

Channel modeling and Propagation Prediction for RIS-Assisted 6G Mobile Communication Systems

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Abstract: Many of the issues and constraints that impair mobile radio systems' performance are primarily caused by the propagation channel. Reconfigurable Intelligent Surfaces (RIS) are expected to play a central role in emerging 6G wireless networks by enhancing coverage and improving energy efficiency. This paper presents a simplified technique for hierarchical beam-training that manipulates electromagnetic waves to establish dominant transmission paths in RIS-assisted propagation prediction. The integration of RIS in near-field at 6G mobile scenarios introduces significant complexity due to the large number of reflecting elements and the inherent structure of the channel through MATLAB-based simulation environment. Extensive simulations are conducted to analyze the path-loss characteristics and spectral efficiency of the RIS Assisted 6G Mobile Communication Systems in comparison with conventional systems over various distances. Several statistical parameters such as, Frequency Bands, average duration of fade, Received Power were performed from the total received signal to characterize the channel modeling and propagation prediction. The results show that the propagation prediction approach accurately captures the RIS beamforming gain and by means of increasing the size of RIS surface is significantly improving the SNR in an effective method and improve the coverage performance of the 6G THz communication system and strongly guarantee the support of the ultra-large bandwidth of THz

Keywords: IRS (Intelligent Reflecting Surface), Channel Modeling, Path-loss, Propagation Prediction, 6G Application, computer simulation, Base Station Side Scheme, Mobile Communication System, Coverage Maximization Algorithm.

I. INTRODUCTION

To accomplish the objective of sending communications to and from any mobile station or terminal regardless of their locations, a wide range of scenarios must be accommodated, including highways, urban and suburban regions, parks, rural areas, and even sites distant from any center of population. To meet these objectives, the size and shape of cells must be modified to fit the local topography and the expected volume of tele-traffic. The varying nature of the required geographical area can be accommodated by using different antennas, transmitter sites, power levels, and carrier frequencies. However, Emerging Hardware Architectures and its Applications suggest that using Reconfigurable Intelligent Surfaces (RIS) for 6G is the best option in densely populated places [1]. Although there is some overlap or a coverage area that is absent, all fixed base transceivers have limited coverage. It is possible to change the coverage area from a specific base by varying the broadcast power, antenna heights, and patterns. It should be possible to create systems with great capacity and high data rates.

Innovative approaches to signal propagation modeling are required as sixth-generation (6G) mobile communications offers previously unheard-of improvements in data speeds, latency, and connection [2], [3]. By cleverly adjusting the propagation environment, reconfigurable intelligent surfaces, or RISs, have become a potential technology to improve wireless communication. In difficult propagation situations, RISs, which are made up of many passive reflecting parts, can be dynamically managed to steer and focus radio waves, increasing coverage and capacity [4]. The design and optimization of 6G networks depend on accurate RIS-assisted propagation prediction. This entails comprehending how radio waves interact with RISs while taking into account variables like the operating frequency, the RIS setup, and the surrounding environment [5].

II. RIS ASSISTED 6G MOBILE COMMUNICATION

The main purposes of RISs, a new and promising transmission technology, are to improve signal transmission [7], [8], and to help with signal offsetting [9], [10]. Additionally, because of RISs' remarkable characteristics, more significant RIS applications in wireless communications have been eagerly awaited, including RIS-assisted Simultaneous Wireless system and Power Transfer [11], [12], secure communication [13], [14], and more Reconfigurable intelligent surfaces are an important advancement for 6G wireless systems, especially in high mobility scenarios enabled by aerial unmanned vehicles (UAVs), which are characterized by dynamic channel variations, spectral inefficiencies, and heterogeneous user demands [15,16]. A summary of the existing RIS path-loss model and the fundamentals of RIS design are shown in Figure 1. As a result, the channel model and propagation prediction have taken into account the simulated power radiation pattern and received power distribution using the corresponding path-loss model of discrete phase shift.

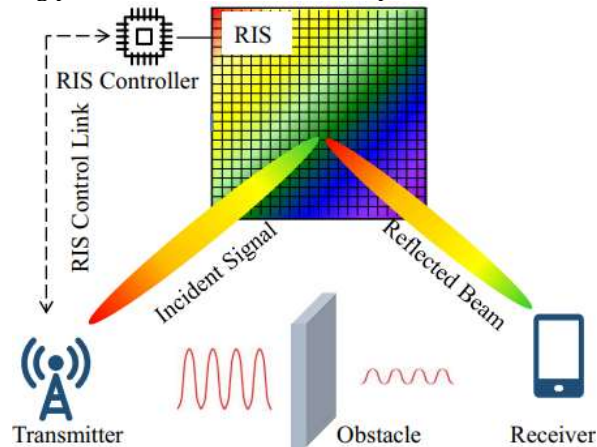


Fig 1: Conceptual architecture of RIS-assisted wireless communication system [17]

Future sixth generation (6G) technologies are expected to successfully integrate terrestrial and non-terrestrial networks [18]. Particularly, non-terrestrial networks comprise satellites, high-altitude platforms, and aerial unmanned vehicles (UAVs), whereas terrestrial networks comprise mobile communication systems and fixed infrastructure on the ground [19]. The way cars interact and communicate within the transportation ecosystem could be drastically changed by vehicular communication networks, one kind of mobile communication system [20], [21]. In order to enhance mmWave networks, the authors demonstrated the anticipated benefits and challenges of integrating RIS in a joint mobility and network simulation framework [22], [23].

Ultra-high data rates, huge interconnection, and intelligent control of the propagation environment are all necessary for the transition to 6G wireless networks [24]. Particularly at millimeter-wave and terahertz frequencies, traditional wireless systems treat the environment as uncontrollable, which results in coverage gaps and significant route loss [25], [26]. By allowing for the programmed reflection and phase manipulation of incident electromagnetic waves, reconfigurable intelligent surfaces (RIS) help to overcome these difficulties [27], [28]. Constructive signal combining can be accomplished at the receiver by adjusting the phase shifts of RIS elements, greatly increasing connection coverage and dependability [29], [30].

The transition to sixth generation (6G) wireless networks assisted RIS systems is being driven by the need for extremely high data speeds surpassing 1 Tbps, huge connection, and ultra-low latency [31]. Both sophisticated transmission methods and clever management of the propagation environment are necessary to achieve these needs [32].

III. RIS SIGNAL AND CHANNEL MODELING

RIS stands for reconfigurable intelligent surfaces, which is a paradigm shift. The phase and amplitude of reflected waves can be intelligently controlled by RIS by applying metasurfaces with reconfigurable elements to indoor surfaces, walls, or buildings [33]. This capability turns a passive setting into a programmable, active part of the wireless system. In this work, RIS-assisted propagation in a 6G scenario is modeled using constructed MATLAB simulation framework. The framework produces six figures that together show how RIS affects channel prediction and wireless propagation. Severing path loss at mmWave (30–300 GHz) and THz bands, sensitivity to obstruction, restricted coverage because of narrow beams, and uncontrollable reflections from objects and buildings are some of the major drawbacks of traditional 5G/6G systems [34].

In order to thoroughly investigate these capabilities, this paper creates a MATLAB simulation environment that designs an intelligent 6G communication system, which show the basic behaviors of RIS assisted propagation. The Comparison of Channel Modeling Approaches for RIS-Assisted 6G Systems in table 1 shows the best cases while applying different modeling approaches. In order to meet the richer service requirements and provide the best possible user experience in the 6G era, advancements in a number of critical core technologies and new network technologies are needed. Based on the current spectrum resources, the 6G network will further extend to higher frequency bands like terahertz (THz) and millimeter wave (mmWave). Additionally, the various spectrum resources will be fully and effectively utilized to satisfy the service requirements of various 6G application scenarios.

Table 1: Comparison of Channel Modeling Approaches for RIS-Assisted 6G Systems

Modeling Approach	Description	Strengths	Limitations	Best Use Cases
Geometry-Based Stochastic Models (GBSMs)	Models Tx–RIS–Rx links, using geometric relationships and statistical distributions.	Accuracy and complexity are well balanced; spatial correlation is captured;	Limited capacity to model specific electromagnetic effects; and less accurate in complex environments.	Large-scale network models; RIS-assisted MIMO performance and early 6G system design.
Deterministic Ray-Tracing (RT)	Applicable for multipath propagation, accurate defining RIS controlled reflections, best in site specific 3D maps and electromagnetic reflection models.	High physical accuracy, suitable for mmWave/THz bands, captures material characteristics and RIS element patterns	computationally costly, requires intricate maps of the environment, and is challenging to scale to simulations at the city level.	Best practice in Indoor/outdoor site specific planning; suitable for THz/mmWave propagation prediction, and RIS optimization condition.
Electromagnetic (EM) Full-Wave Models	models RIS scattering, mutual coupling, and near-field effects by solving Maxwell's equations	Maximum physical fidelity; accurate near-field behavior; models hardware limitations	Very expensive to compute; unsuitable for simulations at the system level.	Near-field characterization, material/structure optimization, and RIS element design

	(FDTD, MoM, and FEM).	and mutual coupling.		
Hybrid EM–Stochastic Models	combines stochastic channel modeling with EM-based RIS characterization to produce accurate and scalable simulations.	More realistic compared to pure GBSM; it captures RIS physics without full EM cost and offers a good balance between accuracy and complexity.	Limited environmental generalization still needs EM preprocessing.	Simulations of 6G systems with RIS awareness; performance assessment under hardware limitations
Machine Learning-Based Models	learns the behavior of RIS-assisted channels and forecasts future states using neural networks (CNNs, RNNs, GNNs, Transformers)	Effective for channel aging and mobility; learns nonlinear RIS effects; lowers pilot overhead; and, once trained, makes inferences quickly.	Large datasets are needed; it's challenging to generalize across environments; and physical interpretation is challenging.	Best practice in mobility Channel prediction, Real time RIS configuration;
Hybrid Machine Learning Ray-Tracing Models	ML models developed using ray-tracing generated data to lower computational expenses while keeping precision	RT-generated data was used to create machine learning models that reduce computational costs without sacrificing accuracy.	RT modeling biases may be inherited; quality is dependent on RT training data	RIS deployment planning and city-scale propagation prediction.
Measurement-Based Models	derived from actual RIS channel sounding campaigns in the THz, mmWave, and sub-6 GHz bands.	Maximum realism shows that theoretical models are valid, records environment-specific effects and hardware impairments.	costly and time-consuming; difficult to scale across environments and frequencies; limited generalizability	GBSM/ML model calibration; standardization initiatives; and model validation.

IV. RIS SIGNAL AND CHANNEL MODELING

use tunable phase shifts to intelligently reflect incident electromagnetic waves, allowing for manipulation of the wireless propagation environment, Reconfigurable Intelligent Surfaces (RIS) allow the wireless propagation environment to be manipulated. A cascaded BS-RIS-UE link and a direct BS-UE link make up the end-to-end channel in a BS-RIS-UE architecture. By using passive beamforming, the RIS increases the strength of the received signal [35]. Both direct and reflection paths are included in the Reconfigurable Intelligent Surfaces (RIS) signal model.

V. SYSTEMATIC MODEL FLOWCHART

A methodical simulation approach for simulating and assessing a wireless communication system supported by Reconfigurable Intelligent Surfaces (RIS) is presented in the flowchart shown in figure 2.

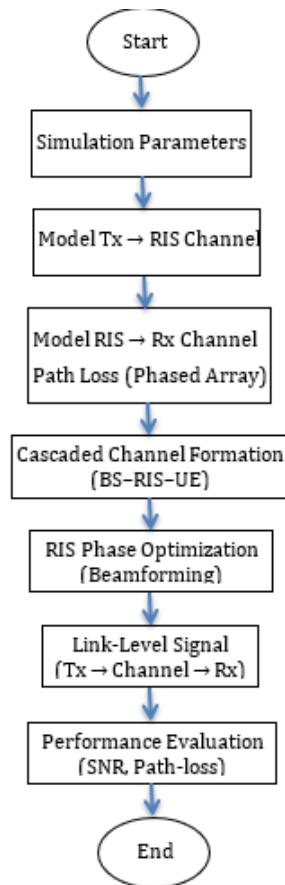


Fig 2: RIS Phase Optimization and System Model

The framework incorporates link-level performance evaluation, cascaded channel construction, RIS phase optimization, phased array based path loss computation, and deterministic propagation modeling. This methodical approach for link-level performance assessment and RIS-based propagation modeling in a 6G wireless communication system taking BS-RIS-UE into account. Therefore, MATLAB performance evaluation under programmable electromagnetic wave manipulation is guaranteed by the methodology as shown in the flowchart.

Setting up the simulation environment is the first step in the process. This entails establishing system-level assumptions and computing parameters. All system, propagation, and simulation parameters needed for RIS-assisted communication modeling are defined in

this block, including carrier frequency f_c (e.g. A. RIS element number (N), bandwidth (B), transmit power (Pt), and mmWave/sub-THz for 6G.

A. SIMULATION PARAMETERS

A single base station running at 28 GHz, which is typical of 6G/mmWave communications, is taken into consideration in the simulated system. An RIS with N reflecting elements helps with the transmission when a user is situated at different distances. These are the primary parameters: Table 2 displays the preliminary broad carrier frequency of 3 to 300 GHz, with consistent 64 RIS elements, using suitable single path loss exponent of 2, and a distance of 10 to 500 m as acceptable range. These are good starting values for 5G, but 6G primarily uses sub-Terahertz (sub-THz) and THz bands, which drastically alters the channel modeling requirements (such as massive arrays and molecular absorption).

Table 2: The main simulation parameters

Parameter	Proposed 6G Value
Carrier Frequency (f_c)	100 GHz – 300 GHz
System Bandwidth (B)	10 GHz – 30 GHz
Number of RIS Elements (N)	$8 \leq N \leq 128$
RIS Element Spacing	$\lambda/2$
Path Loss Exponent (LOS)	2.0
Path Loss Exponent (NLOS)	3.0 – 3.5
Fading Distribution	Rician (LOS) / Rayleigh (NLOS)
Distance Range (Tx - Rx)	10 m – 500 m
Antenna Gain (Tx/Rx)	10 dBi – 30 dBi

B. Model Tx → RIS Channel Modelling

This model provides the equivalent channel responses as a free space path loss at a reference distance of one meter. Engineers often use a one-meter reference distance when modeling wireless environments or computing link budgets. In addition to providing a baseline for determining signal loss at any other distance, FSPL evaluation at precisely one meter simplifies the intricate mathematics of radio wave propagation as standard norms stated in eq (1).

$$PL_0 = 32.4 + 20 \log_{10}(f_c/1 \text{ GHz}) \quad \text{..... (1)}$$

The norms of the modeling for mmWave and sub-THz propagation is followed by this expression. For a transmitter-receiver separation of d , the large-scale path loss is: The path loss model is: Distance Dependent Path Loss as shown in eq (2).

$$PL(d) = PL_0 + 10\alpha \log_{10}(d) \quad \text{..... (2)}$$

where the path loss exponent is denoted by α . Because of its accuracy and ease of use in both LOS and NLOS scenarios, this log distance model is frequently utilized in RIS channel modeling [5]. An approximate array gain is provided by RIS with N reflecting elements as per the details in eq (3).

$$G_{\text{RIS}} = 10 \log_{10}(N^2) \quad \dots\dots\dots (3)$$

C. BS-RIS-UE Channel Structure

The wireless propagation channel between the RIS and the Base Station (BS) is modeled in this step. The performance of the entire system is largely determined by the BS-RIS link, which is the initial hop of the cascaded RIS-assisted transmission. Let the RIS be made up of N passive reflecting elements and the BS have M antennas. The matrix represents the channel between the BS and RIS as shown in eq (4).

$$\mathbf{H}_{BR} \in \mathbb{C}^{N \times M} \quad \dots\dots\dots (4)$$

where, for a narrowband geometric channel model, each entry $[\mathbf{H}_{BR}]_{n,m}$ indicates the complex baseband channel coefficient between the m -th BS antenna and the n -th RIS element.

$$\mathbf{H}_{BR} = \sqrt{\beta_{BR}} \sum_{\ell=1}^{L_{BR}} \alpha_{\ell} \mathbf{a}_{RIS}(\theta_{\ell}^{RIS}) \mathbf{a}_{BS}^H(\theta_{\ell}^{BS}) \quad \dots\dots\dots (5)$$

Where:

β_{BR} is large-scale path loss

α_{ℓ} is small-scale fading coefficient

$\mathbf{a}$ are array response vectors

C. Element Efficiency for RIS Phase Optimization

One key mechanism in the study of RIS is phase optimization, which enables the surface to sharply shape the radio conditions. RIS is thought to be perfectly efficient in ideal case of theoretical models, indicating a 100% reflection of the incident signal with faultless polarization alignment. To make the model more realistic for 6G system, we add a multiplicative efficiency term in equation (6) to improve the RIS phase optimization.

$$F_{n,m}^{\text{total}} = F_{n,m}^{\text{dir}} \times \eta_{n,m} \times |\mathbf{e}_{tx}^T \mathbf{e}_{rx}|^2 \quad \dots\dots\dots (6)$$

Polarization Loss and Element Efficiency, which frequently appear as phase dependent amplitude loss, are two of the most important practical signal impairments that need to be incorporated into phase optimization algorithms according to RIS Element Efficiency Factor shown at eq (7).

$$\eta_{n,m} \in (0, 1] \quad \dots\dots\dots (7)$$

Consider frequency-dependent efficiency (important for THz), tunable impedance loss, Ohmic loss, and substrate loss the matching factor used to penalizes polarization mismatch as shown at eq (8)

$$|\mathbf{e}_{tx}^T \mathbf{e}_{rx}|^2 \quad \dots\dots\dots (8)$$

Where:

$\mathbf{e}_{tx}$: Incident wave polarization vector

$\mathbf{e}_{rx}$: Reflected wave polarization vector

Modeling Reconfigurable Intelligent Surfaces must completely change in order to move from sub-6 GHz to the mmWave system and Terahertz (THz) bands that are intended for 6G. At these extremely high frequencies, the RIS's simplified model as flawless phase shifters totally fail. The precise angles at which electromagnetic waves strike meta-atoms, their physical size, and their proximity to one another become mathematically entangled when wavelengths are reduced to millimeters or micrometers. We must move to a framework that clearly distinguishes the physics of incidence from the physics of reflection while treating the

RIS as a single electromagnetic surface rather than a collection of separate pixels in order to develop an EM consistent RIS model one that strictly adheres to Maxwell's equations and is appropriate for 6G as shown at eq (9).

$$F_{n,m}^{dir} = \underbrace{(\cos \theta_{n,m}^{tx})^{p_t}}_{\text{Tx illumination}} \underbrace{(\cos \theta_{n,m}^{inc})^{p_{inc}}}_{\text{RIS incidence}} \underbrace{(\cos \theta_{n,m}^{ref})^{p_{ref}}}_{\text{RIS reflection}} \underbrace{(\cos \theta_{n,m}^{rx})^{p_r}}_{\text{Rx reception}} \quad .. (9)$$

Where.

$\theta_{n,m}^{tx}$ BS to RIS angle

$\theta_{n,m}^{inc}$ incident angle at RIS

$\theta_{n,m}^{ref}$ Reflection angle from RIS

$\theta_{n,m}^{rx}$ RIS to BS angle

$p_t, p_{inc}, p_{ref}, p_r$: environment-based condition dependent

VI. RESULTS AND ANALYSIS

The outcomes verify that RIS has the potential to significantly alter wireless transmission. RIS offers a significant increase in received power, SNR gains proportional to the square of the number of elements, broader and more consistent coverage, and compatibility with machine-learning-based channel prediction, even with a simplified model. A useful tool for teaching and preliminary research is the MATLAB framework. A visual representation of the relationship between path loss and physical distance between transmitter and receiver is shown in Figure 3. The decrease in an electromagnetic wave's power density during its spatial propagation is known as path loss. This increase is "monotonic" in a 6G link, which means that it continuously trends upward without fluctuating downward as distance increases. is usually determined by the Log-Distance Path Loss Model.

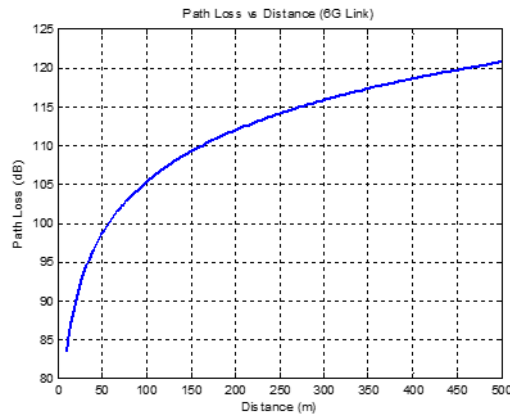


Fig 3 Path Loss vs Distance in 6G link

It is crucial to comprehend the curve shows in figure (1) in the development of 6G for several reasons, such as Higher frequency challenges in 6G due to the sub-THz and THz frequencies. In this case, path loss is much worse at these higher bands than it is at the previous generation. Figure 1's line would probably have a reasonable slope. Using this relationship of distance versus path loss will determine the link budget, which makes reliable that the transmitter power is enough to withstand the path loss at a given distance. To sustain cell density a high-speed connectivity over shorter ranges of 6G networks will probably need a significantly higher base stations due to path loss increases with distance.

Figure 4 shows that the path loss increases in proportion to the physical distance between the transmitter and the receiver. When an electromagnetic wave travels through space, its power density decreases, a phenomenon known as path loss. The signal strength decreases with increasing distance in a RIS-assisted link because of this consistent decay. Generally, higher frequency bands like those found in 6G experience more path loss over the same distance than lower bands.

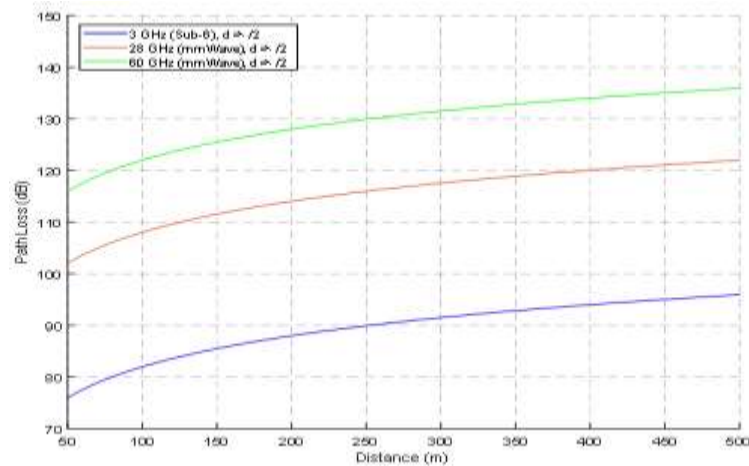


Fig 4: Distance versus Path Loss for Various Frequency Bands in RIS Systems

Reconfigurable Intelligent Surfaces are frequently used in these systems to counteract high path loss by "reflecting" or "focusing" signals in the direction of the user, so increasing the communication range.

By measuring Received Power against Distance, Figure 5 shows how Reconfigurable Intelligent Surfaces (RIS) significantly affect signal strength. Two different wireless communication link situations are depicted in the graph. demonstrates how receiving power is greatly increased. This figure displays a typical decline in received power as the distance from the transmitter rises in the absence of RIS (Baseline). This is consistent with the basic rules of electromagnetic transmission, which state that signal energy disperses and weakens with distance. With RIS (Enhanced), on the other hand, this curve is significantly higher than the baseline. The network can "reflect" or "beamform" signals toward the receiver by implementing a RIS, so increasing the power levels that would otherwise be lost to the environment, as it illustrates.

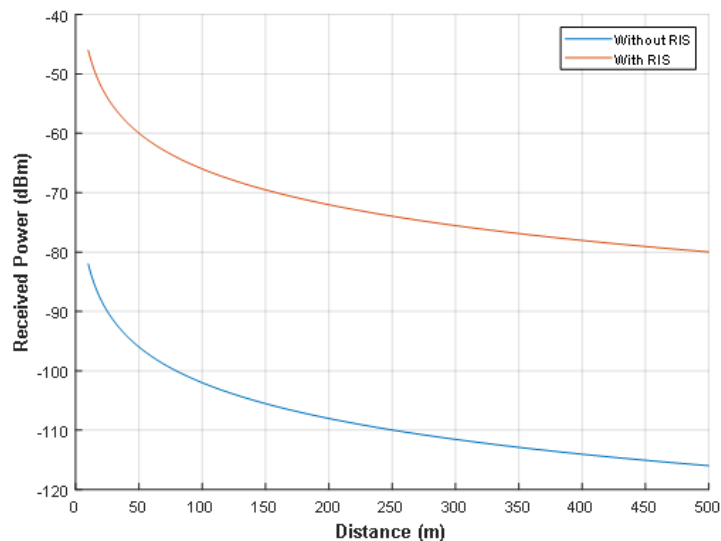


Fig 5 Received Power (with and without RIS)

One of the most basic trade-offs is the connection between Transmitter Power and Spectral Efficiency (Bandwidth Efficiency). Plotted on a logarithmic scale, the figure shows the link between Spectral Efficiency (in bits/s/Hz) on the Y-axis and Transmit Power (in dBm) on the X-axis. It contrasts RIS-assisted systems with different numbers of reflecting elements ($N = 8, 16, 64, 128$) with a typical wireless system without one. For every curve, the spectral efficiency rises in tandem with the transmit power (which moves from left to right on the X-axis). This is consistent with the basic Shannon capacity theorem, which states that increasing the power applied to a channel raises the Signal-to-Noise Ratio (SNR), hence enabling faster data rates. Figure 6: RIS transmitter power vs Spectral Efficiency (Bandwidth Efficiency)

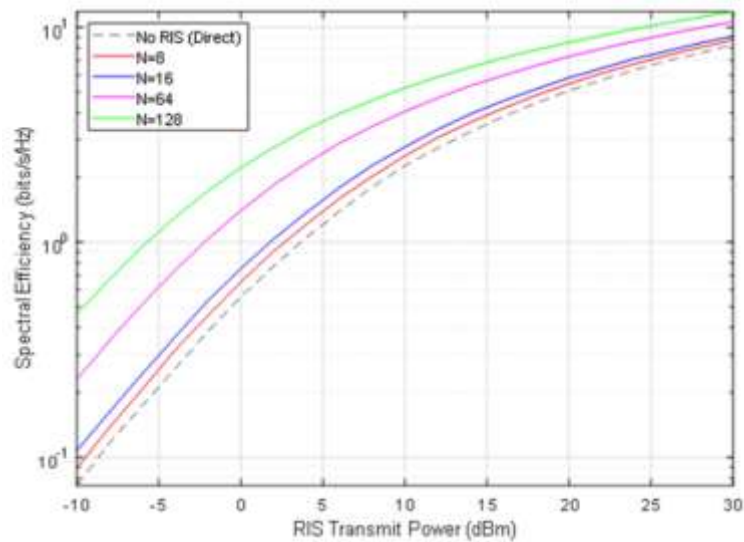
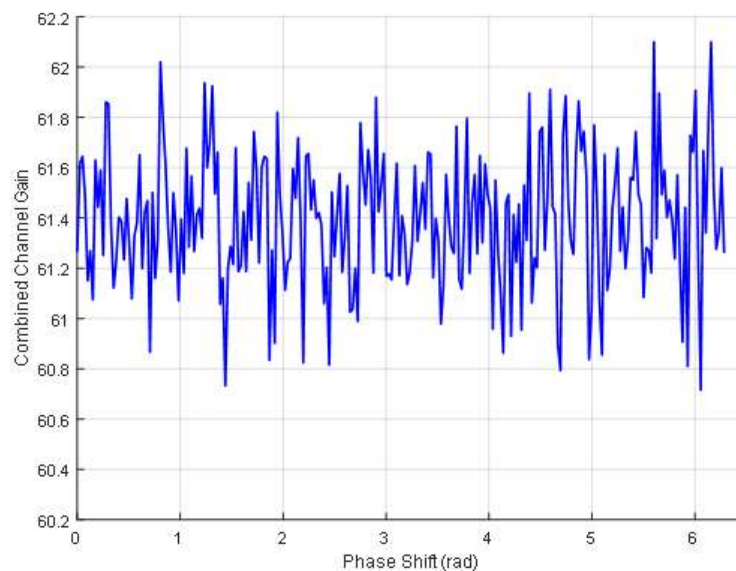


Fig 6: RIS transmitter power vs Spectral Efficiency (Bandwidth Efficiency)

The crucial function of phase optimization in reconfigurable intelligent surfaces (RIS) and its effect on the overall signal strength is depicted in Figure 7. Multipath propagation is the process by which signals travel over several pathways to reach a receiver in a wireless environment.

Fig 7: RIS transmitter power vs Spectral Efficiency (Bandwidth Efficiency)



Destructive interference is the term for what happens when these signals arrive at separate times or "out of phase," canceling each other out. Each reflecting element on the RIS must have its phase shifts adjusted in order to preserve the Coherent Phase Alignment. This surface makes sure that the reflected signals reach the receiver in time with the transmitter's direct signal. Maximized Combined Gain, on the other hand, is achieved when the amplitudes of these signals align, which results in a substantially larger combined channel gain than in a system without RIS.

Figure 8 shows how the Signal-to-Noise Ratio (SNR), a measure of a wireless network's performance, scales with the physical size of the Reconfigurable Intelligent Surface (RIS). The relationship between the number of reflecting elements (N) and the resulting SNR is the most important lesson to be learned from this image. The SNR in a RIS-optimized system has a quadratic gain trend (N^2), in contrast to conventional relay systems that may exhibit linear improvement.

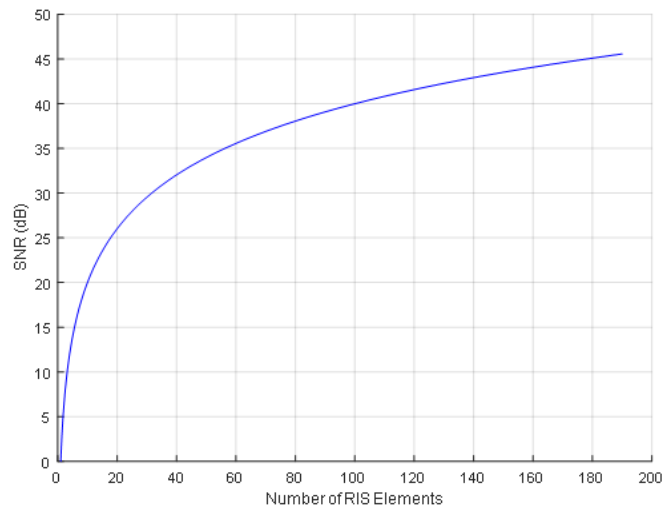


Fig 8 Number of RIS Elements vs SNR gain

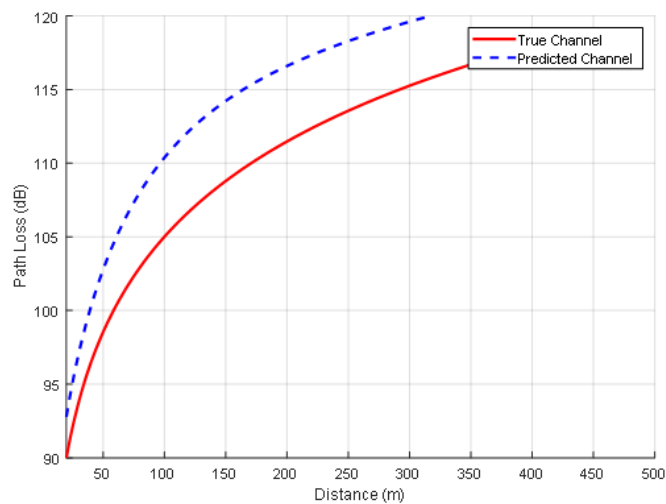


Fig 9 Propagation prediction in intelligent 6G systems based on RIS Channel Modeling

Figure (9) compares the actual channel data for RIS system with the expected outcomes to demonstrate the precision and efficacy of including a multiplicative efficiency element in wireless environment modeling. The intelligence component of contemporary 6G propagation

models is highlighted in this picture. The observed physical behavior of the signal as it passes through a complex environmental scenario such as bouncing off buildings or being absorbed by obstacles is represented by the true channel.

The output of the model has been trained to predict these intricate signal characteristics is known as the predicted channel. Regarding the accuracy mapping, in this figure it may effectively capture the complex details of signal propagation and expectation for prediction.

VII. CONCLUSION

Two emerging technologies, RIS and terahertz communication, will have a significant impact on 6G communications in the future and be crucial to innovative applications like massive industrial IoTs. The wireless channel model of RIS-based terahertz-enabled communication systems is theoretically studied in this study by combining these two technologies. In this research, we use simulation to investigate the link between SNR and the operating frequency and RIS surface size. However, the size, quantity, and arrangement of RIS reflective units present unique and significant difficulties for RIS channel modeling in contrast to conventional wireless communication systems. Numerous elements must be taken into account when building the RIS channel model, including the RIS's properties, deployment strategy, and operating frequency spectrum. Hence, utilizing perceived data, such as position to support RIS channel modeling and channel estimate may become popular as integrated communication and perception technology advances. Artificial intelligence (AI) technology can also be used to handle the complicated scenarios and uncertainties in real communication systems in order to fully utilize the diverse data collected. By significantly lowering computational overhead, it is possible to achieve performance that is superior to that of conventional technology. We may also investigate shape-adaptive RIS, narrower beamforming RIS, in the next research cycle.

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