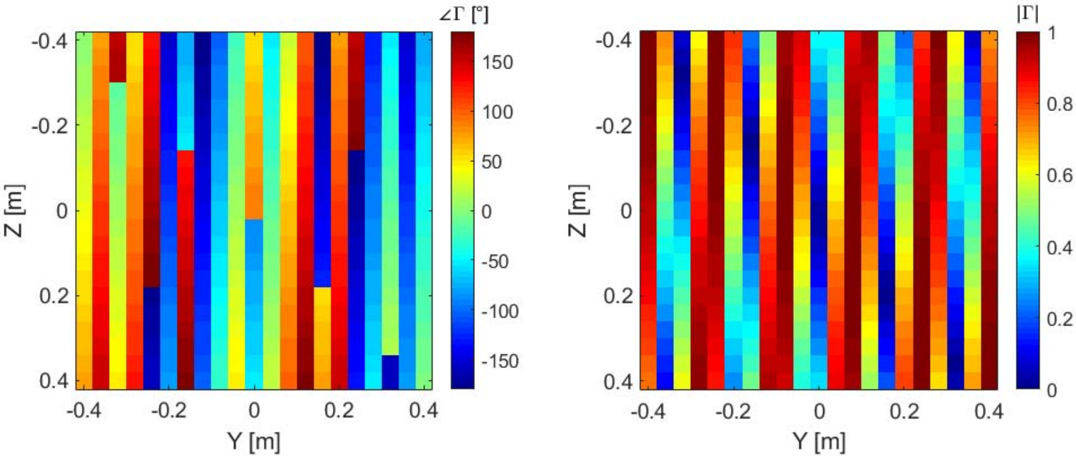
It should be noted that, the term $\frac{1}{K}$ is added because the reflection coefficient magnitude cannot be higher than one. If for every single beam all the RIS elements have unity reflection magnitude, i.e. $\forall\ m, n$: $\left|\gamma_{m,n}\right| = 1$, equation (8) can be reduced to:

$$\boldsymbol{\Gamma} = \frac{1}{K}\sum_{k=1}^{K} e^{j\varphi_k}\left[e^{j\angle\gamma_{m,n}}\right]_k \tag{9}$$

The outcome $\boldsymbol{\Gamma}$ possesses a magnitude different from unity. Therefore, this approach requires controlling both the RIS reflection -phase and -magnitude.

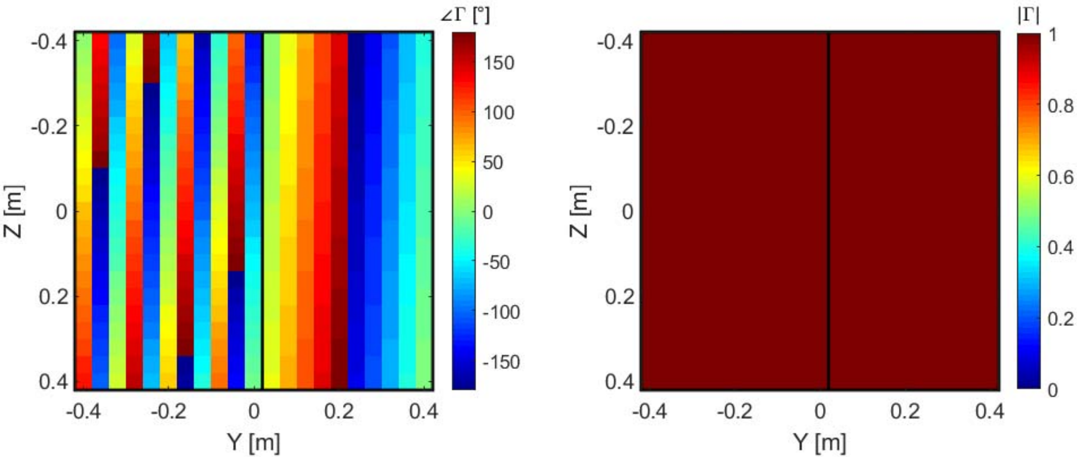
An alternative approach to circumvent the necessity of magnitude control involves employing multi-tiles RISs. This method involves subdividing the RIS into K tiles to simultaneously serve all K users; where every tile is configured to serve a different user. As mentioned, this approach necessitates only adjusting the RIS reflection phase, but the smaller number of RIS elements per tile results in widened beams, compromising spatial efficiency.

To illustrate, consider a scenario where a RIS is employed to serve two users simultaneously. This scenario demonstrates two distinct approaches; superposition method setting $\varphi_k = 0$ and multi-tiles method. Consider a RIS in the YoZ plane and a transmitter (Tx) and receiver (Rx) in the XoY plane. This RIS, of a 21×21 elements, is designed for 3,75 GHz 5G's band with an inter-element distance of half a wavelength. Using spherical coordinate system $(r, \theta, \emptyset)$, the RIS is centred at $(0m, 0°, 0°)$ and the Tx is located at $(40\ m, 90°, -10°)$ and two Rxs are located at respectively $(160\ m, 90°, -30°)$, and $(120\ m, 90°, 0°)$. A DFT-based codebook is used to generate a beam in the direction of every Rx. Figures 6.1.1-1 and 6.1.1-2 show the required RIS reflection coefficient using the superposition and multi-tiles methods respectively. Figures 6.1.1-3, 6.1.1-4 and 6.1.1-5 show respectively obtained 3D, 2D horizontal plane and 2D vertical plane reflection patterns using the two methods. The superposition method achieves a better pattern in the horizontal plane. The Half Power Beamwidth (HPBW) of the two beams is respectively around 5,4° and 4,8° in the superposition method and 11,6° and 10,4° in the multi-tiles method. As mentioned earlier, this is mainly because the superposition method uses all the elements for every user while the multi-tiles method only uses half of the elements for every user. The two methods have similar patterns in the vertical plane. The HPBW of the two beams is around 4,8° in the two methods.



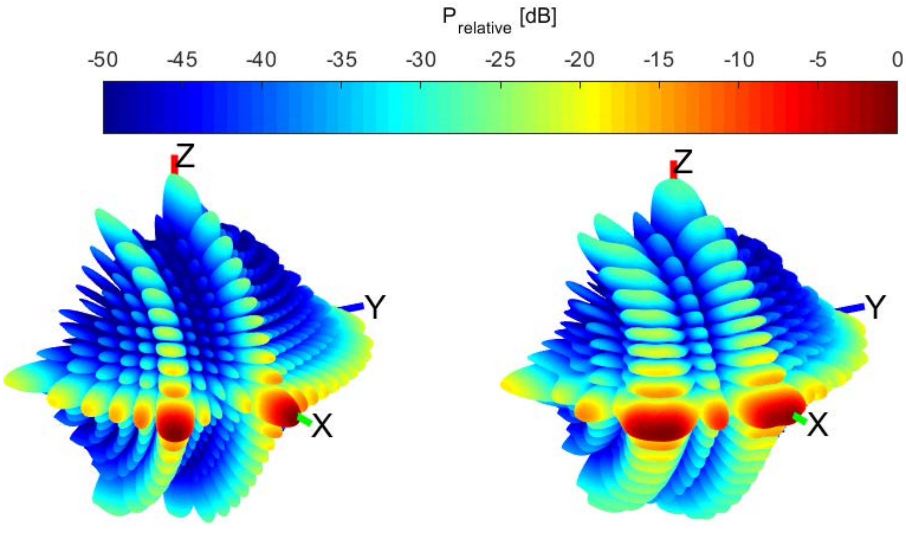
a) Reflection phase b) Reflection magnitude

Figure 6.1.1-1: Required reflection coefficient in the superposition method



a) Reflection phase b) Reflection magnitude

Figure 6.1.1-2: Required reflection coefficient in the multi-tiles method



a) Superposition b) Multi-tiles

Figure 6.1.1-3: Obtained normalized 3D reflection patterns using the two methods

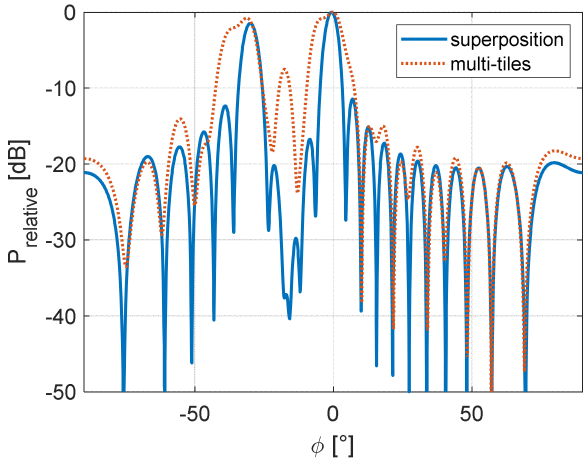
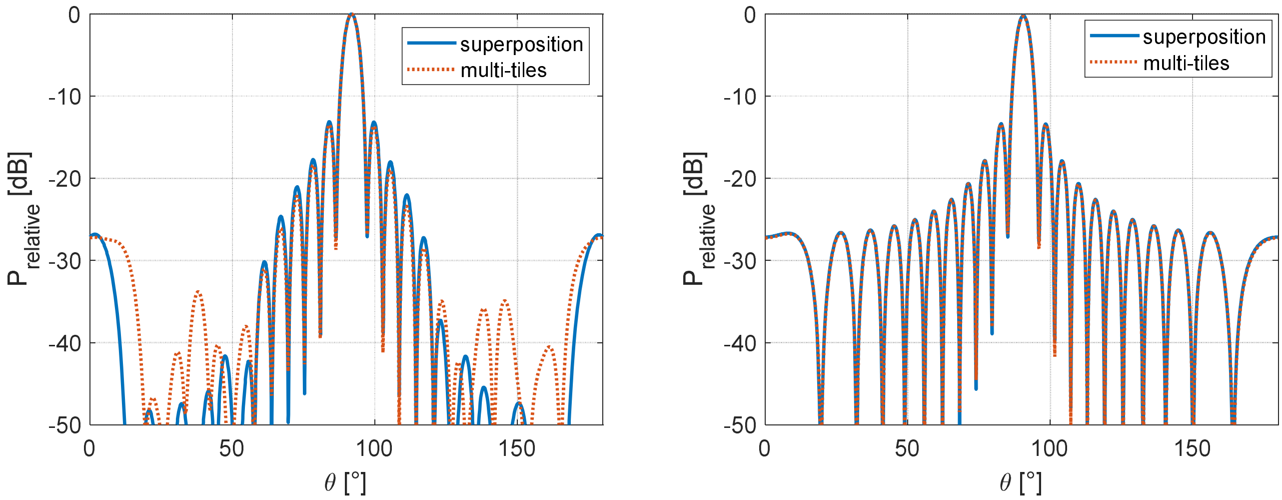


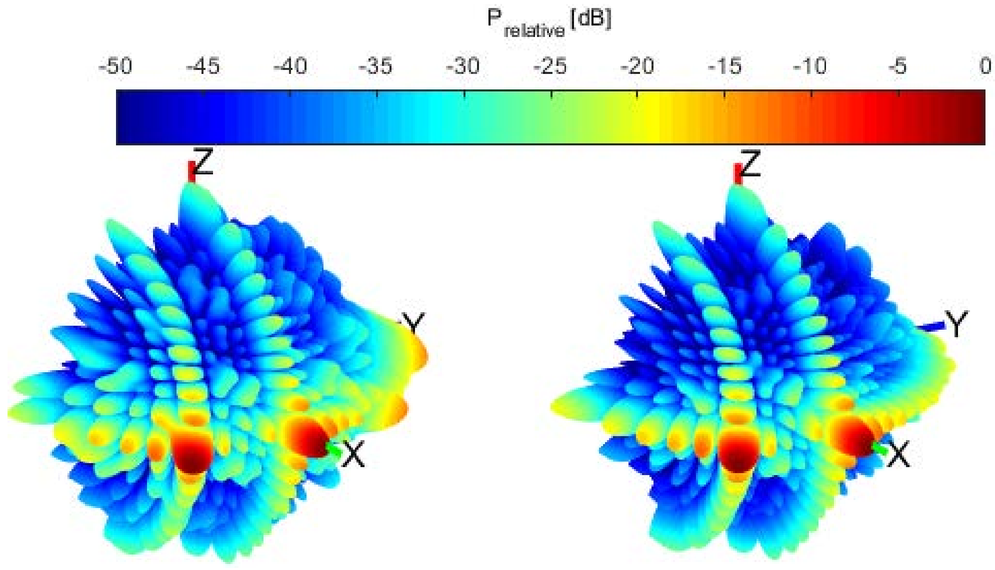
Figure 6.1.1-4: Obtained normalized 2D reflection patterns in the horizontal plane using the two methods



a) For $\phi = -30°$ **b) For $\phi = 0°$**

Figure 6.1.1-5: Obtained normalized 2D reflection patterns in the vertical plane using the two methods

It should be noted that, since superposition method achieves better beamforming capabilities than the multi-tiles method, the former is better suited to support high number of users. It should also be noted that while the above results were obtained assuming a continuous RIS reflection magnitude control in superposition method, this method still presents very interesting results when using a limited number of bits for reflection magnitude control as shown in figure 6.1.1-6.



a) 1-bit quantization **b) 2-bit quantization**

Figure 6.1.1-6: Obtained normalized 3D reflection patterns using superposition method with magnitude quantization

6.1.2 Space-Division Multiplexing for Discrete Phase Control RIS

Another alternative approach to generate multiple RIS reflection beams is to utilize the correlation characteristic between different single beam RIS reflection patterns for the large-scale discrete phase-control RIS element matrix. For the ideal phase control RIS, the optimal RIS pattern $\{\varphi^{opt}\}$ for a given beam direction is to modify the reflecting phase of each RIS element making the reflected signal arriving at the receiver with the same phase, as described in equation (10) for the optimal phase of k^{th} RIS element:

$$\varphi_k^{opt} = mod\left(\frac{2\pi}{\lambda}\left|d_{BR,k} + d_{RU,k}\right|, 2\pi\right) \tag{10}$$

where $d_{BR,k}$ and $d_{RU,k}$ denote the distance from base station to k^{th} RIS element and from k^{th} RIS element to UE. When another RIS pattern $\{\varphi^{conf}\}$ is configured, the RIS reflected signal power at the given beam direction is derived as:

$$\mathrm{y} = \sum_{k=1}^{N} \alpha_k e^{-j\frac{2\pi}{\lambda}d_{BR,k}} \beta_i e^{-j\frac{2\pi}{\lambda}d_{BR,k}} \cdot e^{j\varphi_k^{conf}} + n_0$$

$$= \alpha\beta \sum_{k=1}^{N} e^{j\left(\varphi_k^{conf} - \varphi_k^{opt}\right)} + n_0 \tag{11}$$

where α_k and β_k denote the channel pathloss from base station to RIS and from RIS to UE, in the far field scenario, same path loss among the RIS element matrix can be assumed, $\alpha_k = \alpha$ and $\beta_k = \beta$ for $\mathrm{k} = 1, \cdots \mathrm{N}$. According to equation (11), for a configured RIS reflection pattern, the reflected signal power or beamforming gain at an observation direction is proportional to the correlation between the configured pattern and the optimal pattern of the observation direction.

For the discrete phase control RIS, an additional operation of phase quantization is performed to the optimal RIS pattern, and thus involves a phase quantization error to the reflected signals of each RIS elements. Thanks to the law of large numbers, the expectation of the phase quantization error (the effective power contributed to the desired direction) approximately equals to the average error (average power contribution) of the RIS reflected signals when RIS element matrix is very large:

$$\mathbb{E}[e_k] \approx \lim_{N\to\infty} \frac{1}{N} \sum_{k=1}^{N} e_k \tag{12}$$

where $e_k = e^{j\varphi_k^{opt}} - e^{j\varphi_k^{1bit}}$ denotes the power loss due the phase quantization error of the k^{th} RIS element. It reveals that although the effective power of one single RIS element is different from each other, the sum of the effective power from a group of RIS elements selected randomly approaches to the expectation of the RIS effective power.

The beam manipulation method for the discrete phase control RIS aims to control the power gain (beamforming) of the observation directions (user directions). The details of the proposed RIS pattern generation method can be described as below:

1) determine the optimal RIS reflection pattern according to the user direction;

2) derive the correlation target based on the required beamforming gain of the user direction;

3) select randomly a set of RIS elements from RIS matrix, and flip the reflecting status of the selected RIS elements to satisfy the derived correlation.

If multiple beams for multiple users is needed, multiple correlation requirements should be derived to guide the RIS pattern generation. It should be noted that the multi-tile method could be considered as a special case with the tile-wise selection. Figure 6.1.2-1 shows the performance of correlation method for 1bit phase control RIS compared with the multi-tile method.

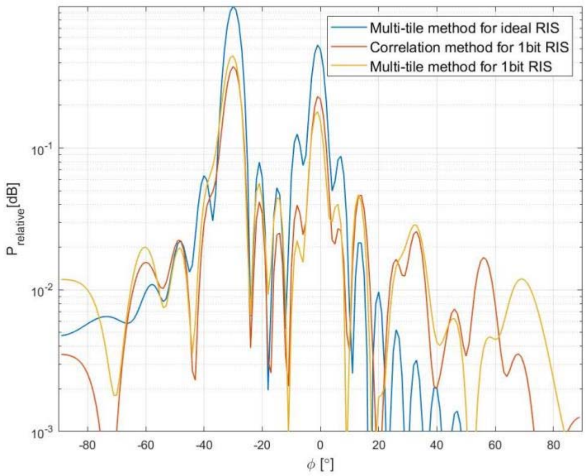


Figure 6.1.2-1: RIS reflection power distribution in X-Y plane using multi-tile method and correlation method

Based on the space-division multiplexing, three examples of the RIS beam manipulation scenarios can be realized based on the correlation method. These examples are theoretically achievable under certain ideal assumptions, such as an efficiently large number of RIS elements, far field propagation assumptions, purely LOS channel conditions between RIS elements and BS / UE, among others.

Use case 1

Null beam generation for interference mitigation from the neighbour cell. In the multiple cell scenario, the networks could configure RIS to generate a null beam for interference mitigation. For example, the networks determine the optimal RIS pattern according to the position of neighbour cell BS and RIS and UE direction. RIS pattern of null beam is achieved by flipping the status of half of the RIS elements in RIS matrix.

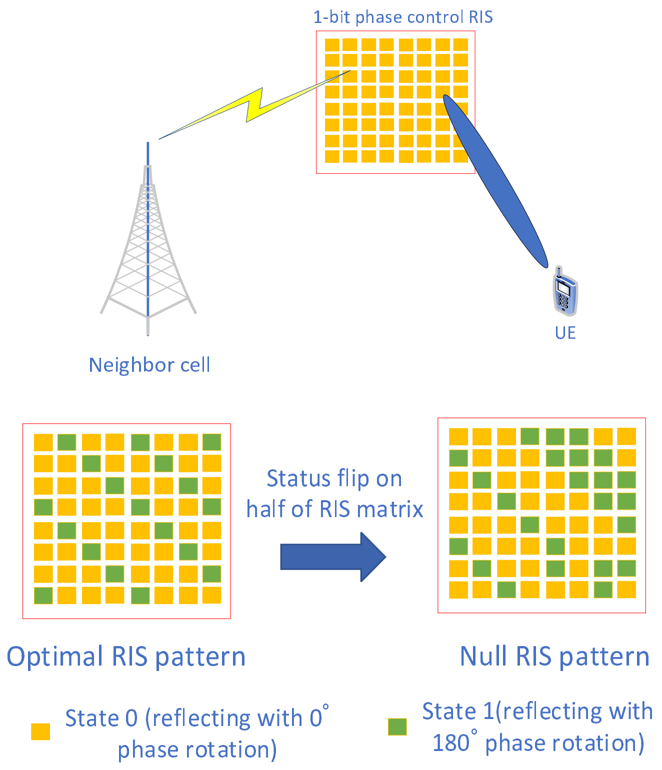


Figure 6.1.2-2: The example of null RIS pattern generation

Use case 2

Multi beam generation for serving multiple users at different directions. For case of two user multiplexing using 1-bit phase control RIS, the networks could determine the optimal RIS patterns according to the position of two users. Furthermore, RIS elements in RIS matrix could be classified into two groups: group 1 corresponds to the RIS elements that the reflecting status is same in the two optimal RIS patterns, while group 2 corresponds to other RIS elements with different reflecting status in two optimal RIS patterns. One of the optimal RIS patterns, could be used as the initial pattern, the flipped RIS elements is selected from group 2 to decrease the correlation of initial pattern and increase the correlation of the other pattern.

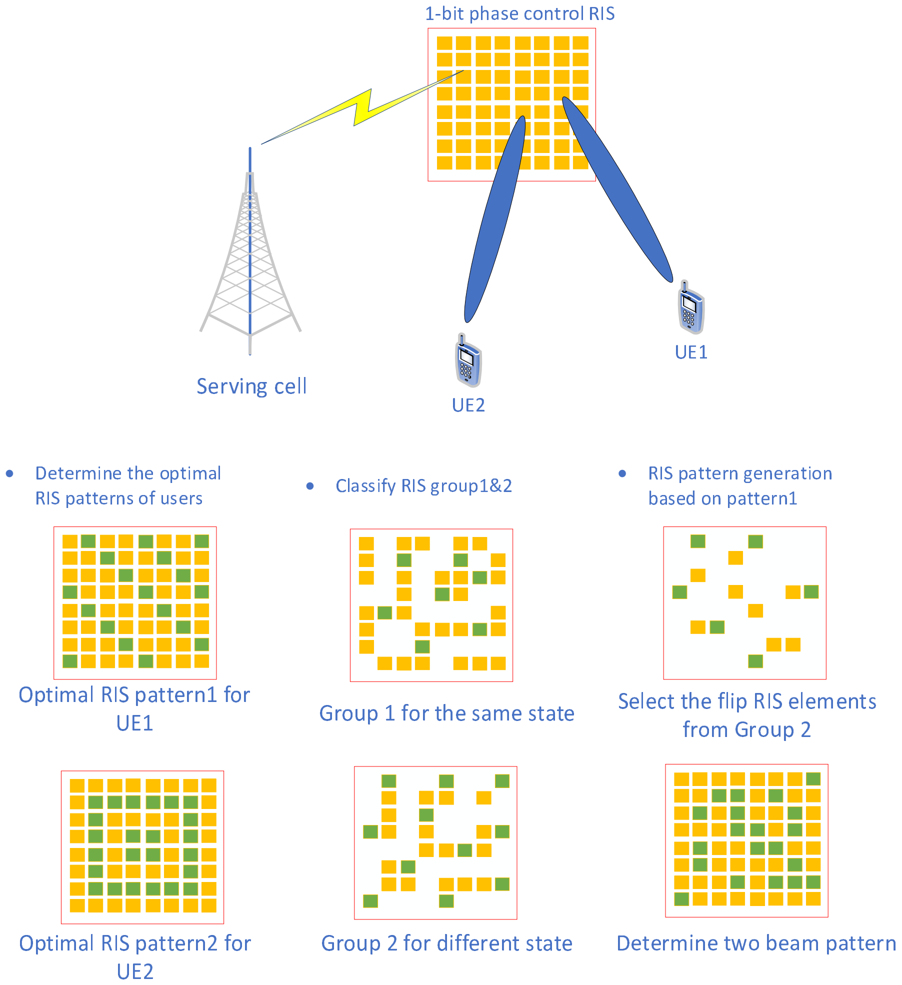


Figure 6.1.2-3: An example of two beam RIS pattern generation

Use case 3

RIS beam generation for maximizing SINR. For the multiple cell scenario, one serving BS and one neighbour BS are considered. The network aims to configure a proper RIS pattern to maximize SINR performance for UE. Two optimal RIS patterns of serving cell and neighbour cell could be determined according to the positions of serving cell, neighbour cell, RIS and UE direction, i.e. pattern 1 for serving cell and pattern 2 for neighbour cell. Pattern 1 is used as the initial pattern, and a number of flipped RIS elements is selected from group 1 to decrease the correlation of pattern 2.

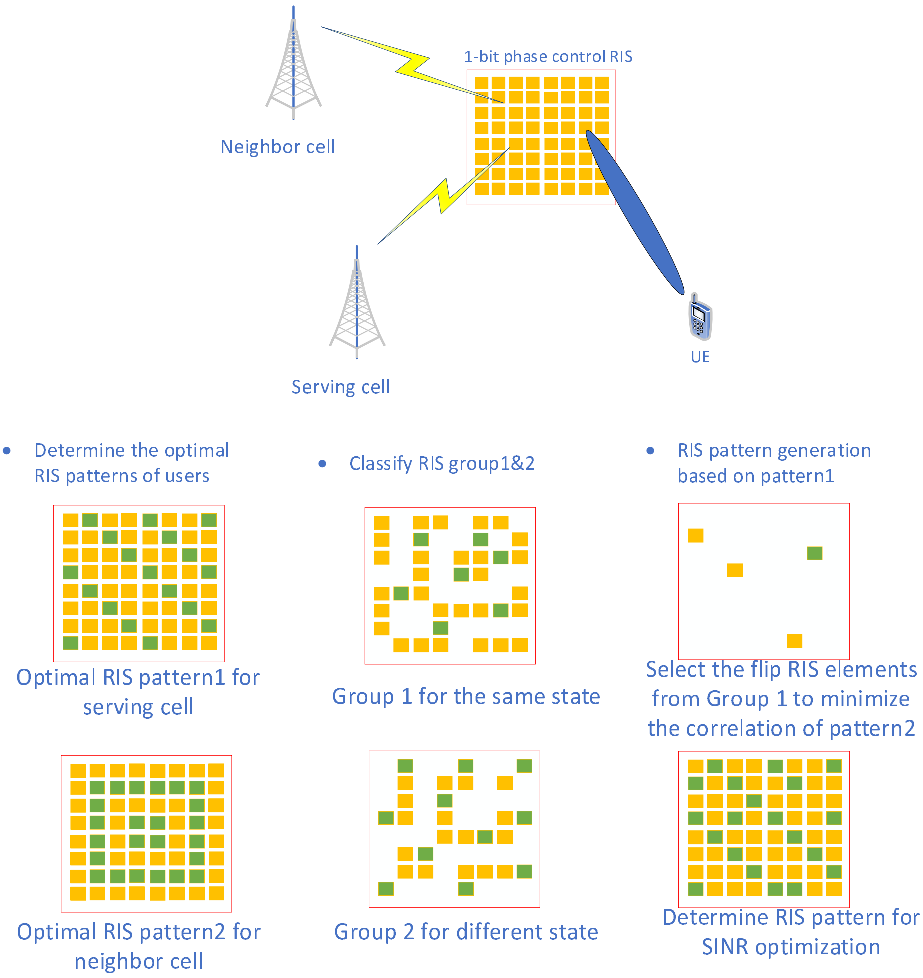


Figure 6.1.2-4: An example of RIS pattern generation for SINR optimization

6.2 Other Multiplexing Techniques

In addition to the space-division multiplexing scheme, a RIS-aided communication system can use most conventional multiplexing schemes, including time-division multiplexing, frequency-division multiplexing, code-division multiplexing, polarization-division multiplexing, etc., to serve a single UE with multiple streams or multiple UEs in the same network. In these scenarios, enabling such conventional multiplexing schemes do not require any additional operations on RIS side. However, given that RIS is a passive and analog device, most multiplexing schemes (except time-division multiplexing) require RIS to serve all UEs with the same set of re-radiation coefficients, posing limitation to the multiplexing gain in practical network. With 1 BS and 1 RIS, UEs that can be served simultaneously should be located in angular vicinity to maintain the beam coverage, except that space-division multiplexing schemes introduced in clause 6.1 are implemented to generate multiple beamforming directions.

When RIS is sufficiently large, however, such limitation can be relaxed due to the beam squinting effect. Given the same re-radiation coefficients, the RIS beams corresponding to different sub-bands can point to different directions, hence enabling frequency-division multiplexing for angular-separated UEs, as is shown in figure 6.2-1. Multiplexing with squinted RIS beams can also avoid the beamforming gain loss when multiple main lobes are generated on the same sub-band.

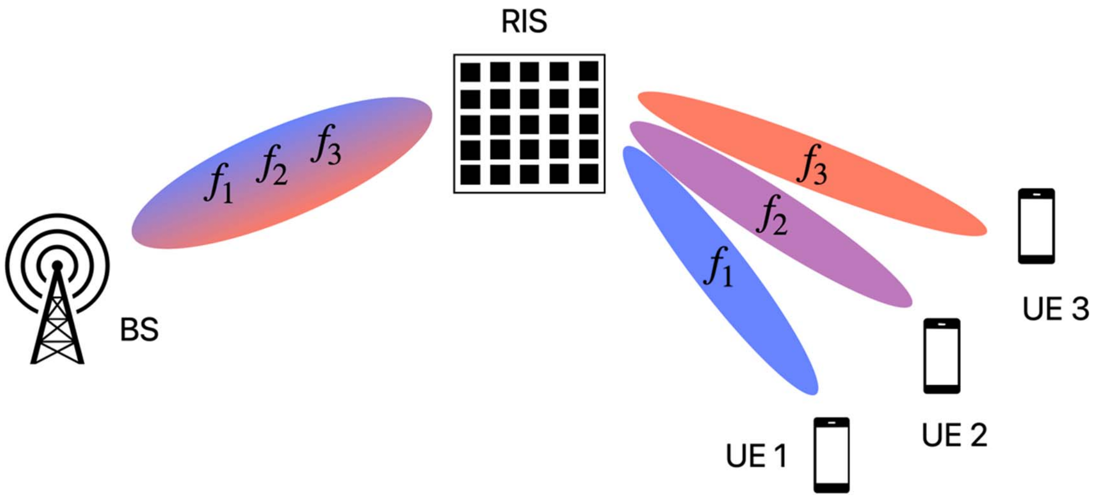


Figure 6.2-1: Illustration of frequency division multiplexing for angular separated UEs utilizing beam squinting effect

7 Other Multi-Antenna Technologies

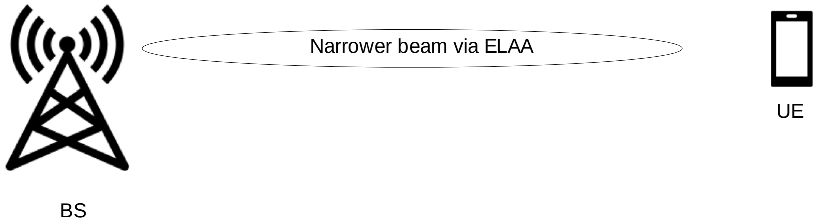
7.1 Beamforming

Beamforming is an essential technique, especially for wireless communication in mmWave and beyond to direct the signals in the direction of intended receiver. In mmWave and beyond, i.e. subTHz range, the requirement for narrower beam is even more essential to improve the link budget between the transmitter and receiving by increasing the beamforming gain. RIS-assisted beamforming is an important use-case, as also described in clause 5.3 of ETSI GR RIS 003 [i.2]. As described in ETSI GR RIS 003 [i.2], RIS elements can be configured.

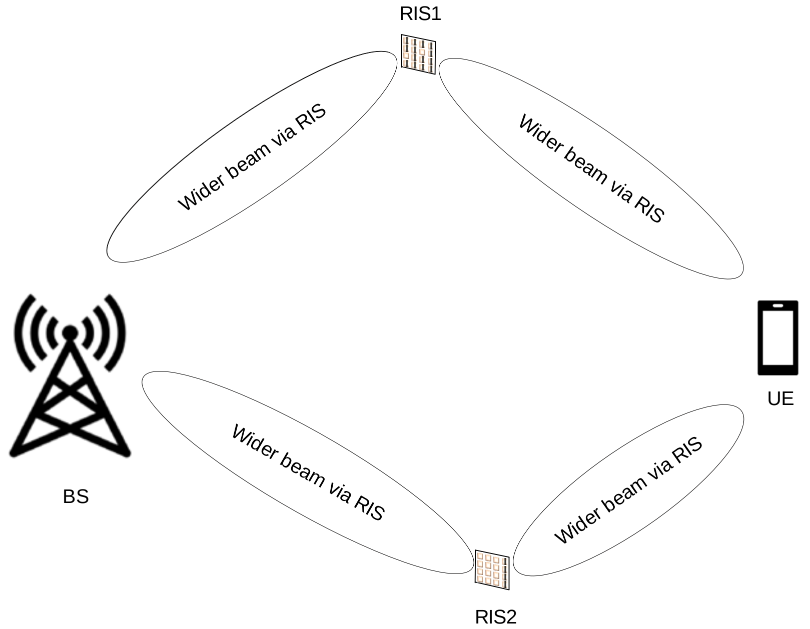
From system perspective, RIS-aided beamforming can better facilitate future networks in terms of supporting Extremely Large Antenna Arrays (ELAA) and cell-free massive MIMO. For further multiplying the beamforming gains in higher frequency range, ELAA are needed to enable very narrow pencil beams for increased coverage. However, practical deployment of such ELAA have their own challenges including potentially bigger form-factors for network node, design of extremely large codebooks for efficient beamforming and additionally supporting operation in near-field region. Furthermore, if ELAA based BSs and TRPs are deployed, then UEs would also need relatively larger number of antennas for generating narrower beams for transmission as well as reception. In terms of operation in near-field region, dedicated codebooks are needed as the far-field codebooks are designed with planar wave assumption. Considering the issues associated with ELAA at single node, RIS-assisted beamforming could help to alleviate these issues by creating a distributed array of antennas for beamforming that is relatively smaller than ELAA. Essentially, multiple RIS panels can be deployed in distributed manner to replicate similar beamforming gain as with ELAA nodes, as illustrated in figure 7.1-1. For example, if $\boldsymbol{G}_{beam_{UE}}^{BS}$ is the beamforming gain between BS and UE for the narrow beam generated via ELAA at BS, $\boldsymbol{G}_{beam_{RIS1}}^{BS}$ is the beamforming gain for the beam between BS and RIS1, $\boldsymbol{G}_{beam_{RIS2}}^{BS}$ is the beamforming gain for the beam between BS and RIS2, $\boldsymbol{G}_{beam_{UE}}^{RIS1}$ is the beamforming gain for the beam between RIS1 and UE, and $\boldsymbol{G}_{beam_{UE}}^{RIS2}$ is the beamforming gain for the beam between RIS2 and UE. For the sake of simplicity, the above beamforming gains from RIS can be considered to be effective beamforming gain after taking reflection coefficient into account. Based on above beamforming gains, ideal deployment should result in beamforming gain via RISs such that following simple relation is achieved:

$$\boldsymbol{G}_{beam_{UE}}^{BS} \sim \boldsymbol{G}_{beam_{RIS1}}^{BS}\boldsymbol{G}_{beam_{UE}}^{RIS1} + \boldsymbol{G}_{beam_{RIS2}}^{BS}\boldsymbol{G}_{beam_{UE}}^{RIS2} \quad (13)$$

This is also beneficial from UEs point of view by offloading the multiple antenna array requirement to RIS that are deployed in its vicinity. Especially for UE-controlled RIS, instead of relying on multiple antennas on UE for narrow beamforming, UE could configure the RIS elements for beamforming towards the intended BS.



a) Narrow beam between BS and UE via ELAA at BS



b) Beams via RISs with similar beamforming gain

Figure 7.1-1: RIS-enabled beamforming by network (to replicate beamforming from ELAA)

Similarly, for facilitating cell-free massive MIMO, a distributed network of nodes is typically deployed for beam-based operation in high frequency range. Joint coherent transmission among the distributed nodes enables beamforming towards an intended user and consequently increasing the beamforming gain. With RIS-aided beamforming, cell-free massive MIMO can be facilitated in a more cost-efficient and power-efficient manner. Instead of deploying traditional network nodes such as TRPs and/or remote radio heads, multiple RIS could be deployed for beam-based operation.

7.2 RIS Antenna Array Selection

7.2.0 RIS Antenna Array Selection schemes

When a RIS is deployed in a network, it can be selected and configured to improve communication between Tx and Rx. When the direct Tx-Rx path is not available, any selected RIS without blockage can provide an alternative path and enable the data transmission. However, when the direct Tx-Rx path is available, Tx-Rx and Tx-RIS-Rx paths can add up constructively / destructively depending on phases on specific bands. Therefore, the interaction between Tx-Rx path and Tx-RIS-Rx path needs to be considered in RIS selection.

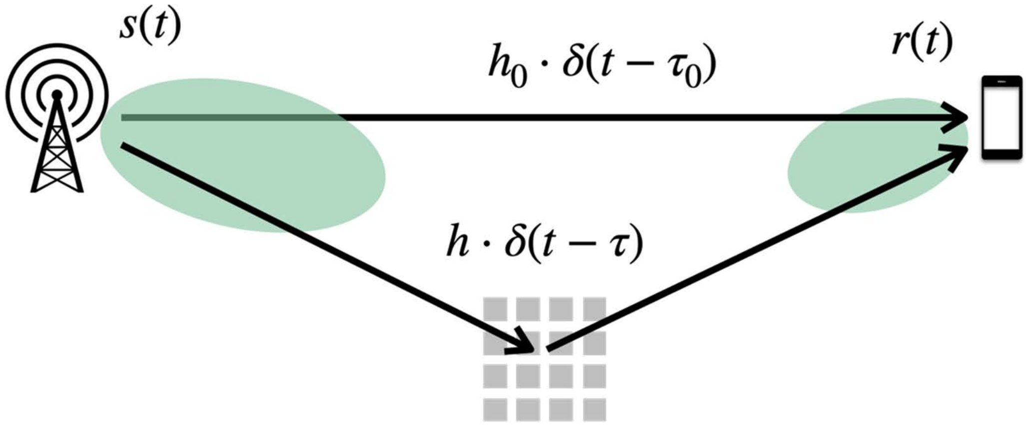


Figure 7.2-1: Channel modelling for RIS-aided communication and the impact of RIS selection

Determination of composite Tx-Rx channel requires direct measurements or very accurate knowledge of separate Tx-Rx and Tx-RIS-Rx channels. However, as the channel can be time-varying due to UE mobility and rotation and the RIS beam training overhead can be significant, it is challenging to acquire such measurement and knowledge for each RIS available for selection. Even if the channel can be measured in one slot, RIS may not adapt its configurations quickly enough to the variation over time. If a RIS is randomly selected to aid the communication, it may not boost the performance and can even cause performance degradation in some scenarios. An example analysis shown in figure 7.2-1 is discussed as follows. It is assumed that Tx sends the same signal $s(t)$ to Rx via both Tx-Rx path and Tx-RIS-Rx path. The received signal will be represented by $r(t)$. The channel of direct Tx-Rx path is assumed to be $h_0\delta(t-\tau_0)$, while the channel of Tx-RIS-Rx path is assumed to be $h\delta(t-\tau)$. τ_0 and τ are the corresponding path delays. Without losing generality, here the multi-paths are not considered for simplification. Then the received signal can be represented by:

$$r(t) = s(t) * \left(h_0\delta(t-\tau_0) + h\delta(t-\tau)\right) + n(t) \quad (14)$$

Here $n(t)$ is the noise. Then in the frequency domain, the received signal is:

$$R(f) = S(f)\ (h_0 e^{-j2\pi f\tau_0} + he^{-j2\pi f\tau}) + N(f) \quad (15)$$

Here $R(f)$, $S(f)$, and $N(f)$ are the Fourier transform of the received signal, transmitted signal, and noise. The equivalent composite channel can be represented by $H(f) = h_0 e^{-j2\pi f\tau_0} + he^{-j2\pi f\tau}$, which is periodic and frequency selective. An illustration of the channel gain is shown in figure 7.2-2. The frequency period of channel response if $1/(\tau-\tau_0)$. The worst-case channel power gain is $(|h_0| - |h|)^2$, which will result in an even lower SNR than that without RIS, while the best-case channel power gain is $(|h_0| + |h|)^2$. If σ^2 is used to represent noise power, then for a wide-band signal containing subcarriers $\{f_n\}$, the channel capacity can be represented by:

$$C \propto \sum_n \log_2\left(1 + \frac{\left|h_0 e^{-j2\pi f_n\tau_0} + he^{-j2\pi f_n\tau}\right|^2}{\sigma^2}\right) \quad (16)$$

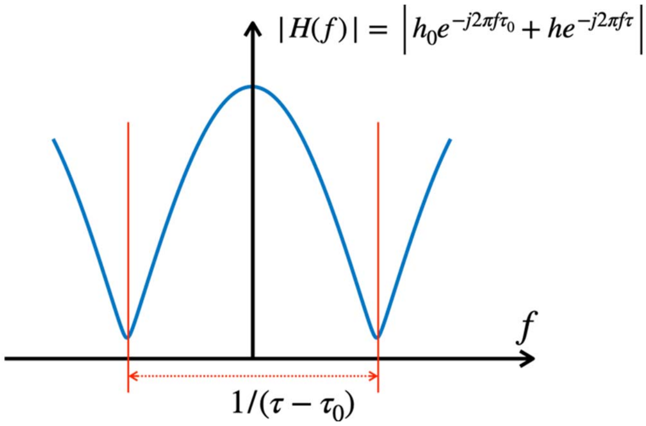
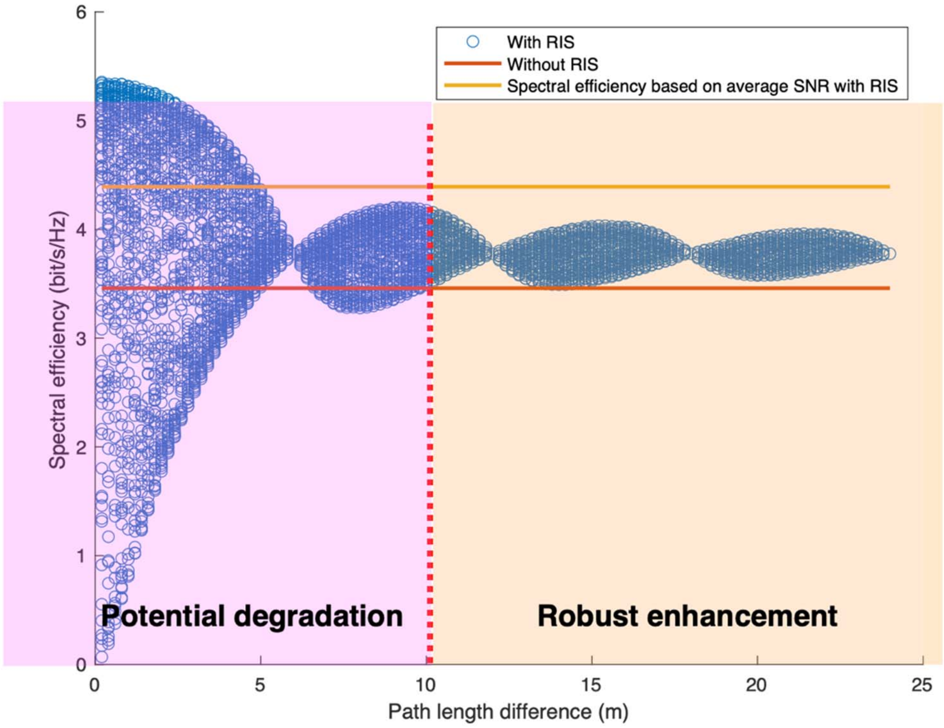


Figure 7.2-2: Illustration of channel gain in the frequency domain

As is shown in figure 7.2-2, the frequency selectivity of RIS-aided communication depends on the delay profile of the link. When the channel only varies slowly over time, having sub-band based channel measurements allow the joint selection of RIS and sub-band, given the dependence of best sub-bands on RIS and link path lengths. Such frequency-selective RIS selection can be utilized to maximize link SNR and capacity or achieve perfect interference mitigation. If the channel is static or if the RIS can adapt its configurations quickly, RIS can also change its own phase configurations to align the phases of Tx-Rx and Tx-RIS-Rx paths on any selected sub-band. When accurate channel measurements are not available, the RIS selection can also be conducted to optimize certain KPIs, as introduced in following clauses.

7.2.1 RIS Selection for Robust Capacity Enhancement

When the accurate channel knowledge is not available, a narrow band signal may suffer from the deep fading in figure 7.2-2 due to the randomness of channel phases. One method to prevent the whole band from experiencing deep fading in figure 7.2-2 is to enlarge the band width or reduce the frequency period $1/(\tau - \tau_0)$, so that more frequency periods can be covered by the band and the deep fading effect can be mitigated. When the band width is sufficiently large with respect to the frequency period of channel response spectrum, the average channel power gain over the whole band will converge to $|h_0|^2 + |h|^2$, implying a robust enhancement of SNR and channel capacity compared to the scenario without using RIS.



NOTE: Each circle represents the channel with one random set of channel phases.

Figure 7.2.1-1: Illustration of spectral efficiency with respect to path length difference between Tx-RIS-Rx path and Tx-Rx path

An example in figure 7.2.1-1 demonstrates the necessity of selecting RIS with large $\tau - \tau_0$ values. Without losing generality, it is assumed that channels have random phases and $|h_0|^2 = |h|^2 = 10$ dB, and the noise power $\sigma^2 = 1$. When the band width is $B = 50$ MHz and the delay difference $\tau - \tau_0$ ranges from 0 ns to 80 ns (corresponding to path length difference of 24 m), the channel spectral efficiency is shown in figure 7.2.1-1. In the figure, each circle represents the spectral efficiency given one random set of channel phases for h_0 and h. As is shown in the figure, when the path length difference between Tx-RIS-Rx path and Tx-Rx path (equivalent to $\tau - \tau_0$) is smaller than a threshold, there is a significant chance that the spectral efficiency will be lower than that without RIS (denoted by the red line). On the other hand, if $\tau - \tau_0$ is larger than the threshold, there will be a robust enhancement in channel capacity. Therefore, only RIS satisfying this delay difference condition should be selected in real-world communication systems.

The value of path length / delay difference threshold generally depends on the SNR of both paths. Figure 7.2.1-2 shows the path length difference threshold (denoted by colours) with different path gains. The y-axis denotes the Tx-Rx path gain, while the x-axis denotes the path gain difference between Tx-RIS-Rx and Tx-Rx. As is shown in the figure, the threshold value generally increases as Tx-Rx SNR increases and Tx-RIS-Rx SNR decreases. The performance degradation is much more likely to happen if the channel gain of RIS path is smaller than that of the direct path. Given the location information of Tx, Rx, and RIS as well as the map of distance difference thresholds, RIS can be appropriately selected to provide robust communication capacity enhancement.

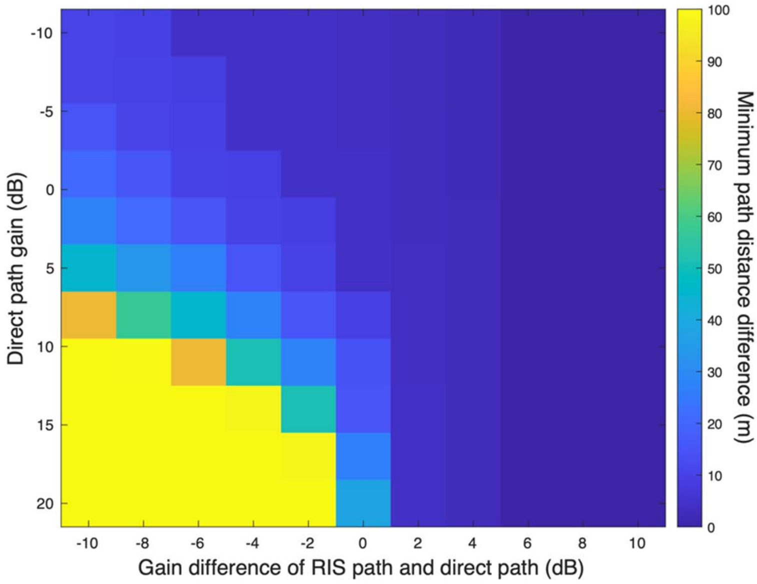


Figure 7.2.1-2: Illustration of path length difference threshold dependent on the SNR of both paths

7.2.2 RIS Selection for Outage Probability Reduction

The path length / delay difference between Tx-RIS-Rx path and Tx-Rx path not only affects the channel capacity, but also impacts the outage probability of the aided link. Although involving a RIS can reduce the outage probability of a link in most scenarios, the RIS that minimizes outage is not necessarily the one with the best RIS channel gain. An example analysis is demonstrated in figure 7.2.2-1. It is assumed that in the model shown in figure 7.2-1, h_0 and h are both i.i.d. random Rayleigh fading channels, and $|h_0|^2 = 4$ dB. The channel power gain of the RIS path, $|h|^2$, ranges from 2 - 8 dB. An outage is defined as the scenario in which the channel capacity is smaller than a threshold C_{th}:

$$\sum_n \log_2\left(1 + \frac{\left|h_0 e^{-j2\pi f_n \tau_0} + h e^{-j2\pi f_n \tau}\right|^2}{\sigma^2}\right) \leq C_{th} \quad (17)$$

Without losing generality, consider the channel capacity at 0 dB SNR as the threshold value. Then the outage probability calculated based on a large number of channel realizations is illustrated in figure 7.2.2-1. The reduction of outage probability not only depends on the SNR of RIS path, but also relies on the path length difference. Given the same RIS path SNR, the outage probability decreases when path length (delay) difference increases and converges as $B(\tau - \tau_0) \geq 1$. When SNRs of two RIS paths are similar, selecting RIS with larger $\tau - \tau_0$ can result in lower outage probability. Therefore, the selection of RIS can be location-based, which needs to take RIS path gain, path length difference, and channel capacity threshold into account to minimize the outage probability.

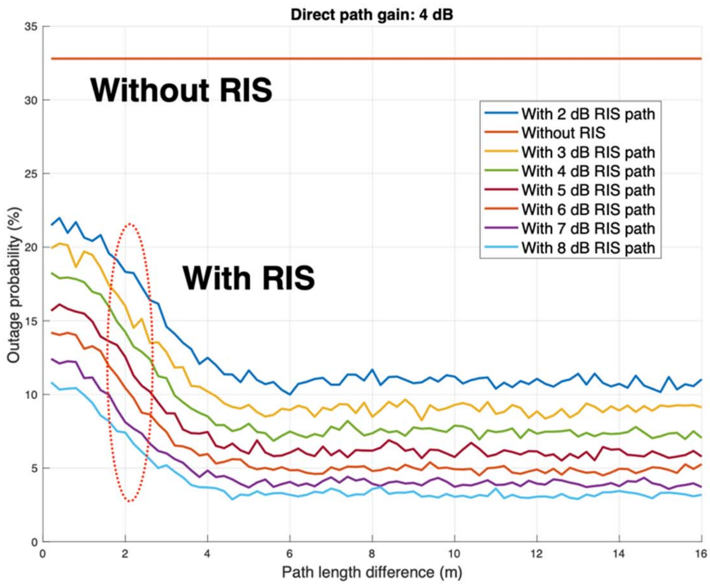


Figure 7.2.2-1: Illustration of path length difference threshold dependent on the SNR of both paths

8 Channel Estimation and CSI Acquisition Schemes

8.0 CSI Considerations

The knowledge of Channel State Information (CSI) is necessary to enable many diversity and multiplexing schemes discussed in clauses 5 and 6. Compared with conventional communication that only relies on Tx-Rx channel, RIS-aided communication involves another Tx-RIS-Rx path, whose channel affects the diversity and multiplexing gain of the communication and can be dynamically configured given the application requirement. As is shown in clause 7.1.4 in ETSI GR RIS 003 [i.2], in many scenarios, the direct Tx-Rx path is not completely blocked and coexists with the Tx-RIS-Rx path. Although some channel estimation procedures have been discussed in clause 7 in ETSI GR RIS 003 [i.2], those methods are mainly focused on the channel associated with RIS elements and the determination of RIS re-radiation patterns. In the present document, however, the discussion of channel estimation is mostly focused on the end-to-end Tx-Rx and Tx-RIS-Rx channels, investigating the corresponding impact on diversity and multiplexing schemes.

For diversity schemes that only involve Tx / Rx, only the knowledge of the composite channel from Tx to Rx (combining both Tx-Rx and Tx-RIS-Rx) may need to be acquired. However, some multiplexing or diversity schemes, e.g. SFBC and STBC discussed in clauses 5.5.3.1 and 5.5.3.2, require the channel state information of Tx-Rx path and Tx-RIS-Rx path separately. Different channel estimation schemes can be applied to acquire either the composite channel state information or separate channels of both paths.

8.1 Estimating Composite Channel

The estimation of the composite channel basically assumes the Tx-RIS-Rx path to be an ordinary multi-path and estimates the end-to-end channel from Tx to Rx. Conventional channel estimation methods can generally be used for acquiring the composite channel. However, since the Tx-RIS-Rx path can significantly change the time / frequency selectivity as is discussed in clauses 5.1.3 and 5.2.3, the time-frequency resource for channel estimation needs to be allocated according to the specific scenarios.

8.2 Estimating Separate Channel

Separately estimating Tx-Rx and Tx-RIS-Rx channel is necessary in many scenarios, including enabling diversity or multiplexing schemes, assisting RIS selection, supporting RIS-aided positioning, etc. Due to the coexistence of the Tx-Rx and Tx-RIS-Rx channel, separate estimation of the Tx-Rx and Tx-RIS-Rx channel requires additional operations other than conventional sounding of allocated time-frequency resources (e.g. CSI-RS sounding) to separate the measurements. An illustration of the separate channel estimation is shown in figure 8.2-1, in which Tx-Rx channel h_0 and Tx-RIS-Rx channel h_1 need to be acquired.

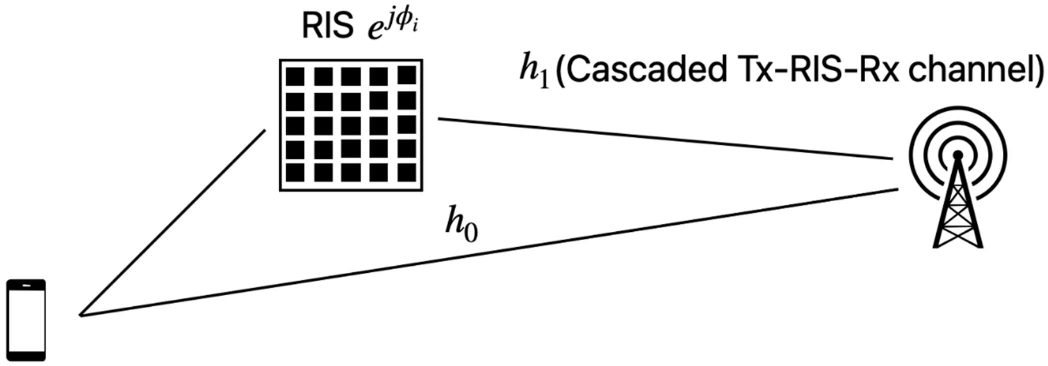


Figure 8.2-1: Illustration of separate channel estimation in RIS-aided communication

8.2.1 Time Separated Channel Estimation

8.2.1.1 On-Off Channel Estimation

One of the simplest channel estimation methods is to measure the end-to-end Tx-Rx channel twice, with RIS turned on and off. When RIS is on and re-radiate signals from Tx to Rx, conventional channel estimation methods can be used to acquire $h_1 + h_0$; when RIS is off (i.e. in absorptive mode or is not re-radiating to Rx), the channel measurement will be h_0. The difference between the two measurements is the Tx-RIS-Rx channel h_1. The limitation of this method is that the time-frequency resources allocated for channel estimation should be doubled, or the received energy of Reference Signals (RSs) for each measurement will be halved if the total amount of resource is the same as in conventional systems.

8.2.1.2 Spatially Separated Channel Estimation on Different Time Resources

In many scenarios, with respect to Tx / Rx, the AODs / AOAs of Tx-RIS-Rx and Tx-Rx paths are not the same. Therefore, Tx / Rx could use narrow beams pointing to Rx / Tx or RIS to measure the channels separately and minimize the interference on the other path. Depending on the capability of Tx / Rx, Tx / Rx can generate narrow beams pointing to different directions on different time resources but on the same frequency resources, as is shown in figure 8.2.1.2-1.

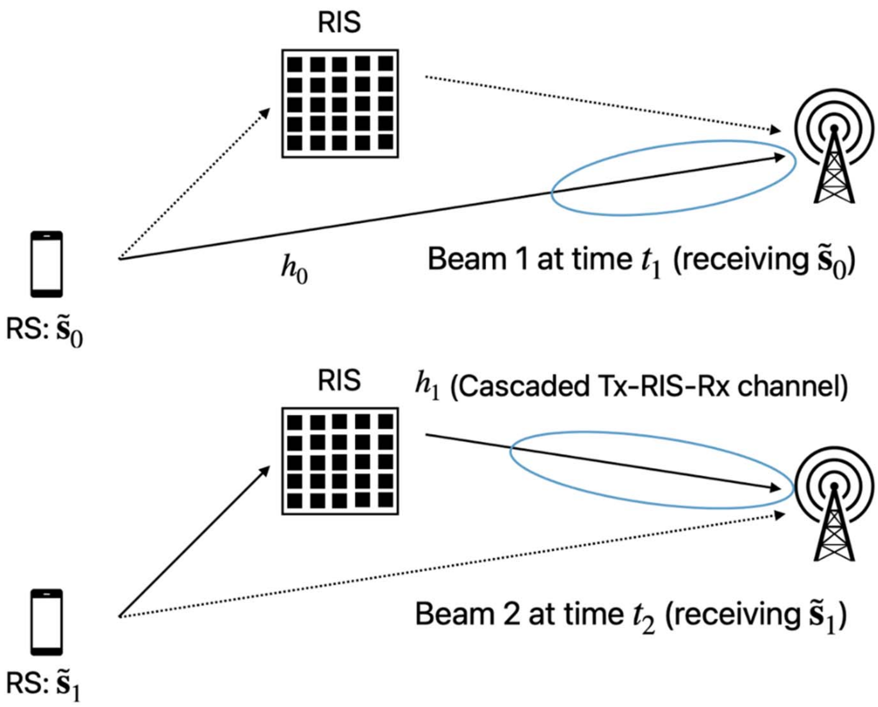


Figure 8.2.1.2-1: Illustration of separate channel estimation with different beams at different times but on the same frequency

8.2.1.3 Separate Channel Estimation Based on Windowing Method

When a RIS is capable of adding group delays to re-radiated waveforms using either full passive circuits (LC delay, RC delay) or low-power active circuits (switched capacitor delay line, true time delay line, etc.), the channel of Tx-Rx path and Tx-RIS-Rx path can be distinguished. E.g. when the Tx-Rx channel is h_0 and Tx-RIS-Rx channel is h_1, the delay spread of Tx-Rx channel could be estimated. Then a group delay that is larger than the delay spread of h_0 can be introduced by RIS circuits, creating separate windows for h_0 and h_1 estimation as illustrated in figure 8.2.1.3-1. One method to estimate the delay spread is to configure RIS into absorption mode to reduce the impact of Tx-RIS-Rx multi-paths.

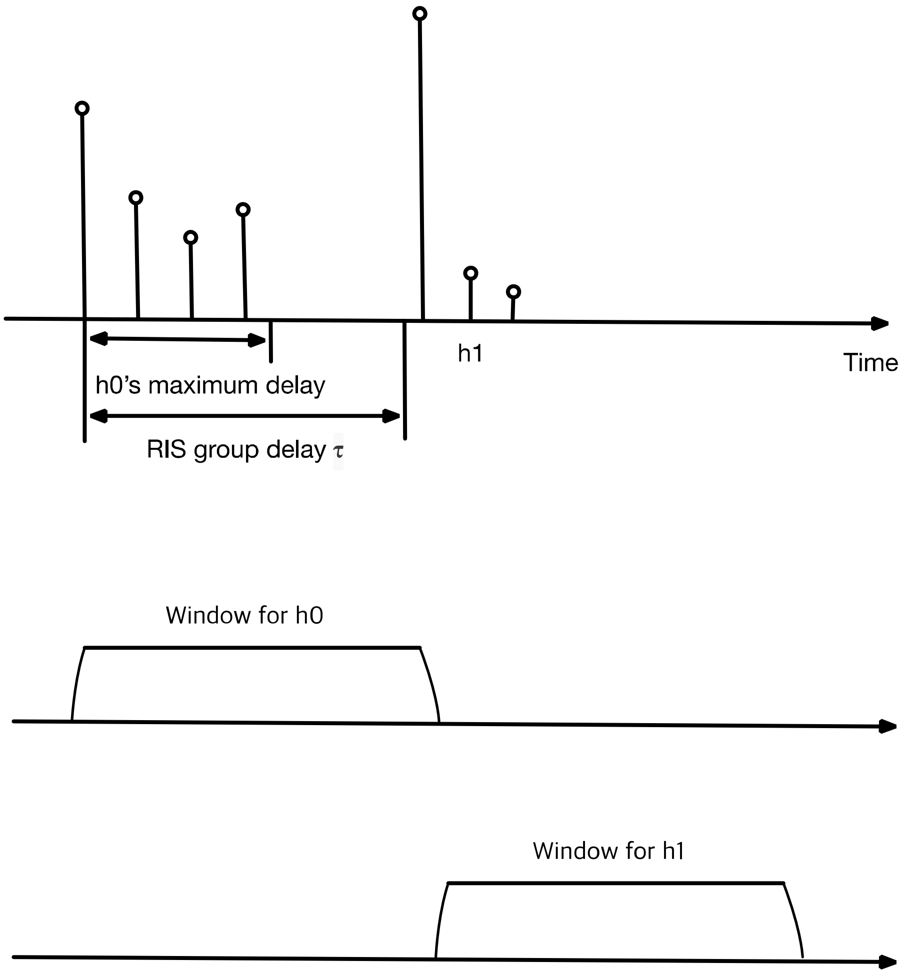


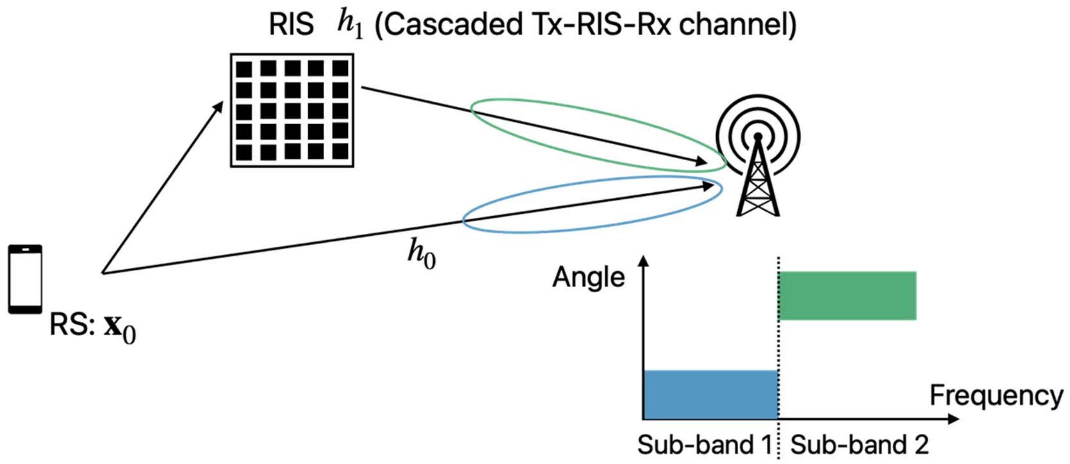
Figure 8.2.1.3-1: Illustration of separate channel estimation with RIS group delay

8.2.2 Frequency Separated Channel Estimation

8.2.2.1 Frequency Separated Channel Estimation on Same Time-Resources but Different Beams

In many scenarios, with respect to Tx / Rx, the AODs / AOAs of Tx-RIS-Rx and Tx-Rx paths are not the same. Therefore, Tx / Rx could use narrow beams pointing to Rx / Tx or RIS to measure the channels separately and minimize the interference on the other path. Depending on the capability of Tx / Rx, Tx / Rx can simultaneously generate narrow beams pointing in different directions with each beam separated in frequency.

In the frequency domain, Tx / Rx can generate different beams on different sub-bands pointing to Rx / Tx and RIS simultaneously, as is shown in figure 8.2.2.1-1. The methods that can be used to generate different beams include utilizing beam squinting effect [i.9] or using phase-time array architectures [i.10] at Tx / Rx.



NOTE: To measure both channels for 2 sub-bands, another estimation with switched sub-band on each beam is necessary

Figure 8.2.2.1-1: Illustration of separate channel estimation with different beams on different sub-bands

8.2.2.2 Separate Channel Estimation with Orthogonal Reference Signal (RS) in Frequency Domain

When a RIS can change the configuration at a high speed and equivalently modulate the incoming narrow-band signal according to a time-varying function, the carrier frequency of the incident waveform will be shifted in the frequency domain [i.6]. E.g. if the RIS could modulate an incident waveform at frequency f_c with a function $R(t) = \cos 2\pi f_r t$, the re-radiated waveform will only carry information on two neighbour carriers $f_c + f_r$ and $f_c - f_r$. Given such capability of RIS, an RS transmitted on one sub-band travelling via the two paths can arrive at Rx on different frequency sub-bands and be distinguished without interference, as is shown in figure 8.2.2.2-1. When Tx sends RS s_0 to Rx using non-adjacent sub-carriers, the received effective RS via Tx-RIS-Rx path will be s_1, which contains RS symbols only on sub-carriers that are not occupied in s_0.

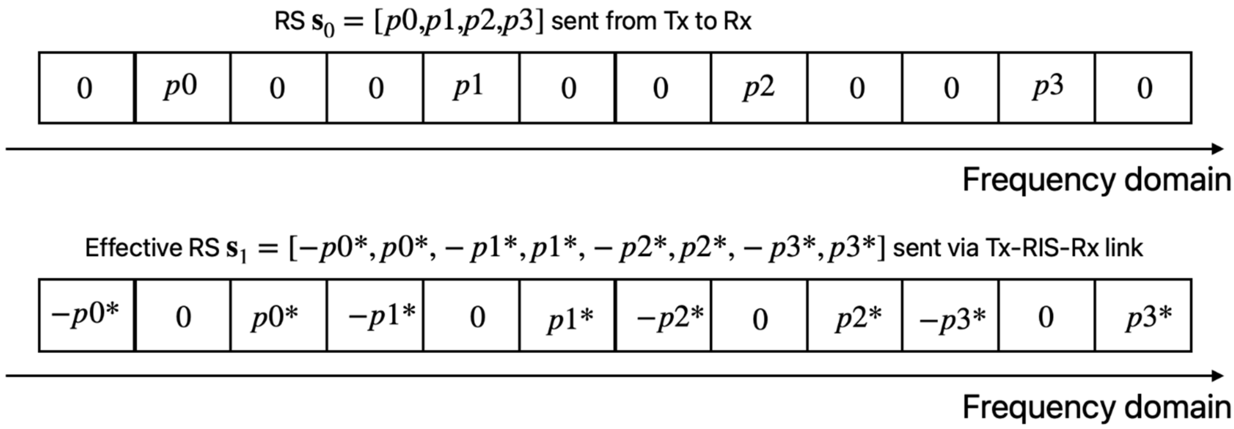


Figure 8.2.2.2-1: Illustration of separate channel estimation with orthogonal RS in frequency domain

8.2.3 Spatially Separated Channel Estimation

8.2.3.1 Spatially Separated Channel Estimation on Same Time-Frequency Resources but Different Beams

In this case, channel estimation is done at the receiver on the same time-frequency resources on two different beams for the two different paths. Tx / Rx can generate narrow beams pointing to different directions on the same time-frequency resource.

8.2.4 Code Division Multiplexed Based Channel Estimation

8.2.4.1 Separate Channel Estimation with Orthogonal Reference Signal (RS) in Code Domain

The requirement for separately estimating both Tx-Rx and Tx-RIS-Rx channels is to separate the received RS via both paths on Rx side. This requirement can be achieved as long as the effective RS sequences travelling through the two paths have good auto-correlation and cross-correlation properties within the interested time shift zone. The length of the interested time shift zone should be longer than the delay different between the two paths. More specifically:

- For a single sequence its auto-correlation has:
  - a peak for in-phase correlation coefficient;
  - zeros for out-of-phase correlation coefficients within the interested time shift zone.
- For two sequences their cross-correlation coefficients are zero within the interested time shift zone.

Jointly with smart RS sequence design and RIS phase shifter changes, the effective RS sequences travelling through Tx-Rx and Tx-RIS-Rx channels can have such correlation properties and thus enable separate channel estimation at the receiver side.

An example of such design is described as follows. Assume the time-domain RS sequence sent from the transmitter is in the format of $\tilde{\boldsymbol{s}}_0 = [\boldsymbol{cp}_{s0}, \boldsymbol{s}_0, \boldsymbol{cp}_{s0}, \boldsymbol{s}_0]$, where $\boldsymbol{cp}_{s0}$ is the cyclic prefix of $\boldsymbol{s}_0$ which is no shorter than the maximum channel delay. Moreover, consider $\boldsymbol{s}_0 = [\boldsymbol{x}_0, -\boldsymbol{x}_1, \boldsymbol{x}_0, \boldsymbol{x}_1]$ where $\{\boldsymbol{x}_0, \boldsymbol{x}_1\}$ is a pair of Golay complementary sequences. Then, RIS varies its phase shifters within the transmission of RS $\tilde{\boldsymbol{s}}_0$, so that the effective RS for Tx-RIS-Rx link becomes $\tilde{\boldsymbol{s}}_1 = [\boldsymbol{cp}_{s0}, \boldsymbol{s}_0, -\boldsymbol{cp}_{s0}, -\boldsymbol{s}_0]$. More specifically, assume the phase configuration for each RIS element i to re-radiate signals from Tx to Rx is represented by ϕ_i, e.g. which is determined via RIS beam management process. Then, the RIS maintains its phase shifters as ϕ_i when reflecting the first half of $\tilde{\boldsymbol{s}}_0$; while modifies its phase shifters to be $\phi_i + \pi$ when reflecting the second half of $\tilde{\boldsymbol{s}}_0$. In this way, for the Tx-RIS-Rx link the effective RS sequence becomes $\tilde{\boldsymbol{s}}_1 = [\boldsymbol{cp}_{s0}, \boldsymbol{s}_0, -\boldsymbol{cp}_{s0}, -\boldsymbol{s}_0]$. This is illustrated in figure 8.2.4.1-1.

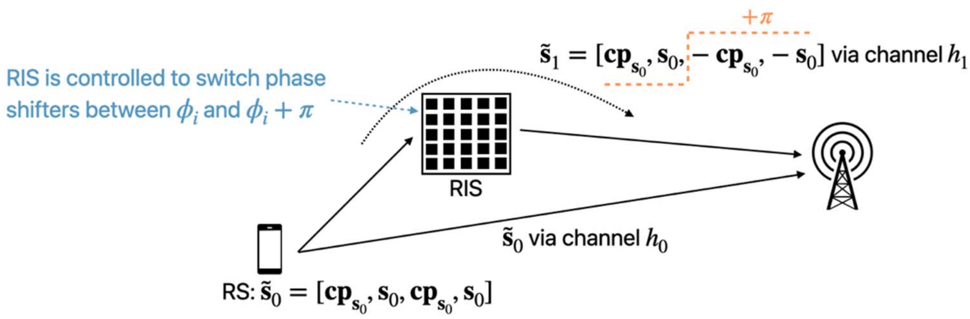


Figure 8.2.4.1-1: Illustration of overall RS transmission via RIS phase shifter changes

Finally at the receiver side, after removing CP it can correlate the received signal with $[\boldsymbol{s}_0, \boldsymbol{s}_0]$ for estimating h_0 and with $[\boldsymbol{s}_0, -\boldsymbol{s}_0]$ for estimating h_1.

9 Conclusions and Recommendation

The present document summarizes ETSI ISG RIS views on multi-antenna technologies in RIS-aided communication, especially focused on diversity and multiplexing schemes, RIS beamforming and selection, channel estimation schemes, etc. The contents can serve as a reference point for relevant specifications and standards to further investigate and implement multi-antenna technologies that can generalize the use cases and enhance the performance of RIS-aided communication systems.

Annex A:
Change history

Date	Version	Information about changes
2023-06	0.0.1	Initial Draft
2023-10	0.0.2	Revised Draft: Section 5.1
2023-12	0.0.3	Revised Draft: Section 5.2 and Correction to Section 5.1
2024-08-21	0.0.7	1. RIS(24)TM11008 (Apple France - TP to GR05 on Use Cases and Deployment Scenarios for RIS-Aided Communication) 2. RIS(24)TM11011r1 (Apple France - TP to GR05 on Channel Robust RIS Selection)
2024-08-21	0.0.8	1. RIS(24)TM11010 (Apple France - TP to GR05 on Reference to Channel Estimation in GR03)
2024-10-24	0.0.9	1. RIS(24)TM014019r1 (Apple France - General TP to GR05)
2024-11-20	1.0.0	Editorial changes based on RIS(24)015016r1

History

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