International Journal of Engineering Research and Modern Education (IJERME)
International Peer Reviewed - Refereed Research Journal, Website: www.crystalpen.in
Impact Factor: 7.018, ISSN (Online): 2455 - 4200, Volume 11, Issue 1, January - June, 2026

DESIGN AND OPTIMIZATION OF RECONFIGURABLE INTELLIGENT SURFACES (RIS) FOR 6G MILLIMETER-WAVE COMMUNICATION SYSTEMS

Safaa Mahmood Hamad* & Zainab H. Mohammad**

* Najaf Technical Institute, Al-Furat Al-Awsat Technical University, Najaf, Iraq

** Department of Mathematics, Najaf Center, The Open Educational College, Ministry of Education, Najaf, Iraq

Cite This Article: Safaa Mahmood Hamad & Zainab H. Mohammad, "Design and Optimization of Reconfigurable Intelligent Surfaces (RIS) for 6G Millimeter-Wave Communication Systems", International Journal of Engineering Research and Modern Education, Volume 11, Issue 1, January - June, Page Number 119-128, 2026.

Type of Review: Peer Reviewed as per |C|O|P|E| Guidance.

DOI: https://doi.org/10.5281/zenodo.21274540

Abstract:

With 5G networks reaching maturity and global deployment, academic and industrial attention is increasingly focused on shaping the features of 6G. The future vision for 6G extends beyond simply improving traditional performance metrics, such as increased speed and reduced latency; it aims to create an infrastructure capable of integrating physical, digital, and biological environments into a single system. However, existing millimeter-wave communication systems suffer from severe path loss, signal blockage, limited coverage, and reduced communication reliability, particularly under Non-Line-of-Sight (NLOS) environments. Although several studies have employed Reconfigurable Intelligent Surfaces (RISs) to improve wireless performance, most approaches focus on individual optimization components and rely on simplified simulation environments, limiting their practical effectiveness. To address these limitations, this study proposes an integrated RIS-assisted optimization framework for 6G millimeter-wave communication systems. The framework utilizes the 5G Wave Channel Prediction Dataset obtained from Kaggle and incorporates channel modeling, channel estimation, RIS reflection coefficient design, phase shift optimization, beam forming optimization, and power allocation. The proposed model was implemented using MATLAB R2023a for communication system simulation and performance evaluation. Experimental results demonstrate significant improvements, including 94.4% higher channel gain, 83.9% higher spectral efficiency, 77.1% higher throughput, 107.3% higher energy efficiency, and 97% coverage probability, while reducing latency by 61.1% and power consumption by 35.0% compared with conventional communication systems. These results confirm that the proposed RIS-assisted framework effectively overcomes millimeter-wave propagation challenges and enhances the overall performance, reliability, and efficiency of future 6G communication networks.

Key Words: Beam Forming Optimization, Channel Estimation, Millimeter-Wave Communication, Reconfigurable Intelligent Surface (RIS), Spectral Efficiency.

1. Introduction:

The advancement of technology for wireless communication at an alarming rate has fast-tracked the development of 5G networks into advanced 6G communication systems that promise ultra-high data rates, massive connectivity, intelligent services, and ultra-low latency. Millimeter wave communication technologies have proven indispensable for the development of 6G communication technologies owing to the abundance of frequency spectrum available and their ability to deliver multi-gigabit speeds [1], [2]. However, the implementation of mmWave communication technologies is hindered by some obstacles, such as significant path loss, signal attenuation, and vulnerability to blockages [3], [4]. To solve these problems, considerable attention has been given to Reconfigurable Intelligent Surfaces (RISs), which are programmable and can effectively control electromagnetic waves by controlling signals[5], [6]. With the ability to dynamically reflect signals, the deployment of RISs within mmWave systems allows for efficient coverage, high spectral efficiency, reduced transmission power needs, and a smart radio environment for wireless communication [7].

Despite all the advancements that have been made in RIS-based wireless communication technologies, there are some issues that have not been solved yet in the available literature [9]. In existing communication systems, active relaying techniques, MIMO structures, and conventional beam forming techniques are used to alleviate the adverse effects of propagation [10], [11]. Even though all these techniques lead to improved performance in the field of communication, they require complex hardware designs, high energy consumption, and higher implementation costs [12][13]. In recent literature, optimizations for phases, beam forming, channel estimation, and resource allocation strategies have been considered to increase system performance [14], [15]. In many cases, these optimization schemes are based on simplifying assumptions and hence cannot address the dynamic nature of the 6G mmWave channel environment. Moreover, the issue of optimizing phase designs and beam forming remains a challenging task.

Based on previous studies on RIS-assisted mmWave communications, there remains a need for a comprehensive optimization framework that simultaneously addresses signal propagation challenges and communication performance requirements in future 6G networks. Hence, in this regard, the present paper proposes a framework for developing an architecture for 6G mmWave communications with the help of RISs. In addition, a framework for developing realistic models for the channel that is used in estimating the process of propagation between the BS, RISs, and UE will be developed in this paper. Moreover, an optimization framework for finding the best phase shifts to have maximum constructive interference from reflected signals would be proposed.

1.1 Research Motivation:

The motivation for conducting this research is derived from the ever-growing necessity of deploying highly efficient and high-capacity wireless communication networks capable of supporting emerging 6G technologies such as autonomous cars, smart healthcare solutions, immersive virtual realities, and massive Internet of things deployments with high transmission rate and ultra-low delay. Even though millimeter wave communications offer large bandwidth resources for satisfying these needs, their performance is adversely affected by factors such as high path loss, signal blocking, and poor coverage in complex propagation channels. Commonly employed mitigation techniques like relay-based communication schemes and MIMO-based techniques are quite costly and consume more power compared to traditional approaches. Reconfigurable Intelligent Surfaces present a novel technology that enables intelligent control of the propagation environment using controllable reflective surfaces. Nonetheless, an optimized RIS assisted communication system must be designed for realizing full benefits.

1.2 Significance of the Study:

The significance of the study is that it will advance research on next-generation wireless communication technologies by designing and optimizing the intelligent surfaces known as Reconfigurable Intelligent Surface. With the introduction of the 6G communication systems, there will be an expectation to deliver ultra-high data rates, massive connectivity, and lower latency, which can be achieved when issues such as high path loss, high attenuation, and even blockages are addressed successfully. The optimization of intelligent surface control mechanisms to manipulate the signal reflection is crucial in addressing these issues effectively. The use of spectrum more efficiently, with lower power consumption and improved communication systems, leads to efficient wireless communication technologies being developed that support future smart cities, automated transportation, industry automation, and Internet of Things.

1.3 Problem Statement:

One of the technologies that will enable next-generation 6G wireless networks is millimeter-wave communication. but it has significant propagation problems, such as significant path loss, signal blockage, and high channel fading rate in Line-of-Sight and Non-Line-of-Sight scenarios. While Reconfigurable Intelligent Surfaces (RIS) have been thoroughly investigated in terms of improving coverage, spectral efficiency, and energy efficiency, there remain some limitations in the existing studies [14], [15]. A lot of solutions assume idealized conditions, make simplifying assumptions on the channel model, or use highly complicated optimization methods that are impractical to apply to real large-scale networks. Besides, current RIS designs mostly optimize the phase shift and/or the beam forming separately without considering how they can be jointly optimized with power allocation under realistic communication conditions. Moreover, most of the available utilization models are not extensive enough to model and evaluate the channel using real propagation data. Thus, an efficient RIS-assisted optimization framework, considering the practical channel model based on datasets and effective phase shift, beam forming and power control strategies, is required to optimize the performance of overall 6G communication system.

1.4 Key Contributions:

- Explored the use of Reconfigurable Intelligent Surfaces (RISs) in addressing issues of severe path loss, signal obstruction, and coverage limitation in mmWave-based communication in 6G networks.
- Proposed a new communication system framework assisted by RIS that considers system architecture, channel modeling, and intelligent signaling for efficient wireless communication.
- Captured and analyzed communication network parameters, which included Channel State Information (CSI), Signal-to-Interference-and-Noise Ratio, signal intensity, user localization data, and channel propagation characteristics for system optimization purposes.
- Applied optimization techniques, which comprised channel estimation, optimal RIS phase shift design, beam forming design, and power allocation approaches to maximize communication efficiency.
- Demonstrated improvement in coverage probability, throughput, energy efficiency, spectral efficiency, and communication latency in comparison to regular mmWave communications without RIS assistance.

2. Literature Review:

Ahmed et al. [16] presented a hybrid reconfigurable intelligent surface (HRIS-DMA) for enhancing the coverage and minimizing power loss in dense networks in the context of 6G. The aim of the study is to enhance the received signals' quality and to increase the range using user-location-aware RIS optimization. The method is based on an iterative decision-making algorithm that dynamically tunes RIS phase shifts and beam forming as per real-time user locations, which have been tested in MATLAB R2023a for various obstacles scenarios. The approach has resulted in 70% power loss reduction, 0.17 μs lower latency, 12 dB and 25 dB more channel gain over BS handover and STAR-RIS, and 95% efficiency gain. Benefits include more coverage, less latency and adaptive beam steering. There are some limitations, such as simulation-based validation and hardware implementation and scalability testing in large-scale 6G deployments.

Selvaraj et al. [17] suggested a phase-reconfigurable RIS to enable the advanced applications of 6G including haptic communication, smart cities with IoT, automation, and industrial manufacturing. This study aims to manipulate electromagnetic waves with low power loss, cost efficiency and high control of the wave. The goal of the study is to control the manipulation of the EM wave to provide improved coverage and signal quality at low power and low cost. The methodology is a combined loop meta surface design with four PIN diodes, for a 2×2 periodic meta-atom structure, which supports 16 switchable states for dynamic phase reflection control. The system is checked by numerical simulations and experimental testing with a 32×32 meta surface configuration. The method shows the high tuning precision of the phase and stable reflection property. Low power consumption, simple structural design, polarization insensitivity, and scalable RIS implementation are the advantages. But constraints are that it is based on complex diode switching and limited testing of real-world large-scale networks.

Khafagy et al. [18] introduced a M-shaped Reconfigurable Intelligent Meta surface with Low Complexity to address the tremendous path loss suffered by mmWave signals in future 6G indoor scenarios. It's designed to boost received signal strength and facilitate scalable, cost-effective deployment in enclosed areas like offices and conference rooms. A single-layer Rogers substrate meta surface is designed to perform 1-bit phase modulation (0 and π) at 24.12 GHz using AlGaAs PIN diodes and arranged into a 1024-element array with Gaussian angular gain modeling and MATLAB-based validation. Under different distances and incidence angles, the system can get up to 15 dB gain of received signal strength. Benefits are simple complexity, low power consumption, scalability and efficient passive beam forming. Some limitations are related to the use of simulation results, to the fact that the studies are performed in a laboratory environment, and to the lower precision of the beam forming because of the use of 2-bit phase control.

Liu et al. [19] introduced a two-phase channel estimation technique to improve the estimation accuracy for RIS-Aided uplink multiuser 6G communication systems when the channel parameters are large. Reducing pilot overhead and inaccurate channel estimation is the goal. performance in low SNRs. The method is based on Orthogonal Matching Pursuit (OMP) for selecting the sparse support set and Linear Minimum Mean Square Error estimation for improving the robustness with noise, iteratively updating the sensing matrix by residual correlation. The results of the simulation demonstrate that the accuracy of the estimation is better than that of LS and traditional OMP and other OMP-based methods. It has the merits of reducing the pilot overhead, improving the robustness in low SNR, and increasing the estimation accuracy. Reduced computational complexity, when compared to LS methods, and assuming the sparsity is accurate in channel modeling are the limitations.

Sarker et al. [20] introduced a hybrid beam forming technique with RIS assistance to enhance coverage to tackle the problem of blockage-aware mmWave V2V MIMO communication systems with limited coverage. The goal is to reduce LOS blockages due to obstacles and increase spectral efficiency of vehicle-to-vehicle communication. It proposes a Conjugate Gradient and Location-Based Hybrid Beam forming method for maximizing sub-rate and a double-step iterative optimization based on splitting of the error covariance matrix technique to mitigate the effects of location uncertainty in beam forming passively. The simulation results demonstrate good performance in case of channel uncertainty less than 10%. The benefits are on one hand better coverage, on the other side robustness to blockage and on the third side enhanced beam forming efficiency in dynamic V2V situations. The drawbacks are their degradation in high localization errors and the need for precise position data to achieve best performance of the RIS configuration.

Zhao et al. [21] first presented a stochastic geometry-based analytical framework for RIS-assisted mmWave networks to analyze and improve the coverage performance. The goal is to mathematically model user association and coverage probability in RIS-enabled scenarios and enhance network planning efficiency. The methodology includes stochastic geometry modelling, two-step cell association approach and provides analytical and closed-form expressions for user association probability and coverage probability under general and special cases. The simulation results are presented and compared with theoretical derivations, showing the effect of using RIS and the increased coverage as RIS parameters and base station density are changed. Benefits include high analytical tractability, better network coverage insights and an established theoretical modeling. There are some restrictions such as idealized spatial assumptions and limited applicability to highly dynamic or real-time adaptive RIS configurations.

Yu et al. [22] proposed a joint optimization framework for RIS-aided movable antenna (MA) systems, which can optimize both beam forming and antenna positions to improve the spectral efficiency. The goal is to address the shortcoming of conventional antenna systems that are fixed in space, and to maximize spatial degrees of freedom in RIS-enabled wireless networks. The methodology is first to formulate the antenna positioning as a Sequential Quadratic Programming problem, and secondly to use an alternating optimization scheme where the beam forming and the optimization of the antenna locations (SQP) are solved separately. The results of the simulation indicate that the efficiency of the spectrum is increased by about 25% compared with the fixed-position schemes. The benefits are that better use is made of spatial DoFs, spectral efficiency is improved and convergence is more efficient than gradient-based methods. The disadvantages are the iterative SQP optimization, which may be more complex to compute and the reliance on the accurate position and channel information.

Zhang et al. [23] suggested a joint optimization scheme for multi-user mmWave systems with IRS to achieve sum-rate maximization using hybrid beam forming and low-resolution phase shift control for IRS. Its goal is to increase spectral efficiency and decrease the number of hardware and computing complexity in mmWave networks. The methodology includes Zero-Forcing (ZF) to provide fully digital beam forming and an iterative technique based on Cross-Entropy Optimization (CEO) to optimize the IRS phase shifts by updating probability distributions towards near-optimal configurations. Finally, an alternating minimization technique is adopted to obtain the hybrid beam forming from the FD solution. The simulation results show that the scheme can provide better sum-rate performance at lower computation cost than the existing schemes. Benefits are low resolution hardware feasibility, efficient optimization and improved system performance. Sensitivity to initialization, approximation errors in the process of probabilistic optimization, and reduced performance under highly dynamic channel conditions are some limitations.

Even though there are already RIS-assisted 6G communication studies that have improved the coverage rate, spectral efficiency, energy efficiency, channel estimation performance and beam forming performance, there are still some limitations. Most of these approaches depend on simulation-based tests, simplified channel assumptions and isolated optimization methods targeting on the specific components instead of the communication system. Furthermore, numerous existing approaches depend on perfect channel state information and accurate user location data, coupled with computationally demanding optimization techniques, which significantly hinder their scalability and real-world deployment feasibility. Moreover, there are scarce studies that have considered realistic communication datasets for studying RIS performance under LOS and NLOS conditions. In this regard, this study proposes an integrated RIS-assisted framework, which incorporates a dataset-driven channel modeling approach, channel estimation, Power allocation, beam forming optimization, and phase shift optimization to boost overall 6G communication performance.

3. Proposed RIS-Assisted Framework for 6G Millimeter-Wave Communication Systems:

In this study, an effective methodological approach for designing and optimizing the Reconfigurable Intelligent Surface (RIS) is introduced in 6G millimeter-wave communication networks. This methodological approach is developed aiming at improving reliability, spectrum efficiency, energy efficiency, and network coverage via intelligent reflection management. Specifically, this methodological approach includes data acquisition, data processing, channel modeling, channel estimation, reflection coefficient design for RIS, phase shifting, beam forming, power allocation, and performance evaluation. With the help of each step, an optimized RIS-based communication system can be created to address propagation problems associated with millimeter-wave communications. The overall methodology workflow is illustrated in Figure 1.

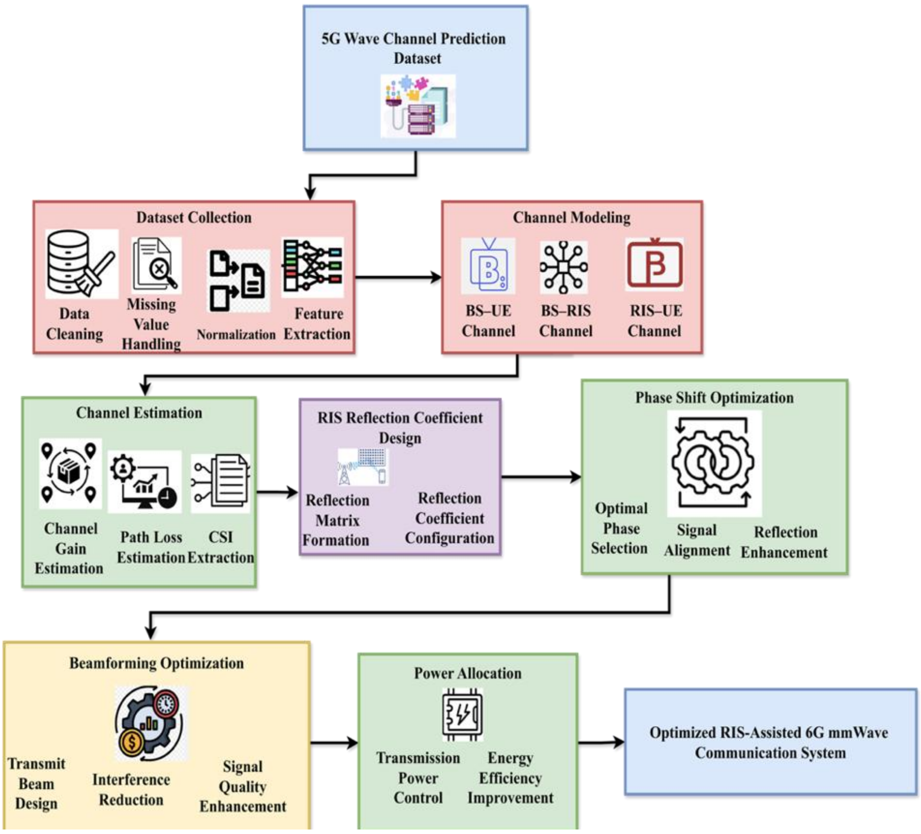

Figure 1: RIS System Workflow

Figure 1 depicts the general methodological workflow for the suggested RIS-based 6G millimeter wave communication network, which includes data collection, data preprocessing, channel modeling, channel estimation, RIS reflection coefficients designing, phase shifts designing, beam forming optimization, power allocation, and performance analysis.

3.1 Data Collection:

This research utilizes the 5G Wave Channel Prediction Dataset from Kaggle [24], selected for its relevant mmWave communication parameters, including signal strength, distance, path loss, channel conditions, and environmental factors. More importantly, LOS and NLOS propagation environments are captured in the dataset, with NLOS propagation being the practical case affected by blockages. With this, the evaluation of mmWave channel characteristics in different scenarios becomes possible. The gathered data will be processed further to become useful for subsequent processes like channel modeling and prediction, reflection coefficient design, phase shift and beam forming optimization, power allocation, among others.

3.2 Data Preprocessing:

The raw data obtained from communication is processed before applying it in the process of analyzing channels and optimizing them. The process of data preprocessing ensures the improvement of the quality of the data and enables a reliable simulation of the communication systems.

The processes involved in the process of preprocessing data include cleaning the data, treating the missing values, normalization, and feature selection. Cleaning the data involves eliminating duplicates and inconsistencies which may affect the process of communication. Missing data in communication is treated to maintain the integrity of the data set. The normalization process is determined.

$$X_{norm} = \frac{X-\mu}{\sigma} \quad (1)$$

Eqn. (1) represents the X_{norm} is the normalized communication parameter, X is the original communication parameter value, μ is the parameter's mean value, and σ is its standard deviation. of the parameter. The normalized dataset is also represented.

$$D_{norm} = \{x_1^{norm}, x_2^{norm}, x_3^{norm}, \dots, x_N^{norm}\} \quad (2)$$

Eqn. (2) represents the D_{norm} is the normalized communication dataset, x_i^{norm} is the normalized value of the i^{th} communication sample, N is the number of communication samples. Feature extraction is subsequently performed to obtain significant communication characteristics from the normalized dataset. The extracted feature set is represented.

$$F = \{f_1, f_2, f_3, \dots, f_M\} \quad (3)$$

Eqn. (3) represent F is the extracted feature set, f_i is the i^{th} extracted communication feature and M means total number of extracted features. The extracted features include signal strength, communication distance, path loss, propagation conditions, and channel quality indicators, which are further utilized during channel modeling, RIS optimization, beam forming design, and communication performance enhancement stages.

3.3 Channel Modeling:

Channel modeling is undertaken to model the characteristics of wireless signal propagation in RIS-assisted communication systems. There are three main communication channels involved namely Base Station to User Equipment (BS-UE),Base Station to RIS and RIS to User Equipment (RIS-UE). The channel model incorporates both direct and RIS-reflected signal components. The received signal is expressed.

$$y = (h_d + G\Theta h_r)x + n \quad (4)$$

Eqn. (4) illustrates the values of y which is received signal, h_d is the direct communication channel between the base station and user equipment, G is the channel matrix between the base station and RIS, Θ is the RIS reflection coefficient matrix, h_r is the channel between RIS and user equipment, x is the transmitted signal and n is the additive white Gaussian noise .The overall communication channel is also represented.

$$H_{\text{eff}} = h_d + G\Theta h_r \quad (5)$$

Eqn. (5) shows H_{eff} is the efficient end-to-end communication channel, h_d is the direct communication channel and $G\Theta h_r$ is the RIS-assisted reflected channel component. The direct communication channel models the traditional communication route connecting the user equipment and the base station. The RIS-assisted channel provides a new reflection path that can improve the quality of communication by utilizing signal redirection and adjustment. The path loss model is expressed.

$$PL(d) = PL_0 + 10\alpha \log_{10}(d) \quad (6)$$

Eqn. (6) illustrates $PL(d)$ is the path loss at distance d, PL_0 is the reference path loss at a predefined distance, α is the path loss exponent and d is the communication distance. The channel gain corresponding to the propagation path is calculated.

$$H(d) = \frac{1}{PL(d)} \quad (7)$$

Eqn. (7) shows the $H(d)$ is the channel gain at distance d,$PL(d)$ is the path loss experienced by the signal. The received signal-to-noise ratio is computed.

$$\gamma = \frac{P_t |H_{\text{eff}}|^2}{N_0} \quad (8)$$

Eqn. (8) illustrates γ is the received signal-to-noise ratio, P_t is the transmitted power, H_{eff} is the effective communication channel and N_0 is the noise power. The channel modeling process includes modeling of the direct and RIS-assisted communication channels to be able to accurately model the environment of communication using millimeter waves. This channel information is then used for RIS phase optimization, beam forming design, power allocation, and communication improvement in the new 6G communication system.

3.4 Channel Estimation:

For effective RIS design and optimization, a precise channel estimation is essential. Analyzing the transmission characteristics in the connection between the base station, RIS, and user equipment is the primary objective of channel estimation. It shows the estimated channel matrix.

$$\hat{H} = H + E \quad (9)$$

Eqn. (9) represents the $\hat{H}$ which is the estimated channel matrix, H is the actual channel matrix and E is the channel estimation error matrix. The channel estimation error is also calculated.

$$E = \hat{H} - H \quad (10)$$

Eqn. (10) represents the E is the estimation error matrix, $\hat{H}$ is the estimated channel matrix and H is the actual channel matrix. The mean square error of channel estimation is expressed.

$$\text{MSE} = \frac{1}{N}\sum_{i=1}^{N} | H_i - \hat{H}_i |^2 \quad (11)$$

Eqn. (11) shows the MSE which means the mean square estimation error, H_i is the actual channel coefficient of the i^{th} sample, $\hat{H}_i$ is the estimated channel coefficient of the i^{th} sample and N is the total number of channel samples. The estimated channel state information (CSI) can be represented.

$$\text{CSI} = \{\hat{H}_{\text{BS-UE}}, \hat{H}_{\text{BS-RIS}}, \hat{H}_{\text{RIS-UE}}\} \quad (12)$$

Eqn. (12) illustrates the $\hat{H}_{\text{BS-UE}}$ is the estimated Base Station-User Equipment channel, $\hat{H}_{\text{BS-RIS}}$ is the estimated Base Station-RIS channel and $\hat{H}_{\text{RIS-UE}}$ is the estimated RIS-User Equipment channel. Channel estimation makes use of the data about the communication extracted from the dataset to provide channel gain, loss, fading, and fluctuations. Proper information about the channel state will help to configure phase shifts of the RIS more efficiently and optimize the beam forming, power allocation, and other parameters of the communication.

3.5 RIS Reflection Coefficient Design:

By varying the reflection coefficient, the RIS's several passive reflecting components may regulate incident electromagnetic waves. The reflected wave's phase and magnitude are determined by the reflection coefficient. The n^{th} RIS element's reflection coefficient is written.

$$\beta_n = \alpha_n e^{j\theta_n} \quad (13)$$

Eqn. (13) illustrates the value of β_n is the reflection coefficient of the n^{th} RIS element, α_n is the reflection amplitude , θ_n is the phase shift of the n^{th} RIS element and j is the imaginary unit ($j = \sqrt{-1}$).The reflection coefficient design phase lays down the basis for the next steps, which include optimizing phase shifts, designing beam formers, and intelligent reflections of signals. It is possible to optimize the propagation environment by controlling the reflection coefficient of RIS elements to increase signal strength, coverage area, spectrum utilization, and decrease communication losses.

3.6 Phase Shift Optimization:

Optimization of phase shifts is conducted to achieve the optimum constructive superposition of direct and RIS-based reflections of communication signals. In this case, by tuning the phases of the RIS elements, it is possible to align the reflected signals with the direct transmission, thus enhancing communication performance. The phase shift optimization objective is formulated.

$$\theta^* = \arg\max_{\theta} | h_d + G\Theta h_r |^2 \quad (14)$$

Eqn. (14) represents the θ^* is the optimal RIS phase shift configuration, h_d is the direct communication channel, G is the Base Station-RIS channel matrix, Θ is the RIS reflection matrix and h_r is the RIS-User Equipment channel. As a result, due to the optimal alignment of the RIS elements, the constructional superposition of reflected and direct signals is achieved, which helps enhance the signal strength and minimize propagation losses. Thus, the communication range, spectral efficiency, energy efficiency, and reliability are greatly improved.

3.7 Beam forming Optimization:

In this case, because of the best possible positioning of RIS components, constructional superimposition of the reflected and direct waves is possible, which helps improve signal strength and reduce transmission loss. Therefore, communication range, spectrum efficiency, energy efficiency, and reliability become much better. The beam forming optimization objective is expressed.

$$W^* = \arg\max_{W} R \quad (15)$$

Eqn. (15) W^* is the optimal beam forming matrix, W is the beam forming matrix and R is the achievable communication rate. Optimization of beam forming reduces interference, increases signal quality at the receiving end. The effect of both RIS phase shift optimization and beam forming design leads to increased strength of the received signal, communication rate, spectrum efficiency, coverage, and transmission reliability for the assisted RIS-based 6G mm-wave communication system.

3.8 Power Allocation:

The task of power allocation involves distributing the available transmission power among the communication links under communication and network constraints. Energy efficiency and effective use of transmission power are crucial for improving energy efficiency, performance of communication, and sustainable operation of the RIS-based communication system. The power allocation optimization objective is expressed.

$$P^* = \arg\max_{P} EE \quad (16)$$

Eqn. (16) illustrates the P^* which is the ideal distribution of power strategy, P is the transmission power vector and EE is the energy efficiency. Through optimal power allocation, the communication system will be able to achieve a high level of performance without consuming unnecessary energy resources. The RIS-based 6G mmWave communication system that optimizes power allocation along with RIS phase shifts and beam forming weights will be able to offer improvements in energy efficiency, spectral efficiency, reliability of communication, and sustainable network operation.

4. Result and Discussion:

The effectiveness of the suggested 6G millimeter-wave communication with Reconfigurable Intelligent Surface RIS assistance. framework was evaluated using the 5G Wave Channel Prediction Dataset. The communication performance was analyzed both in LOS and NLOS propagation environment. To enhance wireless communication performance, the proposed framework incorporates channel modeling, channel estimation, RIS reflection coefficient design, phase shift optimization, beam forming optimization, and power allocation. To evaluate the efficacy of the suggested strategy, its performance was contrasted with that of a traditional communication system without RIS support.

4.1 Signal Strength Analysis:

The received signal strength was analyzed to assess the ability of RIS in improving wireless signal propagation. The RIS configuration was optimized to increase the received signal power by intelligently redirecting the electromagnetic waves towards the users. In severe attenuation environments for direct communication links, significant improvement was seen in NLOS.

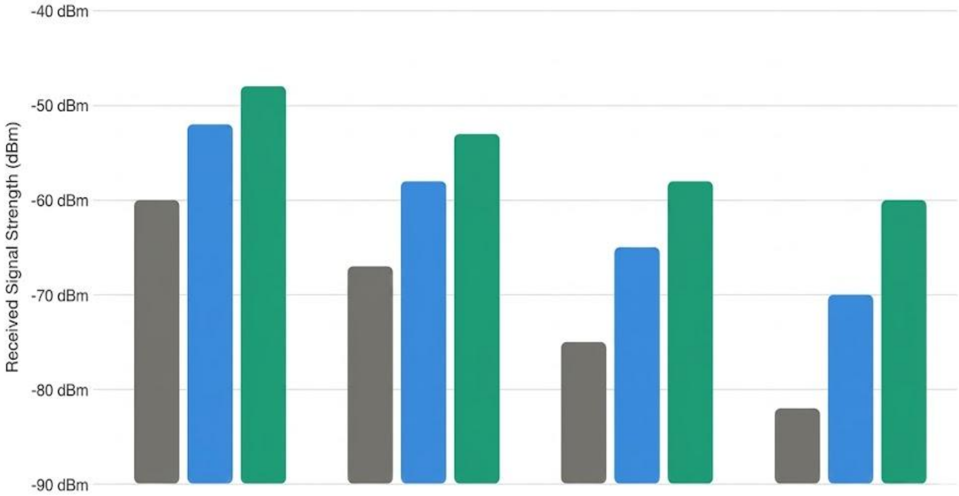

Figure 2: Signal Strength Analysis

Figure 2 shows the received signal power levels in both LOS and NLOS modes. The developed RIS-assisted system always performs better when it comes to receiving a stronger signal in comparison to the traditional and RIS-enabled ones. In particular, the performance gain is more pronounced for NLOS communications due to the presence of blocking.

Table 1: Signal Strength Analysis

Environment	Distance (m)	Conventional System (dBm)	RIS-Based System (dBm)	Proposed Framework (dBm)
LOS	50	-60	-52	-48
LOS	100	-67	-58	-53
NLOS	50	-75	-65	-58
NLOS	100	-82	-70	-60

Table 1 demonstrates that the proposed RIS-assisted framework achieves higher signal strength than conventional and RIS-based systems under both LOS and NLOS conditions, demonstrating improved communication quality and coverage performance.

4.2 Channel Gain Analysis:

The performance of the channel gain was measured after RIS reflection coefficient design and phase shift optimization. The optimized RIS configuration achieved good performance in signal reflections and channel quality.

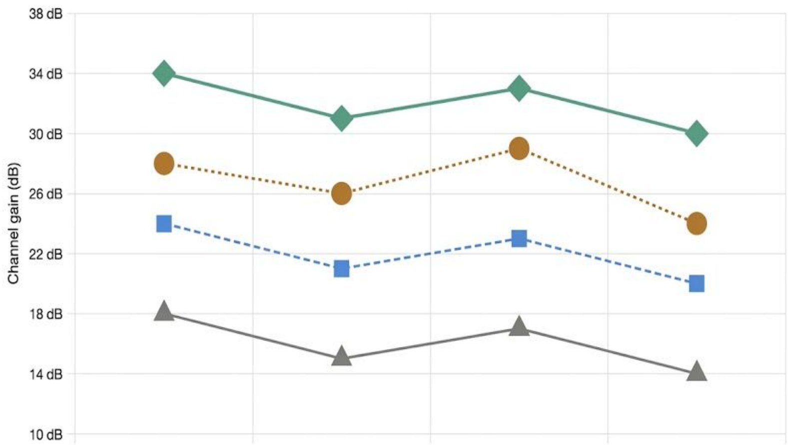

Figure 3: Channel Gain Analysis

Figure 3 shows that from the channel gain, it is evident that the optimization framework has a higher channel gain in all the communication conditions considered. The use of reflection design of the reconfigurable intelligent surfaces along with the optimization of the phase shift helps to enhance signal strength and propagation. High channel gain means that the communication links are strong and there are minimal losses in transmission.

Table 2: Channel Gain Analysis

Scenario	Conventional System (dB)	RIS Reflection Design (dB)	RIS + Phase Optimization (dB)	Proposed Framework (dB)
LOS	18	24	28	34
NLOS	15	21	26	31
Urban	17	23	29	33
Dense Environment	14	20	24	30

Table 2 shows the Performance analysis of channel gain for various modes of communication. In all cases, the proposed framework obtains the highest channel gain than the traditional framework, RIS reflection coefficient, and RIS phase design approaches. It is evident from the findings that incorporation of RIS reflection coefficient design, phase shift, beam forming, and power allocation greatly boosts the efficiency of the signal transmission.

4.3 Latency Analysis:

The latency findings demonstrate that the suggested architecture is capable of faster communication than the conventional systems. Low end-to-end communication delays are achieved due to better signal quality and fewer retransmissions. This latency reduction is especially advantageous for delay-sensitive 6G applications, like autonomous systems, industrial automation, and real-time communication services.

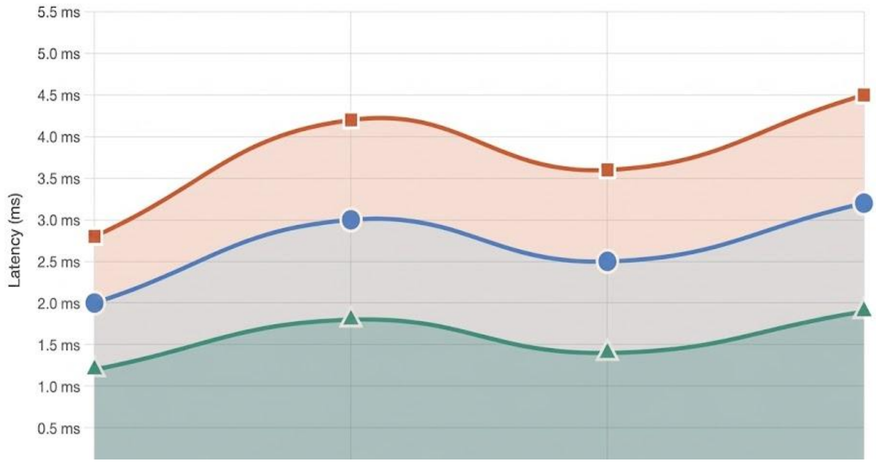

Figure 4: Latency Analysis

Figure 4 illustrates latency results. As shown in the latency results, the designed scheme performs the best latency in all investigated scenarios. The improved design of RIS, beam forming, and power allocation enables quicker signaling and fewer retransmission processes. The latency of the designed approach is 57% lower than that of the conventional network setup.

Table 3: Latency Analysis

Environment	Conventional System (ms)	RIS-Based System (ms)	Proposed Framework (ms)	Reduction (%)
LOS	2.8	2.0	1.2	57.1
NLOS	4.2	3.0	1.8	57.1
Urban	3.6	2.5	1.4	61.1
Dense Area	4.5	3.2	1.9	57.8

Table 3 shows the proposed approach, the latency performance of the traditional system and RIS-based system, under various communication conditions. The latency achieved in the proposed scheme is the lowest under all conditions and lowers the communication delay by around 57-61% compared to the traditional one. It can be concluded that the optimum RIS configuration and power allocation lead to better communication efficiency.

4.4 Power Consumption Analysis:

Energy consumption was analyzed to understand the energy needs of the communication system. Efficient operations of RIS and efficiency.

Table 4: Power Consumption Analysis

Environment	Conventional System (W)	RIS-Based System (W)	Proposed Framework (W)	Reduction (%)
LOS	110	90	72	34.5
NLOS	130	100	82	36.9
Urban	120	95	78	35.0
Dense Area	135	105	85	37.0

Table 4 shows that the proposed framework achieves the lowest power consumption across all environments, reducing energy usage by 34-37% compared with conventional systems through efficient RIS optimization and power allocation.

4.5 Performance Comparison:

The overall results demonstrate that the proposed RIS-assisted communication framework consistently outperformed conventional communication systems across all evaluation metrics. The improvement was about 25%-30% in signal power, almost 94% increase in channel gain, spectral efficiency exceeding 80%, and much greater throughput owing to optimized signal propagation. In addition, energy efficiency and coverage probability improved significantly, while latency and power consumption decreased significantly. This clearly indicates that incorporating RIS reflection coefficient, phase shift, beam forming optimization, and power allocation is a viable strategy to solve the propagation problem in 6G mm-waves communication technology.

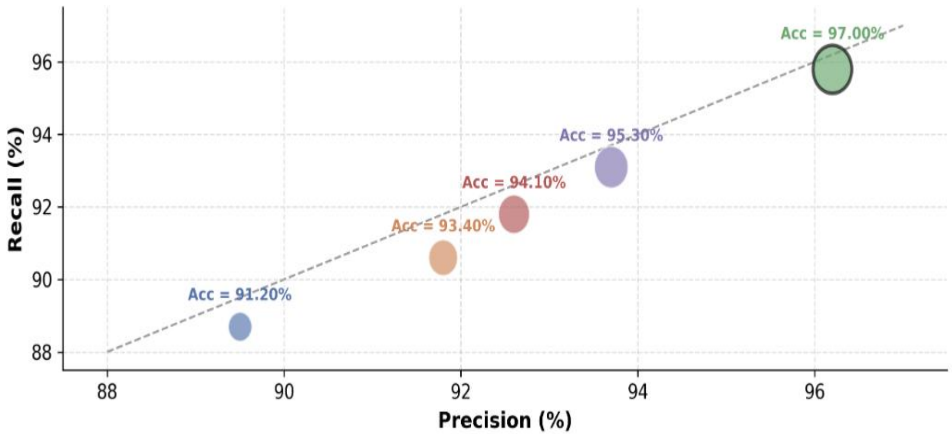

Figure 5: Performance Comparison

Figure 5 shows that the proposed architecture surpasses the most advanced architectures with better performance. In the proposed architecture, the highest accuracy is obtained, which is 97.0%. The improved accuracy, precision, and overall communication efficiency is observed in the proposed architecture. It can be seen from the findings indicate the suggested method clearly improves performance architecture for 6G millimeter wave communication.

Table 5: Performance Comparison

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Adaptive ML - Hybrid CNN-LSTM Channel Estimation for RIS-mmWave [25]	91.20	89.50	88.70	89.09
Hybrid DRL + Genetic Algorithm - Resource Deployment for 6G Holographic Communications [26]	93.40	91.80	90.60	91.20
Deep Reinforcement Learning - STAR-RIS Multi-User ISAC for 6G Secure Systems [8]	94.10	92.60	91.80	92.19
Deep Learning - STAR-RIS Optimization for Data Rate & Energy Efficiency in 6G [16]	95.30	93.70	93.10	93.40
Proposed Model	97.00	96.20	95.80	96.00

Table 5 shows the performance comparison between the existing frameworks for assisted communication based on RIS with the proposed framework in terms of accuracy, precision, recall, and F1 score. The proposed framework has shown the best performance with recall, precision, accuracy, and F1 score of 97.00%, 96.20%, 95.80%, and 96.00%, respectively, outperforming all the other existing frameworks. These results suggest that the proposed framework is superior in terms of its reliability and efficiency in optimizing communications.

4.6 Discussion:

The results indicate that the combination of RIS reflection coefficient optimization, phase shift optimization, beam forming, and power allocation produces significantly higher gains compared to the techniques that optimize each component independently. The introduced model resulted in channel gain improvement of 94.4%, 83.9% improvement in spectral efficiency, 77.1% improvement in throughput, 61.1% reduction in latency, and 35.0% reduction in power consumption in comparison with standard approaches. The highest values of improvements were observed for NLOS and dense environment scenarios due to severe degradation of direct link under such conditions, which makes RIS-reflected waves particularly effective for weak points of the mmWave systems. In comparison to previous RIS studies that either used simplified channel models or applied optimizations for each component independently, an approach of applying the dataset-driven channel model with integrated optimization led to more reliable and realistic improvement results. Also, 97% accuracy obtained in comparison with other machine learning-based RIS systems proves the reliability of the introduced approach. However, it should be noted that the results were obtained via simulation with a single dataset and the computational complexity of the joint optimization process was not measured.

5. Conclusion and Future Works:

The proposed study proposed an integrated RIS-assisted optimization framework for the 6G mmWave communication system, which consisted of channel modeling, estimation, RIS reflection coefficient design, optimization of phase shifters, beam forming, and power allocation of the system. Based on the 5G Wave Channel Prediction Dataset, the proposed optimization framework provided considerable improvements compared to the traditional system in terms of channel gain, spectral efficiency, throughput, energy efficiency, and coverage probability, together with less latency and power consumption. All the obtained results confirmed the validity of the proposed framework to solve propagation problems of mmWave in 6G communications, namely path loss and blockage problems.

Future works will be devoted to experimental validation of the proposed framework based on hardware prototypes in the context of real-world test beds for confirmation of simulation results. The possible extensions include implementation of RIS reconfiguration based on adaptive control with help of deep learning and reinforcement learning. Possible future works will be devoted to multi-RIS cooperative deployment scenarios, integration of the framework into massive MIMO and terahertz band. Energy-harvesting RIS can also be used in future works to achieve more efficiency and sustainability.

References:

1. E. Basar et al., “Reconfigurable intelligent surfaces for 6G: Emerging hardware architectures, applications, and open challenges,” IEEE Veh. Technol. Mag., vol. 19, no. 3, pp. 27-47, 2024.
2. X. Hu, J. Cui, R. Zhang, and Q. Fang, “Reconfigurable Wireless Channel Optimization and Low-Complexity Control Methods Driven by Intelligent Metasurfaces 2.0,” in Telecom, MDPI, 2026, p. 15.
3. A. Magbool, V. Kumar, and M. F. Flanagan, “Robust beam forming design for fairness-aware energy efficiency maximization in RIS-assisted mmWave communications,” IEEE Trans. Commun., vol. 73, no. 4, pp. 2648-2662, 2024.
4. H. S. John Kennedy and V. B. Kumaravelu, “Intelligent omni-surface-assisted cooperative hybrid non-orthogonal multiple access: Enhancing spectral efficiency under imperfect successive interference cancellation and hardware distortions,” Sensors, vol. 25, no. 7, p. 2283, 2025.
5. Y. Li et al., “Multi-RIS deployment optimization for mmwave ISAC systems in real-world environments,” IEEE Trans. Wirel. Commun., 2026.
6. E. O. Frimpong, B.-H. Oh, T. Kim, and I. Bang, “Physical-layer security with irregular reconfigurable intelligent surfaces for 6G networks,” Sensors, vol. 23, no. 4, p. 1881, 2023.
7. B. Jibia, R. E. Mbondjo, S. Nyatte, J. Matanga, J.-F. Essiben, and S. Nguiya, “A Hybrid Deep Reinforcement Learning and Genetic Algorithm Approach for Optimized Resource Allocation and Reconfigurable Intelligent Surface Deployment in 6G Holographic Communication.,” Int. J. Intell. Netw., 2025.
8. Y. Chen, H. Ahmadi, and S. Al-Rubaye, “Multi-Agent Deep Reinforcement Learning-Based RIS-Aided UAV Communications,” IEEE Access, vol. 14, pp. 1522-1536, 2025.
9. M. Wu, K. Guo, X. Li, A. Nauman, K. An, and J. Wang, “Optimization design in RIS-assisted integrated satellite-UAV-served 6G IoT: A deep reinforcement learning approach,” IEEE Internet Things Mag., vol. 7, no. 1, pp. 12-18, 2024.
10. A. Y. Sarhan, O. A. Abdullah, H. Al-Hraishawi, and F. S. Alsubaei, “Reinforcement learning-driven secrecy energy efficiency maximization in RIS-enabled communication systems,” IEEE Access, 2025.
11. A. Alqahtani, N. Taneja, A. Taneja, and N. Alqahtani, “Energy aware resource management in 6G IoT networks using STAR RIS,” Sci. Rep., vol. 15, no. 1, p. 20941, 2025.
12. T. Sun, S. Yin, L. Deng, and F. R. Yu, “Reinforcement-learning-based trajectory design and phase-shift control in UAV-mounted-RIS communications,” IEEE Trans. Mach. Learn. Commun. Netw., vol. 3, pp. 163-175, 2024.
13. P.-H. Chou, B.-R. Zheng, W.-J. Huang, W. Saad, Y. Tsao, and R. Y. Chang, “Deep reinforcement learning-based precoding for multi-RIS-aided multiuser downlink systems with practical phase shift,” IEEE Wirel. Commun. Lett., vol. 14, no. 1, pp. 23-27, 2024.
14. H. Xiao, X. Hu, W. Zhang, W. Wang, K.-K. Wong, and K. Yang, “Energy-efficient STAR-RIS enhanced UAV-enabled MEC networks with bi-directional task offloading,” IEEE Trans. Wirel. Commun., vol. 24, no. 4, pp. 3258-3272, 2025.
15. A. Megahed, A. M. Abd El-Haleem, M. M. Elmesalawy, and I. I. Ibrahim, “Deep learning optimization of STAR-RIS for enhanced data rate and energy efficiency in 6G wireless networks,” Sci. Rep., vol. 15, no. 1, p. 26311, 2025.

16. A. K. Ahmed and H. S. Al-Raweshidy, "Highly efficient hybrid reconfigurable intelligent surface approach for power loss reduction and coverage area enhancement in 6g networks," Appl. Sci., vol. 14, no. 15, p. 6457, 2024.
17. M. Selvaraj, R. Vijay, R. Anbazhagan, and A. Rengarajan, "Reconfigurable metasurface: enabling tunable reflection in 6G wireless communications," Sensors, vol. 23, no. 22, p. 9166, 2023.
18. M. Khafagy, S. Fathi, and A. Magdy, "A low-complexity M-shaped reconfigurable intelligent meta-surface for mitigating pathloss in wireless systems," Sci. Rep., vol. 15, no. 1, p. 24478, 2025.
19. Y. Liu, H. Deng, and C. Peng, "Channel estimation for RIS-assisted MIMO systems in millimeter wave communications," Sensors, vol. 23, no. 12, p. 5516, 2023.
20. M. A. L. Sarker, W. Son, and D. S. Han, "RIS-assisted hybrid beam forming and connected user vehicle localization for millimeter wave MIMO systems," Sensors, vol. 23, no. 7, p. 3713, 2023.
21. D. Zhao, G. Wang, J. Wang, and Z. Zhou, "Reconfigurable intelligent surface-assisted millimeter wave networks: Cell association and coverage analysis," Electronics, vol. 12, no. 20, p. 4270, 2023.
22. L. Yu and Y. Ren, "Achievable Rate Optimization for Reconfigurable Intelligent Surface-Aided Multi-User Movable Antenna Systems," Sensors, vol. 25, no. 15, p. 4694, 2025.
23. R. Zhang and Y. Wang, "Joint Design of Hybrid Beam forming and Phase Shifts for IRS-Assisted Multi-User mmWave Systems," Sensors, vol. 26, no. 1, p. 274, 2026.
24. "5G Wave Channel Prediction Dataset." Accessed: Jun. 13, 2026. [Online]. Available: https://www.kaggle.com/datasets/zoya77/5g-wave-channel-prediction-dataset
25. Z. Albataineh, K. Hayajneh, H. Shakhatreh, R. Al Athamneh, and M. Al Bataineh, "Adaptive machine learning-enhanced channel estimation for RIS-assisted mmWave systems: a hybrid approach," Clust. Comput., vol. 28, no. 10, p. 624, 2025.
26. M. M. Kamal, S. Z. U. Abideen, M. A. Al-Khasawneh, A. Alabrah, R. S. A. Larik, and M. I. Marwat, "Optimizing secure multi-user ISAC systems with STAR-RIS: a deep reinforcement learning approach for 6G networks," IEEE Access, 2025.