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OUTDOOR TO INDOOR COVERAGE ENHANCEMENT WITH TRANSMISSIVE METASURFACE

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Abstract

Indoor coverage remains a major hurdle for millimeter wave (mmWave) communication, an emerging technology for next generation wireless networks. While mmWave technology delivers impressive data speeds and low latency, its deployment in indoor environments present a major challenge due to severe signal attenuation. To tackle this problem, reconfigurable intelligent surfaces (RIS), i.e metasurface, offers a promising solution. These innovative surfaces can control and redirect electromagnetic waves, helping to overcome signal losses and improve coverage in complex indoor environments. In this study, ray tracing simulations are used to create a detailed representation of a room with hole, windows, frames and other obstructions for understanding signal propagation behaviour i.e. reflections, diffractions, and scattering effects. To further enhance coverage, the potential of transmissive metasurface is explored into these simulations evaluating its ability to improve signal strength. This study examines multiple scenarios, comparing room setup with and without windows and hole, as well as setups with and without metasurface. The results highlight the effectiveness of metasurface in addressing mmWave limitations and possibility of significantly improving signal strength to ensure reliable coverage even in challenging conditions. By positioning the metasurface several centimeters outside the external wall, focusing signal power through the hole inside the room. This approach leverages existing architectural features, such as ventilation holes commonly found in Southern European buildings and provides a possible cost-effective and energy-efficient framework for designing solutions for beyond 5G (B5G) and 6G networks. This approach is a critical step toward achieving seamless outdoor-to-indoor (O2I) connectivity, which will be essential for the smart wireless environments of the future.

Index Terms—Millimeter Wave (mmWave) Communication, Reconfigurable Intelligent Surface (RIS), Metasurface, Indoor Coverage, Outdoor-to-Indoor (O2I) Connectivity, Ray Tracing Simulations, 5G and Beyond (B5G/6G Networks), Cumulative Distribution Function (CDF), Received Power Distribution.

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1. Introduction

The rapid growth of wireless communication technologies demands the need for faster data rates and more reliable connectivity, especially in the context of 5G and future networks. Millimeter-wave (mmWave) communication stands out as a potential solution as it offers extremely high bandwidth and data throughput [1]. However, the adoption of mmWave technology comes with significant challenges. The shorter wavelengths associated with mmWave frequencies result in very high path loss, poor diffraction, and sensitivity to blockages, making it difficult for signals to propagate effectively, especially in indoor environments [2]. Walls, furniture, and other obstacles attenuate the signal, limiting coverage and reducing network performance.

To address these challenges, many innovative solutions are being explored, and one such solution is the use of Reconfigurable Intelligent Surfaces (RIS). RIS is an advanced technology with the potential to revolutionize wireless communication by active manipulation of the electromagnetic wave propagation [3]. These surfaces consist of an array of meta-atoms or reflecting elements that can dynamically adjust the phase, amplitude, and polarization of incoming signals. By intelligently reflecting and steering signals toward specific regions, a simple representation is shown in Fig. 1.RIS can mitigate the challenges posed by mmWave communication [4].

Fundamentally, when a wireless signal, or in general an EM wave reaches the boundary between two isotropic mediums, the relationship between the angle of incidence and the angle of reflection and refraction is governed by Snell's law. Particularly for the reflection, for regular surface of the medium, the angle of incidence is the same as the angle of reflection as shown in Fig 1(a). Recent research advances on the reflect arrays with metasurface make it possible to change the impedance of the surface and achieve a certain phase shift between the incident and scattered waves. When the surface is divided into many closely spaced elements and each metasurface element is made to have appropriate phase shifts, the EM wave is tuned to some other angle instead of the symmetric reflective wave based on Snell's law. Ideally, as shown in Fig 1(b), if the phase shift of each metasurface element can be configured to any value, a reflected beam at any angle can be formed [5].

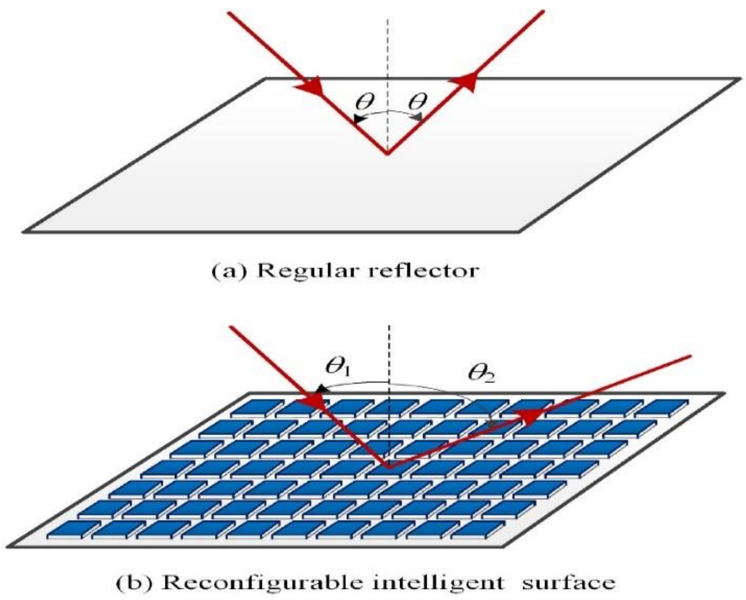

Fig. 1 Reconfigurable surface. Adapted from [5]

RIS can play a critical role in improving mmWave coverage for both outdoor-to-indoor and fully indoor scenarios. By reradiating signals in both forward (transmission) and backward (reflection) directions as shown in Fig. 2. For outdoor-to-indoor scenarios, transmissive RIS can be particularly effective, as it can redirect signals through windows or hole to overcome penetration losses [6]. In fully indoor environments, RIS can be placed on walls, ceilings or windows to redirect signals and improve the signal strength, ensuring coverage in locations where mmWave signals would otherwise fail to reach. The combination of mmWave communication and RIS provides a possible solution for conventional wireless systems and ensures reliable signal coverage in complex indoor scenarios [7].

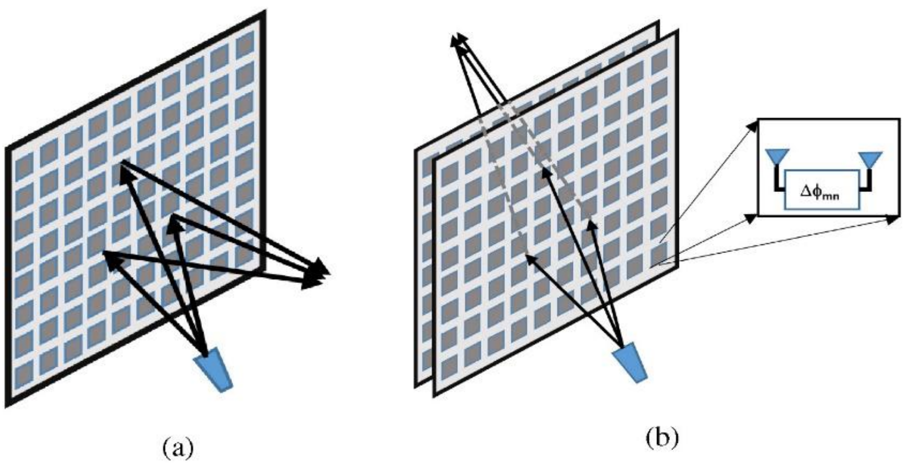

Fig. 2 Illustration of (a) reflective metasurface and (b) transmissive metasurface. From [5]

1.1. Research objectives

As mentioned above, millimeter-wave (mmWave) frequencies have emerged as a key enabler for 5G and B5G (Beyond 5G) communications. However, indoor coverage in the high frequency regime remains a significant challenge due to high penetration loss as the signal passes through walls and windows. To address these challenges, Metasurface as a reconfigurable intelligent surface has been proposed a possible solution to control behaviour of the electromagnetic wave, therefore engineering the wireless environment. The primary objective of this research is to investigate how metasurface can be a feasible solution for improving mmWave indoor coverage, specifically by integrating metasurface with ray tracing simulations adapting two step approach as current ray tracing tools lack support for RIS integration. To achieve this, the following objectives are defined:

1. Using Ray tracing to create realistic outdoor to indoor setup
    a. Construct a detailed simulation environment in MATLAB to analyze how mmWave signals propagate in an outdoor to indoor setup.
    b. Interactions with various obstacles such as hole, windows and other diffracting elements in an indoor room setup.
    c. Examine the effects of reflection, diffraction, and transmission on the received power distribution.
2. Evaluation of the indoor coverage with and without the aid of RIS
    a. Simulate a realistic outdoor to indoor setup to analyze coverage.
    b. Quantify the impact of material properties on received signal strength.
    c. Incorporate metasurface into the simulation framework to redirect and enhance coverage.
    d. Use a microscopic RIS model that modifies wavefront properties by adjusting phase and amplitude of incident signals.
    e. Simulate and compare coverage maps with and without RIS involved.
3. Comparative analysis of received power using CDF: Evaluate Metasurface integration

a. Generate received power distributions for various scenarios, including a simple room and a room with a hole, windows, and their frames. Subsequently, analyze the impact of placing a metasurface several centimeters outside the external wall to evaluate its effectiveness.

b. Use Cumulative Distribution Function (CDF) plots to compare the overall improvement in signal levels.

c. Propose the integration of metasurface into building structures as a conceptual solution for enhancing indoor communication in future networks

By achieving these objectives, this research aims to explore the potential of integrating RIS technology into building structures for improvement of signal strength in indoor scenarios. Using ray tracing as a simulation tool, we evaluate the potential of this solution to effectively address coverage challenges. This study provides valuable insights into how metasurfaces can be strategically utilized to enhance signal strength and reliability in complex indoor environments.

1.2. Scope of the thesis

The research reported in this thesis has focused on deploying RIS within indoor environment. The key focus of this work is to simulate the effect of RIS deployment for outdoor to indoor coverage improvement. This is done by using an in-house Ray tracing simulator in the simplest case of outdoor to indoor scenario as depicted in Fig. 3. The setup includes a transmitter (Tx) positioned 150 meters away from the building, with 40x40 receiver grids placed at various horizontal levels inside the room, ranging from 4.2 meters to 7.0 meters in height. The room setup includes two scenarios: a simple room and a room with windows and a hole. These settings are designed to evaluate the impact of signal attenuation caused by walls and to study how openings such as windows and hole influence signal propagation and coverage.

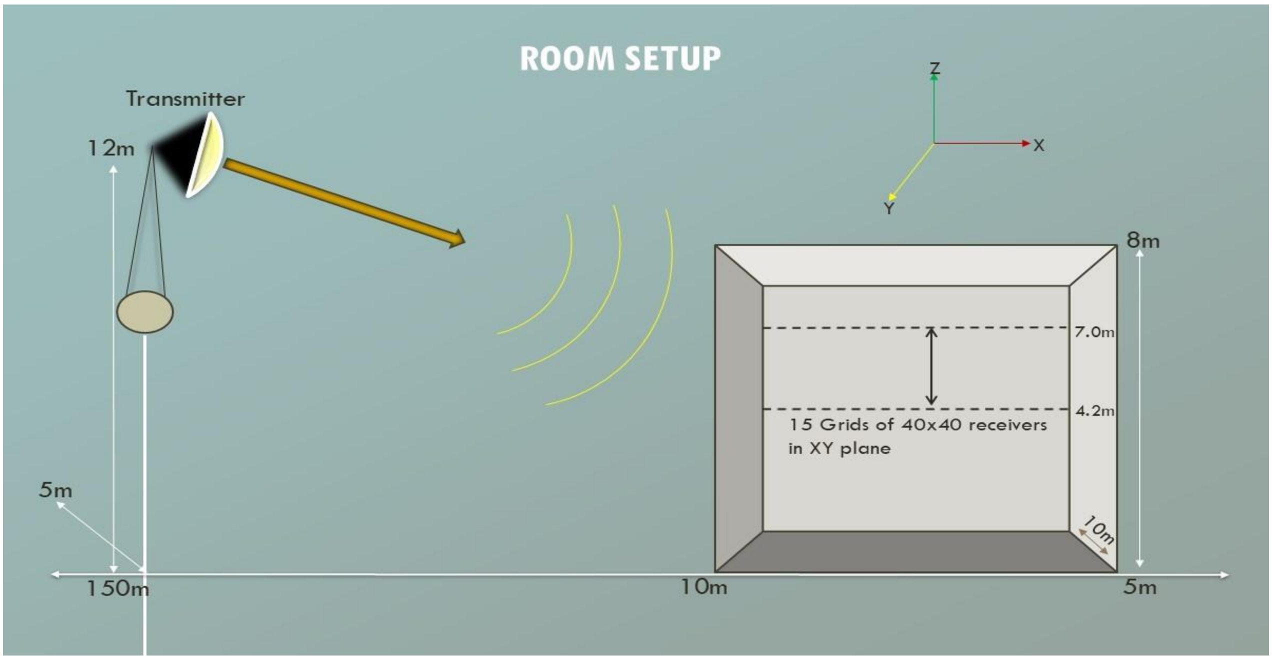

Fig. 3 A schematic representation of a room setup

Then, an RIS is added to the scenario as described schematically in Fig. 4. By doing so, this study analyzes the possibility of improving indoor coverage by strategically placing an RIS on the rooms external wall.

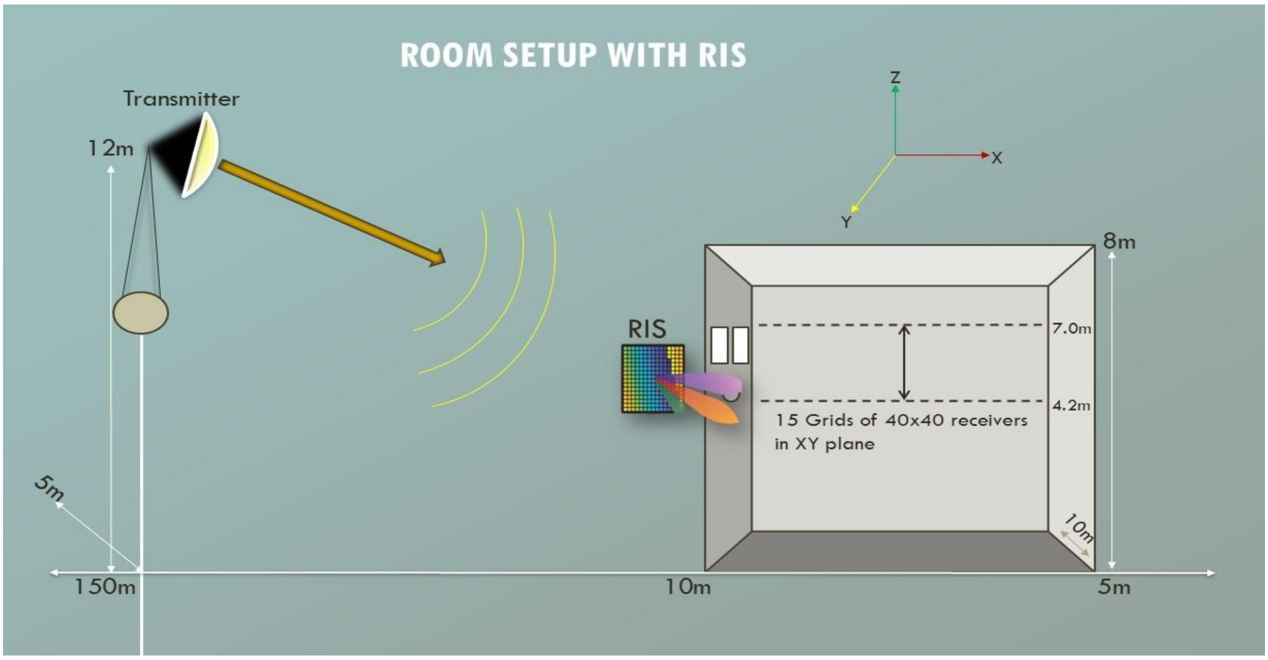

Fig. 4 An enhanced setup incorporating Reconfigurable Intelligent Surface

The setup with RIS follows a similar configuration as described earlier, with the addition of windows, a hole, and a reconfigurable intelligent surface (RIS). The concept of placing the RIS outside the external wall is inspired by the ventilation holes commonly found in many European buildings. These pre-existing openings provide a unique opportunity to deploy metasurfaces without requiring additional structural modifications. By leveraging these architectural features, the proposed approach offers a cost-effective and energy efficient solution to overcome indoor mmWave coverage challenges.

1.3. Fundamentals of ray tracing for mmWave propagation

The discovery of electromagnetic (EM) waves by Hertz in the 1880s marked the beginning of a new era in the scientific exploration of wireless communication. A major breakthrough occurred in 1901 when Marconi successfully transmitted radio signals across the Atlantic Ocean, demonstrating the feasibility of long-range wireless communication and laying the foundation for modern radio-based technologies [8]. Over the past two decades, wireless communication has seen explosive growth, driven largely by mobile and internet technologies. In 2014 alone, there were approximately 2.7 billion smartphone subscriptions worldwide, a figure projected to reach 6.1 billion by 2020 [9].

A key component of any wireless communication system is the wireless channel, which serves as the medium through which radio waves propagate to carry signals between the transmitter and receiver. While Maxwell's equations fundamentally govern EM wave propagation, solving them analytically for realistic environments is often infeasible due to complex boundary conditions and environmental obstructions. To address this, propagation models are used to estimate signal strengths based on parameters such as transmission frequency, terrain characteristics, and antenna configurations.

The simplest propagation model is the Friis free-space equation, introduced in 1946 which calculates received power (Pr) as a function of transmitted power (Pt), the distance (r) between two antennas, and the wavelength (λ) of the EM waves [10]. The relationship incorporating antenna gains (Gt and Gr) are shown in Equation 1.

$$\frac{\mathrm{Pr}}{\mathrm{Pt}} = \mathrm{GtGr}\left(\frac{\lambda}{4\pi \mathrm{r}}\right)^2$$

Equation 1 Friis Free-space equation

This model assumes an idealized free-space scenario where no obstacles exist between the transmitter and receiver. However, in real-world scenarios, objects in the environment cause reflections, diffractions, and scattering, which alter signal propagation. When we have obstacles in the first Fresnel zone, the free-space assumption breaks down, faces additional propagation effects.

Ray tracing is a widely used technique for modelling these propagation effects, particularly at mmWave frequencies, where signals exhibit high directionality and are affected by even smaller environmental interactions. This method simulates the behaviour of EM waves by tracing multiple rays from the source, considering their interactions with surfaces, edges, and objects. A simplified representation of how rays are affected when they impinge on different types of surfaces is illustrated in Fig. 5. Reflection calculations are relatively straightforward, following Snell's Law [11], which is given by:

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_t)$$

Equation 2 Snell's Law, describing the relationship between the angles of incidence and refraction at the interface of two media with refractive indices

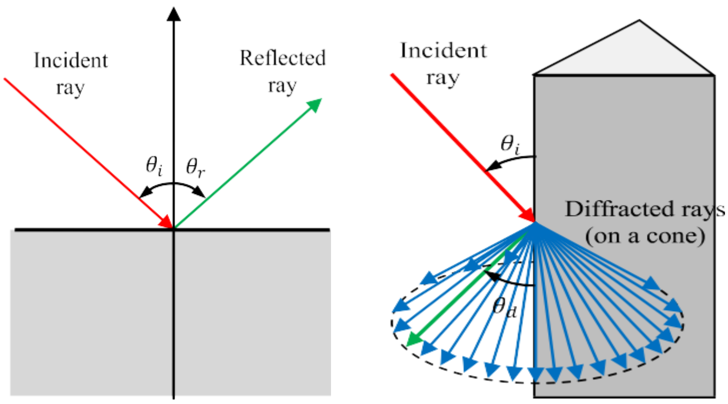

Fig. 5 The reflected ray (left) from a planar interface between two different mediums and the diffracted rays (right) from an edge. Note that there is only one single reflected ray but a continuum of diffracted rays (on a cone). Adapted from [11]

In the above given Equation 2, n_1 and n_2 are the refractive indices of the two media and θ_i, θ_r are the angles of incidence and refraction, respectively. Diffraction effects, particularly around sharp edges and small apertures require more complex modelling approaches, such as the Knife-edge and Uniform Theory of Diffraction (UTD) [11].

For mmWave communication, ray tracing is crucial due to the high sensitivity of signals to blockages and the strong dependency on line-of-sight (LOS) conditions. However, non-line-of-sight (NLOS) communication is possible via reflections and diffractions, which ray tracing helps predict. Advanced ray tracing models incorporate material properties (e.g., permittivity, conductivity) to enhance accuracy and provide insights into the impact of different surfaces on signal behaviour.

Given the challenges of mmWave propagation in complex environments, ray tracing serves as an essential tool for designing and optimizing wireless networks. It is particularly useful for evaluating Reconfigurable Intelligent Surfaces (RIS), which can intelligently control wave reflections to improve coverage and signal degradation in indoor and outdoor scenarios.

1.4. mmWave and Reconfigurable Intelligent Surfaces

Millimeter-wave (mmWave) communication represents one of the key technological developments in modern wireless systems. Wave signals provide ultra-fast communication, which are important for modern networks, augmented reality, and high-resolution streaming [12],[13]. Despite their potential, mmWave signals face severe propagation challenges as discussed above. The high frequency leads to increased path loss and signals struggle to propagate through obstacles like walls, ceilings, floors, furniture and other objects found indoor. This makes indoor mmWave coverage particularly problematic, because the signals are easily blocked or attenuated, creating coverage gaps with reduced network reliability.

Reconfigurable Intelligent Surfaces (RIS) offer a potential solution to overcome these limitations. RIS consists of engineered surfaces composed of many reflecting elements, which can alter the behaviour of incident electromagnetic waves [14]. By dynamically adjusting the phase shifts and amplitudes of reflected signals, RIS can focus and redirect signals towards the desired directions. For example, in a typical indoor environment, RIS panels can be strategically placed on walls or windows to guide mmWave signals to receiver locations that would otherwise remain in shadowed regions [14],[15]. With the integration of RIS in wireless communication systems, significant improvements in coverage and connectivity can be achieved. In indoor settings where external walls block signals, an RIS panel placed on a wall, window or ceilings can reflect incoming signals, enabling them to reach areas that face weak or no coverage issues. This makes RIS a powerful tool for enhancing signal strength and reliability [15]. However, future challenges arise with the increasing adoption of high-efficiency buildings designed for thermal and sound insulation. This will pose even greater challenges for indoor coverage in the future.

RIS can play a transformative role in addressing these challenges by introducing controlled reflections. For instance, in high-efficiency buildings where signals struggle to penetrate walls, RIS can redirect and amplify signals to reach shadowed areas, improving overall wireless network performance. To better understand this, let's consider a typical indoor scenario of a large hall, as illustrated in Fig. 6. In such a setup, a line-of-sight (LOS) link benefit from strong signal and enjoy higher data rates as compared to NLOS. The propagation characteristics at the higher frequency bands will give rise to these scenarios more often. By deploying RIS, the wireless environment can be engineered to achieve higher data rates. RIS can be used to alter wireless channels in these scenarios and improve overall system performance [16].

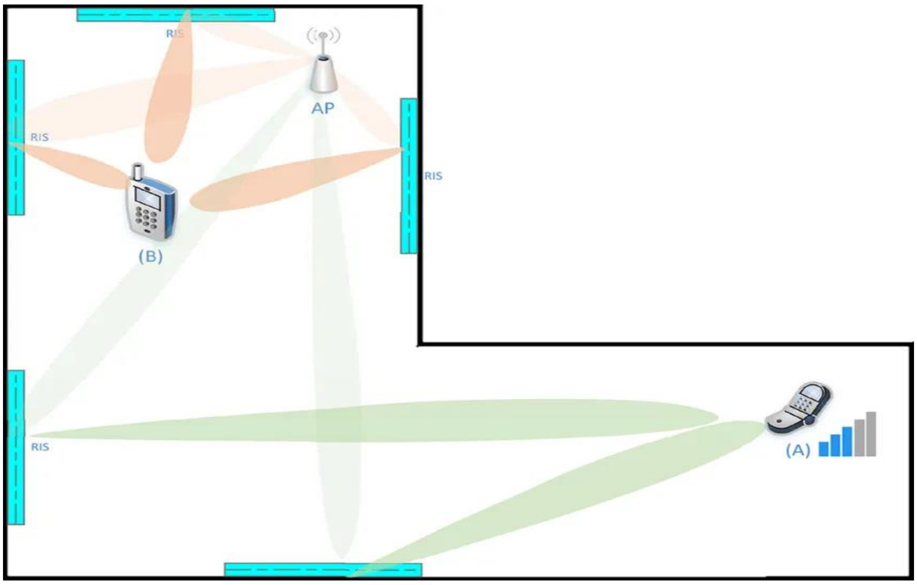

Fig. 6 The RISs can be optimized to improve signal strength even in NLOS case. From [17]

1.5. Metasurface for O2I coverage enhancement

Metasurfaces such as Reconfigurable Intelligent Surface, will make it easier to improve outdoor-to-indoor coverage by controlling electromagnetic wave propagation through phase shifts and amplitude modulation. These metasurfaces can enhance signal coverage, making efficient signal redirection through windows or walls. The benefits of metasurfaces lie particularly in high path loss and weak diffraction of mmWaves.

A relevant figure Fig. 7 shows a typical use case of a reconfigurable intelligent surface (RIS) involve in receiving a signal from a transmitter and re-radiating it in a focused manner toward the receiver. In this scenario, the RIS acts as a smart reflector, strategically placed to overcome obstacles or extend coverage in challenging environment. For the RIS to function effectively, it must be properly configured to ensure the beam is directed precisely toward the intended receiver. This configuration involves adjusting the phase and amplitude of the incoming signal at each unit cell of the RIS, enabling it to manipulate the electromagnetic waves and steer the signal in the desired direction [18].

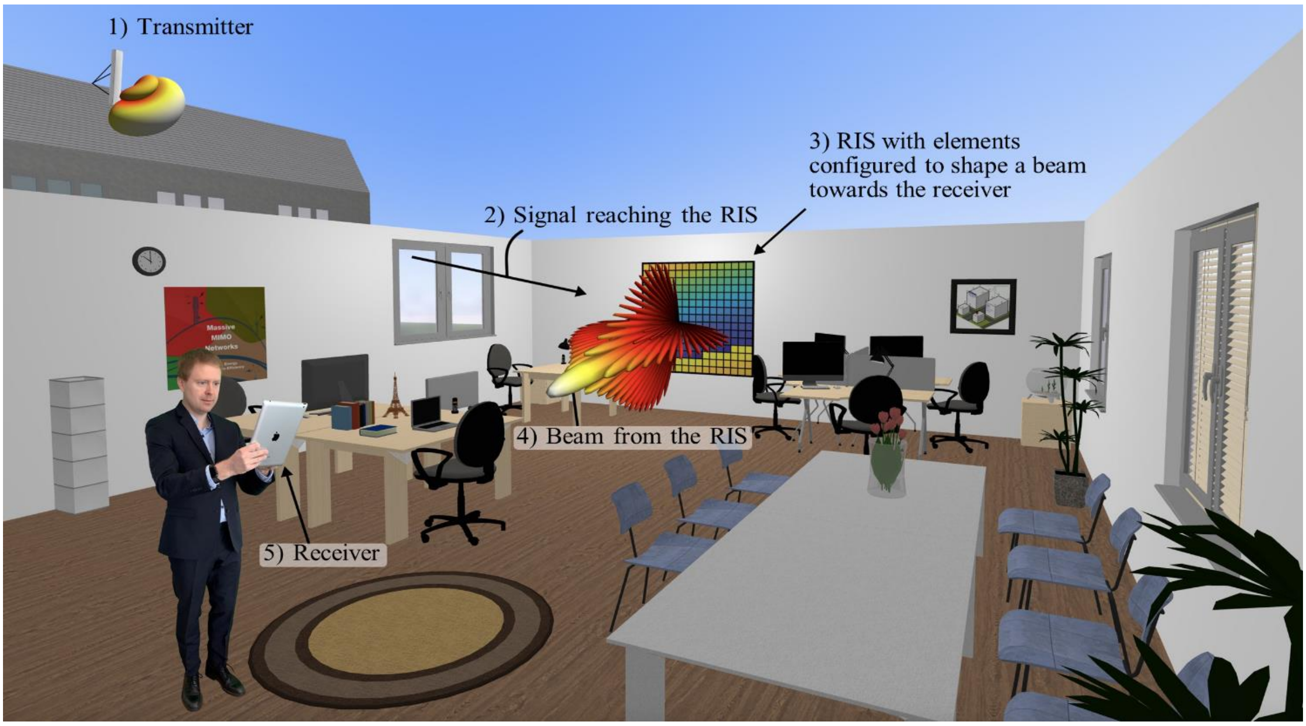

Fig. 7 A typical use case of an RIS, where it receives a signal from the transmitter and re-radiates it focused towards the receiver. To focus the beam in the right direction, the RIS must be configured properly. From [18]

2. Metasurfaces operating principles

The wireless environment is by its nature unpredictable, and the presence of objects in it affects quality of communication. In outdoor environments, the space is often dominated by structures commonly found in urban areas, whereas in the indoor environment multiple communicating devices can cause interferences besides obstructions. At low frequencies the objects act as electromagnetic wave scatters. Therefore, at mmWave or TeraHertz frequencies even smaller objects can behave as substantial scatterers.

The concept of metamaterials emerged in the early 2000s, primarily driven by the need to overcome limitations in traditional materials used for antennas, lenses, and cloaking devices. One of the key breakthroughs was the development of negative-index materials (NIMs), which can bend light and radio waves in the opposite direction compared to conventional materials, leading to unprecedented control over wavefront shaping [19].The use of planar metamaterial structures or metasurfaces is receiving major attention from the wireless community as discussed in [14]. The reason lies, as mentioned, in the reduced losses and less complex design of two-dimensional (either planar or conformal) metasurfaces as compared with three-dimensional metamaterials. A metasurface is a metamaterial sheet of sub-wavelength thickness. Metasurfaces are negligibly thin when compared to the wavelength of the electromagnetic waves. They can be as effective in wave manipulation as metamaterials without inheriting some of their drawbacks. This is guaranteed by the surface equivalence theorem, which states that the electromagnetic fields excited by arbitrary sources located in a volumetric material sample can be equivalently created by surface currents enclosing the volume. Thus, any metamaterial sample may be replaced by electrically thin metasurfaces that are engineered to produce the same electromagnetic waves [20]. RIS is usually defined as a nearly-passive reconfigurable engineered surface that (i) is implemented by using passive scattering elements, (ii) does not require high-cost active components, such as power amplifiers, (iii) does not possess sophisticated signal processing capabilities, but only the necessary low power electronic circuits for enabling its reconfigurability, and (iv) is not equipped with multiple radio frequency chains for data transmission, but requires a simple front-end to receive and send control signals.

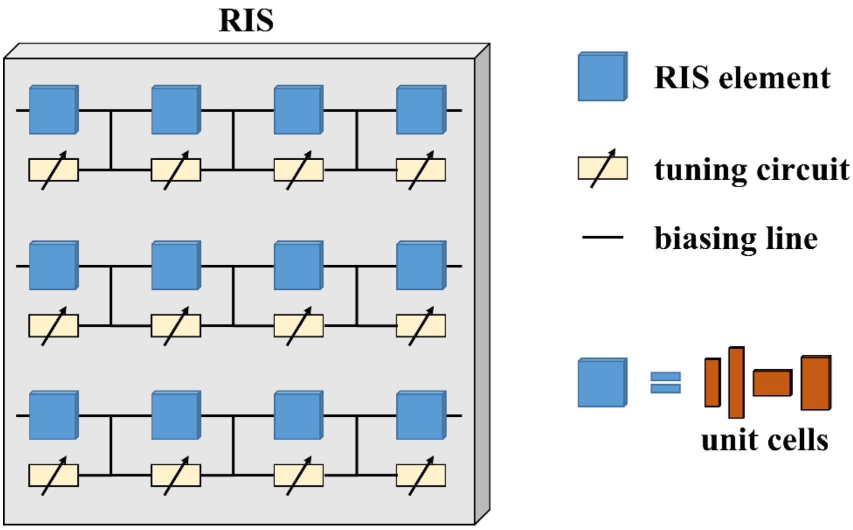

Fig. 8 Conceptual architecture of a reconfigurable intelligent surface. Adapted from [20]

The conceptual structure of an RIS is sketched in Fig. 8. As illustrated, an RIS is a planar surface that consists of an array of scattering elements, each of which can independently impose the required phase shift, and possibly an amplitude gain, on the incident electromagnetic waves. By carefully adjusting the phase shifts (and the amplitudes) of all the scattering elements, the reradiated electromagnetic waves can be shaped to propagate towards specified directions. Each RIS element may consist of multiple constitutive elements, which are usually referred to as unit cells [20].

Metamaterials are fundamental in shaping the overall behavior of surfaces at a macroscopic level. Reconfigurable Intelligent Surfaces (RIS) are typically built using metasurfaces. These metasurfaces are made up of arrays of tiny, tunable elements called unit cells, each smaller than the wavelength of the signals they interact with. What makes these unit cells special is their ability to be programmed in real time to modify key properties of incoming electromagnetic waves, such as their phase, amplitude, or polarization. This programmability allows RIS to act as smart surfaces that can redirect and manipulate electromagnetic signals to enhance communication coverage and efficiency. The way an RIS behaves, whether it functions as a reflector, a beamformer, or a wave manipulator, is determined by how these unit cells respond to electromagnetic waves. By dynamically adjusting the properties of the unit cells, RIS can optimize wireless signal propagation, making them a powerful tool for improving communication networks. This flexibility and adaptability are what make RIS a promising technology for future wireless systems [21].

2.1. Reconfigurable intelligent surfaces and meta-atom design

With the continuous development of modern information technology, the multifunctional and intelligent features are critically required for wireless communication systems. This section provides the necessary background knowledge on metasurfaces, discussing dimensions and composition, operating principles and supported functionalities. The following concise description targets a wireless communications audience, given the topic of the present paper. A more detailed introduction can be found in [22].

Metasurfaces are made of smaller, repeated conductive elements called meta-atoms which are usually placed on a dielectric substrate, as shown in Fig. 9(a). which illustrates a well-studied metasurface design comprising split-ring resonators as the meta-atom pattern. Such design rely on a static meta-atom, naturally yield a static interaction with EM waves. The need for dynamic alteration of the EM wave control type has given rise to dynamic metasurfaces, In the dynamic case as shown in Fig. 9(b), the meta-atoms and their interconnected switch elements serve as control factors that regulate the electromagnetic response of the metasurface. By adjusting these elements, the metasurface can manipulate the phase, amplitude, or polarization of incident waves, enabling precise control over wave reflection and transmission [23]. Metasurfaces are planar structures which can manipulate EM waves and thereby create a controllable wireless system such as Smart Radio Environment.

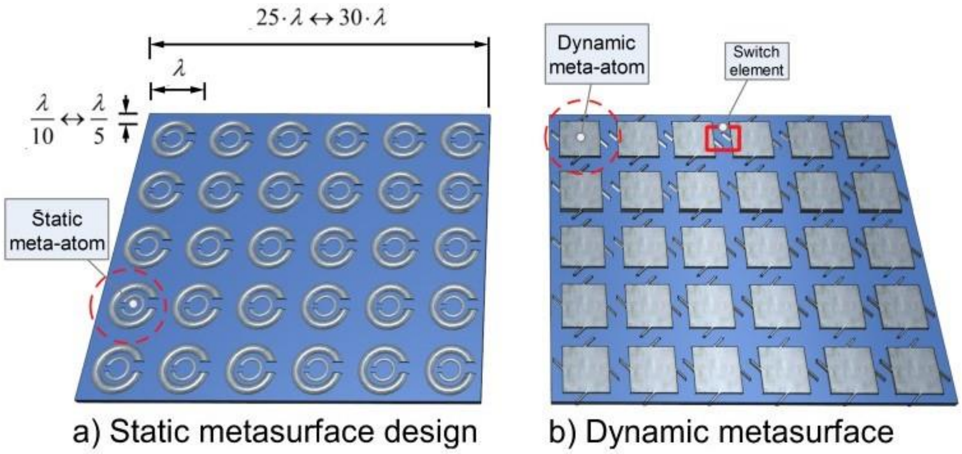

Fig. 9 Example of static and dynamic meta-surfaces made of meta-atoms. From [23]

The conceptual design of RIS has been influenced by both metasurface technology and antenna array theory. From metasurfaces, it borrows the concept of using tiny, tuneable elements to control electromagnetic waves. From antenna arrays, it adopts the ability to manage multiple signals in a coordinated way to achieve specific outcomes such as focusing or redirecting waves [24].

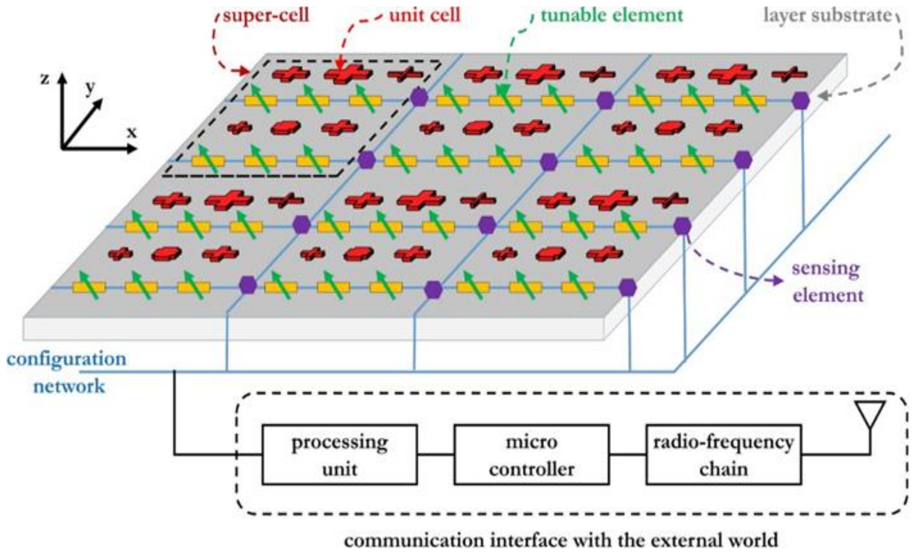

Fig. 10 Conceptual structure of a reconfigurable intelligent surface. From [14]

RIS design is based mainly on three factors. The first factor is the two-dimensional structure of RIS, this means that the transverse size of the model is much larger than its thickness. The second factor is the composite layers based on meta-atoms. Fig. 10 shows that, the RIS is constituted to be composite material layer made of patches printed on dielectric substrate. These patches are responsible for the macroscopic behaviour of the surface and the outcome can be different based on the material with which the unit cells are made of, their size, and the inter- distance among them. Last element is the phase reconfiguration controller. RIS can operate dynamically, and it is possible by using low power electronic circuits such as Positive Intrinsic Negative (PIN) diodes [25]. These surfaces can also be referred to by various names, each with its own unique focus as explained in [14]:

- **Large Intelligent Surfaces (LIS):** LIS takes the concept of RIS to a larger scale, representing the next step beyond massive MIMO (Multiple-Input-Multiple-Output) technology. While RIS focuses on smaller, localized wave manipulation, LIS expands this capability over much larger areas, offering greater control over electromagnetic environments.

- **Intelligent Reflecting Surfaces (IRS):** IRS refers to surfaces designed specifically as smart reflectors. They're made up of individually tunable elements that can adjust their phase response to optimize functions like beam steering or focusing.
- **Digitally Controllable Scatterers (DCS):** DCS is a term closely related to RIS, emphasizing the digital control of surfaces to manipulate how objects or devices interact with electromagnetic waves.

RIS itself is a type of metasurface—a thin, adaptive material sheet designed to manipulate radio waves in precise and customizable ways. Currently, RIS is realized in two main designs: programmable thin wallpaper and programmable thin glass. Both designs operate in a nearly passive and dynamic manner, meaning they don't generate new radio waves but instead modify existing ones. Key characteristics of RIS include:

- No power amplification required during normal operation.
- Minimal digital signal processing is needed to configure the surface.
- Low power consumption for both configuration and operation.

Hence, the RIS is made of low power electronic circuits and can be configured to control the departing directions of the impinging waves.

2.2. Electromagnetic functionalities of metasurfaces

The presence of the RIS in a propagation environment provides an opportunity to engineer the wireless channel in ways that not possible until now. RIS can also be used to mitigate the effects of Doppler spread and multipath fading. It can operate in multiple modes to satisfy diverse objectives [26]. One of the most notable features of metasurfaces is their ability to support a wide range of electromagnetic (EM) functions as shown in Fig. 11.

Some of the fundamental functionalities are outlined below:

- **Wave reflection and refraction**

  They enable the bending of electromagnetic waves, steering them toward a desired direction that is not necessarily aligned with the direction of arrival.

- **Energy absorption:**

  Metasurfaces have the unique ability to significantly reduce the amount of energy reflected or transmitted by incoming waves, ensuring that most of the energy is absorbed instead.

- **Polarization control:**

  They can alter the orientation of the electric and magnetic fields of an electromagnetic wave, effectively changing its polarization.

Metasurfaces also support more advanced functionalities such as focusing an impinging wave towards a specified direction, collimation i.e. redirecting a diverging wave in the same direction, splitting which consists of creating multiple reflected or refracted radio waves for a given incident radio wave and analog processing, which involves the realization of mathematical operations directly at the EM level.

- **Beamforming:**
  Concentrating incoming waves to a specific target or direction, enhancing signal strength and focus.
- **Wave collimation:**

  Transforming a diverging wavefront into a parallel one, ensuring the waves travel in a uniform direction.

- **Wave splitting:**

  Generating multiple reflected or refracted waves from a single incident wave, enabling multi-path signal propagation.

- **Analog wave processing:**

  Implementing mathematical operations directly at the electromagnetic wave level. For instance, a metasurface can modify a refracted wave such that it represents the derivative or integral of the incoming wave.

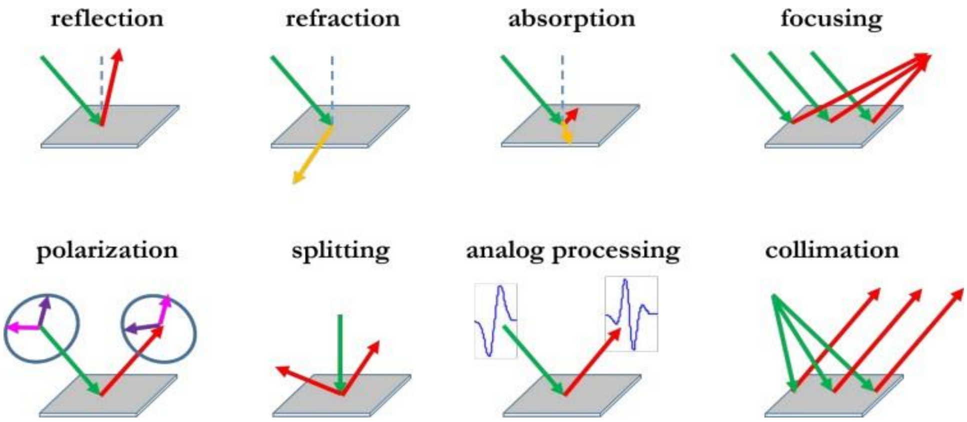

Fig. 11 Electromagnetic based elementary functions. From [26]

3. Ray tracing and metasurface simulations

This chapter explores the principles and application of ray tracing as a proof of concept to demonstrate how Reconfigurable Intelligent Surfaces can possibly improve coverage compared to simple free-space (Friis) propagation models. It also highlights the importance in understanding signal behaviour in complex indoor environments and examines the integration of transmissive metasurface to enhance coverage by mitigating attenuation exhibited by external wall. The chapter details the simulation setup, including room modelling, transmitter and receiver placements, and placement of RIS in the vicinity of external wall façade that has a hole on it, to optimize signal distribution. Results from ray tracing simulations with and without RIS are analyzed to demonstrate the impact on indoor signal propagation and coverage improvement.

3.1. Simulation environment and room setup

A ray-tracing-based simulation was conducted using MATLAB to analyze the propagation behavior of signals in an indoor environment. The study aimed to understand how these high-frequency signals interact with common indoor obstacles, such as walls, floors, ceilings, and windows, which can significantly affect signal behavior. Key wave propagation mechanisms—including reflection, diffraction, transmission, and scattering—were considered to provide a comprehensive analysis of how mmWave signals propagate and interact with the environment.

The simulation was designed to replicate a realistic indoor room setting. A Base station transmitter that equipped with an isotropic antenna was positioned at a fixed outdoor location. An isotropic antenna is an ideal antenna that radiates power uniformly in all directions. At the receiver side, the receiver's grids were distributed throughout the room at various positions and heights to capture the received power levels across different volume points inside the room. This setup allowed for a detailed assessment of signal strength and coverage.

The room layout was carefully modeled to include structural elements like walls and transparent surfaces such as windows. Material properties, including permittivity and conductivity, were assigned to these elements based on ITU (International Telecommunication Union) standards to ensure accurate representation of real-world conditions.

Table 1 Material properties. Adapted from [27]

Material class	Real part of relative permittivity		Conductivity S/m		Frequency range
	a	*b*	*c*	*d*	GHz
Concrete	5.31	0	0.0326	0.8095	1-100
Brick	3.75	0	0.038	0	1-10
Glass	6.27	0	0.0043	1.1925	0.1-100

The frequency ranges given in above table are not hard limits but are indicative of the measurements used to derive the models [27]. The frequency dependence of material properties can be characterized using ITU-defined formulas for conductivity (σ) and relative permittivity (η'). The conductivity trend follows:

$$\sigma(f) = \mathrm{c}.f^{d}$$

Equation 3 Conductivity equation. Adapted from [27]

Equation 3 defines frequency dependent conductivity model, where c and d are material-specific constants. For relative permittivity, when frequency dependence is observed, it can be modeled as:

$$\eta(f) = a.f^{d}$$

Equation 4 Permittivity equation. Adapted from [27]

Equation 4 defines frequency dependent permittivity model, where a and b are material specific constants. However, in most cases, relative permittivity remains constant across frequencies and a mean value is used. ITU provides specific guidelines for assigning a, b, c and d based on frequency ranges and material properties. These parameters are determined through empirical data fitting and statistical analysis [27].

Considering these material characteristics the simulation was executed using MATLAB. Room is representing second floor of the building. The transmitter was positioned at a height of 12 meters and 150 meters away aligned with the room. The receiver grid was designed to cover the entire room in three dimensions (3D). To achieve this, receivers were placed at different heights starting from 4.2 meters up to 7.0 meters, creating a 3D representation. The spacing between receivers was set to 0.25

cm along the Y-axis and 0.125 cm along the X-axis making it 40x40 receiver grid to ensure a dense and uniform distribution of measurement points throughout the room. The following key parameters were considered in Table 2:

Table 2 Parameters for room setup

Parameter	Value
Frequency	27 GHz
Transmitter Power	40 dBm
Transmitter Position	X=150m, Y=5m, Z=12m
Receiver Grid	40 × 40 (covering the entire room)
Receiver Grid Height	4.2 m - 7.0 m (increments of 0.2 m)
Building Dimensions	X=5m, Y=10m, Z=8m
Walls Material	Concrete

The below given Fig. 12, presents a 3D plot of a building consisting of two floors, where walls are depicted as line plots and the receiver grid is represented by yellow points. The grid of 40x40 receivers is placed in a room at second floor at the height of 4.2m which is 20cm above the first floor. Height of the modelled building is 8 meters in Z-axis, 5 meters in X-axis (extended from 5 to 10 meters) and 10 meters in Y-axis as mentioned in Table 1. First floor is 0 to 4 meters in Z-axis, and the room on second floor is 4 to 8 meters in Z-axis.

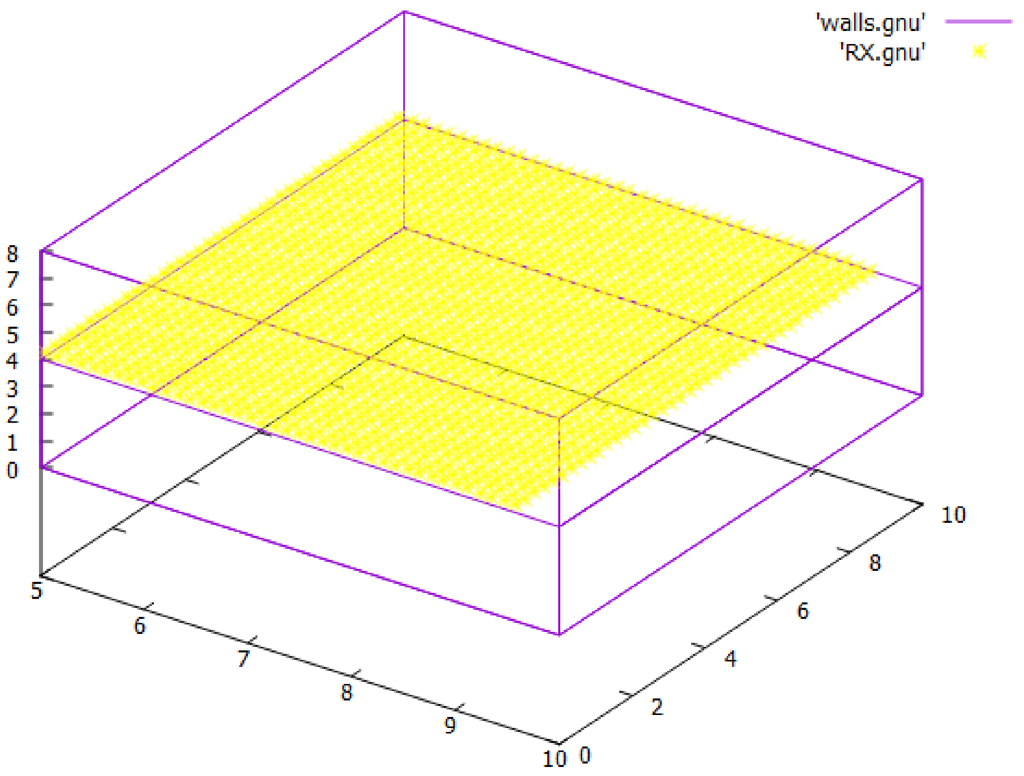

Fig. 12 3D plot of the building with grid of receivers at 4.2m on second floors room

Given Table 3 presents the key parameters of the building scenario with windows and hole used in the simulations. It includes details about the room dimensions, transmitter placement, receiver grid, and structural elements such as windows, hole and the frames. The inclusion of window and hole is essential for understanding diffraction effects, which play an important role in wave propagation. By considering these structural elements, the simulation provides a more realistic representation of indoor signal behaviour, particularly in complex environments with multiple diffraction points.

Table 3 Room setup with windows, hole and frames

Parameter	Value
Frequency	27 GHz
Transmitter Power	40 dBm
Transmitter Position	150 m away from the room
Receiver Grid	40 × 40 (covering the entire room)
Receiver Grid Height	4.2 m - 7.0 m (increments of 0.2 m)
Building Dimensions	X=5m, Y=10m, Z=8m
Walls Material	Concrete
Obstacles	Windows, hole, frames
Diffraction Considered	Yes

Below given Fig. 13, presents a 3D plot of the two-floor building with the room at second floor having diffraction elements. The inclusion windows, hole, and frames allow more in-depth analysis of diffraction and its effects on signal behaviour. The building dimensions are already explained in previous room setup section and also in both above given Table 2 and Table 3. The sizes of the windows and the hole are as follows: Window 1 measures 1.5 meters in width (Y-axis) and 1.6 meters in height (Z-axis). Similarly, Window 2 has the same dimensions as Window 1. In contrast, the hole is significantly smaller, with a width of 0.2 meters (Y-axis) and a height of 0.2 meters (Z-axis). Both hole and windows are placed on the external wall and distance between both windows is 3.5 meters.

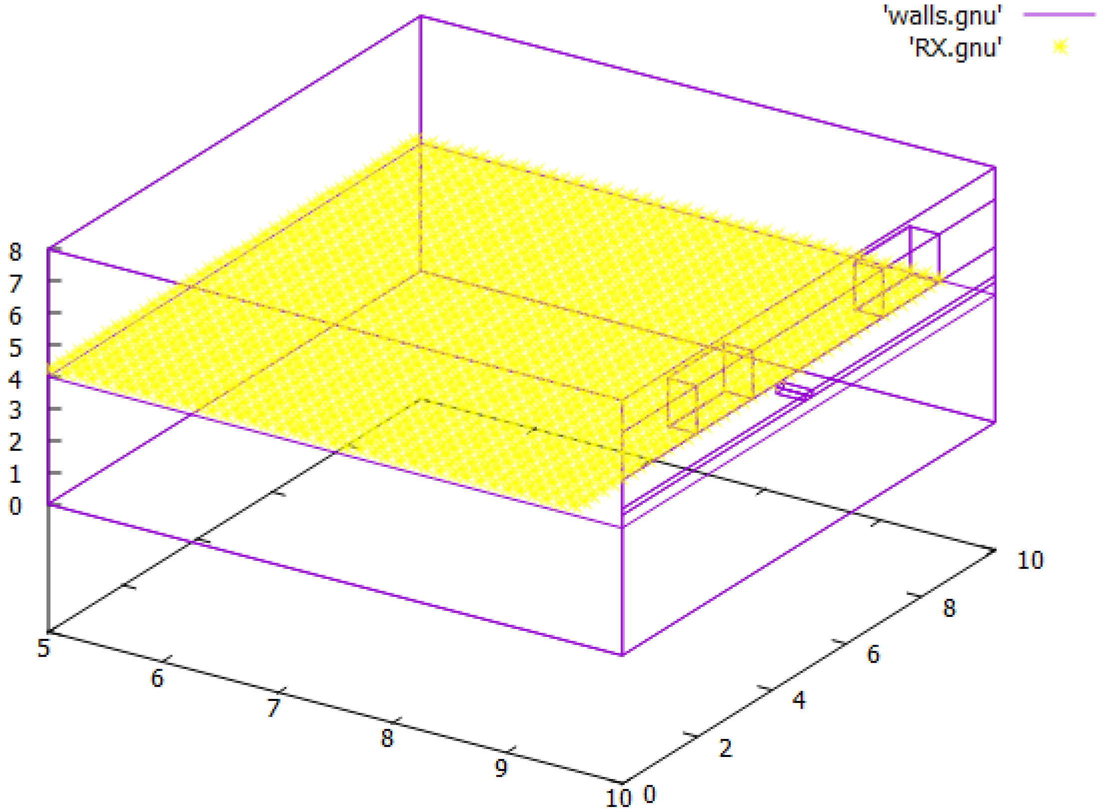

Fig. 13 3D plot of simulation environment with walls, windows, hole and their frames that contribute to diffraction effects.

Ray tracing is implemented to track multiple propagation paths, including line-of-sight (LOS) rays, reflected rays from surfaces, and diffracted rays at edges and corners. The simulation also considered multipath effects, where multiple rays from the transmitter reached the receiver via different propagation mechanisms, causing constructive or destructive interference.

To analyze coverage, the received powers are recorded in multiple cases placing receiver grids starting from the height of 4.2m to 7.0m making it to 15 receiver grids for the room with only walls without windows and hole and same for the room with windows and ventilation hole. All powers for each receiver are stored in separate datasets. These datasets were later used to generate cumulative distribution function (CDF) plots, providing insights into signal distribution.

3.2. Coverage maps and statistical analysis of received power

The field plots below illustrate the received power distribution across six receiver grids in the indoor environment, three each for simple room and room with windows and hole, capturing signal strength at different heights. The plots represent the received power in a simple room and room with presence of openings at various heights 4.2m, 5.8m, and 7.0m. Fig. 14(a) show received power across receiver grid in room cases without windows and hole. Fig. 14(b) represents received power in the room with the presence of hole and windows which impact signal behaviour through reflection, diffraction, and transmission effects. By comparing these plots, the influence of obstacles on wave propagation is analyzed, highlighting coverage gaps.

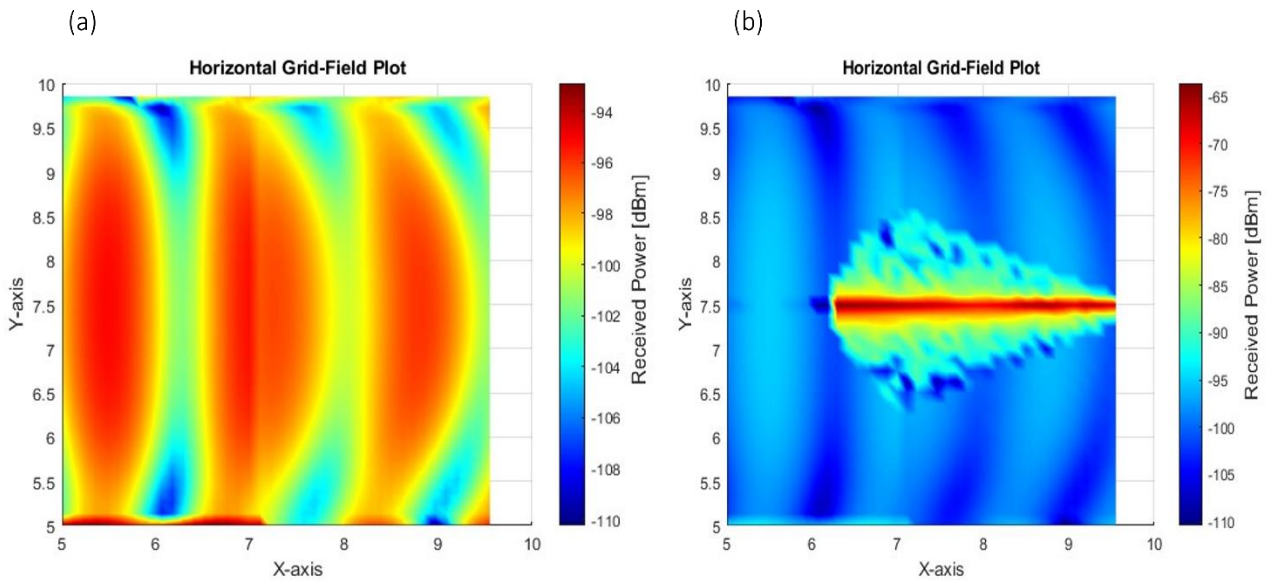

Fig. 14 Coverage map of the receiver grid at the height of 4.2m: (a) Room without windows and hole, (b) Room with windows and hole

The behavior of electromagnetic waves in the room is analyzed by placing the receiver grid horizontally at the height of 4.2m as shown in Fig. 14. The transmitter is located 150 meters away align with the room, employs an isotropic antenna which radiates waves uniformly in all directions. The plot depicts the received power distribution across the room, captured by a grid of receivers. Fig. 14(a) showing the waves are severely attenuated by the wall resulting in uniformly low power levels ranging from -90 to -110 dBm across the room. In Fig. 14(b) the scenario shown represents the room with windows and hole which contribute to diffraction and reflection effects. As this grid is placed in front of the hole, rays continue to propagate in a relatively focused manner with some spreading due to the isotropic nature of the transmitter and the finite size of the hole. The significant increase in received power from a maximum of -90 dBm (simple room) to -65 dBm (room with windows and hole) can be attributed to the fact that some rays propagate directly through the hole, minimizing interaction with the external wall.

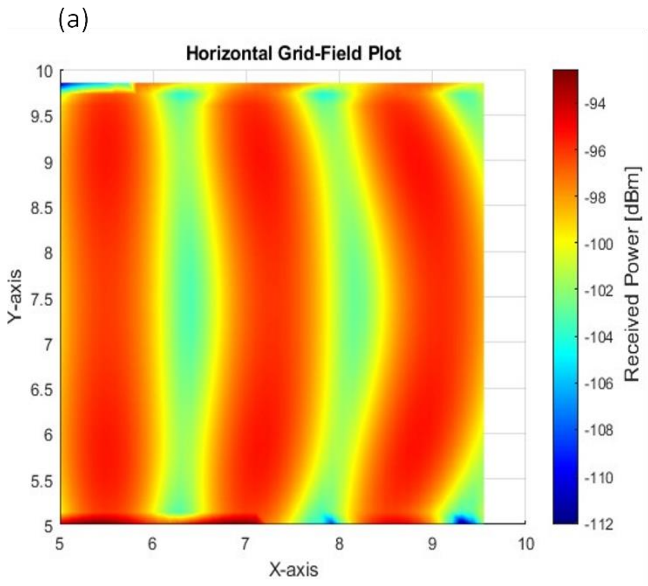

Fig. 15 Coverage map of the receiver grid at the height of 5.8m: (a) Room without windows and hole, (b) Room with windows and hole

In this figure the receiver grid is placed at the height of 5.8m. In Fig. 15(a), the waves emitted by the isotropic transmitter are approximately planar in the far field similarly as shown in Fig. 14(a) as well. In contrast, Fig. 15(b) shows waves entering in a room by passing through two windows. However, as the waves pass through the windows, they diffract, spread out and create interference patterns. This results in a non-uniform power distribution, with higher power levels in front of the windows and lower power on other receivers in the room.

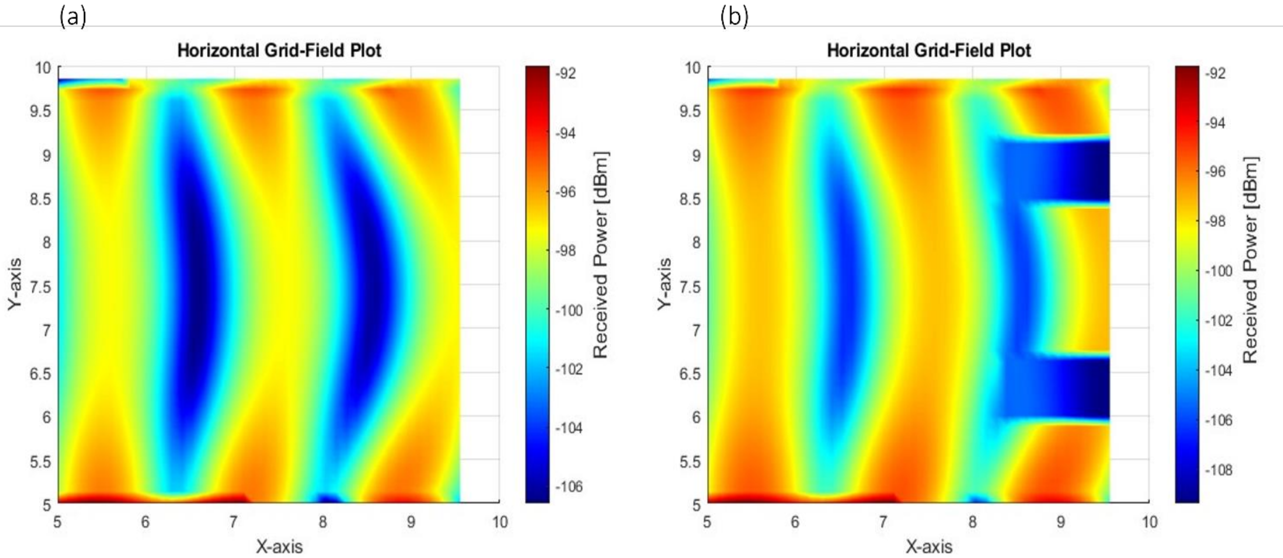

Fig. 16 Coverage map of receiver grid at the height of 7.0m: (a) Room without windows and hole, (b) Room with windows and hole

In above given Fig. 16 the receiver grid is placed at a height of 7.0 meters. The power at this height remains nearly the same, ranging from -90 dBm to -108 dBm. In Fig. 16(a), the signal experiences attenuation as rays passes through the external wall facing transmitter. Fig. 16(b) represents a grid positioned above the windows and the hole in the room. Since the windows are located below the grids, the rays encounter attenuation from the external wall in a manner similar to Fig. 16(a). The placement of the receiver grid above the windows and hole demonstrates how the height of the receivers affects wave propagation in the room. The power is almost same in both the figures the signal is attenuated due to the wall.

For understanding, the plots for Receiver grids placed at only three heights are shown. Similar coverage maps and received power analyses are conducted for all 15 grids to create a 3D representation of receivers. To quantify the impact of these variations across all receiver grids, a CDF (Cumulative Distribution Function) is used to compare power distributions as shown in Fig. 17. The CDF plot presents the probability of the received power being below a certain threshold across all measurement points. By analysing the CDF, we can assess the effectiveness of signal propagation with and without windows and hole. A steeper CDF curve indicates a more uniform power distribution, whereas a wider spread suggests significant variations due to obstacles. The coverage maps were generated without considering the material properties of the walls. As a result, the maximum achieved power in both scenarios—the simple room and the room with windows and a hole—is shifted by -24 dBm.

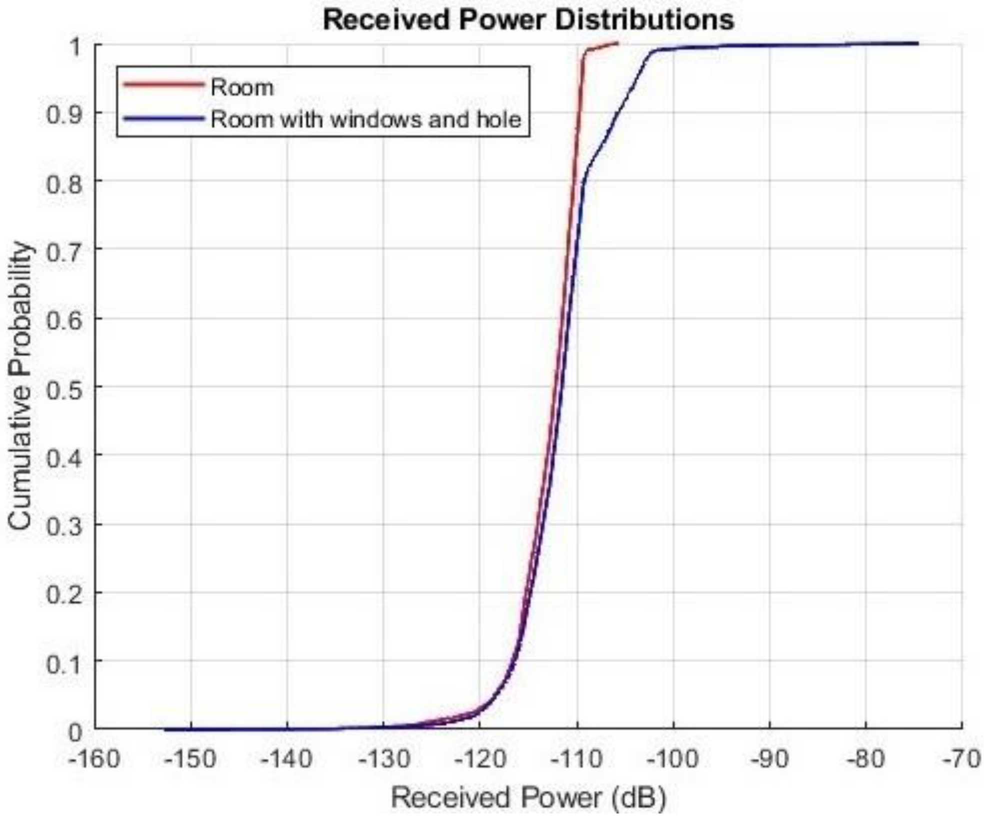

Fig. 17 CDF for simple room and room with hole and windows

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The results revealed several challenges associated with indoor mmWave propagation. Due to the high frequency, signals experienced severe attenuation when passing through walls, while reflections from windows and hole created strong multipath components. Diffraction at hole and window edges played a crucial role in enabling signal penetration into shadowed regions. However, significant coverage gaps remained, particularly in areas located far from the transmitter.

To address these limitations, the next section explores the integration of metasurface into the ray tracing model. The goal is to enhance coverage by intelligently reflecting and directing mmWave signals into shadowed areas, mitigating signal loss and improving overall indoor power distribution.

3.3. Integration of metasurface in ray tracing simulation

This study adopts a two-step approach to integrate RIS into the ray tracing simulation, as existing ray tracing software does not yet support RIS integration. First, the reradiation pattern of the RIS is generated using the model described in [6], [28]. This pattern is then integrated as a secondary antenna into a ray tracing model to analyze its impact on indoor signal coverage. The secondary antenna is positioned inside the room at coordinates X=9.65m, Y=5m, and Z=4.5m in front of the ventilation hole. It is assigned a transmitting power of −20 dBm. This secondary antenna utilizes the reradiation pattern generated through RIS simulations.

The RIS is 1m×1m metasurface operating at 27 GHz. It captures incoming signals and focuses power inside the hole. The reradiation pattern is computed using a MATLAB-based simulation framework, incorporating key RIS parameters such as efficiency (m = 0.25), phase modulation, and radiation properties. Efficiency 0.25 means that only 25% of the incident power is reradiated, while the rest is either absorbed or scattered. To generate the reradiation pattern, a grid of receivers is placed in the far field of the RIS, arranged along a half-sphere. The received power is calculated at each receiver point, considering the RIS's phase profile, incident wave parameters, and the desired steering direction. The program outputs the electric field components along the three Cartesian coordinates (Ex, Ey, Ez). However, since the ray tracing (RT) model requires the magnitude and phase of the electric field components in spherical coordinates (Eθ, Eφ), a conversion from Cartesian to spherical coordinates is performed.

Table 4 RIS specifications

Parameter	Value
Frequency	27 GHz
Aperture	1.0 m × 1.0 m
Polarization direction	Horizontal (TE mode)
Beam scanning range	π/3=60°
- Elevation angle (θ)	360° (full spherical coverage)
- Azimuth angle (ϕ)	360° (full spherical coverage)
Receiver Grid Placement	Far field (190 m from RIS)

The Given Table 4 summarizes the key specifications of the RIS. It consists of multiple unit cells, arranged dynamically, enabling precise wavefront manipulation. It is designed to redirect and focus incoming signals through the ventilation hole. The Rayleigh coefficient (R) is set to 1, assuming ideal scattering conditions. The RIS is configured to steer signals at a beam steering angle of 60° (π/3 radians), with a focal distance of 0.15m, ensuring proper signal redirection. These parameters were used to generate a reradiation pattern, later integrated into the ray tracing model. It supports horizontal polarization (TE mode). The receiver grid is placed 190 meters away in the far field, covers the full spherical range with 360° in elevation and azimuth for high resolution analysis.

The phase profile of the RIS is dynamically adjusted to steer the reradiated wave in the desired focusing point. The surface is modelled with discretized elements that modify the phase and amplitude of the incident wave to achieve controlled reradiation. Reradiation pattern of the RIS can be seen in Fig. 18,

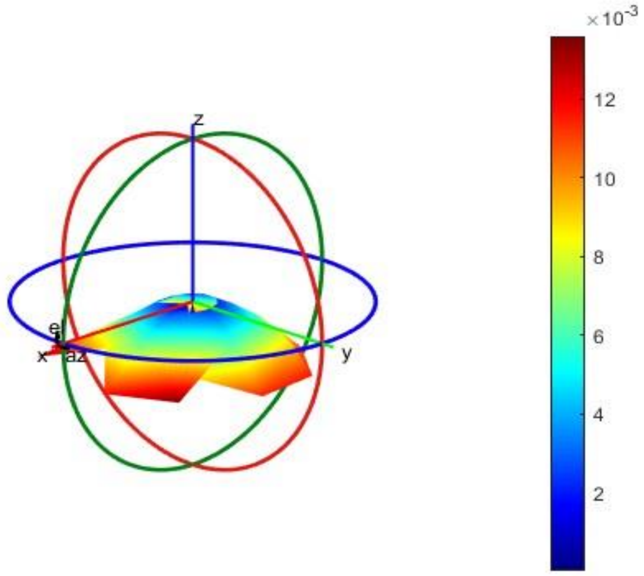

Fig. 18 Simulated re-radiation pattern of the RIS

The pattern shows how the RIS reradiates the incident electromagnetic waves. The asymmetry in the pattern suggests that the RIS is designed to redirect energy in certain directions rather than isotropically. The maximum intensity (red) is concentrated in specific directions, implying a beamforming effect which is a key feature of RIS technology. This reradiation pattern helps analyze how the RIS modifies the wave propagation environment.

Once the RIS reradiation pattern is generated, it is incorporated into a ray tracing simulation by replacing the isotropic antenna file with the RIS radiation pattern. A secondary transmitter is placed just inside the room at the focal point where the RIS directs the signal. This secondary transmitter is directing energy into the room with the power -20dbm as already mentioned. This integration allows the study of how RIS modifies indoor wave propagation by improving signal coverage in previously shadowed areas. The received power is analyzed across 15 grids of 40x40 receivers spanning the entire room horizontally as already mentioned in the room setup of previous section.

3.4. Coverage map with RIS and CDF for all cases

Coverage maps are essential for identifying areas with strong or weak signal reception. We have seen in the previous section for two cases i.e. simple room and room with windows and hole. Now we are considering with RIS source. By analyzing these plots, we can evaluate the effectiveness of the RIS in controlling wave propagation and improving signal coverage. These plots reveal areas of high and low signal strength, indicating the effectiveness of the RIS in focusing the reradiated wave.

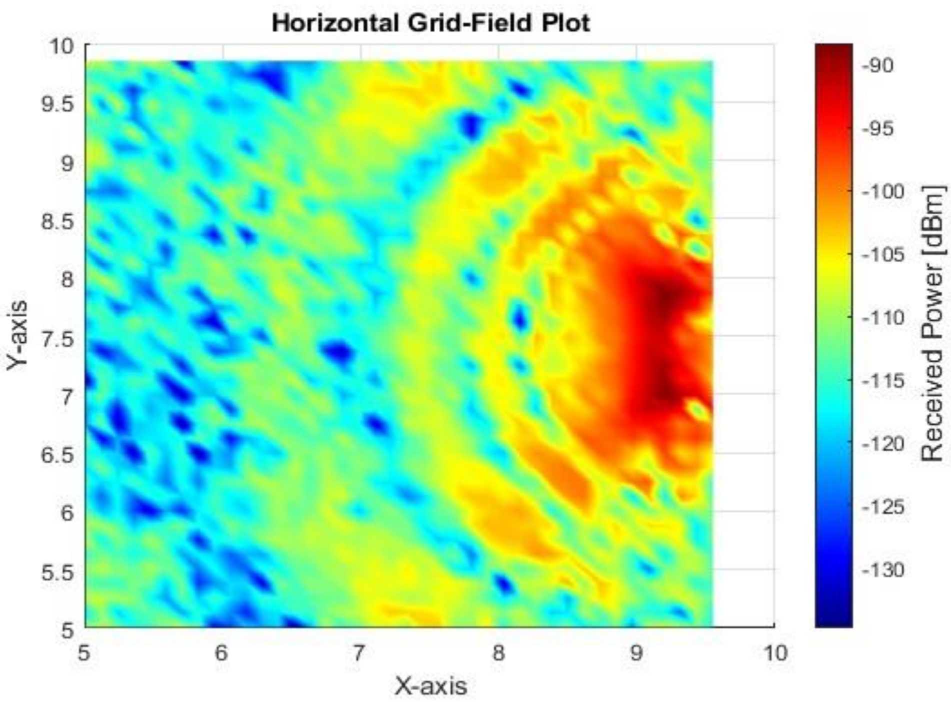

Fig. 19 Coverage map of the receiver grid at 4.2m with RIS

Fig. 19 illustrates how the RIS effectively collects and redirects incident electromagnetic energy into the room. RIS refracts the incoming waves, focusing them through the hole and distributing the energy across the indoor environment. This demonstrates the RIS's ability to enhance signal coverage and optimize wave propagation.

Like the previous cases of the simple room and the room with windows and a hole, coverage maps are also generated for the scenario with RIS integration. These maps are plotted for all 15 receiver grids, covering heights from 4.2 meters to 7.0 meters, with a vertical shift of 20cm between each grid. To evaluate the impact of RIS, previously discussed CDF analysis for the two cases (simple room and room with windows and hole) is extended to include the third scenario: room with RIS. The CDF plot compares the received power distributions across all three cases, demonstrating the improvements achieved by RIS in enhancing signal strength and uniformity.

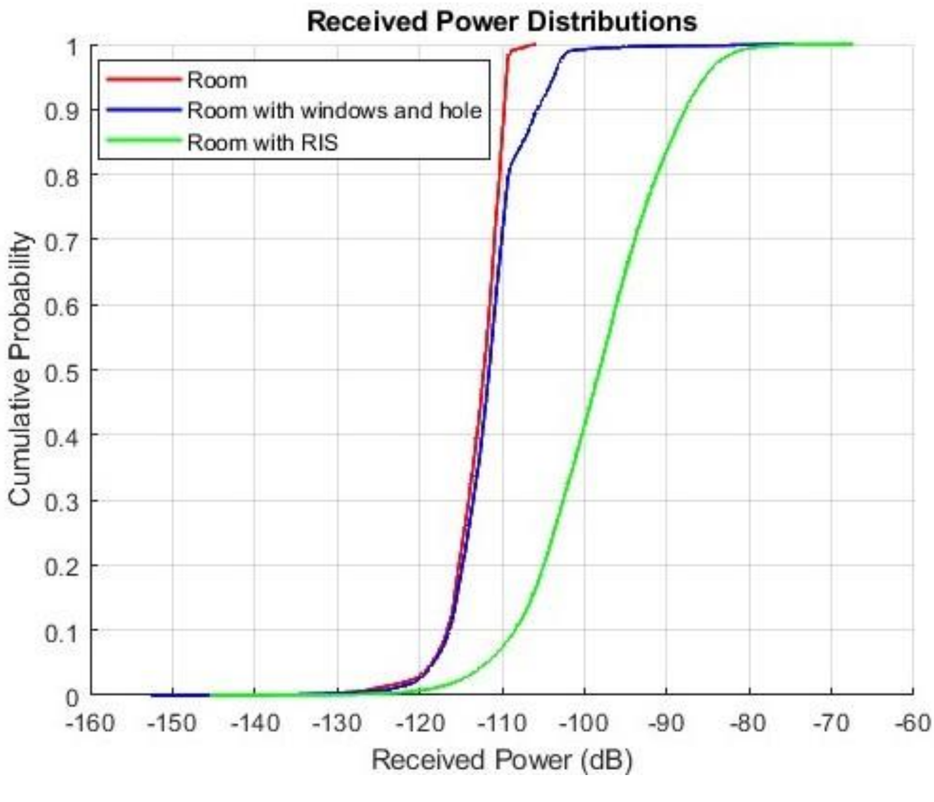

Fig. 20 CDF for three cases: Simple room, room with windows and hole, room with RIS

Given Fig. 20 shows the room without RIS relies on natural signal propagation mechanisms, including reflections, diffractions, and transmissions through walls and obstacles. CDF plot for this case shows wide distribution of received power levels, with a significant portion of the receivers experiencing low power levels due to attenuation and shadowing. In the case where RIS is integrated into the room. The CDF plot shows moderate improvement, with higher median received power. The deployment of an RIS significantly improves the received signal strength compared to the scenario without RIS.

4. Conclusions

This work explores the impact of building walls on indoor signal propagation and evaluates the potential of Reconfigurable Intelligent Surfaces in improving coverage lapses. By analyzing the received power across multiple receiver locations in cases with and without the use of RIS and utilizing Cumulative Distribution Function plots, we gained a deeper understanding of how RIS integration can affect indoor signal strength and uniformity.

The study focused on a simple scenario with a two-floor building. We analyze the indoor coverage in the second-floor room, using first a simple room with external walls, second with the addition of windows and a ventilation hole into the external wall and last with an RIS above the ventilation hole. Coverage maps for received power analyses were conducted for each of these setups and CDF plots were generated to evaluate the power distribution across all measurement points in the room. The results were compared across all three cases to assess the variations in signal strength and the effectiveness of RIS in mitigating these variations. In the first scenario, the power distribution was relatively uniform, but significant weak received power was observed due to the attenuation caused by the external thick wall. When windows and hole were introduced into the external wall, the received power distribution became more widespread, with noticeable drops in power in certain regions. The windows and the hole created a non-uniform signal environment, resulting in a wider spread in the CDF plots, indicating significant power loss and interference due to diffraction and scattering effects.

However, the introduction of RIS significantly improves the overall signal propagation. The CDF plots for the room with RIS demonstrate an marked improvement in received power distribution. The RIS effectively mitigates the attenuation effects due to walls and effects caused by windows and the hole, offering a more consistent signal strength across the entire room. The CDF curve for the room with RIS indicates that the received power remains closer to the desired threshold and ensures a more stable and improved power distribution, which is critical for ensuring reliable communication. It was evident that RIS played a crucial role in enhancing signal propagation in an indoor environment. This improvement could potentially lead to better coverage and higher data rates in future communication systems where efficient signal distribution is paramount.

Furthermore, the study highlights the potential of RIS compared to traditional wireless technologies, such as beamforming and repeaters which often struggle in complex environments. Beamforming requires precise alignment and complex hardware, while repeaters can degrade signals and add latency. In contrast, RIS offers real-time control over electromagnetic waves as it can dynamically adjust the phase, amplitude and direction of the signal. It is energy-efficient and can be easily integrated into existing infrastructure, making it a practical and scalable solution for next-generation networks.

In conclusion, CDF analysis provides a clear and quantitative way to evaluate the impact of RIS to enhance signal strength and mitigate coverage gaps. The results reinforce that RIS can be a valuable tool in the design of future wireless communication systems. Future research should explore the practical deployment and optimization of RIS placement, configuration, and integration with other emerging technologies to fully realize its potential in building smarter more reliable communication systems for the future.

References

[1] S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter-wave cellular wireless networks: Potentials and challenges," Proc. IEEE, vol. 102, no. 3, pp. 366–385, Mar. 2014

[2] E. Dahlman, S. Parkvall, and J. Skold, 5G NR: The Next Generation Wireless Access Technology. Academic Press, 2020

[3] A. Shahmansoori, G. E. Garcia, G. Destino, G. Seco-Granados, and H. Wymeersch, "5G position and orientation estimation through millimeter wave MIMO," in Proc. IEEE GLOBECOM Workshops, San Diego, CA, USA, 2015

[4] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," IEEE Transactions on Communications, vol. 69, no. 5, pp. 3313–3351, 2021.

[5] Miguel Dajer, Zhengxiang Ma, Leonard Piazzi, Narayan Prasad, Xiao-Feng Qi, Baoling Sheen, Jin Yang, Guosen Yue "Reconfigurable Intelligent Surface: Design the Channel -- a New Opportunity for Future Wireless Networks" arXiv:2010.07408 [eess.SP] 14 Oct 2020

[6] Silvi Kodra, Enrico M. Vitucci, Senior Member, IEEE, Marina Barbiroli, Matteo Albani, Fellow, IEEE, Vittorio Degli-Esposti, Senior Member, IEEE "A macroscopic bilateral modeling approach for reflective and transmissive metasurfaces"

[7] F. Boccardi et al., "Five Disruptive Technology Directions for 5G," IEEE Commun. Mag., vol. 52, no. 2, Feb. 2014, pp. 74–80.

[8] W. Gordon, ''A hundred years of radio propagation,'' IEEE Trans. Antennas Propag., vol. 33, no. 2, pp. 126–130, Feb. 1985.

[9] Ericsson. Stockholm, Sweden. (Nov. 2014). Ericsson Mobility Report. [Online]. Available on :http://www.ericsson.com/res/docs/2014/ericsson-mobility-report-november-2014.pdf

[10] H. T. Friis, ''A note on a simple transmission formula,'' Proc. IRE, vol. 34, no. 5, pp. 254–256, May 1946.

[11] Zhengqing Yun, (Member, IEEE), Magdy F. Iskander, (Life Fellow, IEEE) "Ray Tracing for Radio Propagation Modeling: Principles and Applications"

[12] Jean-Baptise Gros, Vladislav Popov, Mikhail Odit, Vladimir Lentes, Geoffroy Lerosey "A Reconfigurable Intelligent Surface at mmWave based on a binary phase tunable metasurface," April 2021

[13] E. Bjornson, E. G. Larsson, and T. L. Marzetta, "Massive mimo: ten myths and one critical question," IEEE Communications Magazine, vol. 54, no. 2, pp. 114–123, 2016

[14] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. de Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2450–2525, 2020.

[15] L. Subrt and P. Pechac, "Intelligent walls as autonomous parts of smart indoor environments," IET Communications, vol. 6, no. 8, pp. 1004–1010, 2012

[16] "Metamaterials and Reconfigurable Intelligent Surfaces" by Vladan Jevremovic, PhD

[17] Emil Björnson, Henk Wymeersch, Bho Matthiesen, Petar Popovski, Luca Sanguinetti, Elisabeth de Carvalho “Reconfigurable Intelligent Surfaces: A Signal Processing Perspective with Wireless Applications” arXiv:2102.00742v2 [eess.SP] 31 Dec

[18] E. Bjorrnson, O. Ozdogan, E,G, Larsson: “Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions”, IEEE Communications Magazine, December 2020

[19] Smith, D. R., Pendry, J. B., & Wiltshire, M. C. (2000). Metamaterials and negative refractive index. *Science, 305*(5685), 788-792.

[20] Marco Di Renzo, Fellow, IEEE, Fadil H. Danufane, and Sergei Tretyakov, Fellow, IEEE “Communication Models for Reconfigurable Intelligent Surfaces: From Surface Electromagnetics to Wireless Networks Optimization” arXiv:2110.00833v1 [cs.IT] 2 Oct 2021

[21] Cui, T. J., Qi, M. Q., Wan, X., Zhao, J., & Cheng, Q. (2014). Coding metamaterials, digital metamaterials and programmable metamaterials. *Light: Science & Applications, 3*, e218.

[22] B. Banerjee, An introduction to metamaterials and waves in composites. Boca Raton, FL: CRC Press/Taylor & Francis Group, 2011.

[23] Christos Liaskos, Shuai Nie, Ageliki Tsioliaridou, Andreas Pitsillides, Sotiris Ioannidis, Ian Akyildiz “Realizing “Wireless Communication through Software-defined HyperSurface Environments”, arXiv:1805.06677v1, May 2018.

[24] S. B. Glybovski et al., "Metasurfaces: From microwaves to visible," *Physics Reports*, vol. 634, pp. 1–72, 2016.

[25] Y. Liang, R. Long, Q. Zhang, J. Chen, H. V. Cheng and H. Guo, "Large Intelligent Surface/Antennas (LISA): Making Reflective Radios Smart," in *Journal of Communications and Information Networks*, vol. 4, no. 2, pp. 40-50, June 2019, doi: 10.23919/JCIN.2019.8917871

[26] Marco Di Renzo, Alessio Zappone, Merouane Debbah, Mohamed-Slim Alouini, Chau Yuen, Julien de Rosny, Sergei Tretyakov, “Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How it Works, State of Research, and Road Ahead”, arXiv:2004.09352v1, April 2020.

[27] Recommendation ITU-R P.2040-1 (07/2015)

[28] Wanchen Yang (Senior Member, IEEE), Jinghao Li, Dongxu Chen, Yue Cao, Quan Xue (Fellow, IEEE), Wenquan Che (Fellow, IEEE) "Metasurface-Based Beamforming for 5G and Beyond" (IEEE Transactions on Antennas and Propagation).

Appendix

"In writing this paper, I made use of generative artificial intelligence tools, ChatGPT-4 (version released in March 2024) and Deepseek-V3 (released in December 2024). Such tools were mainly used between February 2025 and March 2025, with the aim of improving the clarity and coherence of certain paragraphs”