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Examining the ability of Advanced Systems of Wireless Communication Enhanced by IRS Technology

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ABSTRACT

Intelligent Reflecting Surfaces (IRSs) represents a pivotal component of technology, facilitating the enhancement of wireless communication performance and the manipulation of electromagnetic propagation environment. IRS technology has the remarkable capability to transform wireless channels from highly probabilistic to notably deterministic, effectively mitigating the substantial losses encountered in the millimeter-wave (mmWave) band. Our analysis emphasizes how this innovative technology has ushered in a new era in wireless communications. Within the scope of this study, we delved into investigating the effectiveness of IRS-assisted wireless transmissions across various scenarios, encompassing both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. Our investigation involved the simulation of a 32×32 IRS array with a wavelength of 1 meter and an incident angle of 45 degrees. By manipulating the phase shifts of individual IRS elements, we examined their impact on achievable data rates concerning the number of elements. We also explored the relationship between throughput and separation distances, highlighting the significance of IRS placement in achieving optimal data rates. Channel capacity analysis was conducted for single IRS configurations with 50 and 100 elements, as well as dual IRS setups, shedding light on the capacity improvements achievable in different arrangements. Additionally, our study delved into Bit Error Rate (BER) performance in cooperative doubled IRS-aided wireless communication, employing a range of digital modulation techniques across various Signal-to-Noise Ratio (SNR) levels. This insight offers a valuable perspective on the reliability of IRS-aided systems across diverse modulation schemes. We also undertook a comprehensive Spectral Efficiency (SE) analysis, investigating IRS-assisted Multiple-Input, Single-Output (MISO) and Multiple-Input, Multiple-Output (MIMO) communications using various modulation schemes. Finally, we examined path loss characteristics across indoor encompassing different environments, especially at 20 GHz and 28 GHz using vertical to vertical (V-V) polarization. The culmination of this thorough simulation study underscores the tremendous potential of IRS technology in revolutionizing wireless communication across diverse scenarios, offering invaluable insights for future design and development endeavors.

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1. INTRODUCTION

Intelligent reflecting surfaces (IRS) stand as a pivotal technology for the forthcoming wireless communication technologies of the sixth-generation (6G), possessing the ability to reshape the propagation environment of electromagnetic waves and significantly improve communication performance through the intelligent adjustment of the incident electromagnetic wave's amplitude and phase shift. This fine-tuning is achieved by harnessing the power of numerous cost-effective elements integrated within the IRS [1]. Current wireless technologies are insufficient to accommodate the evolving and upcoming technologies such as Artificial Intelligence (AI) abetted communication and Internet of Things (IoT), as well as applications like Virtual Reality (VR), Autonomous Vehicles (AVs), health-associated, smart cities, and indoor positioning [2-5]. The Cisco annual report, released in February 2020, predicts that by 2023, fifth- generation (5G) technology will need to accommodate 10% of connections on mobile devices, delivering an ordinary rate of 575 Mbps. This translates to a wireless network velocity that is 13 times swifter compared to the existing wireless connections. Furthermore, it will be required to facilitate around 14.7 billion machine-to-machine (M2M) communications links, marking a 50% growth from the 6.1 billion connections recorded in 2018 [6]. Given that upcoming data-intensive applications rely on existing wireless networks to meet their desired data transfer rates, a substantial increase in network capacity is essential [7]. Expectations include enhanced spectrum efficiency, reduced communication latency, and greater user connection density due to the emergence of 5G and upcoming mobile communication technologies [8]. The vision for 5G and the future of mobile communication encompasses three potential application situations: massive machine-type communications (MMTC), ultra-reliable low-latency communications (URLLC), and enhanced mobile broadband (eMBB) [9]. Similar to earlier generations of cellular technology, 5G and subsequent iterations require a substantial shift in the communication paradigm [10]. Wireless communications currently utilize sub-6 GHz frequency bands. The International Telecommunication Union (ITU) has endorsed mmWave frequencies, ranging from 10 GHz to 70 GHz, to maximize the capabilities of 5G and future technologies [11-12]. Enhancing bandwidth by a factor of 100 can be achieved through the adoption of mmWave spectrum for transmission. Historically, mmWave was considered unsuitable because of mobile communication owing to its challenging propagation characteristics, including factors like signal weakening, atmospheric conditions, rain interference, limited diffraction and penetration through obstacles, high phase noise, and elevated costs. The conventional view in the unregulated frequency ranges near 60 GHz primarily focused on short-range transmissions. At mmWave frequencies, obstructions and human presence hinder signal propagation and reduce diffraction. Nevertheless, advancements in semiconductor miniaturization have made it feasible to overcome these limitations, while also reducing costs and power consumption. Furthermore, specific frequencies are susceptible to absorption by gases with resonant frequencies, like 60 GHz for oxygen. Additionally, the current wireless network optimization paradigm operates in an uncertain radio environment, where signals encounter reflection, diffraction, scattering, and fading, which presents challenges in optimizing both energy efficiency (EE) and spectral efficiency (SE) in wireless networks [13]. To address the significant free space path loss in the mmWave frequency range, the beamforming method employed in massive multiple-input and multiple-output (mMIMO) has been implemented for this objective [14-15]. Even with beamforming, achieving sufficient coverage from outdoor areas in mmWave frequency bands is severely limited. Thanks to recent progress in metamaterial technology, a novel technology referred to as the IRS is gaining popularity in both academic and industrial circles. IRS represents an advanced hardware innovation capable of mitigating the adverse propagation effects of wireless channels, thereby offering potential cost savings, energy efficiency, and enhanced signal coverage. Other terms of IRS include adjustable reflecting panel, extensive smart façade, and metasurface under software control. The ability to control the communication environment digitally, programmably, and adaptively through the use of IRS has become achievable, owing to advancements in artificial electromagnetic materials [16-18]. As a result, an IRS offers a more EE alternative in contrast to amplify-and-forward (AF) relays, as it solely reflects incoming signals without the need for signal amplification. Due to these advantages, the IRS, which is the central focus of this work, has emerged as a pivotal technology with promising implications for future wireless communications. A lot of work has been done on IRS technology so far, some of which are mentioned here. The author in [19] provide an introduction to IRS technology, offering insights into its core applications within wireless communication, its advantages in comparison to rival technologies, hardware structure, and the corresponding novel signal model. In accordance with the findings presented in [20], the IRS network is capable of governing both the sender and receiver, and the paper also delves into aspects such as signal attenuation and eventual beamforming improvement. In [21], addresses passive holographic MIMO surfaces utilizing microscopic scattering particles, be they metallic or dielectric in nature. A paper [22] explores the involvement of IRS within the forthcoming integrated sensing and communications (ISAC) paradigms. Although there exists a substantial body of recent research concerning IRS-supported communications, IRS-assisted radar systems and ISAC have received comparatively limited scrutiny. This work also offers a broad examination of associated signal processing methodologies and the design complexities involved, which encompass aspects like wireless channel estimation, waveform engineering, and security considerations of IRS. The systematic deployment of both active and passive IRS in wireless communication is described in [23]. It suggests using a variable microstrip patch unit cell for passive IRS and a PIN diode loaded microstrip patch unit cell for active IRS to create a 20 × 20 periodic array in the X band. In [24], introduce a method for efficiently training an IRS with minimal overhead and achieving moderate combining advantages across different modes. Additionally, the document offers guidance on selecting the most suitable mode according to the user's mobility and quality of service needs in a flexible way. Another research suggested employing an IRS as an intermediary between a hybrid access point (HAP) and several wireless-powered users within a wirelessly powered communication network. This setup is designed to enhance the effectiveness of both uplink information transmission and downlink energy transfer. The IRS comprises numerous economical passive reflecting components [25]. One more work provides a comprehensive analysis of employing IRS technology to enhance wireless communication system coverage. It delves into the fundamental principles of IRS, explores different deployment scenarios, and assesses the performance improvements, particularly in terms of the attainable data rates, achieved through IRS-assisted communication [26]. Authors [27], initiated their exploration by elucidating the core concepts underpinning the IRS and the methods through which its adaptability is put into practice. They subsequently delve into topics encompassing beamforming within IRS-supported wireless networks, the utilization of deep learning techniques in IRS applications, and the concurrent optimization of the phase control of the IRS and transmission control of transceivers within diverse network design scenarios. These scenarios include capacity optimization and EF minimization challenges. In article [28], developed diagnostic approaches for IRS systems aimed at detecting issues with the reflecting elements and obtaining information about the failures. They explored three different scenarios where they have accessed to channel state information (CSI). In the first scenario, where full CSI is available, they also proposed a diagnostic strategy based on compressed sensing that greatly diminishes the quantity of measurements needed. In the second scenario, which involved partial CSI, they leverage the sparsity of both the failure and the mmWave channel, employing a low-rank matrix recovery algorithm with compressed sparse data to distinguish between the failure and the channel. In the third scenario, where no CSI is accessible, they formulated the diagnosis problem as a joint sparse recovery challenge and introduced a novel atomic norm as the sparsity-inducing norm for the cascaded channel. A study investigated how transceiver hardware imperfections affects the performance of wireless systems with the assistance of IRS. This analysis focuses on evaluating the SE, EE, and outage probability of IRS-supported wireless systems [29]. Another correspondence discusses a wireless communication system with full-duplex capabilities, in which two users establish communication with each other via the utilization of an IRS [30]. Our work contributes to the advancement and understanding of IRS technology in several key points: We conducted a detailed investigation into the performance of wireless transmissions facilitated by IRS in various scenarios, encompassing both LOS and NLOS conditions. Through simulated experiments utilizing a 32 × 32 IRS array, we explored the impact of phase shifts on individual elements within the IRS on achievable data rates, particularly focusing on the influence of the number of elements. Additionally, we analyzed the relationship between throughput and separation distances, emphasizing the critical importance of optimal IRS placement for maximizing data rates. Our study delved into channel capacity, evaluating configurations with single IRS setups featuring different numbers of elements as well as dual IRS arrangements. This analysis provided insights into the capacity enhancements achievable in different IRS configurations. We conducted a comprehensive analysis of BER performance in cooperative dual IRS-assisted wireless communications, incorporating various digital modulation techniques across a range of Signal-to-Noise Ratio (SNR) levels. This investigation offered valuable insights into the reliability of IRS-assisted systems across different modulation schemes. Our study assessed SE in IRS-assisted MIMO and MIMO communications, considering various modulation schemes. We also explored path loss characteristics across indoor and outdoor settings, spanning diverse environments and utilizing different frequencies (20 GHz and 28 GHz) and antenna types (Horn and Omnidirectional antennas). By addressing these aspects, our work contributes to a comprehensive understanding of the capabilities and potential applications of IRS technology in future wireless communication systems.

The remainder of the document follows this structure: Section one contains introduction. Section two describes IRS technology for advanced wireless communications. Section three outlines the upsides and mathematical analysis of IRS-supported wireless communications. Section four contains the architectural structure and design principles of IRS, section five outlines path loss of an indoor environment with IRS including the performance of IRS throughput and channel modeling with SE. Section six shows the potential limitations of implementing IRS technology in wireless communication systems. Section seven demonstrates the comparison between IRS technology with existing wireless communication systems. Section eight shows simulated results and discussion, and lastly, section nine outlines the conclusions.

2. IRS TECHNOLOGY FOR ADVANCED WIRELESS COMMUNICATIONS

IRS technology is an innovative approach poised to revolutionize wireless communication systems. IRS employs passive reflecting elements, often implemented using meta-surfaces or reconfigurable intelligence surfaces (RIS), to control and manipulate electromagnetic waves in the environment. By dynamically adjusting the properties of these elements, such as phase, amplitude, and polarization, IRS optimizes signal propagation, enhancing coverage, capacity, and energy efficiency in wireless networks. IRS functions by intelligently manipulating the propagation of electromagnetic waves in the environment. This is achieved through a large number of passive reflecting elements deployed strategically in the vicinity of wireless communication devices. These elements, often composed of meta-materials, are capable of altering the phase, amplitude, and polarization of incident electromagnetic waves. The operation of IRS relies on a centralized or distributed controller, which coordinates the behavior of individual reflecting elements based on real-time feedback from the wireless network. By analyzing channel conditions, user locations, and other relevant parameters, the controller optimizes the configuration of the reflecting elements to achieve desired communication objectives, such as maximizing signal strength, minimizing interference, or extending coverage. IRS enables precise beamforming and steering of wireless signals, allowing for targeted transmission and reception. By focusing energy towards desired directions, IRS enhances signal strength and quality while reducing interference in the surrounding environment [31-33]. In areas with poor signal penetration or shadowing effects, such as indoor environments or urban canyons, IRS can extend wireless coverage by strategically placing reflecting elements to redirect and enhance signal propagation. IRS enhances the capacity of wireless networks by optimizing SE, reducing inter-user interference, and enabling spatial multiplexing. By dynamically adjusting the properties of reflecting elements, IRS maximizes the utilization of available frequency resources. Unlike active RF components, IRS elements are passive and consume minimal power. This contributes to energy efficiency in networks, making IRS an attractive solution for sustainable communication systems. IRS technology holds immense potential for enhancing 5G networks and future generations of wireless communication systems. It can facilitate the deployment of dense networks of small cells in urban areas, improving coverage, capacity, and user experience. IRS is particularly well-suited for indoor environments, such as office buildings, shopping malls, and stadiums, where traditional wireless solutions face challenges related to coverage and capacity. By deploying IRS, operators can provide seamless connectivity and support emerging applications like indoor navigation and location-based services. In satellite communication systems, IRS can mitigate signal attenuation and interference, improving link reliability and performance. By deploying IRS in satellite ground stations or onboard satellites, operators can optimize signal transmission and reception in various scenarios. IRS technology is still undergoing active research and development to optimize its design, deployment, and control algorithms.

3. UPSIDES AND MATHEMATICAL ANALYSIS OF IRS-SUPPORTED WIRELESS COMMUNICATIONS

IRS presents a highly promising technological innovation aimed at improving wireless communication systems, especially in situations characterized by difficult signal propagation conditions. IRS comprises passive surfaces typically constructed from metamaterials, which serve to reflect and strategically manipulate incoming electromagnetic waves with the objective of enhancing signal quality, expanding coverage, and boosting overall capacity [34]. In the realm of wireless communication, signals propagate from a transmitter, which could be a BS or an access point, to a receiver, often a mobile device, through a wireless channel. This channel is susceptible to various issues like path loss, shadowing, and multipath fading, all of which have the potential to degrade signal quality, resulting in unreliable and sluggish data transmission. To tackle these obstacles, IRS technology introduces passive reflecting components strategically positioned within the environment. These components have the capability to manipulate the phase and amplitudes of reflected waves, facilitating constructive interference and beamforming to direct signals toward the receiver. In essence, IRS can effectively bend electromagnetic waves to circumvent obstacles, strengthen signal reception, and diminish interference [35].

Mathematical Analysis: To grasp the advantages of wireless communication with the support of IRS technology, let's examine a simplified situation. In this setup, we have a transmitter (Tx), an IRS, and a receiver (Rx) forming a communication connection. The IRS is positioned between the Tx and Rx and comprises N reflecting elements.

Signal enhancement through phase control: The phase adjustment at each reflecting element allows for coherent addition of signals. Consider a reflecting element with a reflection coefficient denoted as ϕ_k. The signal received at the Rx can be expressed as:

$$\begin{aligned} y_{rec.} &= h_{direct} + h_{reflected} \\ &= \frac{A}{d_{Tx-Rx}} e^{-j\theta_{direct}} + \sum_{k=1}^{N} \frac{A}{d_{Tx-IRS_k} d_{IRS_k-Rx}} e^{j\phi_k - j\theta_{reflected_k}} \end{aligned} \tag{1}$$

where, A is the amplitude of the transmitted signal, $Tx - Rx$ is the distance between Tx and Rx, $Tx - IRS_k$ and $IRS_k - Rx$ are the distance between Tx and the k-th IRS element and between the IRS element and Rx, respectively, θ_{direct}, $\theta_{reflected_k}$ are the phases associated with the direct path and the k-th reflecting element. By optimizing the phase ϕ_k at each IRS element, IRS can ensure constructive interference maximizing the received signal power.

Interference mitigation: Consider a scenario where there are multiple interfering sources affecting the signal received at the receiver (Rx). The goal is to use the IRS to manipulate the reflection phases and amplitudes in such a way that the interference is suppressed, thereby maximizing the SNR at the receiver. The receiving signal at the receiver as:

$$y = h_{direct}x + \sum_{i=1}^{N} h_{int\,erfer,i}x_i + n \tag{2}$$

where, y is the received signal at the receiver, $h_{direct}$is the channel coefficient for the direct path from the transmitter to the receiver, $x$is the transmitted signal, $h_{int\,erfer,i}$is the channel coefficient for the interference from the h_{ith} interfering source, x_i is the signal transmitted by the h_{ith} interfering source, and n is the additive white Gaussian noise (AWGN) at the receiver.

We assume that the receiver has perfect knowledge of the channel coefficients h_{direct} and $h_{int\,erfer,i}$, and it can adjust the reflection phases and amplitudes of the IRS elements. Let $f$denote the reflection coefficients vector of the IRS elements. Then, the reflected signal from the IRS can be represented as $Fh_{IRS}x$, where $F$is the diagonal matrix formed by the elements of f, and $h_{IRS}$is the channel coefficient vector from the IRS to the receiver. The received signal after the IRS reflection can be written as:

$$y_{IRS} = h_{direct}x + \sum_{i=1}^{N} h_{int\,erfere,i}x_i + h_{IRS}^{T} F h_{IRS}x + n \tag{3}$$

To maximize the SNR at the receiver, we aim to optimize the reflection coefficients f of the IRS elements. This optimization problem can be formulated as:

$$max_f = \frac{|h_{direct}|^2|x|^2}{\sum_{i=1}^{N}\left|h_{int\,erfere,i}\right|^2|x_i|^2+\left|h_{IRS}^{T}Fh_{IRS}x\right|^2+\delta^2} \tag{4}$$

where, δ^2 is the variance of the AWGN. This optimization problem can be solved using various techniques such as convex optimization, gradient descent, or alternating optimization, depending on the complexity of the system and the desired performance metrics. By solving this optimization problem (that is out of scope this paper), we can determine the optimal reflection coefficients of the IRS elements that effectively mitigate interference and maximize the SNR at the receiver, thereby improving the overall communication performance.

Increased coverage and improved signal quality: IRS has the potential to expand the coverage area and improve signal quality, particularly in indoor settings and urban canyons, where signal degradation due to intense multipath fading is a common issue. This enhancement is evident in channel capacity assessments, demonstrating that IRS significantly augments channel capacity by reducing path loss and enhancing SNRs.

Energy efficiency: Through the optimization of signal pathways and the reduction of path loss, IRS technology has the potential to promote EE communication. This technology permits the utilization of lower transmitting power at the origin, ultimately leading to decreased energy consumption (E) within the network. The Eduring transmission can be calculated as the product of transmitted power (P_{tx}) and the duration of transmission (T) i.e. $E = P_{tx}.T$. For understanding the impact of IRS on P_{tx}, lets denote $P_{tx}^{/}$as the reduced $P_t$when IRS technology is employed. The relationship between P_{tx} (without IRS) and $P_{tx}^{/}$ (with IRS) can be expressed as $E^{/} = P_{tx}^{/}.T$. Since $P_{tx}^{/} < P_{tx}$, it follows that $E^{/} < E$.

4. ARCHITECTURAL STRUCTURE AND DESIGN PRINCIPLES OF IRS

Since they can manipulate EM waves in innovative manners, such as altering phase, adjusting amplitude modulation (AM), and converting polarization, the field of electromagnetic metasurfaces (EM-MM) has experienced substantial growth in recent times. By fine-tuning the phase reflection coefficient and streamlining the design, programmable and digital metasurfaces can serve as a means to encode electromagnetic waves for a diverse range of applications, including those involving mmWave and terahertz frequencies. These waves can be individually regulated through the implementation of a field programmable gate array (FPGA) program, bridging the gap between the digital and physical realms [36]. In Fig 1, an extensive array of passive components allows the metasurface (MS) to swiftly alter the trajectory of incoming EM waves [37]. In Fig. 1(a) a distinct LOS connection is evident between the smartphone and the BS. Consequently, the introduction of IRS serves to facilitate the establishment of a replicated connection and enrich system diversity. In Fig. 1(b) the IRS plays a vital role in enabling communication between the smartphone and the BS, even when the LOS is obstructed by a tall building. The presence of IRS becomes indispensable for the receiver to capture the broadcast signal, leading to an overall enhancement in the system's EE and SE due to the virtual link.

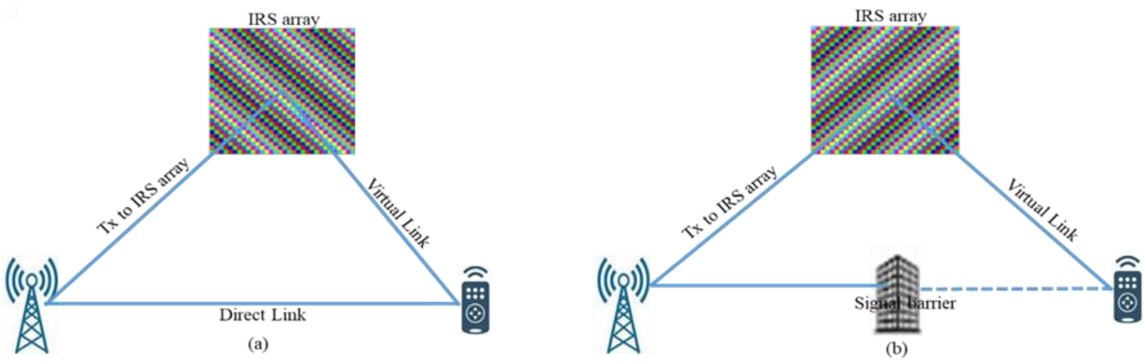

Figure 1. IRS-supported system for wireless transmission: (a) When LoS link is present; (b) When LoS connection is not there.

Segments of IRS: A regular IRS structure comprises three tiers, as illustrated in Fig. 2. The outermost layer features an extensive adjustable passive element array arranged on a dielectric substrate for the manipulation of incoming signal. The middle layer incorporates a copper plate is called CB, aimed at mitigating signal energy losses during the reflection process. The innermost layer stratum houses a CCB equipped with real time control over the phase and amplitude of signal reflection. Typically, FPGA serves as the intelligent controller responsible for governing reflection and configuration, while also acting as a conduit between the BS and the intended destination

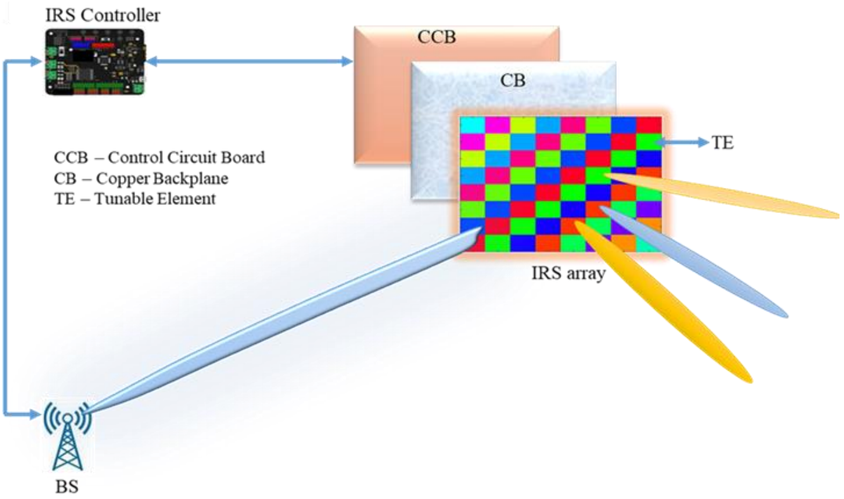

Figure 2. Structure of IRS

5. PATH LOSS OF AN INDOOR ENVIRONMENT WITH IRS

Propagation loss in an indoor environment with an IRS for vertical to vertical (V-V) polarization at different frequencies is considered. The propagation loss in an indoor environment with an IRS is calculated using the indoor path loss model. The path loss model is based on the Friis free-space propagation loss equation with additional components for indoor propagation. The indoor path loss (in dB) is defined as:

$$PL(dB) = 20\,log_{10}\left(\frac{4\pi df}{c}\right) + 20\,log_{10}(\,df) + 32.4 \qquad (5)$$

Where, d is the distance in meters, f is the frequency in Hz, and c is the velocity of light.

IRS path loss (dB): The additional propagation (path) loss introduce by the IRS for V-V polarization can be calculated as:

$$IRS_{PL}(dB) = 10\,log_{10}(\,IRSG_{gain}) \tag{6}$$

where, $IRSG_{gain} = 10^{(ref_{gain}(dB)/10)}$, $ref_{gain}(dB)$ is the reflection gain of the IRS. Additionally, for V-V polarization, the phase shift is taken into account. IRS phase shift for V-V polarization is $\left[IRSG_{gain}.\,e^{i(ref_{phase}(rad))-\pi/2}\right]^2$, where $ref_{phase}(rad)$ is the phase shift of the IRS. Finally, the calculated IRS path loss (dB) is added to the indoor path loss (dB) to obtain the total path loss with IRS for V-V polarization.

Performance of IRS throughput: Consider a scenario where a connection between a random source and its desired destination is interrupted, either on a permanent or temporary basis, due to an obstacle. In this situation, an IRS consist of N elements is employed to establish the connection. Likewise, the channel gain from the IRS to the destination can be expressed as $h_{IRS-d} \in C^N$, and the channel gain from the signal origin to the IRS is denoted as $h_{s-IRS} \in C^N$. Therefore, as described in [38], the achievable data rate is determined by the following equation.

$$R_{adr} = log_2\left(1 + \frac{P_{Tx}\left(\sqrt{\beta_{s-d}} + N\alpha\sqrt{\beta_{IRS}}\right)}{\sigma^2}\right) \tag{7}$$

where, transmit power is P_{Tx}, $\beta_{s-d} = |h_{s-d}|^2$, $\beta_{IRS} = \frac{1}{N}\sum_{n=1}^{N}(h_{s-IRS})_n\,(h_{IRS-d})_n$, and $\alpha \in (0,1)$ interacts with the IRS through the amplitude of the reflected signal, and σ^2 is the variance of noise.

Channel Modeling with SE: Communication Channel modeling with SE and precoder formulation in the context of MIMO systems with IRS introduces additional complexity. In a MIMO-IRS communication system, multiple antennas are used at the transmitter, receiver, and the IRS, consisting of a large number of reflecting elements. The channel matrix, H from the transmitter to the IRS, which is of size $N_{IRS} \times N_t$, where N_{IRS} is the size of the IRS array, and N_t is the number of transmit antennas. The channel matrix, G from the IRS to the receiver, which is size of $N_{IRS} \times N_r$, where N_r is the number of receive antennas. SE for a MIMO-IRS system can be calculated as: $\eta = \log_2(\det(I + \gamma H\Theta G))$, where, γ is the SNR, I is the identity matrix, and Θ is the matrix of phase shifts of IRS reflecting elements in diagonal form. The precoder design in MIMO-IRS systems aims to optimize the transmitted signals while considering the IRS's phase shifts. The signal that is transmitted, X, can be written as: $X = PS$, where, P is the precoder matrix, design to exploit the channel conditions including the IRS, S is the vector of data symbols.

6. POTENTIAL LIMITATIONS OF IMPLEMENTING IRS TECHNOLOGY IN WIRELESS COMMUNICATION SYSTEMS

IRS technology in wireless communication systems offers promising benefits, but it also comes with certain limitations and challenges:

Complexity and Cost: Integrating IRS into existing wireless communication infrastructure can be complex and expensive. The deployment of large-scale IRS arrays requires significant investment in hardware, installation, and maintenance, potentially posing financial challenges for widespread adoption [39].

Power Consumption: IRS elements may require power for operation, especially if they involve active components for signal processing. Managing power consumption efficiently while ensuring continuous operation can be a challenge, particularly in scenarios where energy efficiency is critical [40].

Synchronization and Calibration: Achieving precise synchronization and calibration among IRS elements and other network components is essential for optimal performance. However, maintaining synchronization in dynamic environments with mobility and changing channel conditions can be challenging and may require advanced synchronization techniques [41].

Limited Coverage and Mobility: IRS technology primarily enhances communication within its coverage area by reflecting and manipulating signals. However, the coverage area of IRS is limited to its deployment location, which may pose challenges for mobile communication scenarios where users move across different coverage areas [42].

Deployment Flexibility: Unlike traditional wireless infrastructure components like base station (BS) or antennas, IRS elements are fixed and passive, limiting their flexibility in adapting to changing communication needs or network configurations. Deploying IRS in dynamic environments or retrofitting existing infrastructure may be challenging due to spatial constraints and regulatory considerations [43].

Signal Interference and Crosstalk: In dense deployment scenarios or environments with multiple IRS arrays, signal interference and crosstalk between neighboring IRS elements can occur, impacting communication quality and reliability. Mitigating interference and optimizing signal alignment become critical challenges in such scenarios [44].

Regulatory and Environmental Considerations: Regulatory approvals and compliance with spectrum regulations are essential for deploying IRS technology in wireless communication systems. Additionally, environmental factors such as weather conditions, physical obstructions, and electromagnetic interference can affect the performance of IRS, requiring careful planning and mitigation strategies [45].

7. COMPARISON BETWEEN IRS TECHNOLOGY WITH EXISTING WIRELESS COMMUNICATION SYSTEMS

Cellular Networks: Compared to traditional cellular networks, IRS technology offers potential advantages in terms of coverage extension, capacity enhancement, and interference mitigation. However, cellular networks have well-established infrastructure, standards, and deployment models, making them more readily deployable and scalable [46].

Wi-Fi and WLANs: IRS technology can complement Wi-Fi and Wireless Local Area Networks (WLANs) by improving indoor coverage, extending range, and enhancing data rates. However, Wi-Fi and WLANs are typically deployed using simpler and more cost-effective solutions, making them more suitable for small to medium-scale deployments and indoor environments [47].

Satellite Communications: IRS technology shares similarities with satellite communications in terms of signal reflection and coverage extension. However, satellite systems offer global coverage and are well-suited for long-range communication, while IRS is typically deployed for localized coverage enhancement in specific areas [48].

Mesh Networks: Mesh networks utilize decentralized communication nodes to relay signals, offering flexibility and resilience in dynamic environments. While IRS can potentially enhance the performance of mesh networks by optimizing signal propagation, mesh networks excel in scenarios requiring self-organization, scalability, and adaptability [49].

8. SIMULATED RESULTS AND DISCUSSION

In Fig .3 shows the phase shifts for the IRS based on specified parameters and incident angle. A 16 × 16 IRS array with a 1-meter wavelength of the carrier signal, and 45 degrees incident angle is considered to measure phase shifts. The visualization displays the phase shifts as a color-coded image, where different colors represent different phase angles. A color bar indicates the phase volumes and labels are provided for the columns and rows of the IRS grid.

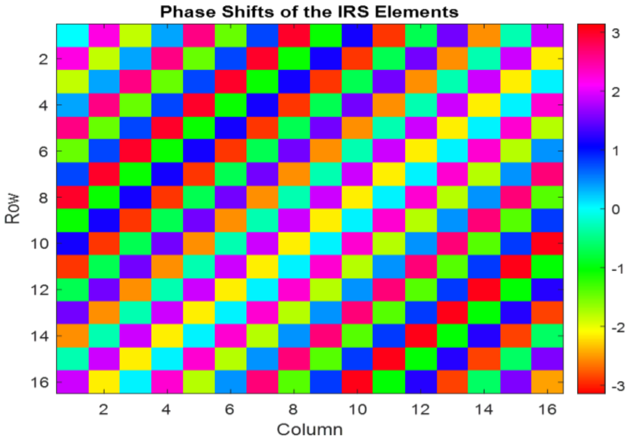

Figure 3. Phase shifts of IRS elements with 16 × 16 array

BER of IRS-assisted wireless systems performance with two cooperative IRSs using different modulation schemes (BPSK, QPSK, 8PSK, and 16-QAM) over a range of SNR is shown in Fig 4. In this simulation total number of IRS elements is taken at 1000, elements on IRS1 and, IRS2, as well as SNR values from -5 dB to 20 dB. As SNR increases, the BER decreases, indicating better the effectiveness of something, as judged by the error rate is noticed in Fig 4.

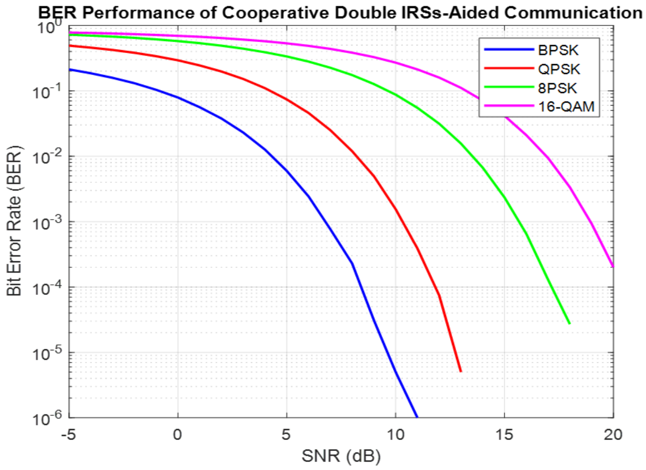

Figure 4. BER efficiency of collaborative dual communication with IRS support

The plot in Fig 5. Showing the channel capacity as a function of the number of elements in IRS1. The plot includes four lines representing different scenarios: One IRS with 50 elements and 100 elements, Two IRS with 50 elements and 100 elements. The findings reveal how the channel capacity changes as the number of elements in the first IRS is varied. This information is important for optimizing the design of IRS-aided communication system. It can provide insights into the trade-offs between the number of elements and channel capacity, helping in the selection and deployment of IRS configurations in real-world applications. This simulation considers different variables, like the number of elements in IRS1 (varying from 1 to 100), the distance from IRS1 to the user is 15 meters with a wavelength of the carrier signal 1 meter including 1-watt transmitting power. The channel gain takes into consideration far-field approximation which is appropriate when the distance between the user and the IRS is much larger than the size of the IRS. It is found that the performance of IRS1 with 50 and 100 elements is identical because both calculations used the same channel gain derived from the far-field approximation formula.

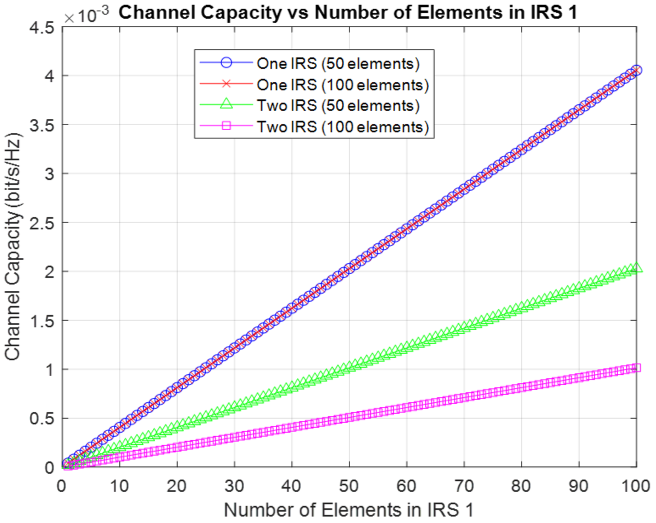

Figure 5. The capacity of the channel as a function of the element count in IRS1.

In Fig 6. demonstrated, how the received SNR at the user varies with different configurations of IRS1. The simulation parameters are considered as: different number of elements for IRS1 (varies from 1 to 800), otherwise, additional factors are taken like as before. This plot depicts the relationship between the SNR received by the user and the number of elements in IRS1. From this simulation figure, it can be observed that the performance of one IRS (400 elements), and one IRS (800 elements) is equal since the received power calculation is solely dependent on the absolute value of channel gain which is determined by number of elements and transmitted power is constant, the received power for both IRS1 configuration (400 and 800 elements) remains the same throughout the loop iterations, resulting in identical SNR values for both cases.

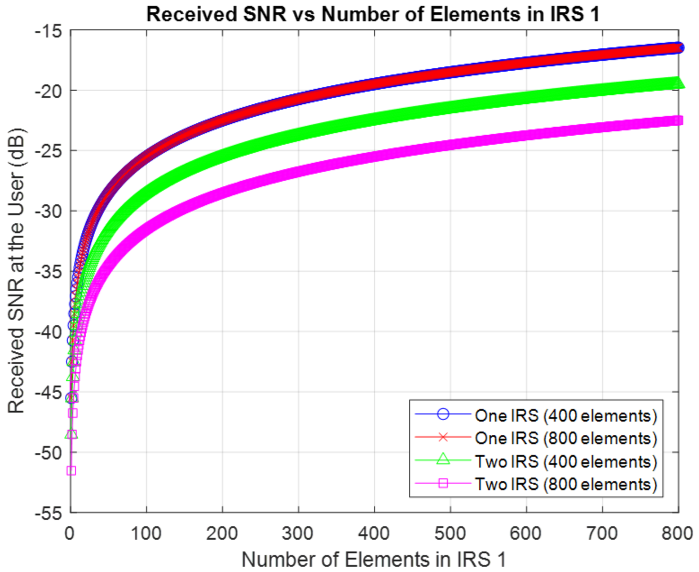

Figure 6. Received SNR at the user (dB) with different configurations of IRS1

The achievable data rates with and without an IRS across a range of SNR is shown in Fig. 7. The figure illustrates the impact of IRS on the achievable data rates. The blue curve depicts the data rates without IRS, while the red curve represents data rates with IRS. We noticed that at lower SNR values, the data rates with IRS are significantly higher compared to data rates without IRS. As SNR increases, the gap between the two scenarios almost diminishes.

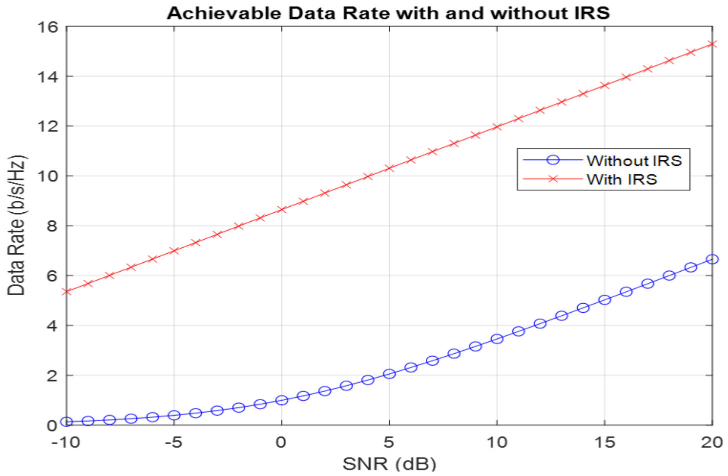

Figure 7. Achievable data rate with and without IRS

The SE of an IRS-backed MIMO communication system across a range of SNR is shown in Fig 8. SE is a measure of the system's capacity to transmit data over a given bandwidth. The analysis considers different ways to encode information onto a carrier signal, including BPSK, QPSK, 16-QAM, and 64-QAM, each with varying bits per symbol. From the simulation output, we observed that, as SNR increases, the SE for all modulation schemes also increases. This relationship is a fundamental characteristic of communication systems, where higher SNR results in improved data transmission rates. The plot also shows the performance of different modulation schemes. 64-QAM achieves the highest SE, while BPSK offers the lowest spectral efficiency. This highlights the trade-off between SE and the complexity of modulation schemes. More complex schemes provide higher data rates but require more sophisticated signal processing. From the plot, it also be noticed that the incorporation of an IRS in the MIMO system significantly improves SE. IRS-enabled systems exploit passive reflection to enhance the effective link between BS and user equipment (UE). IRS-assisted MIMO can be particularly advantageous in scenarios with challenging channel conditions, such as urban environments with fading and interference.

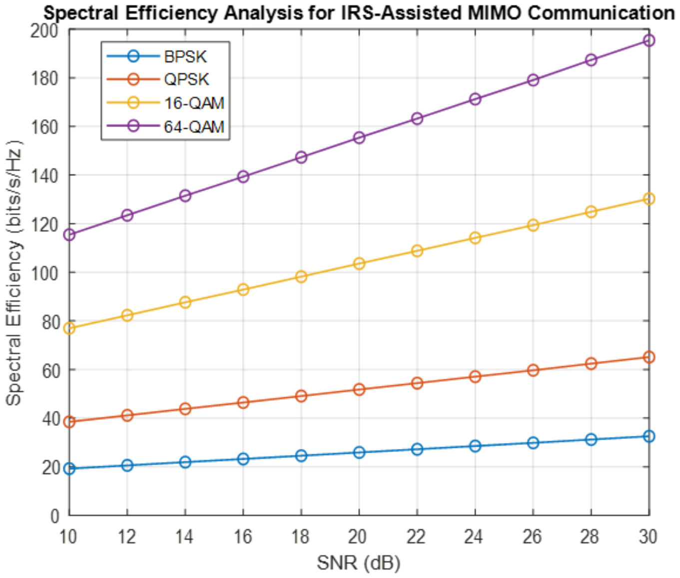

Figure 8. Performance analysis of the SE of an IRS-assisted MIMO communication system

The Fig. 9 illustrates the SE of an IRS-assisted MISO communication system over a range of SNR. SE quantifies the system's ability to transmit data within a specified bandwidth. Various modulation schemes, such as BPSK, QPSK, 16-QAM, and 64-QAM, each with differing bits per symbol, are considered in this analysis. The simulation results reveal a consistent trend: as SNR increases, SE also rises. The plot also shows the performance disparities among different modulation techniques, among them, 64-QAM achieves the highest SE, while BPSK yields the lowest SE. This underscores the trade-off between SE and the intricacy of modulation schemes. Another noteworthy observation from the plot is the substantial improvement in SE with the incorporation of an IRS into the MISO system.

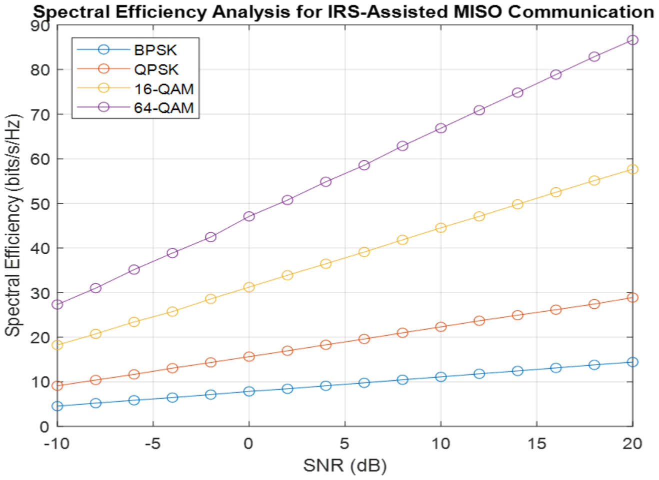

Figure 9. Performance analysis the SE of an IRS-assisted MISO communication system

Fig. 10 represents the BER performance of IRS-aided wireless transmission for both LOS and NLOS communications links across a range of SNR. In the LOS scenario, the wireless channel experiences a direct and unobstructed path between the transmitter and receiver. A relay station amplifies the signal before transmission. As the SNR increases, the BER decreases, illustrating the expected improvement in performance with higher SNR levels. In the NLOS scenario, the wireless channel includes reflections, diffractions, and other obstructions, leading to a less direct path. Similar to the LOS case, the relay station amplifies the signal. However, the NLOS link typically introduces more signal degradation due to the multipath nature of the channel. From the plots, it's evident that the LOS link outperforms the NLOS link in terms of BER, especially at lower SNR values. This is expected because LOS communication benefits from a direct and strong signal path. In contrast, the NLOS link experiences signal degradation, leading to a higher BER, even as SNR increases.

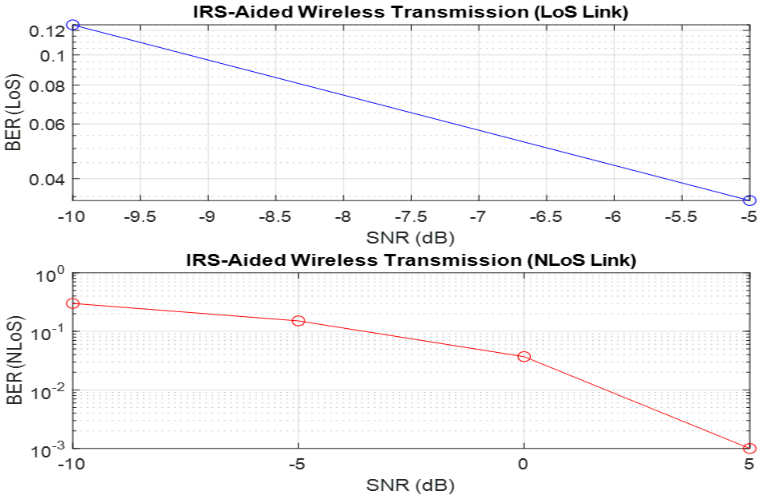

Figure 10. BER performance IRS-aided wireless transmission for LOS and NLOS communication links

The three-dimensional (3D) surface plot represents the achievable data rates in a scenario where an IRS is deployed in wireless communication. The figure illustrates how the data rate varies with the number of elements in the IRS and the minimum separation distance between the source and destination. From this simulation results, we noticed that as the number of elements in the IRS (N) increases, the achievable data rate also increases. This is because a larger IRS can provide more options for manipulate the signal and enhance the overall communication performance. Increasing the minimum separation distance between the source and destination positively affects the data rate. A larger separation distance results in a better LOS condition, which typically leads to higher data rates. The number of elements and other factors, such as cost and performance, must be balanced in the IRS and the minimum separation distance. While more elements in the IRS are beneficial for enhancing the data rate, the impact is more pronounced in scenarios with larger separation distances.

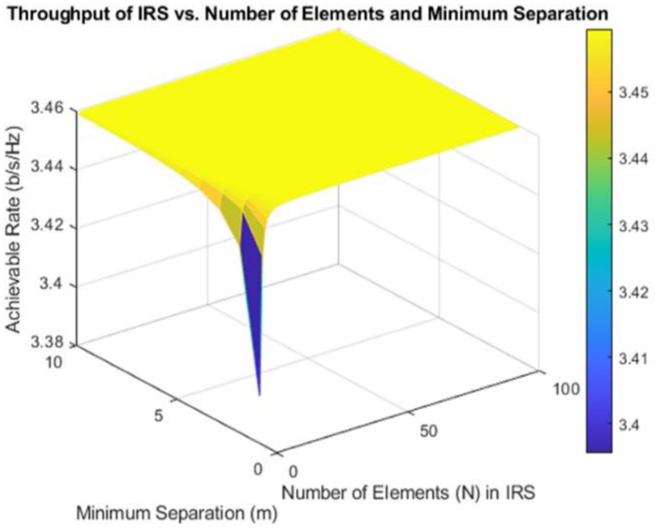

Figure 11. Achievable data rates in a scenario where IRS is deployed in wireless communication

In Fig. 12. Shows Path loss for V-V polarization at different frequencies of an indoor environment with an IRS. From the figure is identified how the path loss varies with distance for different frequencies (2.4 GHz, 5 GHz, 20 GHz, and 28 GHz) and the impact of the IRS on path loss. As the distance increases, path loss generally increases due to the inverse square relationship with distance. The IRS reduces the path loss by adjusting the reflection gain and phase shift, which is especially noticeable at higher frequencies. In this case, a reflection gain of 10 dB and a phase shift of 45 degrees is considered. These values imply that the IRS doesn't perfectly reflect the incident signal but rather attenuates it to some extent.

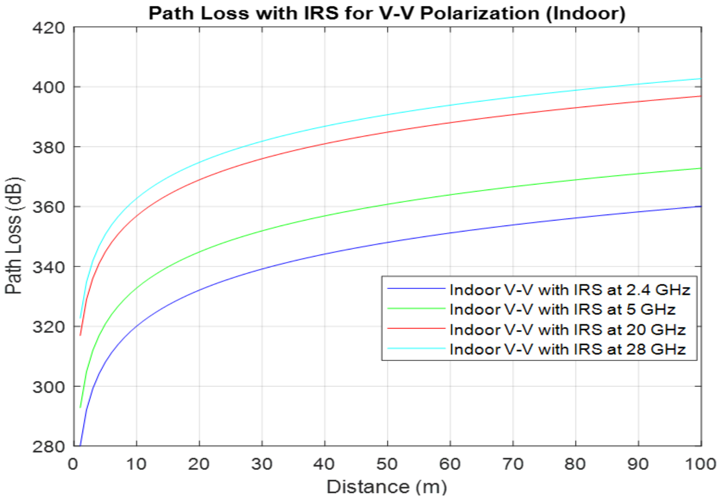

Figure 12. Path loss for V-V polarization at different frequencies of an indoor environment with an IRS

A high reflection gain coupled with a phase shift can result in a significant portion of the incident signal being absorbed or redirected away from the desired direction. The indoor path loss model used in this simulation incorporates various factors such as free-space path loss, near-field effects, and additional loss terms. Even for short distances, the path loss in indoor environments can be significant due to reflections, diffractions, and absorption by walls, furniture, and other obstacles. The model accounts for these effects, leading to higher path loss values even for short distances. In this simulation also evaluates path loss at different frequency bands. Higher frequency signals are more susceptible to attenuation and absorption by obstacles in the environment. Therefore, even for short distances, the path loss can be considerable, especially at higher frequencies.

9. CONCLUSIONS

IRS plays a key role in technology, enabling significant improvements in wireless communication performance and the control of electromagnetic propagation environments. This technology possesses the remarkable ability to transform wireless channels from being highly uncertain to considerably predictable, effectively mitigating the substantial losses that occur in the mmWave spectrum. Our analysis highlights how this groundbreaking technology has ushered in a new era in wireless communications. In our study, we extensively explored the performance of IRS-assisted wireless transmission in different scenarios, including both LOS and NLOS conditions. We conducted simulations using 32 × 32 IRS array with a wavelength of one meter and an incident angle of 45 degrees. By manipulating the phase shifts of individual IRS elements, we investigated their impact on achievable data rates with varying numbers of elements. Additionally, we examined the relationship between throughput and separation distances, emphasizing the critical role of IRS placement in achieving optimal data rates. Our study also encompassed channel capacity analysis for single IRS configurations with 50 and 100 elements, as well as dual IRS setups, shedding light on the capacity improvements attainable in different arrangements. Furthermore, we delved into BER performance in cooperative dual IRS-assisted wireless communication, employing various digital modulation techniques at different SNR levels. This analysis provides valuable insights into the reliability of IRS-aided systems across a range of modulation schemes. We also conducted a comprehensive examination of SE, exploring IRS-assisted MISO and MIMO communications using various modulation schemes. At the end, we investigated path loss characteristics in indoor environments, specially at 20 GHz and 28 GHz, using V-V polarization. This comprehensive simulation study underscores the enormous potential of IRS technology in revolutionizing wireless communication across diverse scenarios, offering valuable insights for future design and development efforts.

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