Non-Reciprocal RIS-Assisted Wireless Communications: Channel Modeling

1st Zahra Taheri
ECE Department
Concordia Univarsity
Montreal, Canada
zahra.taheri@concordia.ca

2nd Mohammad Reza Soleymani
ECE Department
Concordia Univarsity
Montreal, Canada
reza.soleymani@concordia.ca

3rd Gursimran Singh Sethi
LATYS Intelligence Inc.
Montreal, Canada
gursimran@latys.ca

***Abstract*—Non-reciprocal reconfigurable intelligent surface (NR-RIS) has emerged as a promising technology for enhancing the performance of wireless communication systems. Unlike conventional RIS, NR-RIS can support asymmetric signal transmission, which enables different signal paths between the transmitter and receiver. In this paper, we investigate the potential of NR-RIS-assisted wireless communication systems and analyze the impact of various system parameters on performance metrics, including the signal-to-noise ratio (SNR) and the bit error rate (BER). Specifically, we first develop a path loss model for a simple RIS-aided system, and we study the effect of different parameters, such as the number of RIS elements, and the distance between the base station, RIS, and user. We then derive a channel model for nonreciprocal RISs, and we study the effects of non-reciprocity on the channel coefficients and phase shift matrix at RIS in both uplink and downlink channels. Simulation results show that nonreciprocity can significantly affect the performance of RIS-aided systems and that a careful design of the RIS is necessary to achieve optimal performance.**

***Index Terms*—Reconfigurable Intelligent Surface (RIS), Path-loss model, Non-reciprocity, Channel modeling**

I. Introduction

Wireless communication has become an essential part of modern life, connecting people and devices across the globe. However, the growing demand for wireless connectivity is putting a strain on existing wireless networks, leading to issues such as low signal strength, interference, and high power consumption. To address these challenges, researchers have been exploring new technologies to enhance the performance of wireless networks. One such technology that has gained significant attention in recent years is the reconfigurable intelligent surface (RIS) [1]. RISs are passive/ active surfaces composed of a large number of small, reconfigurable reflecting elements that can manipulate the phase and amplitude of incoming electromagnetic waves. By controlling the reflection coefficients of these elements, RISs can focus, amplify, or attenuate the signal power in a desired direction, thereby enhancing the coverage, rate, and energy efficiency of wireless networks [2].

Path loss is a critical factor that affects the performance of wireless communication systems. It refers to the attenuation of the signal strength as it propagates from the transmitter to the receiver, and it is influenced by various factors such as distance, obstacles, and frequency. In the case of RIS-assisted systems, the path loss model needs to take into account the additional effects of the RIS on the signal propagation [3].

In [4] a path loss model based on the geometric properties of the RIS is proposed and derived an analytical expression for the received signal power. They also validated their model through experimental measurements and showed that RISs can significantly improve the signal quality in wireless communication systems. The models explain the relationships between the free-space path loss of RIS-assisted wireless communications and factors such as the near-field/far-field effects of the RIS, and the radiation patterns of antennas and unit cells.

The paper [5] describes a method for calculating the path loss of a wireless communication channel using a passive reflectarray-type RIS. This model takes into account factors such as RIS size, link geometry, and the method used to set the element states. The model is used to compare the path loss of RIS-enabled channels with that of free space direct and specular reflection channels, which is important for the design of networks using RIS technology.

In this paper, we examine a straightforward model for path loss, exploring how different parameters affect the output signal-to-noise ratio (SNR) of the system. Specifically, the impact of factors like the number of RIS elements, the distance between the transmitter and receiver from the RIS, as well as the antenna aperture size, is studied.

Most of the existing studies on RISs have assumed reciprocal channels and reciprocal RIS, where the reflection coefficients of RIS elements are the same for both directions of propagation [6]. However, in reality, RISs may exhibit non-reciprocity, where the reflection coefficient of an RIS element depends on the direction of incidence. In a non-reciprocal RIS, as we can see in Figure.1, the incident signal at angle 1 will be reflected as an outgoing signal at angle 2, but the incident signal at angle 2 will not be redirected to the outgoing signal at angle 1 due to non-reciprocity of the system.

The paper [6] discusses the channel reciprocity in RISs assisted wireless networks. Channel reciprocity is a property that facilitates downlink precoding in TDD multiple-input

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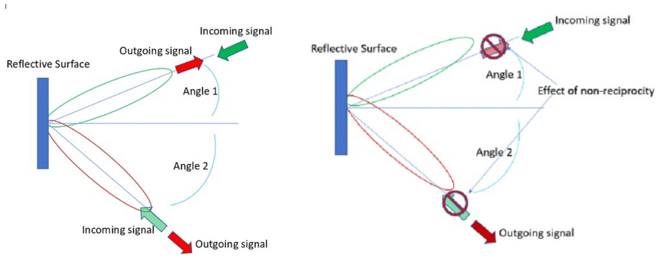

Fig. 1. Reciprocal and non-reciprocal reflective surface

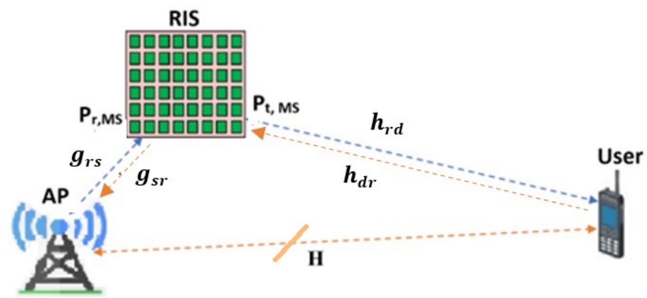

Fig. 2. System Model

multiple-output communications without the need for channel state information feedback. This paper reviews the reciprocity theorem and shows that there is still channel reciprocity for RIS-assisted wireless networks satisfying certain conditions. [6] also demonstrates the reciprocity at sub-6 GHz and millimeter-wave frequency bands using two fabricated RISs. Furthermore, introduces several RIS-assisted approaches to realizing nonreciprocal channels and outlines potential opportunities brought by reciprocal/nonreciprocal RISs and future research directions.

Non-reciprocal RISs have recently emerged as an alternative solution that can overcome some of the limitations of reciprocal RISs and improve the performance of wireless networks.

In [7] nonreciprocal radiation has been discussed, which refers to electromagnetic wave radiation that provides different responses depending on the direction of the incident field. To address the need for versatile apparatuses capable of full-duplex nonreciprocal wave processing and amplification, [7] proposes an architecture that integrates a chain of series cascaded radiating patches with nonreciprocal phase shifters. This architecture results in an ultrathin reflective metasurface that provides directive and diverse radiation beams, large wave amplification, and steerable beams, all of which can be controlled and programmed by changing the bias of the gradient active nonmagnetic nonreciprocal phase shifters.

The paper [8] focuses on investigating the two-way communication between two users with the help of a reconfigurable intelligent surface (RIS) under the scheme of simultaneous communication over Rayleigh fading channels. The channels between the users and the RIS can either be reciprocal or non-reciprocal. The authors in [8] determine the optimal phases at the RIS to maximize the signal-to-interference-plus-noise ratio (SINR) for reciprocal channels. This paper also presents exact closed-form expressions for the outage probability and spectral efficiency for single-element RIS and introduces a gamma approximation to evaluate the performance metrics for multiple-element RIS.

Intelligent metasurfaces are discussed in [9], which are dynamic and programmable structures capable of both reciprocal and nonreciprocal signal wave transmissions in a full-duplex manner. The metasurfaces can be controlled and programmed using a dc bias and RF modulation applied to the active components of the unit cells. [9] highlights that intelligent metasurfaces can improve wireless communication systems' performance by providing real-time signal coding, nonreciprocal-beam radiation, nonreciprocal beamsteering amplification, and advanced pattern-coding multiple access communication.

This paper investigates the channel model for non-reciprocal RISs. Unlike reciprocal RISs, non-reciprocal RISs have different channel coefficients and phase shift matrices for the downlink and uplink channels. We propose a novel optimization approach for the channel coefficients and phase shift matrices based on minimizing the mean square error.

The rest of the paper will be structured as follows: Section 2 will describe the system model and path-loss model for a RIS-aided system. Section 3 will discuss the channel model for non-reciprocal RIS and analyze the implications of non-reciprocity on the wireless network. Section 4 will present the simulation results and discussion. Finally, Section 5 will conclude the paper.

II. System Model and Analysis

The objective of this model is to determine and optimize the signal-to-noise ratio (SNR) between a system enabled with RIS and without the RIS (i.e., baseline mode).

It is assumed that the presence of the metasurface does not block or reduce the original power received from the access point (AP). Isotropic AP and user antennas are considered and the gain of the metasurface is a linear combination of the receive aperture, the active DC gain, and the transmit aperture. The difference between the SNR in the presence of the RIS and the baseline mode is given by:

$$\Delta SNR = SNR_{ON} - SNR_B \tag{1}$$

where SNR_{ON} and SNR_B are the signal-to-noise ratios with the RIS and in the baseline mode, respectively.

A system model is shown in Figure 2. The baseline power received by the user without the RIS is calculated using the Friis Transmission Equation as follows:

$$P_{r,B} = P_t + G_t + G_r - PL \tag{2}$$

The maximum power received by the metasurface is calculated using the Friis equation as:

$$P_{r,Ms} = \frac{P_t A_e}{4\pi r^2} \tag{3}$$

where $G = \frac{4\pi A_e}{\lambda^2}$, $P_L = (\frac{4\pi r}{\lambda})^2$, and $G_{Ms} = G_{AP} + G_{dc}$.

Assuming that the active surface adds a DC amplifier gain which can be decoupled as G_{dc}, the output power (without transmit aperture gain) is given by:

$$P_{t,Ms} = \frac{P_t A_e}{4\pi r^2} \times G_{dc} \tag{4}$$

The received power in the RIS ON state and the baseline mode is given by:

$$P_{r,user} = \frac{P_t A_e^2 G_{dc}}{(4\pi)^2 r^2 d^2} + \frac{P_t \lambda^2}{(4\pi(r+d))^2} \tag{5}$$

So, based on this model, we have,

$$\Delta SNR = \frac{A_e^2 G_{dc}(r+d)^2}{\lambda^2 r^2 d^2} + 1 \tag{6}$$

This model aims to calculate and maximize the difference between the signal-to-noise ratio of the RIS-enabled system with and without the presence of RIS (ON/Baseline), based on a set of assumptions, including no blocking, a simple path loss model, isotropic AP and user, and constant noise power.

III. Non-Reciprocal Channel Model

The channel model for the non-reciprocal RIS-aided wireless network can be represented by two separate uplink and downlink channels, which have different channel coefficients due to the non-reciprocity of the system. Let $\boldsymbol{g}_{sr} \in \mathbb{C}^{N_r \times 1}$ denote the channel vector from the AP to the RIS, and $\boldsymbol{h}_{rd} \in \mathbb{C}^{1 \times N_r}$ denote the channel vector from the RIS to the user in the downlink channel. Similarly, let $\boldsymbol{g}_{rs} \in \mathbb{C}^{N_r \times 1}$ denote the channel vector from the user to the RIS, and $\boldsymbol{h}_{dr} \in \mathbb{C}^{1 \times N_r}$ denote the channel vector from the RIS to the AP in the uplink channel. Here, we consider there is no line-of-sight channel. Then, the received signals at the user and the AP can be expressed as follows:

Downlink channel:

$$y_d = \boldsymbol{h}_{rd} \boldsymbol{\Theta}_d \boldsymbol{g}_{sr} \boldsymbol{x}_s + n_d \tag{7}$$

Uplink channel:

$$y_u = \boldsymbol{h}_{dr} \boldsymbol{\Theta}_u \boldsymbol{g}_{rs} \boldsymbol{x}_u + n_u \tag{8}$$

where $\boldsymbol{\Theta}_d = \operatorname{diag}\left(e^{j\theta_{d,1}}, \ldots, e^{j\theta_{d,N_r}}\right)$ and $\boldsymbol{\Theta}_u = \operatorname{diag}\left(e^{j\theta_{u,1}}, \ldots, e^{j\theta_{u,N_r}}\right)$ are the diagonal matrices of the phase shifts applied to the reflecting elements at the RIS in the downlink and uplink channels, respectively, $\boldsymbol{h}_{rd}$ and $\boldsymbol{h}_{dr}$ are the channel coefficients for the downlink and uplink channels, respectively, $\boldsymbol{x}_s$ and $\boldsymbol{x}_u$ are the transmit signals from the AP and the user, respectively, and n_d and n_u are the additive white Gaussian noises at the user and the AP, respectively. P_s and P_u are the power constraints for the transmit signals from the AP and the user, respectively. $\mathcal{F}$ is the set of feasible phase shifts that can be implemented by the RIS, and $\mathcal{H}$ is the set of feasible channel coefficients for the uplink and downlink channels.

The objective function minimizes the sum of the mean square errors between the received signals at the user and the AP and their corresponding desired signals. The first term in the objective function corresponds to the downlink channel and the second term corresponds to the uplink channel.

The objective function minimizes the mean square error between the received signals at the user and the AP and their corresponding desired signals. This means that the optimization problem aims to find the channel coefficients and phase shifts that result in the best possible approximation of the desired signals at the user and the AP, respectively, given the channel and power constraints. In the optimization problem for non-reciprocal RIS-aided wireless network, the objective function is to minimize the sum of the mean square errors between the received signals at the user and the AP and their corresponding desired signals. To be more specific, the desired signal in the uplink channel represents the signal that the AP wants to receive from the user, and the desired signal in the downlink channel represents the signal that the user wants to receive from the AP. These desired signals can be a known pilot sequence or can be designed based on the specific application requirements.

Therefore, the optimization problem aims to find the channel coefficients and phase shifts for the uplink and downlink channels that result in the best possible approximation of the desired signals at the AP and the user, respectively, given the channel and power constraints.

The optimization problem to minimize the sum of mean square errors between the received signals and their corresponding desired signals can be formulated as follows:

$$\underset{\boldsymbol{h},\boldsymbol{g},\boldsymbol{\Theta}_d,\boldsymbol{\Theta}_u}{\text{minimize}} \frac{1}{2}\left(|\boldsymbol{y}_d - \boldsymbol{h}_{rd}\boldsymbol{\Theta}_d\boldsymbol{g}_{sr}\boldsymbol{x}_s|_F^2 + |\boldsymbol{y}_u - \boldsymbol{h}_{dr}\boldsymbol{\Theta}_u\boldsymbol{g}_{rs}\boldsymbol{x}_u|_F^2\right)$$

subject to

$\boldsymbol{\Theta}_d = \operatorname{diag}\left(e^{j\theta_{d,1}}, \ldots, e^{j\theta_{d,N_r}}\right), \theta_{d,n} \in [0, 2\pi), \forall n,$

$\boldsymbol{\Theta}_u = \operatorname{diag}\left(e^{j\theta_{u,1}}, \ldots, e^{j\theta_{u,N_r}}\right), \theta_{u,n} \in [0, 2\pi), \forall n,$

$0 \leq P_k \leq P_k^{max}, \forall k \in \{s, u\}$ (9)

where $\boldsymbol{y}_d$ and $\boldsymbol{y}_u$ are the received signals at the user and the AP in the downlink and uplink channels, respectively, $\boldsymbol{h}_{sr}$ and $\boldsymbol{h}_{rs}$ are the channel matrices for the uplink and downlink channels, respectively. The optimization variables are the channel matrices and the phase shift matrices at the RIS for the uplink and downlink channels. The constraints ensure that the phase shifts are within the range $[0, 2\pi)$ for all elements of the diagonal matrices.

This optimization problem is difficult to solve in closed form due to the non-convexity of the objective function and the presence of non-linear constraints. One possible approach to solving this problem is to use iterative algorithms such as gradient descent, stochastic gradient descent, or alternating optimization.

For example, one iterative algorithm that can be used to solve this problem is the alternating optimization algorithm, which alternates between optimizing the phase shifts at the RIS and the channel matrices for the uplink and downlink channels. Specifically, in each iteration, we can first keep the phase shift matrices constant at the RIS and optimize the channel matrices using least squares estimation. Then, we can keep the channel matrices constant and optimize the phase shift matrices at the RIS using gradient descent or other iterative algorithms.

While this approach may not yield a globally optimal solution, it can still lead to good performance in practice. Other optimization algorithms may also be used, depending on the specific problem requirements and constraints.

The optimization problem can be solved using the alternating optimization (AO) algorithm, which alternates between optimizing each variable while fixing the others.

The steps of the AO algorithm to solve this optimization problem are as follows:

- Initialize the channel matrices and the phase shift matrices at the RIS for the uplink and downlink channels.

- Repeat until convergence;

- Keep constant the channel matrices and the phase shift matrix at the RIS for the uplink channel, and solve for the channel matrix and the phase shift matrix at the RIS for the downlink channel using the following equation:

$$\boldsymbol{\Theta}_d^*, \boldsymbol{h}_{rd}^*, \boldsymbol{g}_{sr}^* = \underset{\boldsymbol{\Theta}_d, \boldsymbol{h}_{rd}, \boldsymbol{g}_{sr}}{\operatorname{argmin}} \frac{1}{2}\left(|\boldsymbol{y}_d - \boldsymbol{h}_{rd}\boldsymbol{\Theta}_d\boldsymbol{g}_{sr}\boldsymbol{x}_s|_F^2\right) \quad (10)$$

- The channel matrices and the phase shift matrix at the RIS for the downlink channel should be constant, and solve for the channel matrix and the phase shift matrix at the RIS for the uplink channel using the following equation:

$$\boldsymbol{\Theta}_u^*, \boldsymbol{h}_{dr}^*, \boldsymbol{g}_{rs}^* = \underset{\boldsymbol{\Theta}_u, \boldsymbol{h}_{dr}, \boldsymbol{g}_{rs}}{\operatorname{argmin}} \frac{1}{2}\left(|\boldsymbol{y}_u - \boldsymbol{h}_{dr}\boldsymbol{\Theta}_u\boldsymbol{g}_{rs}\boldsymbol{x}_u|_F^2\right) \quad (11)$$

- Update the channel matrices and the phase shift matrices at the RIS for the uplink and downlink channels using the following equations:

$$\boldsymbol{\Theta}_d \leftarrow \boldsymbol{\Theta}_d^*, \boldsymbol{h}_{rd} \leftarrow \boldsymbol{h}_{rd}^*, \boldsymbol{g}_{sr} \leftarrow \boldsymbol{g}_{sr}^* \quad (12)$$

$$\boldsymbol{\Theta}_u \leftarrow \boldsymbol{\Theta}_u^*, \boldsymbol{h}_{dr} \leftarrow \boldsymbol{h}_{dr}^*, \boldsymbol{g}_{rs} \leftarrow \boldsymbol{g}_{rs}^* \quad (13)$$

- Obtain the output of the final channel matrices and phase shift matrices at the RIS for the uplink and downlink channels.

Note that the optimization problem for each step is a least-squares problem, which can be solved efficiently using methods such as the QR decomposition or the singular value decomposition. The AO algorithm converges to a locally optimal solution, and the performance can be further improved by using more advanced optimization methods or incorporating additional constraints or objectives.

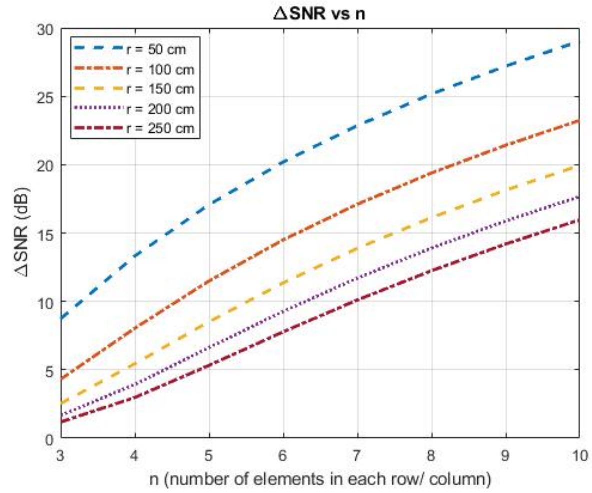

Fig. 3. Signal to noise ratio versus aperture size (element's order)

IV. Simulation Results

We simulated the SNR versus aperture size for different feeding distances based on the path loss model, as shown in Figure 3. As we can see from the figure, increasing the aperture size improves the SNR for all feeding distances. This is because a larger aperture size results in more elements in the RIS surface, which can provide a higher gain for the signal reflected by the RIS. However, the tradeoff of having large number of elements is the complexity and scaling of larger number of elements. Additionally, active Non-Reciprocal RIS' are also power hungry and therefore scaling to an arbitrarily large antenna aperture (n) is also not viable. Therefore, an optimum tradeoff must be developed to suit the needs of the network, this decision is largely application specific.

In Figure 4, the effect of feeding distance on the SNR for different aperture sizes is simulated and increasing the aperture size improves the SNR for all feeding distances. However, we also observe that the improvement in SNR diminishes as the feeding distance increases. This is primarily because the signal attenuation increases with the square of the distance, which reduces the total power captured by the RIS. This is effect is commonly termed as illumination inefficiency, as lesser power washes over the RIS which reduces the overall gain of an individual RIS. This can be compensated by placing the RIS in the vicinity of the source, however this leads to near-field effects which are out of scope for this paper.

In Figure 5, we compare the bit error rate (BER) performance of a non-reciprocal RIS-aided system and a system without RIS. The non-reciprocal RIS-aided system outperforms the system without RIS for all SNR values. This is because the RIS can effectively enhance the signal power and reduce the interference, leading to a better BER performance. Additionally, we observe that the non-reciprocity of the RIS can affect the BER performance. This highlights the importance of carefully designing the RIS to account for non-reciprocal effects.

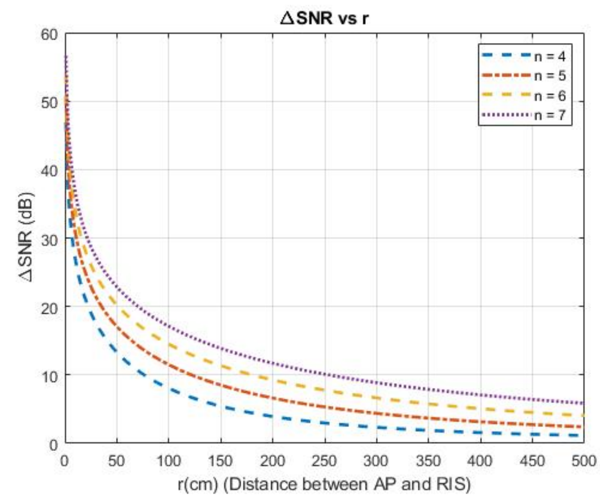

Fig. 4. Signal to noise ratio versus feeding distance

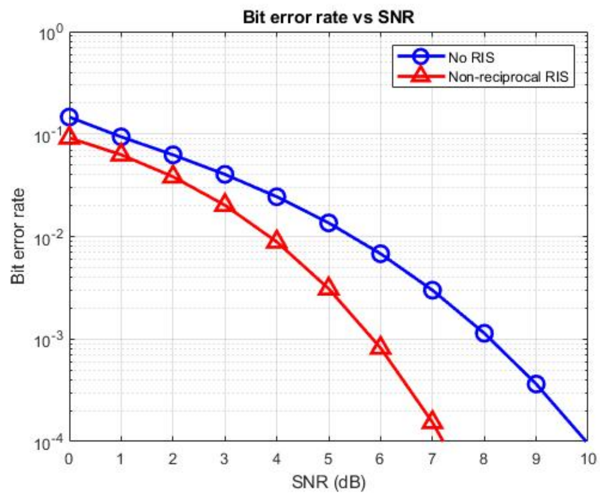

Fig. 5. Bit error rate versus SNR

As mentioned, RIS can enhance the signal-to-noise ratio (SNR) of the communication link, which can result in a reduction in the BER. By reflecting and modifying the incident signals, RIS can improve the channel quality and increase the received signal power. This is particularly beneficial for millimeter-wave (mmWave) communication systems, where the signal strength is typically weak due to high path loss.

V. Conclusion

In this paper, we examine a straightforward model for Path loss, exploring how different parameters affect the output signal-to-noise ratio (SNR) of the system. Specifically, the impact of factors like the number of RIS elements, the distance between the transmitter and receiver from the RIS, as well as the antenna aperture size, is studied. This paper investigates the channel model for non-reciprocal RISs. Unlike reciprocal RISs, non-reciprocal RISs have different channel coefficients and phase shift matrices for the down- link and uplink channels. We propose a novel optimization approach for the channel coefficients and phase shift matrices based on minimizing the mean square error.

In conclusion, our investigation demonstrates that non-reciprocal RIS-assisted wireless communication systems have the potential to significantly improve the performance of wireless communication systems. By supporting asymmetric signal transmission, NR-RIS can enable different signal paths between the transmitter and receiver, which can enhance the channel quality and improve the SNR and BER performance of the system. However, a careful design and optimization of NR-RIS systems are necessary to achieve optimal performance.

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