To RIS or not to RIS: a ray-tracing study of RIS-assisted indoor 5G communications

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***Abstract*—Reconfigurable Intelligent Surfaces (RIS) leverage arrays of programmable elements to manipulate incident electromagnetic waves dynamically. In non-line-of-sight conditions between a 5G base station and user equipment, RIS can act as a passive relay, redirecting signals to get around obstacles.**

In this paper, we use the open-source Sionna library to assess the performance gains of RIS-assisted 5G indoor communication. Specifically, we use Sionna's ray tracing module to reconstruct propagation paths and analyze coverage maps and received signal strength (RSS). The results show that while RIS can improve the received signal, an accurate estimation of the transmitter and receiver locations is required.

***Index Terms*—Reconfigurable intelligent surfaces, ray tracing, channel modeling, Sionna RT, coverage heatmap.**

I. Introduction

Wireless communication systems are rapidly expanding, driven by the need for ultra-fast networks and reliable data transmissions [1], [2], [3]. However, these technologies still face challenges, especially in indoor environments where *Non-Line-of-Sight* (NLoS) connections significantly degrade signal quality. Obstacles such as walls, furniture, and complex layouts increase interference and reduce network coverage [4].

Reconfigurable *Intelligent Surfaces* (RIS) are key enablers for 6G [5]. RIS comprises programmable metasurfaces manipulating electromagnetic waves to enhance signal strength and coverage. Modeling and simulations are valuable tools for evaluating the impact of RIS placement and configuration in RIS-enabled cellular networks [6], [7].

To evaluate the effectiveness of RIS in improving data transmission, state-of-the-art methods rely on statistical channel modeling or deterministic techniques based on physical laws [8]. Ray tracing is now commonly used to compute propagation paths and analyze wireless channels [9]. This approach uses geometric optics and electromagnetic theory to model radio wave propagation, essential to understanding how RIS interacts with its environment.

In this paper, we propose to study whether the RIS can improve signal quality in the case of indoor 5G communications. To that aim, we simulate wave propagation and study the effect of the RIS on the received signal with the NVIDIA *Sionna Ray Tracing* (Sionna RT) library. We consider the short-range indoor environment (decameters) to quantify how much a RIS can improve received signal strength coverage to evaluate the signal on the entire indoor environment, not only at the expected receiver. We selected the short-range indoor 5G cases as they involve relatively low frequencies (sub 6GHz) and because the signal remains relatively strong at the scale of a few meters, no matter what is in the environment.

The main contributions of this paper are:

- We introduce the NVIDIA Sionna RT simulator and provide an up-to-date state-of-the-art of the recent research and development related to this field.
- We present key insights into the Sionna channel model for indoor 5G communications and a workflow to simulate such an environment.
- Based on the simulation results, we show that using the RIS in 5G indoor communications can improve the received signal strength, but it requires accurate knowledge of the transmitter and receiver locations; otherwise, it may degrade signal strength.

The paper is organized as follows. Sec. II gives the necessary background on RIS and how the Sionna RT simulator models them. Sec. III presents how to model indoor RIS-assisted 5G environments with Sionna. Sec. IV then evaluates the benefits of using an RIS indoors regarding signal strength coverage. Finally, Sec. V concludes this work and provides insights for future work.

II. Enhancing wireless signal communication with RIS in NLOS Scenarios

This section describes the application of Sionna RT to a static RIS in an NLOS scenario with a single transmitter and a single receiver. The rest of the section presents a concise overview of the RIS, the Sionna RT simulator, focusing on the description of its channel and system model used for the performance evaluation.

A. Principles and Functionality of the RIS

RIS have recently gained significant interest in wireless communication due to their potential to control electromagnetic waves in several applications [1]. They comprise numerous elements arranged in a periodic structure and exhibiting small dimensions compared to wavelengths. RIS devices utilize this principle of operation and incorporate controllable elements, allowing for gradual changes in the angle over time [1], [10]. Specifically, each RIS element can be configured individually and in real-time to induce controllable manipulation of specific characteristics of the incident signal (e.g., phase, amplitude, polarization, etc.). In this case, RIS enable to control the direction of the reflected signals, allowing them to converge on a point instead of a specular reflection. To achieve this, the electromagnetic response of each of the reflecting elements is first adjusted by setting the surface impedance through electrical stimulation, causing a phase shift of the incoming signals of each reflecting element of the RIS, and thus controlling the main direction of the reflected signals [6]. The proper placement of RIS in the communication chain is crucial for efficient transmission and reception. Various studies have focused on the physics and signal models of RIS to enhance the performances of a wireless network. Communication models for RIS also emphasize the need for a general design framework on the transmitter and receiver sides. Its configuration (phase shifts, amplitude, polarization) is tailored to propagation conditions and desired results.

B. Sionna RT simulation framework

Sionna™ is an open source TensorFlow-based GPU-accelerated framework that emerged as a powerful tool for simulating 6G communication systems [11]. It is built on Python, TensorFlow, and Keras, which minimizes computations and saves time by providing efficient and scalable simulations with high computational effectiveness. For example, the ray tracing engine enables RIS propagation modeling [11]. Some of the most recent studies explored the integration of RIS in various scenarios using Sionna RT. Yet, the documentation on using RIS in Sionna RT [11], [12], and the supporting paper [13] provides valuable guidance and information on how to test the RIS under different conditions to enhance signal power. The work presented in [14] is a good case investigating the optimization of RIS for wireless channels in urban areas with Sionna RT. The authors provide the performance summary of RIS methods under different deployment conditions through different RIS optimization algorithms based on channel estimation. The study proposed in [15] presented a DT-RaDaR method. This approach uses ray tracing for robot navigation, specifically designed for indoor and smart city environments. Although the primary application and interest were robot navigation, this method of ray tracing for RF propagation was also extended to incorporate wireless communication scenarios with RIS. Shabanpour et al. propose a practical framework for designing a physically consistent RIS in [2], addressing the shortcomings of traditional phase-gradient techniques. The study aims at optimizing the RIS reradiation modes using Sionna RT and a gradient-based learning technique for a section of Cape Town. The designed RIS model was validated through full-wave simulations conducted in CST Microwave Studio. In addition, a RIS was fabricated using the parallel plate waveguide technique to validate this approach further and improve the RIS's deployment efficiency in wireless networks. Meanwhile, Zubow et al. introduced NS3-Sionna in [16], which fuses a Sionna RT framework-based ray tracing channel model with the ns-3 network simulator. This integration enables the simulation of realistic channels, such as those aided by RIS, to evaluate network performance.

C. Channel Model with RIS application scenario

This paper uses the Sionna-RIS channel model to simulate a specific scenario involving a RIS in an NLoS environment. We manipulate electromagnetic waves with the RIS to study their impact on received signals and network performance metrics. The channel model relies on ray tracing and geometric optics to represent wave propagation within the environment. Unlike the model of Esad et al. that simplifies RIS interactions [14], the Sionna-RIS channel model considers 3D ray tracing along with ITU/GPP path loss models [11], and polarization effects for realistic signal propagation to simulate signal behavior more realistically. It is based on electromagnetic wave propagation (EM) principles such as scattering and reradiation [11], [12]. However, a key element of the model is the optimization of reradiation modes through the surface impedance Z_s, where the reflection coefficient Γ is given by:

$$\Gamma = \frac{Z_s - Z_0}{Z_s + Z_0} \qquad (1)$$

where Z_0 is the characteristic impedance of the incident wave medium. The behavior of the RIS elements is determined by the impedance matrix Z, which depends on the tangential electric field E_{tan} to the surface current density J as:

$$E_{\text{tan}} = Z \cdot J \qquad (2)$$

In the far field, the reradiation pattern is given by:

$$E_{\text{rerad}}(\theta, \phi) = \frac{jk\eta}{2\pi r} e^{-jkr} \int_S J(x', y') e^{jk(\sin\theta\, x' + \cos\theta\, y')}\, dS \qquad (3)$$

where k is the wavenumber, η is the impedance of the medium, r is the distance to the observation point, $J(x', y')$ is the surface current density on the RIS, and θ and ϕ are the spherical coordinates.

Considering the above and as path loss follows the ITU/3GPP model, it is expressed by:

$$PL(d) = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (4)$$

where d_0 is the reference distance, n is the path loss exponent, and X_σ represents random variations (with zero mean and standard deviation σ) due to environmental interactions. The received signal y is then modeled as:

$$y = \sum_{i=1}^{N} h_i \cdot x + n \qquad (5)$$

where h_i is the channel gain for the i-th path, x is the transmitted signal, and n its additive noise; white Gaussian noise (AWGN) for instance. In this case, the total channel gain h combines a LoS term and NLoS contributions via the RIS, formulated as:

$$h = h_{\text{LOS}} + \sum_{i=1}^{N} h_{\text{Tx-RIS},i} \cdot h_{\text{RIS-Rx},i} \cdot e^{j\theta_i} \qquad (6)$$

where $h_{\text{Tx-RIS},i}$ is the channel coefficient between the transmitter and the i-th RIS element, $h_{\text{RIS-Rx},i}$ is the channel coefficient

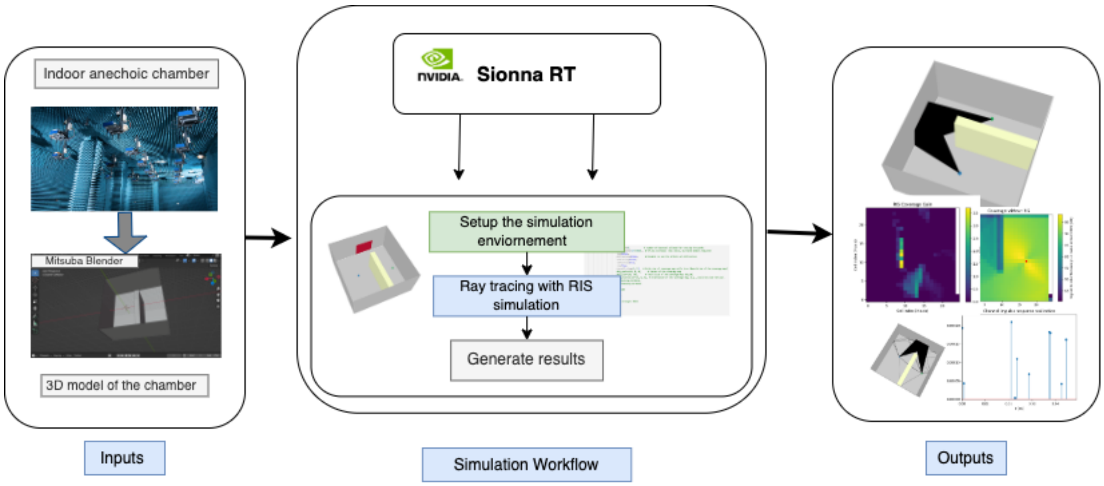


Fig. 1: The simulation workflow of Sionna RT with the RIS-Behavior.

between the i-th RIS element and the receiver, and θ_i is the phase shift applied by the i-th RIS element. Finally, the received power P_r is calculated by:

$$P_r = |E_{\text{received}}|^2 \cdot G_r \qquad (7)$$

where G_r is the receiver gain and E_{received} is the received electric field, resulting from the superposition of multipath components:

$$E_{\text{received}} = \sum_{i=1}^{N} E_{\text{ref},i} \cdot e^{-j\phi_i} \qquad (8)$$

with $E_{\text{ref},i} = \Gamma \cdot E_{\text{inc}}$ and $\Gamma = \frac{Z_s - Z_0}{Z_s + Z_0}$ being the reflection coefficient.

The desired RIS behavior is specified through the surface impedance matrix that defines the interaction of incoming wave with the RIS elements, allowing wave propagation phenomena to be captured. This includes reflections and diffractions, and RIS-assisted paths. Hence, the receiver power is computed from all propagation paths, including the RIS introduced phase shifts and amplitude variations. This enables proper modeling of RIS-assisted communications and optimizing deployments for enhanced signal coverage and efficiency.

III. System Model

To evaluate the benefits of using a RIS in indoor 5G communications we consider scenarios that encompass the position of the RIS with or without an existing LoS connection between the transmitter and the receiver. It uses Sionna RT and its Sionna-RIS channel model, involving a single antenna transmitter (Tx) that sends signals to a RIS. These reflected signals are captured by a single antenna receiver (Rx). Sionna RT aids in the RIS modeling by configuring them with adaptable reflective properties of the amplitude and phase shifts. By manipulating propagation paths, RIS introduces direct and RIS-assisted signal paths. Moreover, the ability of the RIS to adjust reflection phase shifts allows the calculation of the *Channel Impulse Response* (CIR) using the Sionna `compute_paths()` function, CIR is used to characterize the multipath propagation effects and analyze the impact of RIS on the wireless channel. The generated CIR for each path is then converted into the channel frequency response using the `cir_to_ofdm_channel()` function. This process yields the channel coefficients h, which are essential for modeling the wireless channel in RIS-assisted communication systems. Additionally, coverage maps that illustrate signal strength are also generated. The maps are calculated from the squared amplitude of path coefficients at location $\mathbf{r}$, thereby, the path gain is transformed into received signal strength (RSS) as detailed in the Sionna RT documentation [12].

A. Simulation workflow

For all experiments, the simulation workflow is summarized as follows and depicted in Fig. 1.

1) Environment Setup: Involves establishing of the simulation environment by
   - loading the 3D model of the scenario and determining the locations of the transmitter, the receiver, as well as the RIS,
   - configuring their respective antennas,
   - configuring the RIS parameters,
   - defining the material properties for each surface.
2) Ray tracing with RIS simulation: Initiate rays from the transmitter in various directions, according to its antenna parameters, to model radio wave propagation and track these rays as they interact with the environment.
   - Path Computation: Evaluate each ray's impact on the received signal based on direct path, reflections, diffractions, scattering, and RIS interactions.
3) Simulation results:
   - Channel Impulse Response (CIR) Generation: Aggregate the influences of all rays to form the Channel Impulse Response (CIR).
   - Coverage Map Generation: illustrate the spatial distribution of signal power across the simulated area.

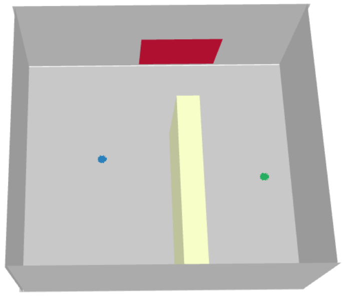
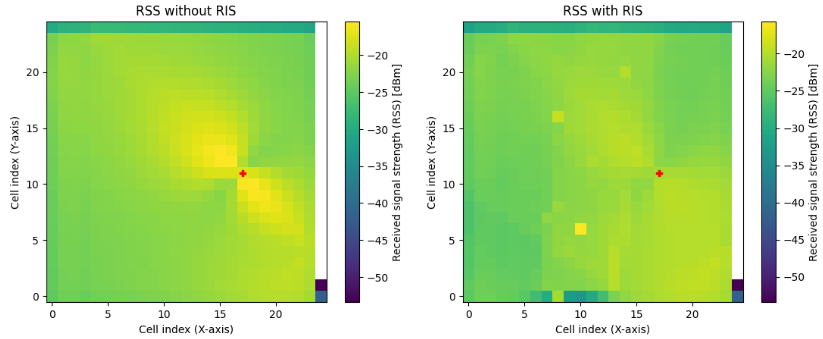


Fig. 2: Simulated environment composed of square room, one transmitter, one receiver, one RIS, and one obstacle.



((a)) Without RIS ((b)) With RIS

Fig. 3: Comparison of signal propagation without and with RIS in the absence of obstacles. The cross indicates the location of the transmitter.

In the following section, we follow this workflow to evaluate the performance gain of adding a RIS in the particular case of short range 5G indoor communications.

IV. Performance Analysis

In this section, we evaluate how a RIS can improve signal coverage and strength in short range 5G indoor communications. To that aim we consider 2 scenarios in a square room. One transmitter and one receiver are in a fixed location, in the first scenario, there is no obstacle between the transmitter and the receiver (LOS); in the second, an obstacle blocks direct communications between them (NLOS). For each scenario we consider the case with and without RIS. The RIS is positioned identically in both scenarios, ensuring it remains in line of sight of both the transmitter and the receiver at all times. Refer to Fig. 2 for a visual representation of the simulated environment.

Performance evaluation is carried out using the parameters described below, by leveraging the capabilities of Sionna RT to integrate RIS into the simulation environment. The performance of both scenarios – with RIS and without RIS – is assessed in terms of coverage maps and CIR. For lack of space, we only present the coverage maps results in this paper.

For reproducibility purpose, the python notebook code and input files used in this paper will be made publicly available at publication.

A. Simulation parameters

To accurately adapt the RIS-assisted wireless channel model to our scenario, the following key simulation parameters were used. The transmitter (Tx) is equipped with a single isotropic antenna, ensuring omnidirectional radiation. Similarly, the receiver (Rx) also utilizes a single isotropic antenna. For the RIS, we adopted a modular structure with 4×3 modules, each containing $M = 256$ reflective elements.

The RIS behavior within the Sionna RT simulation has been modeled as follows:

- The transmitter (Tx) is positioned at $[1, -1, -3]$ meters with an orientation of $\left[\frac{5\pi}{6}, 0, 0\right]$ rad and a transmit power of 40 dBm. The receiver (Rx) is located at $[-13, 1, -3]$ meters with an orientation of $[0, 0, 0]$ rad.
- The RIS is positioned at $[-6, -12, -1.5]$ meters, with a size of $[6.98, 6.98]$ meters and a total of 26,569 cells. Each cell supports a single static mode.
- The target for the RIS is set at the midpoint between the transmitter and receiver positions, calculated as $\frac{\text{Tx Position}+\text{Rx Position}}{2}$.
- The simulation uses a subcarrier spacing of 15 kHz and an FFT size of 48. The maximum number of ray interactions is set to 3, and the simulation is performed with 10^6 samples to ensure statistical accuracy.

B. Simulation Results and Analysis

Fig. 3 shows the RSS inside the room in the absence of obstacles. As expected, the signal strength is only slightly improved as the entire room is in line of sight with the transmitter, meaning that the signal that transits via the RIS is always weaker than the direct one, hence the limited impact.

On the contrary, an improvement is expected to be observed if an obstacle blocks direct transmissions to the receiver. In Fig. 4, we show how signals are propagated in the room if the RIS is used to create a virtual line of sight path between the transmitter and the receiver. We can see that the signals received by the RIS are focused to the receiver, which should improve the quality of the received signal.[1]

In Fig. 5 we show the RSS when an obstacle is present. We can first see that there is less shade behind the obstacle when the RIS is used. However, the quality is less uniform behind the obstacle with some locations with much better signal than without the RIS, but also some locations with far less quality. This is expected as the RIS redirects the signal to a particular direction, at the expenses of other locations that used to benefit from reflections of the environment that do not exist anymore. This behavior is clearly visible in Fig. 5(b) where one can see a rather focused line in the direction from the RIS to the

[1]The obstacle does not touch the floor, which explains the presence of a few reflections under it.

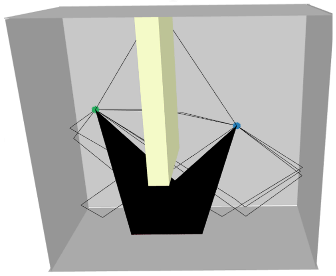
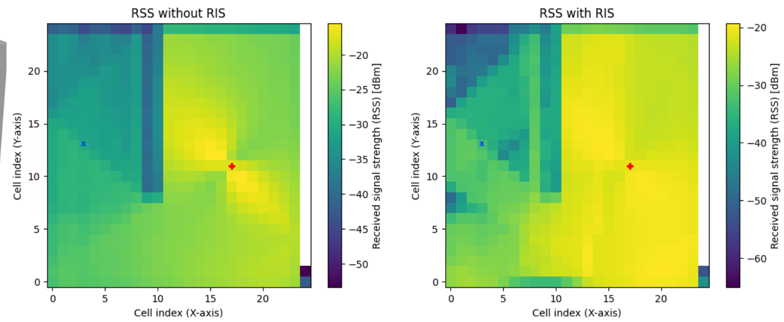


Fig. 4: Simulated paths between the transmitter and the receiver as computed with ray tracing.



((a)) Without RIS

((b)) With RIS

Fig. 5: Comparison of signal propagation without and with RIS in presence of obstacle.

receiver with better RSS than its surroundings that suffer from lower quality than without the RIS.

Our observations show that the choice of using or not using a RIS to assist indoor 5G communications is not straightforward, particularly in case of obstacles. If the location of receivers is well defined, it can bring some advantages, but if the location is not accurate, it may potentially arm the received signal if the receiver is not well aligned with the RIS.

V. Conclusions and Future Work

In this paper, we conducted a first study to determine to what extent RIS can help in 5G indoor communications. We simulated a room with basic geometry and one obstacle with the Sionna ray tracer library. The results show that when RIS can improve the received signal, it is necessary to accurately know the location of the receiver, which is not always feasible.

As future work, we will model more complex and realistic environments that are either larger or with more reflections due to the environment, such as warehouses or large buildings. Furthermore, we plan to assess the advantages of using a RIS at frequencies higher than those in 5G. Indeed, when the frequency increases, the signal is more subject to attenuation or blockage. Then the signal reflected by the RIS may offer a more significant gain than at lower frequencies.

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