Performance Evaluation of ISR-Assisted Wireless Communication

Noor N. Thamir
Iraqi Ministry of Education / General Directorate of Education of Baghdad Governorate, Al-Rusafa II / Department of Education of the Eastern Outskirts of Baghdad
noor.thamir1201@sc.uobaghdad.edu.iq

Abstract:

This research presents a comprehensive MATLAB-based implementation and analysis of a Wireless Sensor Network-Intelligent Reflecting Surface (WSN-IRS) system, focusing on the evaluation of Signal-to-Noise Ratios (SNRs) for both direct signal propagation and signal paths involving IRS reflection. The methodology includes parameter initialization, random phase shift generation for IRS elements, modeling of network layouts with random sensor and access point positions, distance computation, gain calculation, SNR determination, and data visualization. The research discusses challenges associated with IRS technology, including design complexity, channel estimation, real-time adaptability, synchronization, hardware constraints, interference management, security, scalability, regulatory compliance, environmental factors, and hardware imperfections. The core of the proposed methodology lies in the fine-grained control of phase shifts by IRS elements, offering valuable insights into signal quality improvement. The code's adaptability is demonstrated through default parameter settings, random phase shift generation, and modelling of sensor, access point, and IRS locations in a confined space. SNR calculations for various sensor-access point pairs and data visualization provide a clear representation of network performance.

Keywords: Artificial Intelligence (AI), Cybersecurity Improvement, Internet of Things (IoT), Software Defined Networking (SDN).

Introduction:

Wireless communication systems are facing increasing challenges due to spectrum congestion, signal attenuation, and interference [1]. To address these issues, Intelligent Reflecting Surfaces (IRS), also known as reconfigurable metasurfaces, have emerged as a promising technology [2]. IRS comprises a planar array of passive elements that can adaptively control the reflection characteristics of incident electromagnetic waves. By carefully manipulating the phase shifts of reflected signals, the IRS can achieve diverse objectives, including signal enhancement, beamforming, interference suppression, and coverage extension [3].

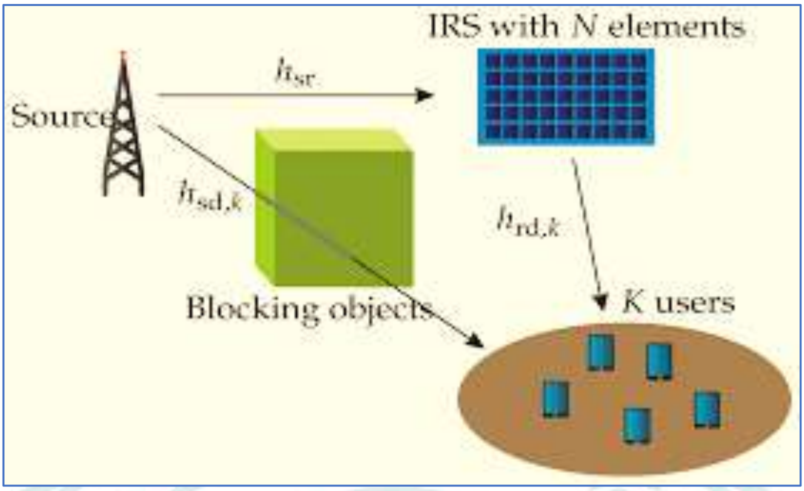

Figure 1: Intelligent Reflecting Surface.

This research study details a MATLAB code implementation and analysis of a Wireless Sensor Network (WSN) system that utilizes an Intelligent Reflecting Surface (IRS) to enhance signal strength. The present experiment appertains to the simulation of the Wireless Sensor Network-Intelligent Reflecting Surface (WSN-IRS) system, wherein a comprehensive analysis is conducted to appraise the Signal-to-Noise Ratios (SNRs) pertaining to both the direct signal propagation and the signal path traversing through the IRS. The methodology section expounds on the sequential processes entailed in the execution of the code, encompassing the initialization of parameters, generation of IRS phase shift, modeling of network layout, computation of distances, calculation of gain, determination of signal-to-noise ratio, and visualization of outcomes.

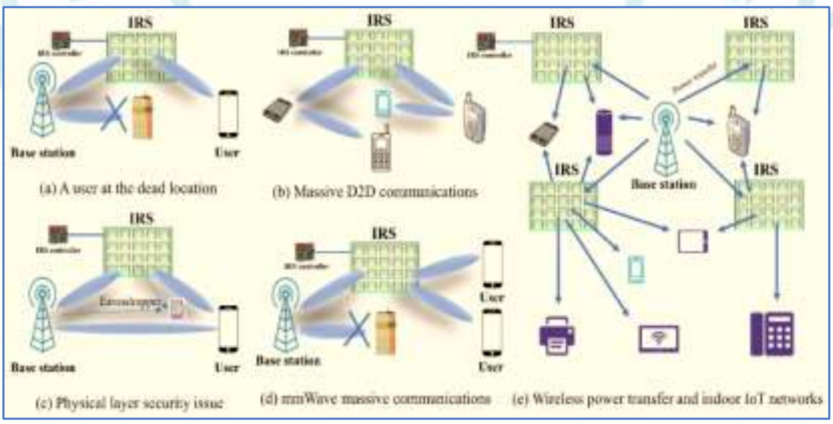

Figure 2: IRS Applications

IRS challenges include complex design and optimization, accurate channel estimation and feedback, real-time adaptability, hardware constraints and cost, synchronization and coordination, interference management, security and privacy, scalability and deployment, regulatory considerations, environmental variability, and hardware imperfections. These issues require sophisticated algorithms, efficient feedback mechanisms, real-time adjustments, synchronization and coordination, interference management, secure communication, scalability, regulatory compliance, environmental variability, and compensating for hardware imperfections [4 – 9].

Figure 3: IRS Challenges

Related work

In this section will be explained the related work about the current research topic will be explained below:

In 2020, Dhanushka Kudathanthirige et al. [10], analyzed the performance limits of intelligent reflective surfaces for wireless communications. The text derives expressions for outage probability, code error probability, and achievable rate limits. The text demonstrates that the IRS can achieve significant diversity gain by controlling the propagation channels, using passive reflective elements instead of active RF chains. The results achieved The attainable diversity order is equal to the number of passive reflective components in the IRS, according to high signal-to-noise ratio (SNR) research. This suggests that IRS may be able to improve the functionality of wireless systems of the newest generation. They contribute to the paper demonstrates the performance of intelligent reflective surfaces (IRS) in wireless communication, demonstrating that the diversity gain can be achieved by controlling propagation channels without active radio frequency chains.

In 2020, Qin Tao et al. [11], Provided a detailed analysis of the performance of intelligent reflective surface (IRS) supported communication systems, taking into account the direct link between sender and receiver. It derives the upper bounds on the ergodic power and the approximation of the interruption probability, and provides simplified expressions in the asymptotic regime. The numerical results confirm the validity of the analysis, showing that increasing the number of reflective elements and having a strong line-of-sight component can significantly improve performance. It is also suggested to deploy the IRS near the sender or receiver rather than in the middle.

In 2021, Mohd Hamza Naim Shaikh et al. [12], They investigated the performance of IRS-assisted wireless systems, analyzing the impact of transceiver hardware imperfections. It derives closed-form expressions for spectral efficiency, energy efficiency, and outage probability. The results emphasize the importance of modelling and compensating for hardware impairments, as they significantly restrict system performance.

In 2021 Xinwei Yue and Yuanwei Liu [13], The paper explores the performance of Intelligent Reflecting Surface (IRS) assisted Non-Orthogonal Multiple Access (NOMA) networks using imperfect and perfect successive interference cancellation. It provides new expressions for outage probability and ergodic rate, discusses diversity order, signal-to-noise ratio (SNR) slope, throughput, and energy efficiency of IRS-NOMA networks. The paper also presents exact expressions for outage probability and ergodic rate in IRS-OMA networks and compares them with conventional cooperative communications. Numerical results show that IRS-NOMA outperforms conventional cooperative communications in terms of outage behaviour and ergodic rate. The paper validates theoretical expressions for IRS-NOMA networks and evaluates the impact of reflecting elements on performance. Monte Carlo simulations are conducted, considering three users and normalized distances. IRS-NOMA outperforms IRS-OMA and conventional orthogonal multiple access schemes in terms of outage behavior and ergodic rate. The M-th user in IRS-NOMA achieves a higher ergodic rate than IRS-OMA and benchmarks. IRS-assisted NOMA networks also show enhanced energy efficiency compared to conventional cooperative communications.

In 2022, Arjun Chakravarthi Pogaku, et al. [14], The survey explores the integration of reconfigurable intelligent surfaces (RIS) with unmanned aerial vehicles (UAVs) in wireless communication systems, highlighting their potential for performance and efficiency enhancement. It discusses applications, techniques, and challenges in optimization, communication, deep reinforcement learning, secrecy, and the internet of things. To improve efficiency in a UAV-RIS system, optimization of UAV movement, RIS phase shift, and power allocation can minimize power consumption. Machine learning techniques like deep reinforcement learning can optimize system behavior and reduce energy consumption. Integrating RIS can reduce energy usage, minimize the Age of Information (AoI), and reduce latency in status updating systems. Multiple UAVs mounted with RISs can communicate in HetNets, minimizing transmit power consumption while maintaining quality of service.

In 2022, Ying Gao et al. [15], The paper explored the use of active intelligent reflecting surfaces (IRS) in a wireless information and power transfer system, aiming to maximize energy usage and information usage. The authors propose computationally efficient algorithms using alternating optimization, semidefinite relaxation, and successive convex approximation, showing significant performance gains compared to benchmark schemes.

In 2023, Weiqiang Tan et al. [16], The study looked at attainable ergodic rate, outage probability, and bit error rate in wireless communication systems helped by intelligent reflecting surfaces (IRS). The system's signal-to-noise ratio (SNR) was optimized by leveraging channel state information to construct the reflection phase. According to the study, performance may be improved by increasing the number of reflecting components and selecting an acceptable SNR regime, and the IRS-assisted communication system performs better than current end-to-end wireless communication systems.

In 2023, L. Yashvanth and Chandra E. Murthy [17], discussed the use of intelligent reflecting surfaces (IRSs) in sub-6 GHz band communications, focusing on opportunistic selection for data transmission. It highlighted enhanced throughput and convergence to optimal beamforming-based throughput. The authors also discussed the extension of these schemes to wideband channels using orthogonal frequency division multiplexing (OFDM) systems, highlighting their superior performance and low implementation cost.

In 2023, Yiming Li et al. [18], examined how Intelligent Reflecting Surface (IRS) may be used for wireless secure communication. IRS may include passive and active reflecting components to automatically change the wireless propagation environment. The article suggests two passive and active IRS techniques as well as an algorithm for maximizing the safety rate. While the active IRS technique employs the first-order Taylor expansion to get the bottom bound of the optimization problem, the passive IRS strategy uses the Dinkel-Bach approach to convert the objective function into a convex problem. According to simulation findings, the active IRS algorithm outperforms the passive IRS algorithm in terms of security rate for the same parameter setup.

In 2023, Yuying Bian et al. [19], looked at the Reconfigurable Intelligent Surface's (RIS) performance in 6G wireless communication systems, concentrating on phase error uncertainty and random user location distribution. It also looked at co-channel interference (CCI) sources and how they affect channel capacity and outage likelihood. For these parameters, the study created closed-form formulas, and to ensure the derivation's precision, Monte Carlo simulations were run. There are some uncertainties in actual communication networks, notwithstanding their promise to increase transmission efficiency.

Methodology

The core functionality of IRS relies on the ability to control the phase shifts of the reflected signals. Each element in the IRS array can be tuned to adjust the phase and amplitude of the reflected waves, enabling constructive or destructive interference. This fine-grained control allows for beamforming and other signal manipulation techniques. Designing an efficient IRS system involves optimizing the positions, sizes, and phase responses of the individual elements. Various algorithms and optimization techniques can be employed to determine these parameters, considering factors such as channel conditions, signal propagation characteristics, and system objectives. The proposed system includes the following steps: -

1. Parameters Initialization

One could argue that the implementation of government policies plays a crucial role in shaping the development of a nation. Parameter initialization refers to the process of assigning initial values to the parameters of a statistical model. This step is crucial to properly calibrate the model and enable accurate estimation of its parameters during the subsequent estimation phase. By setting appropriate initial values, the model can be initialized in a suitable state, enhancing the convergence properties of the estimation algorithm and ensuring reliable inference. Determining the optimal initial values is therefore a crucial aspect of model initialization, as it directly impacts the performance and reliability of the estimation process. The code commences by initializing various system parameters, which include the number of sensors (num_sensors), access points (num_access_points), elements in the IRS (num_elements), the power emitted by the transmitter (tx_power), the power of the noise (noise_power), and the exponent that characterizes the path loss (path_loss_exponent). If the input does not include these parameters, default values will be automatically assigned.

2. IRS Phase Shift Generation

In the realm of academia, a shift towards digital education has become increasingly apparent. This trend is especially magnified in light of the ongoing global Covid-19 pandemic. As a result, traditional classroom settings have been compelled to adapt and integrate online learning platforms into their curriculum. This transition has prompted a significant change in the way education is delivered and received, requiring both educators and students to develop new skill sets in navigating virtual learning environments. Additionally, the prevalence of digital education has introduced a multitude of benefits, such as increased accessibility, flexibility, and interactivity. However, it is also crucial to acknowledge the potential challenges and limitations that come with this transition, including issues of technological infrastructure, student engagement, and the digital divide. Consequently, further exploration and research are warranted to fully comprehend the implications of this shift towards digital education and ensure equitable and effective implementation in the realm of academia. The topic of discussion pertains to the generation of phase shifts in the context of the IRS (Intelligent Reflecting Surface). To replicate the reflection characteristics of the IRS elements, a series of random phase shifts denoted as "phase_shifts," are produced.

Network Layout Modeling

To meet the high demands of the modern educational landscape, educators are compelled to adapt their teaching methods and incorporate innovative approaches that engage students and promote active learning. This necessitates a shift from traditional didactic instructional methods towards more learner-centered pedagogies. By adopting these student-centered approaches, educators will be better equipped to cultivate critical thinking skills, foster creativity, and encourage collaboration among students. This transformation in teaching practices is essential to equip students with the skills necessary to thrive and succeed in the rapidly changing and complex world we live in today. The concept of network layout modelling regards the arrangement and organization of networks. It encompasses the structural design and allocation of resources within a network, aiming to optimize its performance and efficiency. In this academic exploration, we will delve into the principles, techniques, and methodologies employed in network layout modelling, focusing on its significance and potential applications in various domains. The present code has been devised to simulate the spatial configuration of sensors (sensor_locations), access points (access_point_locations), and the IRS (irs_location) within a delimited area. The generation of these locations occurs randomly.\

Computation of SNR

In consideration of the provided text, an academic rewriting would take the following form: The fourth statement or textual passage suggests that a different articulation is required to adhere to the standards of academic writing. The calculation of signal-to-noise ratio (SNR) is a significant aspect in various domains, particularly in communications and signal processing. It serves as a metric for quantifying the quality of a signal by comparing the power of the desired signal to the power of background noise. SNR computation plays a crucial role in assessing the effectiveness of signal transmission and reception, aiding in decision-making processes and system optimization. Its application spans multiple scientific and technical disciplines, focusing on achieving reliable and efficient signal transmission. The algorithm sequentially iterates over the set of sensor-access point pairs and executes the ensuing procedures:

a. Distance Calculation: The computation of Euclidean distances among the sensor, IRS, and the access point is carried out for every pair, leading to the determination of distance_tx_irs, distance_irs_rx, and distance_tx_rx.

$$d_{(p,q)} = \sqrt{\sum_{i=1}^{n} (q_i - p_i)2}$$

(1)

Where,

p,q = two points in Euclidean n-space

q_i, p_i = Euclidean vectors, starting from the origin of the space (initial point)

n = n-space

b. Calculation of Gain and Total Gain: The calculation of gains for three distinct links, namely the transmitter-IRS link (gain_tx_irs), IRS-receiver link (gain_irs_rx), and direct transmitter-receiver link (gain_tx_rx), incorporates the utilization of a path loss model. The aggregate gain of the signal that undergoes reflection by the intelligent reflecting surface (IRS), denoted as gain_tx_irs_rx, is calculated by integrating the individual gains associated with the IRS phase shifts.

$$\text{gain} = 10\log\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)\ \text{dB} \qquad (2)$$

c. Computation of Signal Power: The signal powers received by the receiver for both the direct path and the path through the intelligent reflecting surface (IRS) are computed, yielding the variables signal_power_direct and signal_power_irs.

$$\mathbf{P}_x = \mathbf{A\ 2\ /2}$$

(3)

d. SNR Calculation: The final stage in the proposed system entails the computation of signal-to-noise ratios (SNRs) for both the direct path and the path through the intelligent reflecting surface (IRS), denoted as snr_direct and snr_irs, respectively.

Wanted component

$$SNR = \frac{P_{signal}}{P_{noise}} \quad \textbf{(4)}$$

Unwanted component

Results

The visual representation of signal-to-noise ratios (SNRs) by means of plotted data serves to offer valuable insights into the overall performance of the system. The plot SNRs showcase two subplots illustrating the signal-to-noise ratios (SNRs) for the direct path and the path through the intelligent reflective surface (IRS). Moreover, the network layout is visualized by plotting the spatial distribution of sensors, access points, and the IRS, as evident in the plot Network Layout. Figures (4, and 5)

To elucidate the outcomes of the proposed system, the subsequent aspects need to be expounded upon.

Parameter Defaults: The initial phase of the code involves an assessment to determine if all the obligatory input arguments have been furnished. In the absence of explicit specifications, default values are assigned. This feature facilitates adaptability in conducting simulations with diverse configurations.

Random phase shifts are generated for the individual elements of the IRS. Phase shifts play a crucial role in evaluating the efficacy of the intelligent reflecting surface (IRS) to accurately reflect signals.

The process of generating locations within a confined space for sensors, access points, and the IRS involves the random selection of positions. This observation demonstrates the tangible implementation of Wireless Sensor Network (WSN) deployments.

The SNR computation technique involves the iteration of a script that calculates the distances and path loss gains for both the direct path and the path through the intelligent reflecting surface (IRS), considering all possible sensor-access point pairs. The aggregate increase pertaining to the signal undergoing reflection from the intelligent reflecting surface (IRS) is also calculated. The determination of signal powers at the receiver is conducted for both paths, followed by the calculation of signal-to-noise ratios (SNRs). This step aims to establish a quantification of the signal quality within the network.

SNR Plotting: The Signal-to-Noise Ratios (SNRs) are presented in graphical form; wherein distinct plots are utilized to illustrate both the SNR of the direct signal path and the SNR associated with the path via the Intelligent Reflecting Surface (IRS). These plots offer visual representations that contribute to the understanding of the network's performance by illustrating the comparative evaluation of SNR between various sensor-access point pairs.

One additional visual representation exhibits the network layout, highlighting the spatial arrangement of sensors, access points, and the IRS. This presentation aids in comprehending the spatial organization of network constituents.

Analysis and Interpretation: The assessment of the findings entails the interpretation of the Signal-to-Noise Ratio (SNR) plots. Higher signal-to-noise ratio (SNR) values are indicative of superior signal quality and reliability. To assess the influence of the Intelligent Reflecting Surface (IRS) on signal enhancement, it is possible to conduct a comparative analysis of Signal-to-Noise Ratio (SNR) values across various sensor-access point pairs.

Experimental Analysis: To enhance comprehension, one can engage in experiments that involve manipulating various parameter values, including but not limited to sensor quantity, access point quantity, and IRS element quantity, along with altering parameters such as transmitter power and path loss exponent. This opportunity enables individuals to analyze the impact of varying network configurations on signal-to-noise ratio (SNR) and overall network performance.

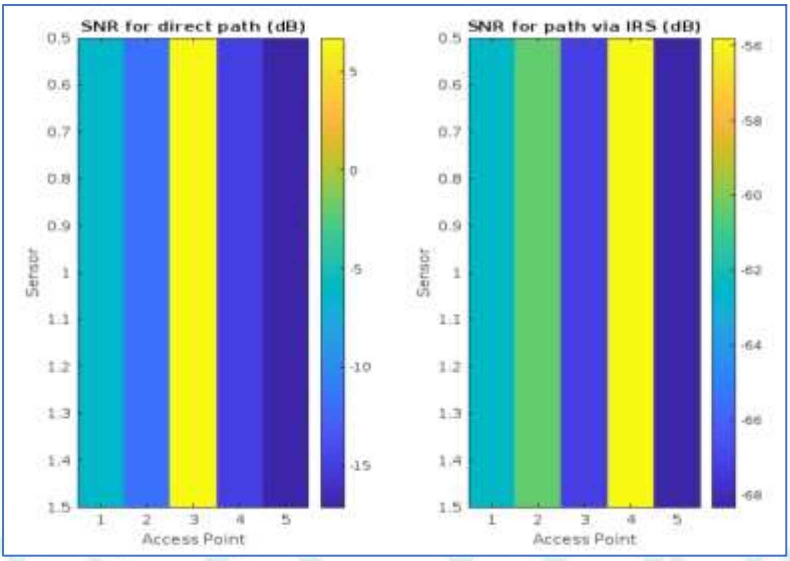

Figure 4: SNRs for direct path and path via IRS

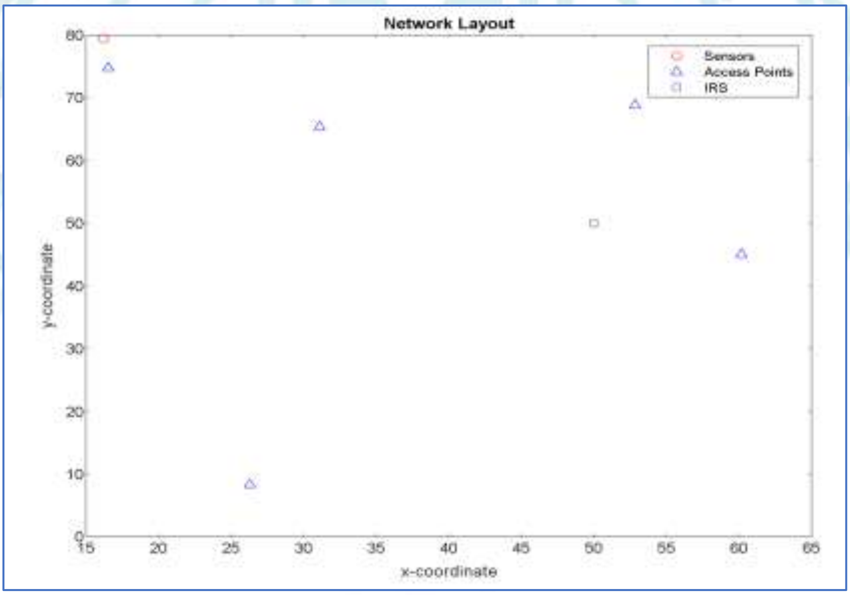

Figure 5: Network Layout.

Conclusion

In summary, this research methodology offers a comprehensive and detailed examination of the challenges involved in using MATLAB for simulating WSN-IRS systems and evaluating their SNRs. The algorithm utilized in this study considers various essential parameters, including system configuration, phase shifts of the intelligent reflecting surface (IRS), network topology, distance estimation, gain computations, and comprehensive signal-to-noise ratio (SNR) analyses. The convergence of these components generates a comprehensive framework to evaluate and optimize the effectiveness of wireless sensor networks which are enhanced by the incorporation of Intelligent Reflecting Surfaces.

One prominent aspect of this study is its noteworthy focus on the utilization of data visualization, which serves as a crucial element in effectively illustrating the significant influence of Intelligent Reflecting Surfaces (IRS) on signal quality in wireless sensor networks. This study employs visual representations to explicate the capacity of an Intelligent Reflecting Surface (IRS) to strategically manipulate the propagation environment, thus leading to improved signal transmission quality. These visual representations not only contribute to the comprehension of IRS technology but also support its implementation by key participants in the realm of wireless communication.

Additionally, the research framework exhibits a remarkable attribute of versatility. This approach offers researchers and practitioners the opportunity to explore and conduct trials with multiple scenarios and configurations, allowing for the inclusion of diverse network setups and parameters. This methodology may be employed by researchers and practitioners to investigate the performance of wireless sensor network-intelligent reflecting surface (WSN-IRS) systems under various conditions. As a result, it can make a substantial contribution to the progression and practical application of intelligent reflecting surfaces in the realm of wireless communication.

In the dynamic realm of wireless technology, characterized by ongoing challenges pertaining to spectrum congestion and signal quality, the insights and tools provided by this research are of profound significance. This methodology furnishes researchers and engineers with a comprehensive guide for the simulation and analysis of Wireless Sensor Network-Intelligent Reflecting Surface (WSN-IRS) systems. As a result of utilizing this approach, it enables them to effectively exploit the capabilities of Intelligent Reflecting Surfaces for enhancing the performance of wireless communication networks. As technological advancements continue to develop and reach a state of maturity, it is anticipated that the discoveries and approaches elucidated in this study will serve as a fundamental basis for future innovations. Consequently, these innovations will play a pivotal role in moulding and determining the trajectory of wireless communication in the times ahead.

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