ETSI GR RIS 003 V1.1.1 (2023-06)

Reconfigurable Intelligent Surfaces (RIS); Communication Models, Channel Models, Channel Estimation and Evaluation Methodology

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Foreword

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

Modal verbs terminology

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1 Scope

The present document is intended to study:

a) communication models that strike a suitable trade-off between electromagnetic accuracy and simplicity for performance evaluation and optimization at different frequency bands;

b) channel models (deterministic and statistical) that include path-loss and multipath propagation effects, as well as the impact of interference for application to different frequency bands;

c) channel estimation, including reference scenarios, estimation methods, and system designs; and

d) key performance indicators and the methodology for evaluating the performance of RIS for application to wireless communications, including the coexistence between different network operators, and for fairly comparing different transmission techniques, communication protocols, and network deployments.

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 TR 138 901 (V16.1.0): "5G; Study on channel model for frequencies from 0.5 to 100 GHz (3GPP TR 38.901 version 16.1.0 Release 16)".

[i.3] Recommendation ITU-R SM.329: "Unwanted emissions in the spurious domain".

[i.4] M. Di Renzo, F. H. Danufane and S. Tretyakov: "Communication Models for Reconfigurable Intelligent Surfaces: From Surface Electromagnetics to Wireless Networks Optimization", in Proceedings of the IEEE™, 2022, doi: 10.1109/JPROC.2022.3195536.

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[i.16] A. Díaz-Rubio and S. A. Tretyakov: "Macroscopic Modeling of Anomalously Reflecting Metasurfaces: Angular Response and Far-Field Scattering", in IEEE™ Transactions on Antennas and Propagation, vol. 69, no. 10, pp. 6560-6571, October 2021.

[i.17] V. Degli-Esposti et al.: "Reradiation and Scattering from a Reconfigurable Intelligent Surface: A General Macroscopic Model", in IEEE™ Transactions on Antennas and Propagation, 2022.

[i.18] B. Sihlbom, et al.: "Reconfigurable Intelligent Surfaces: Performance Assessment Through a System-Level Simulator", in IEEE™ Wireless Communications, 2022.

[i.19] 3GPP TR 37.885: "Study on evaluation methodology of new Vehicle-to-Everything (V2X) use cases for LTE and NR".

[i.20] ETSI TR 137 910: "5G; Study on self evaluation towards IMT-2020 submission (3GPP TR 37.910)".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the terms given in ETSI GR RIS 001 [i.1] apply.

3.2 Symbols

Void.

3.3 Abbreviations

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

2D	2 Dimensional
3D	3 Dimensional
AoA	Angle of Arrival
AoD	Angle of Departure
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
BS	Base Station
CDL	Clustered Delay Line
CDS	Coherent Demodulation Scheme
CSI	Channel State Information
DFT	Discrete Fourier Transform
DFT-S	Discrete Fourier Transform Spread
DL	Downlink
DMRS	Demodulation Reference Signal
DoA	Direction of Arrival
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
gNB	g Node B
HARQ	Hybrid Automatic Repeat Request
HITRAN	High resolution Transmission
HMIMOS	Holographic Multiple Input Multiple Output Surface
LLS	Link-Level Simulator
LOS	Line Of Sight
LS	Least Square
MAC	Medium Access Control
MCL	Minimum Coupling Loss
MCS	Modulation and Coding Scheme
MIL	Hardware link budget
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MPL	Mechanically Pumped fluid Loop
MU	Multi User
NB	Node B
NCDS	Non Coherent Demodulation Scheme
NLOS	Non Line Of Sight
NR	New Radio
nRB	number of Resource Block
nSC	number of Sub-Carriers per resource block
NW	Network
O2I	Outdoor-to-Indoor
O2O	Outdoor-to-Outdoor
OFDM	Orthogonal Frequency-Division Multiplexing
PDSCH	Physical Downlink Shared Channel
PHY	Physical layer
PUSCH	Physical Uplink Shared Channel
RB	Resource Block
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surfaces
RSE	Radiated Spurious Emission
RTT	Round-Trip Time
RX	Receiver
SAR	Specific Absorption Rate
SDU	Service Data Unit
SIMO	Single-Input Multiple-Output
SINR	Signal-to-Interference-Noise Ratio

SISO	Single-Input Single-Output
SM	Spatial Modulation
SNR	Signal-to-Noise Ratio
SV	Saleh-Valenzuela
TBA	To Be Added
TdoA	Time difference of Arrival
ToA	Time of Arrival
TRP	Total Radiated Power
TRxP	Transmission and Reception Point
TxRU	Transmit Radio Unit
UE	User Equipment
UL	Uplink
ULA	Uniform Linear Array
UMa	Urban Macro
UMi	Urban Micro
US	United States
WB	Wide-Band

4 Introduction

4.1 General Description

In this clause, the definition of RIS and relevant scenarios are described.

NOTE: The descriptions provided in the present document are aligned with those in ETSI GR RIS 001 [i.1].

4.2 Definition of RIS

Broadly an RIS is defined as follows:

- It is a surface, i.e. it is not a volumetric material, in order to reduce the implementation complexity, the losses, etc. while still being able to fully control the electromagnetic waves.
- It is an engineered (or intelligent) surface, i.e. it can realize functions that a non-engineered surface (i.e. a metal plate) cannot realize.
- It is reconfigurable, i.e. its response can be adapted over time based on the network conditions. The reconfigurability encompasses multiple functions including controlled reflection, refraction, scattering, modulation, etc.

4.3 Types of RIS

An RIS can be defined in terms of the single or multiple functions that it can realize:

- **Reflecting surfaces:** This is an RIS that is capable of modifying the angle of reflection of an incident wave.
- **Refracting surfaces:** This is an RIS that is capable of modifying the angle of refraction (transmission) of an incident wave.
- **Joint reflecting and refracting surfaces:** This is an RIS that is capable of simultaneously modifying the angle of reflection and refraction of an incident wave.
- **Transmitting or information surfaces:** This is an RIS that is capable of encoding data and to realize single-RF (single-stream or multi-stream) transmitters. Examples include RIS that encode data onto the activations patterns of the unit cells or the synthetized radiation patterns.
- **Surface for ambient backscattering:** This is an RIS that can simultaneously reflect or refract the incident waves and simultaneously modulate data onto the reflected or refracted wave.

- **Surfaced for tuned randomness:** This is an RIS that is configured in order to increase the scattering in a given area.
- **Absorbing surfaces:** This is an RIS that is configured to minimize the scattered field.
- **Communication and sensing surfaces:** This is an RIS with integrated communication and sensing capabilities, i.e. a surface that can simultaneously reflect a wave and detect the presence of objects.

4.4 Deployment scenarios

RIS can be utilized in different scenarios, including the following.

Enhanced connectivity and reliability

- Connectivity and reliability boosted by a single RIS.
- Connectivity and reliability boosted by individually controlled multiple RIS.
- Connectivity and reliability enabled by multiple RIS.
- Connectivity and reliability boosted by a single multitenant RIS.
- RIS-aided mobile edge computing.

Enhanced localization and sensing

- Unambiguous localization under favourable problem geometry with a minimal number of base stations.
- Non Line Of Sight (LOS) mitigation for better service coverage and continuity in far-field conditions.
- Non LOS mitigation for better service coverage and continuity in near-field conditions.
- On-demand multi-user and multi-accuracy service provision.
- Opportunistic detection/sensing of passive objects through multi-link radio activity monitoring.
- RIS-assisted search-and-rescue operations in emergency scenarios.
- Localization without BSs using a single or multiple RIS.
- RIS-aided radio environment mapping for fingerprinting localization.
- Radar localization/detection of passive target(s) with hybrid RIS.

Enhanced sustainability and security

- Deployments of RIS to increase the energy efficiency and reduce the power consumption.
- Deployments of RIS to increase security.

5 Models for RIS

5.1 Models for communications

5.1.1 General description

Three main communication models for RIS can be adopted [i.4]:

- Locally periodic discrete model.
- Mutually-coupled antenna model.
- Inhomogeneous sheets of surface impedance model.

5.1.2 Locally periodic discrete model

A widely used model for RIS is based on a locally periodic design, in which periodic boundary conditions are applied at the unit cell level. Accordingly, each RIS reconfigurable element is associated with a set of complex-valued coefficients (the RIS alphabet). Each element of the alphabet is obtained by appropriately configuring the electronic circuits of the RIS reconfigurable element. For ease of description, it is assumed that the RIS operates as a reflecting surface. From the physical standpoint, therefore, the complex-valued coefficient has the meaning of a reflection coefficient, i.e. the ratio between the reflected electric field and the incident electric field, of an infinite RIS whose elements are all configured to the same state. Therefore, the corresponding equivalent structure is a homogeneous surface that realizes specular reflection. According to this definition, each RIS reconfigurable element is characterized by means of locally periodic boundary conditions, and, since an RIS is not endowed with power amplifiers, the reflection coefficients have an amplitude that is, by definition, less than one. However, this neither necessarily implies that the amplitude is a constant independent of the phase nor that the amplitude and the phase can be optimized independently of one another.

5.1.3 Mutually-coupled antenna model

To account for the mutual coupling among closely-spaced RIS elements, a model based on loaded RIS elements illustrated in Figure 1 can be used.

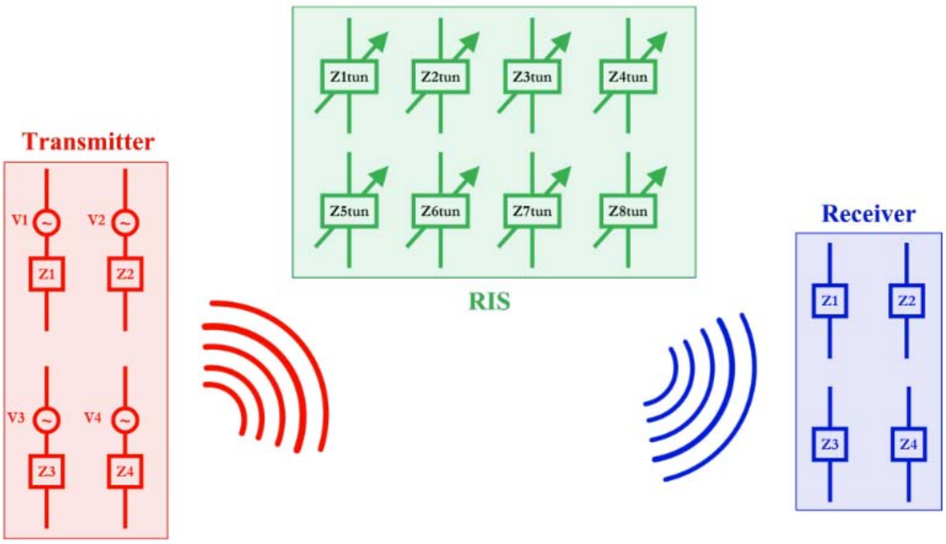


Figure 1: Mutually coupled antenna model

The model resembles a conventional single transmitter-receiver pair Multiple-Input Multiple-Output (MIMO) communication link in the presence of an RIS. The transmitter and the receiver are equipped with multiple-antenna elements. For ease of representation, the antenna elements are assumed to be thin wire dipoles. The model can be utilized for application to radiating elements different from thin wire dipoles. Each antenna element at the transmitter is driven by a voltage generator that models the transmit feed line, and each antenna element at the receiver is connected to a load impedance that mimics the receive electronic circuit. The transmission between the transmitter and the receiver is assisted by an RIS, which comprises several scattering elements that are independently configurable (by an external controller) through tuneable impedances. The end-to-end transfer function that accounts for the scattering from the RIS can be formulated as follows [i.5]:

$$\mathbf{H} = (\mathbf{I}_{L0} + \boldsymbol{\psi}_{r,r}\mathbf{Z}_r^{-1} - \boldsymbol{\psi}_{r,t}\left(\boldsymbol{\psi}_{t,t} + \mathbf{Z}_t\right)^{-1}\boldsymbol{\psi}_{t,r}\mathbf{Z}_r^{-1})^{-1}\boldsymbol{\psi}_{r,t}\left(\boldsymbol{\psi}_{t,t} + \mathbf{Z}_t\right)^{-1}$$

where:

$$\boldsymbol{\psi}_{t,t} = \mathbf{Z}_{t,t} - \mathbf{Z}_{t,s}\left(\mathbf{Z}_{s,s} + \mathbf{Z}_{\text{tun}}\right)^{-1}\mathbf{Z}_{s,t}$$

$$\boldsymbol{\psi}_{t,r} = \mathbf{Z}_{t,r} - \mathbf{Z}_{t,s}\left(\mathbf{Z}_{s,s} + \mathbf{Z}_{\text{tun}}\right)^{-1}\mathbf{Z}_{s,r}$$

$$\boldsymbol{\psi}_{r,t} = \mathbf{Z}_{r,t} - \mathbf{Z}_{r,s}\left(\mathbf{Z}_{s,s} + \mathbf{Z}_{\text{tun}}\right)^{-1}\mathbf{Z}_{s,t}$$

$$\boldsymbol{\psi}_{r,r} = \mathbf{Z}_{r,r} - \mathbf{Z}_{r,s}\left(\mathbf{Z}_{s,s} + \mathbf{Z}_{\text{tun}}\right)^{-1}\mathbf{Z}_{s,r}$$

Each term of the equations can be computed either numerically or in closed-form [i.5]. The proposed model is conveniently formulated in a MIMO-like form, which enables one to use optimization methods for optimizing the tenable loads connected to each scattering element.

In the far-field of each scattering element of the transmitter, receiver, and RIS, the following simplified model can be used [i.5]:

$$\mathbf{H}_{r,t} \approx (\mathbf{I}_{L0} + \mathbf{Z}_{r,r}\mathbf{Z}_r^{-1})^{-1}\left(\mathbf{Z}_{t,t} + \mathbf{Z}_t\right)^{-1}(\mathbf{Z}_{r,t} - \mathbf{Z}_{r,s}\left(\mathbf{Z}_{s,s} + \mathbf{Z}_{\text{tun}}\right)^{-1}\mathbf{Z}_{s,t})$$

This simplified model has wide applicability in wireless communications because it is expected to operate in the far-field of each scattering element, but not in the far-field of the entire surface.

5.1.4 Inhomogeneous sheets of surface impedance

More precisely, an RIS whose unit cells have sizes and inter-distances much smaller than the wavelength is homogenizable and can be modeled as a continuous surface sheet through appropriate surface functions, i.e. surface impedances. This modeling approach is not dissimilar from the characterization of bulk (three-dimensional) metamaterials, which are usually represented through effective permittivity and permeability functions that determine the wave phenomena based on Maxwell's equations. The only difference is that a metasurface is better modeled by effective surface parameters, which manifest themselves in electromagnetic problems that are formulated as effective boundary conditions. These boundary conditions can be expressed in terms of surface polarizabilities, surface susceptibilities, or surface impedances (or admittances). Under these assumptions, an RIS can be modeled as an inhomogeneous sheet of polarizable particles (the unit cells) that is characterized by an electric surface impedance and a magnetic surface admittance, which, for general wave transformations, are dyadic tensors. These two dyadic tensors constitute the macroscopic homogenized model of an RIS. Once the homogenized and continuous electric surface impedance and magnetic surface admittance are obtained based on the desired wave transformations, the microscopic structure and physical implementation of the RIS in terms of unit cells are obtained. Generally speaking, once the macroscopic surface impedance and admittance are determined, appropriate geometric arrangements of sub-wavelength unit cells and the associated tuning circuits that exhibit the corresponding electric and magnetic response are characterized by, typically, using full-wave electromagnetic simulations.

5.2 Models for radio localization and sensing

5.2.1 Scenarios

5.2.1.1 Localization scenarios

With cellular localization, the User Equipment (UE) location can be estimated based on a variety of measurements from the received signal, including the signal strength, Time of Arrival (ToA), Round-Trip Time (RTT), Angle of Arrival (AoA) and Angle of Departure (AoD). The scenarios can be categorized as SISO localization, MISO localization, SIMO localization, and MIMO localization as shown in Figure 2, where the symbols τ, ϕ, and θ indicate ToAs, AoDs, and AoAs, respectively.

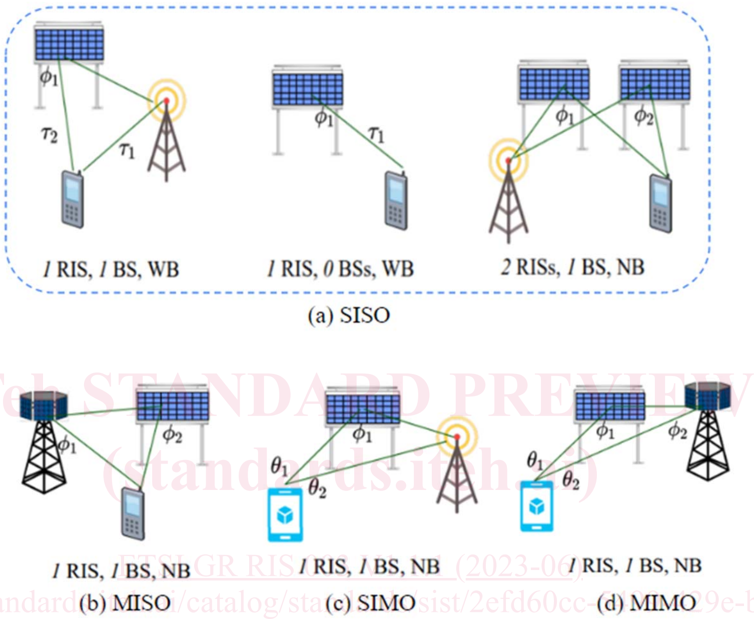


Figure 2: Localization scenarios

5.2.1.2 SISO localization

In this scenario, the Base Station (BS) and UE are both equipped with a single antenna.

In the SISO system with 1 RIS and 1 BS, Wide-Band (WB) pilots should be used to measure the ToAs for the direct (i.e. the path BS-UE) and the reflected (i.e. the path BS-RIS-UE) paths, from which the resulting TdoA can be can calculated and so the corresponding hyperboloid in 3D space. By using different RIS phase profiles at different transmission times, the AoD from the RIS to the UE can be estimated, which geometrically translates to a half-line. Therefore, the UE position can be calculated via the intersection between such half-line and the abovementioned hyperboloid.

In the SISO system with 2 (more than 1) RIS and 1 BS, UE positioning even with NB signalling can be performed, which does not allow ToA estimation. Indeed, the UE position can be estimated via the intersection of the two half-lines corresponding to the AoDs from the RIS. The direct BS-UE path does not carry any position information, thus localization can be performed even when the direct path is blocked.

In the SISO system with 1 RIS in the absence of a BS, the RTT and the AoD from the RIS to the UE can be measured. Geometrically, they respectively correspond to a sphere centered in the RIS and a half-line originated in the RIS, whose intersection returns the UE position estimate.

5.2.1.3 MISO localization

In this scenario, the BS is equipped with multiple antennas while the UE is with a single antenna. The UE position can be estimated by intersecting the two half-lines corresponding to the two AoDs from the BS and the RIS.

5.2.1.4 SIMO localization

In this scenario, the UE is equipped with multiple antennas while the BS is with a single antenna. Two AoAs and one AoD from the RIS can be measured. Using the two AoAs, the user on (part of) a spindle Torus can be located, whose intersection with the line corresponding the AoD locates the UE. Then the UE orientation can be estimated via the two AoAs.

5.2.1.5 MIMO localization

In this scenario, both the BS and the UE are equipped with multiple antennas. The UE position can be estimated via the two AoDs (by intersecting the two corresponding half-lines) while the UE orientation can be derived from the two AoAs.

5.2.1.6 RIS-aided and RIS-standalone

In 3GPP, location (or position) can be estimated from NW (i.e. gNB, TRP, etc.) and/or UE side. For instance, timing difference based (i.e. DL/UL TdoA) and angular based (i.e. DL/UL DoA, AoA, etc.) algorithms are supported in 3GPP standards. When RIS is involved in the localization, two RIS localization scenarios can be considered:

- RIS-aided localization.
- RIS-standalone localization.

RIS-aided localization refers to the case where RIS can assist NW and UE for location estimation as shown in Figure 3 (see scenario (a)). RIS-standalone localization refers to the case where RIS and UE are majorly involved for location estimation but NW can still assist the localization without the awareness of UE as shown in Figure 3 (see scenario (b)).

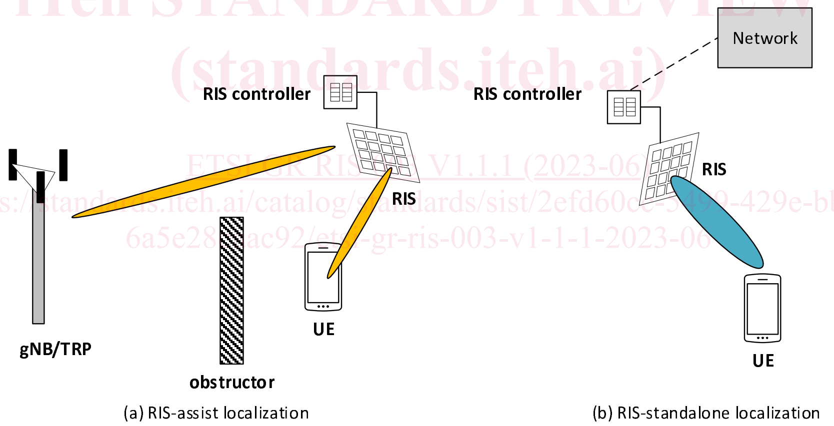


Figure 3: RIS localization scenarios (a) RIS-assisted (b) RIS-standalone

Based on the RIS deployment, RIS localization can be categorized in terms of the following factors for different scenarios, i.e. RIS-aided and RIS-standalone localization:

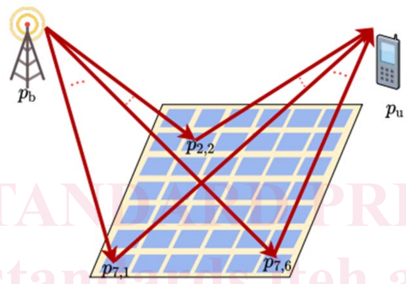
- With or without the direct path between UE and NW.
- Operating regime: far-field or near-field.
- Frequency range: sub-6 GHz or mmWave (i.e. FR2, FR2+, etc.).
- Antenna setting between NW and UE: SISO, SIMO, MISO, and MIMO.
- RIS type: passive, semi-active, or active.
- RIS control setting: e.g. the number of RIS elements used for the localization.

There are three channel paths in the RIS-aided communication (BS-RIS-UE) which can be categorized as the BS-RIS path, the RIS-UE path, and (BS-UE) path (or direct path). Therefore, when considering RIS localization, it needs to be further analysed whether there exists a direct path (i.e. BS-UE) or not. This is because when there is a direct path, the UE localization may reuse existing position techniques or can be enhanced with RIS assistance. In addition, operating regimes such as far-field or near-field may have nominal impact factors for the accuracy of the location estimation. Also, RIS type in terms of semi-active or active RIS, the active RIS and the number of elements used for localization could have an impact for location estimation. Finally, antenna setting between NW and UE can be specified as one of the considered factors for RIS-aided localization. For the standalone RIS localization considered, wherein the direct path is either completely blocked or severely affected and hence may not be utilized for the purpose of localization.

5.2.2 Near-field

5.2.2.1 Near-field regimes

For localization purposes, sparse parametric models are often used, where the channel is represented via a few geometric components. Figure 4 illustrates a one-ray SISO system including one RIS, where both the BS and UE are in the near field of the RIS. In this case, the received signal in the downlink can be calculated as a sum of individual rays reflected from each RIS element at the UE location.



NOTE: The received signal in the downlink can be expressed as function of the UE position.

Figure 4: The near-field regimes of the RIS-enabled signal propagation with respect to the RIS

Assume there are M RIS while each RIS consists of L phase-tuneable meta-atom elements and is implemented with the single-RX-RF architecture. The user broadcasts a pilot symbol s with constant transmit power P. This symbol is received T times by each RIS, where during each repetition a different RIS phase profile is used. In the presence of C_m distinct channel paths, the observation during the t-th reception slot (t = 1, 2,..., T) at the m-th RIS's RX RF chain output can be mathematically expressed as follows:

$$y_{m,t} = \boldsymbol{u}_{m,t}^H \sum_{c=1}^{C_m} h_{m,c}\, \boldsymbol{\alpha}(\mathbf{p}_{m,l}, \mathbf{p}_u) s + \boldsymbol{u}_{m,t}^H \boldsymbol{w}_{m,t}$$

where $h_{m,c} = \sqrt{P_{L_{m,c}}}\, exp(j\varphi_m)\ \forall c = 1,2,\ldots,C_m$ includes the gain of the c-th signal propagation path with parameter $P_{L_{m,c}}$ denoting the free-space pathloss. Without loss of generality, the c = 1 channel path represents the Line Of Sight (LOS), hence, its pathloss $P_{L_{m,1}}$ depends on the Euclidean distance $r_{m,1} = \|\mathbf{p}_m - \mathbf{p}_u\|$ with $\mathbf{p}_m$ denoting the position of m-th RIS; each distance $r_{m,c}$ for $c \geq 2$ is defined similarly considering the position of the corresponding scatterer. In the expression for $h_{m,c}$, $\varphi_m \sim \mathcal{U}(0,2\pi)$ denotes a global phase offset accounting for the lack of phase synchronization between the user and the m-th RIS. The vector $\boldsymbol{u}_{\boldsymbol{m},\boldsymbol{t}} \in \mathbb{C}^{L\times 1}$ is the t-th phase configuration of the m-th RIS. The vector $\boldsymbol{w}_{m,t} \in \mathbb{C}^{L\times 1}$ represents the Additive White Gaussian Noise (AWGN). Finally, the spatial response vector $\boldsymbol{\alpha}(\mathbf{p}_{m,l}, \mathbf{p}_u) \in \mathbb{C}^{L\times 1}$ of the user transmitted signal via multipath propagation given for l= 1, 2,..., L is as follows:

$$[\boldsymbol{\alpha}(\mathbf{p}_{m,l}, \mathbf{p}_u)]_l = \boldsymbol{exp}\left(j\frac{2\pi}{\lambda}\|\mathbf{p}_{m,l} - \mathbf{p}_u\|\right)$$

with $\boldsymbol{\lambda}$ as the signal wavelength.