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Performance Analysis of Tera Hertz Frequencies on Intelligent Reflecting Surfaces for 6G Communications

Yegireddi Satya Vinod[1], Thoram Saran Kumar[2], K. Baboji[3], V Venkata Lakshmi Dadala[4], K. Kalyani[5*], Venkata Ramana Kammampati[6], and U. S. B. K. Mahalaxmi[7]

[1]*Department of Electronics and Communication Engineering, Bonam Venkata Chalamayya Engineering College(A), Odalarevu; India; satyavinod55@gmail.com;*
[2]*Department of Electronics and Communication Engineering, Bonam Venkata Chalamayya Engineering College(A), Odalarevu, India; saran.thoram455@gmail.com;*
[3]*Dept of Electronics and Communication Engineering, Sri Vasavi Engineering college, Tadepalligudem, Andhra Pradesh, India; baboji.ece@srivasaviengg.ac.in;*
[4]*Dept of Electronics and Communication Engineering, Pragati Engineering College (A), Surampalem, Andhra Pradesh, India; lakshmi.dvv@gmail.com;*
[*5]*Department of Electronics and Communication Engineering, Aditya University, Surampalem, India; kalyani.kapula@gmail.com;*
[6]*Department of Electronics and Communication Engineering, Aditya University, Surampalem, India; venkat.ramana489@gmail.com*
[7]*Dept of Electronics and Communication Engineering, Aditya University, Surampalem, India; aumahalakshmi@gmail.com*

*__Correspondence:__ *kalyani.kapula@gmail.com*

ABSTRACT- The rapid advancements toward 6G networks have powered interest in the terahertz (THz) frequency band due to its potential for delivering ultra-high data rates. It provides massive connectivity. However, THz communication faces significant challenges. It includes high path loss, molecular absorption and blockage sensitivity. These are severely degrading signal quality over distance. Intelligent reflecting surfaces (IRS) emerged as a promising solution to address these issues. IRSs reflect and direct signals to desired locations. This improves communication quality. It does not require extra power sources. In this study, we look at how different factors affect performance. These factors include the distance between the transmitter and IRS, transmit power, number of IRS elements, LoS/NLoS path-loss ratio, number of transmit antennas and frequency in the THz band. We find the best configurations for IRS-aided THz systems. Using pathloss and channel models, measure spectral efficiency and achievable rate. This helps identify key factors for improving system efficiency and reliability. Using more IRS elements improves signal quality and data rates. With every 100 added elements (up to 700), data rates increase by 20–30%. After 700 elements, the improvements become smaller. This shows the need to choose a balanced IRS size for best performance. The results show that the distance between the transmitter and IRS affects spectral efficiency. Closer IRS placements improve efficiency.

Keywords: 6G, Beamforming, BER, IRS, NLoS, LoS, Terahertz.

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Author(s): Yegireddi Satya Vinod, Thoram Saran Kumar, K. Baboji, V Venkata Lakshmi Dadala, K. Kalyani, Venkata Ramana Kammampati, U. S. B. K. Mahalaxmi;

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1. INTRODUCTION

The demand for faster and more reliable wireless communication is growing rapidly. The world is moving towards the 6G of wireless networks [1,2]. This new generation aims to achieve ultra-high data rates, low latency and support for massive connectivity. The 6G networks are expected to enable new applications such as virtual reality, augmented reality and the Internet of Things. To meet these demands, researchers are exploring new frequency bands and advanced technologies. One promising frequency range for 6G is the THz band [3,4]. This range covers frequencies between 0.1 and 10 THz. The THz band offers high bandwidth. This helps to support very fast data transfer. However, communication in the THz band faces many challenges. The high frequency of THz waves means they experience significant path loss. Signal distortion happens over distance. THz waves are also highly sensitive to blockages, such as walls and objects. These are also suffered from molecular absorption in the atmosphere. This absorption is especially strong at certain frequencies within the THz band. These effects are reducing the signal strength further [5].

To overcome these challenges, researchers and academicians are investigating new ways to boost signal strength and reliability in THz communication. One promising solution is the use of IRS. An IRS is a surface made up of many small elements. Each signal can reflect incoming signals [6,7]. By adjusting the phase of each element, an IRS can control the direction of reflected signals. These are focused on specific users [8].

Studies by Han et al. [9] highlight the potential of THz frequencies for short-range applications like wireless backhaul and ultra-dense networks. Furthermore, the use of reconfigurable hardware and advanced channel models is improving THz performance. Researchers emphasize the need for integrated THz communication systems with machine learning (ML) for real-time adaptation. IRS technology has gained attention as a key enabler for 6G [10,11]. IRS consists of passive elements, often made of meta-materials, which can reflect and manipulate signals without consuming much power. Research shows IRS can reduce power consumption, enhance coverage, and mitigate interference in high-frequency bands.

Di Renzo et al. [12] describe IRS as programmable surfaces that control wave phases and amplitudes. By aligning reflected signals, IRS boosts signal strength at the receiver. This is especially useful for overcoming the short-range limitations of THz waves. Experimental setups confirm the feasibility of IRS-enhanced communications in real-world scenarios. Combining THz frequencies with IRS creates powerful systems for 6G. IRS can redirect and amplify THz signals, reducing path loss and extending range. Researchers are exploring IRS designs optimized for THz wavelengths. These include ultra-thin structures with precise phase-shifting capabilities. Wu et al. [13] conducted simulations demonstrating how IRS improves THz signal quality in urban areas. Results show a significant increase in signal-to-noise ratio (SNR) and data rates. Another study by Basar et al. [14] highlights the importance of optimizing IRS placement for maximum performance. Researchers are working on ML-based methods to optimize IRS configurations in real-time. Another issue is the energy consumption of IRS control systems. Passive IRS elements consume minimal power, but active elements for THz applications may require external energy sources. Studies by Tang et al. [15] suggest hybrid IRS designs with a mix of active and passive components.

The following are the key contributions of the work:

- Developed an IRS-aided THz-MIMO system to address high path loss, molecular absorption and LoS blockages in the THz band.
- Identified placing the IRS close to the transmitter maximizes spectral efficiency, reduces path loss and improves signal quality.
- Increasing the IRS element count and transmit power improves SNR and rate. However, the improvement slows down, so a balanced setup is needed for best performance.
- Showed that lower THz frequencies and strong LoS paths improve spectral efficiency, guiding the choice of operating frequencies and IRS placement for 6G.

2. IRS Aided MIMO System Model

Figure 1 describes the working principle of IRS-assisted massive MIMO system in a THz band. The setup involves a single transmitter equipped with multiple antennas. It communicates with multiple users through multiple IRS. It has many passive reflecting elements. Each user has a single antenna. The transmitter cannot directly send signals to users due to blockage in the line of sight. To solve this, the IRS creates an artificial LoS link. This link restores communication by redirecting signals from the transmitter to the users. Let the channel from the transmitter to the IRS be represented by the matrix $\mathrm{H}_r \in \mathbb{C}^{N_t \times M}$. The channel from the IRS to the n^{th} user as $\mathbf{g}_n \in \mathbb{C}^{M\times 1}$. Here, N_t is the number of antennas at the transmitter, and M is the number of elements on the IRS.

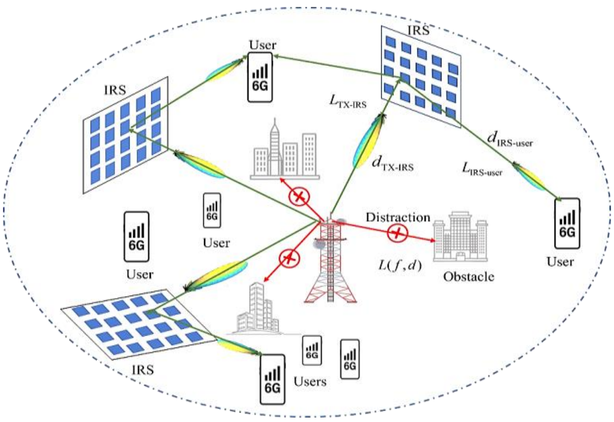

Figure 1. IRS-assisted MIMO system model for THz frequency bands

The channel matrix modeled as in *equation (1)*[16].

$$\mathrm{h}_n = \alpha_n^{(0)}\beta_n^{(0)}\,\mathrm{a}_t(\theta_{n,az}^{(0)},\theta_{n,el}^{(0)}) + \sum_{i=1}^{L}\alpha_n^{(i)}\beta_n^{(i)}\,\mathrm{a}_t(\theta_{n,az}^{(i)},\theta_{n,el}^{(i)}) \qquad (1)$$

The channel model here includes both LoS and NLoS components. The first term, $\alpha_n^{(0)}\beta_n^{(0)}\mathbf{a}_t(\theta_{n,az}^{(0)},\theta_{n,el}^{(0)})$ represents the LoS component, while the summation term represents NLoS components. The channel fading coefficients are given by $\alpha_n^{(i)}$ and path-loss coefficients by $\beta_n^{(i)}$ .Here, $i = 0,1,\ldots,L$. The path loss in these windows can be calculated using *equation (2)*.

$$|\beta|^2 = L_{\text{spr}}(f,d)L_{\text{abs}}(f,d) = \left(\frac{c}{4\pi fd}\right)^2 e^{-k_{\text{abs}}(f)d} \qquad (2)$$

Here, L_{spr}, L_{abs} are the spreading loss, molecular absorption respectively. Here, c, f, d and $k_{\text{abs}}(f)$ are the speed of light, frequency, distance and absorption coefficient respectively.

The transmitter sends a common message $s \sim \mathcal{CN}(0,1)$ to all users, where s is a complex signal. The phase shift of the m^{th} reflector at the IRS is represented by a complex number ϕ_m with $|\phi_m| = 1$. Each user receives a reflected signal y_n from the IRS. This signal can be expressed as in *equation (3)* [17];

$$y_n = \sqrt{P_t}\,\mathrm{g}_n^H\,\Phi\,\mathrm{H}_r\,\mathrm{f}_{\text{RF}}\,\mathrm{f}_{\text{BB}}\,s + n_k \qquad (3)$$

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Here, P_t is the transmit power, $\Phi \in \mathbb{C}^{M\times M}$ is the diagonal phase-shifter matrix. f_{RF} is the analog beamformer and f_{BB} is the digital beamformer. The term n_k represents additive noise for the n^{th} user. In a multicast system, the achievable rate for user n is given by *equation (4)*.

$$r_n = \log\left(1+\frac{P_t\,|\mathrm{g}_n^H\,\Phi\,\mathrm{H}_r\,\mathrm{f}_{\mathrm{RF}}\,\mathrm{f}_{\mathrm{BB}}|^2}{\sigma^2}\right) \tag{4}$$

Here, σ^2 is the noise power. Since the same message is multicast to all users, the multicast rate is defined as the minimum achievable rate among all users:

$$R = \min_{1\le n\le N} r_n \tag{5}$$

The goal is to maximize the multicast rate R. This is formulated as shown in *equation (6)*.

$$\begin{aligned} &\max_{\Phi,\mathrm{f}_{\mathrm{RF}},\mathrm{f}_{\mathrm{BB}}} \mathrm{R} \\ &\text{s.t.}\quad \|\mathrm{f}_{\mathrm{BB}}\,\mathrm{f}_{\mathrm{RF}}\| = 1, \\ &\qquad \|\mathrm{f}_{\mathrm{RF}}[i]\| = 1, \quad \forall i, \\ &\qquad |\Phi[m,m]| = 1, \quad \forall m. \end{aligned} \tag{6}$$

Here, the constraints include a power budget for the hybrid beamformer, phase constraints for the analog beamformer and IRS reflector adjustments [18, 19]. In the THz frequency range, channels often exhibit a property called angular orthogonality. In this system, the THz channel from the transmitter to each user includes a dominant LoS path. The direct LoS connection is blocked. So, the signal reaches each user by reflecting off the IRS. The channel response vector $\mathrm{a}_t(\theta_{az},\theta_{el})$ is influenced by the structure and orientation of the antenna array at the transmitter. Here, θ_{az} and θ_{el} represent the azimuth and elevation angles respectively. Since the NLoS paths have significantly higher path loss. These are often ignored in analysis. Including only the LoS path simplifies the channel model without major loss of accuracy. Let ϕ_m be the phase shift applied by the m^{th} element. All elements collectively form a phase-shift matrix Φ. This is diagonal with entries $\{\phi_1,\phi_2,\ldots,\phi_M\}$. The optimal design of this matrix enhances signal quality by aligning the reflected signals towards each user. The IRS phase control allows us to maximize the SNR for each user. In a multicast scenario, the goal is to optimize the IRS phase shifts to achieve the highest possible data rate across all users.

3. OPTIMAL BEAMFORMING DESIGN AND COMPLEXITY ANALYSIS

Analog Beamforming is process involves adjusting the phases at the antennas to steer the beam direction. The analog beamformer, denoted as f_{RF}, is applied at the transmitter and only controls the phase. Digital Beamforming is applied in the digital domain and allows more precise control of the transmitted signals. The digital beamformer f_{BB}, manages the amplitude and phase of each signal sent to different users. The hybrid beamforming design reduces power consumption and hardware complexity. In this IRS-aided system, a single RF chain at the transmitter is often sufficient and reducing costs. In large-scale MIMO systems, the concept of asymptotically optimal beamforming can help achieve the best possible data rates as the number of antennas increases. The optimal hybrid beamformer can be approximated as *equation (7)*.

$$\mathrm{f}_{\mathrm{Hybrid}} = \frac{\mathrm{h}^H}{\|\mathrm{h}\|} \approx \mathrm{a}_t(\theta_{r,az}^{(0)},\theta_{r,el}^{(0)}) \tag{7}$$

Here, h represents the combined channel response to all users, and a_t is the channel response vector for the LoS path between the transmitter and IRS. The optimal analog, digital and hybrid beamformer are respectively in *equation (8), (9)* and *(10)*.

$$\mathrm{f}_{\mathrm{RF}} = \mathrm{a}_t(\theta_{r,az}^{(0)},\theta_{r,el}^{(0)}) \tag{8}$$

$$\mathrm{f}_{\mathrm{BB}} = \sqrt{\frac{1}{\|\mathrm{f}_{\mathrm{RF}}\|}} \tag{9}$$

The structure of the reflecting beamformer Φ can be optimized using angular information. When the number of IRS elements M is very large, we can divide the elements across users. These creates virtual channels that maximize the signal power for each user. This leads to the following structure for the diagonal entries of Φ :

$$\mathrm{diag}(\Phi) = \left[\mathrm{a}_t(\theta_{1,az},\theta_{1,el})^H, \mathrm{a}_t(\theta_{2,az},\theta_{2,el})^H, \ldots, \mathrm{a}_t(\theta_{N,az},\theta_{N,el})^H\right] \tag{10}$$

Here, each $\mathrm{a}_t(\theta_{n,az},\theta_{n,el})^H$ is selected to direct the reflection toward user n. The specific azimuth and elevation angles are calculated to ensure minimal interference and maximum signal power for each user. The multicast rate optimization problem aims to find the best values for Φ, f_{RF} and f_{BB} to maximize the minimum rate across all users. This problem can be solved using iterative methods or optimization algorithms. One common approach to solve this is semi-definite relaxation (SDR). This transforms the non-convex problem into a convex one by relaxing certain constraints. However, SDR is computationally intensive Spectral efficiency.

Increasing transmit power improves spectral efficiency but may be limited by hardware constraints and interference. Number of Antennas and Reflectors are Higher antenna and reflector counts generally improve spectral efficiency by providing more spatial gain. The following equation models the spectral efficiency for user n:

$$\eta_n = \log_2\left(1+\frac{P_t\,|\mathrm{g}_n^H\,\mathrm{F}\mathrm{H}_r\,\mathrm{f}_{\mathrm{RF}}\,\mathrm{f}_{\mathrm{BB}}|^2}{\sigma^2}\right) \tag{11}$$

Here, η_n represents the spectral efficiency for user *n* and the overall system efficiency increases with the number of elements in Φ .

3.1 Computational Complexity

The asymptotic design simplifies the computational complexity compared to conventional methods. The complexity of obtaining the hybrid transmitter beamformers $\mathrm{f_{RF}}$ and $\mathrm{f_{BB}}$ is $O(N_t)$. Hence, the complexity of calculating the IRS beamformer Φ is $O(N+M)$. The overall complexity is therefore $O(N+N_t+M)$. This complexity is significantly lower than that of conventional methods like SDR. This is often involving high computational costs. In an IRS-aided THz system, the multicast rate is optimized when all users achieve approximately the same SNR. This condition can be expressed in *equation (12)*.

$$r_n = r_{n'} \quad \forall n, n' \in \{1, 2, \ldots, N\} \tag{12}$$

Here, r_n is the achievable rate for user *n*. By balancing the SNR across all users, the multicast rate is maximized that the overall performance of the system. This is remains high even for the user with the weakest channel. To satisfy this equal-SNR constraint, we can solve a set of equations for the IRS reflecting beamformer. This leads to a solution for the reflecting beamformer that maximizes the multicast rate:

$$m_i = m_{i-1} + \sqrt{\frac{1}{\eta \cdot \alpha_i \alpha_i^H}}\; n \tag{13}$$

Here, m_i represents the number of IRS elements allocated to each user, and η is an auxiliary parameter derived from the total number of IRS elements *M*.

4. RESULTS AND DISCUSSION

The simulation parameters are presented in *table (1)*.

Table 1. Simulation Parameters

Description	Symbol	Value
Noise power	σ^2	1
Carrier frequency	f	100 – 300 GHz
Transmit power	P_t	0 – 40 dBm
Distance between nodes	d	1 – 30 meters
Speed of light	c	3×10^8 m/s
Number of transmit antennas	N_t	100 – 500
Number of IRS elements	M	100 – 1000

Figure (2) illustrates path loss as a function of distance for both LoS and NLoS components. The LoS path loss decreases from -70 dB at 0 meters to -95 dB at 30 meters. The NLoS path loss starts at -100 dB. It declines steeply to -130 dB over the same distance. Path loss is given by *equation (2)*.

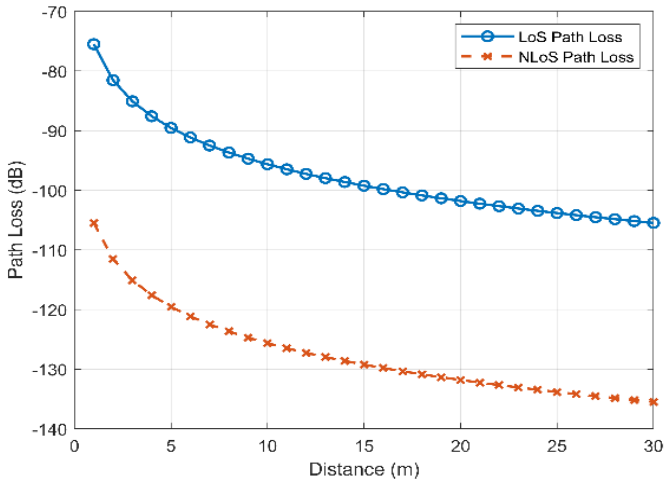

Figure 2. Path loss versus distance for both LoS and NLoS components

Figure (3) examines how SNR varies with the transmit power P_t. In this analysis, the SNR is directly proportional to the transmit power. This helps to increasing P_t linearly enhances the SNR on a dB scale. Additionally, the SNR increases with the number of IRS elements *M*. Hence, more elements allow for improved control over signal reflections and focusing the signal more effectively towards each user. For lower transmit power levels, the impact of the IRS element count is less significant. But P_t increases, the benefit of a larger *M* becomes more evident. This trend highlights the importance of both sufficient transmit power and a large IRS element count in achieving high SNR. This is crucial for effective communication in a THz-MIMO system. The *figure (3)* shows that SNR improves linearly as transmit power increases from 0 to 40 dBm for all values of M. Higher values of (M = 1000) consistently achieve better SNR compared to lower values (M = 300), with a clear gap between the curves.

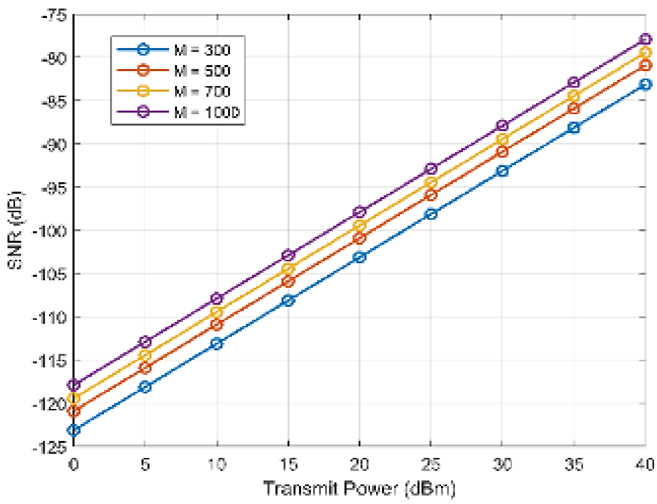

Figure 3. Transmit power versus SNR for different IRS elements

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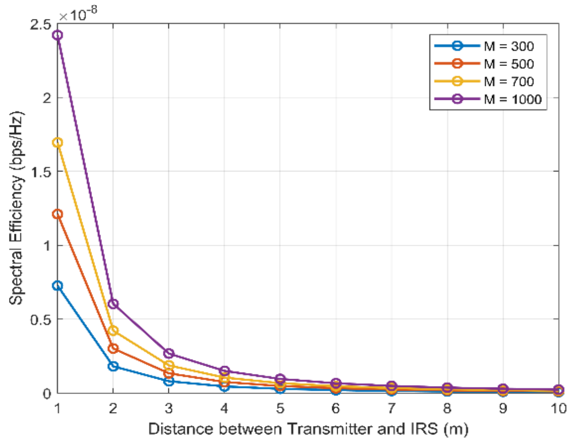
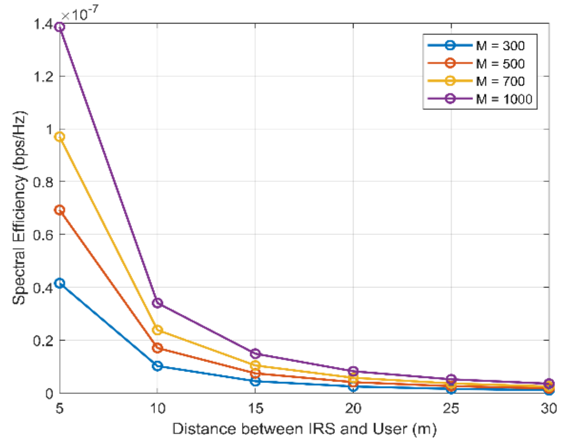
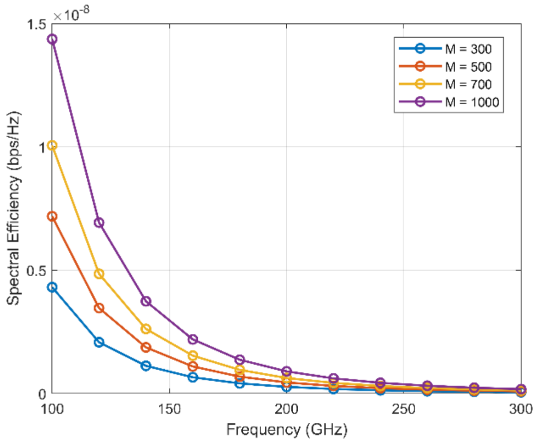


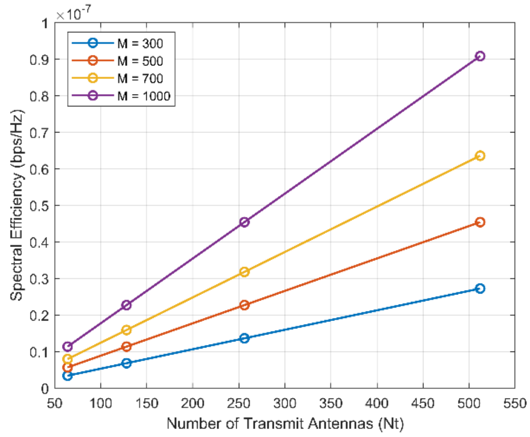
(a) Distance between Tranmisster amd IRS



(b) Distance between IRS and user



(c) Frequency



(c) Number of Transmit Antennas

Figure 4. Analysis of spectral efficiency for different IRS elements (a) Distance between Transmitter and IRS versus Spectral Efficiency; (b) Distance between IRS and user versus Spectral Efficiency Interchange figures 4(c) and 4(d); (c) Number of Transmit Antennas versus Spectral Efficiency; and (d) Frequency versus Spectral Efficiency

From the *figure 4(a)* it is observed that spectral efficiency decreases sharply as the distance between the transmitter and IRS increases from 1 to 10 meters. Higher values of (M = 1000) consistently provide better efficiency but the impact diminishes beyond 5 meters.

Figure 4(b) explores the impact of the distance ($d_{\text{IRS-user}}$) between the IRS and the user on spectral efficiency. According to *equation (11)*, spectral efficiency depends on the path loss $L_{\text{IRS-user}}$ from the IRS to the user. With greater distance, path loss decreases that results in reduction in spectral efficiency. This reduction occurs because the received signal power decreases as the distance between the IRS and the user increases. This analysis highlights the importance of strategically placing the IRS closer to the users to maximize spectral efficiency. It is observed that from the *figure 4(b),* the spectral efficiency drops significantly as the distance between IRS and the user increases from 5 to 30 meters. Larger M values maintain higher efficiency levels compared to smaller M, but the difference reduces at greater distances. The spectral efficiency η as a function of the number of transmit antennas N_t is presented in *figure 4(c). Equation (11)* shows that spectral efficiency is proportional to both the received signal power and the spatial diversity offered by the antenna array. As N_t increases, the transmitter can focus more power towards the IRS. It improves the overall received signal strength and consequently enhancing spectral efficiency. The impact shows diminishing returns beyond a certain number of antennas. However, in the context of high-frequency, large-scale antenna systems, maintaining a high N_t remains essential for achieving robust performance in multi-user scenarios. It is concluded that from *figure 4(c)*, Spectral efficiency improves linearly as the number of transmit antennas increases from 100 to 500. Higher *M* values achieve greater efficiency, with M = 1000 shows the steepest improvement. *Figure 4(d)* depicts spectral efficiency across a range of frequencies in the THz band. *Equations (11)* shows spectral efficiency is inversely related to path loss. It degrades with increasing frequency due to molecular absorption in the THz range. The path loss $L(f,d)$ in *equation (2)* increases as frequency *f* rises. *Figure 4(d)* shows that the spectral efficiency decreases rapidly as frequency increases from 100 GHz to 300 GHz. Systems with higher values (M = 1000) achieve better efficiency significantly at lower frequencies. *Figure 5* shows the achievable rate *R* as a function of the number of IRS elements. It is derived in *equation (4)*. As *M* increases, the achievable rate improves logarithmically. This is due to the enhanced signal focusing capability provided by additional IRS elements. A higher *M* value enables the IRS to redirect more power towards the users.

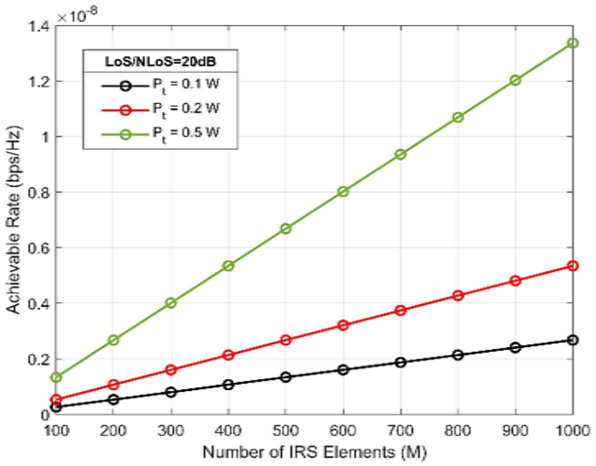


Figure 5. Analysis of achievable rate for different IRS elements and Path losses

5. CONCLUSION

This paper shows that IRS-aided THz-MIMO systems can improve 6G network performance. They help reduce the high path loss and sensitivity to blockages in the THz band. The results show that placing the IRS 2–5 meters from the transmitter increases spectral efficiency by lowering path loss. Using larger IRS setups with around 500 or more elements gives big gains in SNR and data rates. For each 100 extra IRS elements up to 700 the data rates improve by 20–30%. After 700 elements, the gains are smaller that shows that need for a balanced IRS size. Lastly, using lower THz frequencies helps maintain high spectral efficiency by reducing losses from molecular absorption.

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