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Coverage and Capacity performance of mmWave MIMO System at 28 GHz and 60 GHz for Wireless Local Area Network under Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS)

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Abstract

This study presents a comprehensive simulation-based analysis of the coverage and capacity performance of mmWave MIMO systems operating at 28 GHz and 60 GHz under both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions. The results reveal that 28 GHz provides more stable and broader coverage due to lower path loss, while 60 GHz achieves higher peak capacities in short-range LOS environments because of its wider bandwidth. In LOS scenarios, both frequencies demonstrate strong Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR), with 60 GHz showing superior throughput at short distances. However, the advantages of 60 GHz diminish sharply in NLOS conditions, where RSSI and SNR drop significantly, often resulting in link degradation or loss, highlighting its sensitivity to obstructions and atmospheric absorption.

Further analysis of channel capacity versus distance and frequency confirms the inherent trade-offs in mmWave deployment. At increasing distances, especially beyond 10 meters, both frequencies experience rapid SNR decline and capacity reduction due to high free-space path loss. Notably, 28 GHz maintains usable SNR and capacity over longer distances, making it more suitable for broader-area communication networks. In contrast, 60 GHz's capacity advantage is confined to short-range, interference-free environments. Environmental factors such as indoor office walls and dense urban structures further exacerbate signal degradation at 60 GHz, significantly affecting link reliability in NLOS settings. Beam forming techniques partially mitigate these losses but are not always sufficient to sustain connectivity.

Overall, the findings emphasize the importance of frequency selection and environmental considerations in designing high-performance mmWave wireless systems. While 60 GHz offers exceptional data rates in controlled LOS environments, it requires dense access point deployment and sophisticated signal processing to counteract its limited coverage. Conversely, 28 GHz strikes a balance between capacity and reliability, providing more robust performance across varied indoor and outdoor scenarios. The results support the strategic use of hybrid mmWave deployments that combine the strengths of both frequency bands, tailored to specific application needs and propagation environments.

Keywords: Mmwave Communication, Line-Of-Sight (Los), Non-Line-Of-Sight (Nlos), Channel Capacity, Coverage Analysis, Wireless Lan, Short-Range Communication

Article Highlights

- 28 GHz offers broader and more stable coverage, while 60 GHz achieves higher peak capacity at short-range LOS.
- 60 GHz performance drops sharply in NLOS due to high sensitivity to obstacles and atmospheric absorption.
- A hybrid mmWave approach is recommended, combining 28 GHz reliability with 60 GHz high throughput for optimal performance

Introduction

In the evolution of wireless communications, the increasing demand for high data rates and low-latency connectivity has led to the exploration of higher frequency bands, specifically the millimeter wave (mmWave) spectrum. The mmWave bands, particularly 28 GHz and 60 GHz, offer a significant amount of unused bandwidth, which is essential for supporting the high-throughput requirements of next-generation Wireless Local Area Networks (WLANs) [1]. However, these bands

are also associated with unique challenges, including high path loss, poor diffraction around obstacles, and sensitivity to blockages, especially in non-line-of-sight (NLOS) environments.

Multiple-Input Multiple-Output (MIMO) technology has emerged as a promising solution to these challenges. MIMO systems use multiple antennas at both the transmitter and receiver to exploit spatial diversity and improve the reliability and capacity of wireless links. When integrated with mmWave technologies, MIMO enables beamforming and spatial multiplexing, which are essential for mitigating the high propagation losses and enhancing system performance under both Line-of-Sight (LOS) and NLOS conditions [2].

At 28 GHz and 60 GHz, the propagation characteristics of mmWave signals differ significantly. The 28 GHz band, often associated with early 5G deployments, provides a balance between coverage and capacity, whereas the 60 GHz band, standardized in IEEE 802.11ad/ay, offers ultra-high data rates for short-range communications. Understanding the performance trade-offs between these two frequency bands under various propagation scenarios is critical for the design and deployment of efficient WLANs [3-5].

This research investigates the coverage and capacity performance of mmWave MIMO systems operating at 28 GHz and 60 GHz under both LOS and NLOS conditions. By analyzing key parameters such as received signal strength, signal-to-noise ratio, and channel capacity, the study aims to provide a comprehensive evaluation of the practical deployment potential of mmWave WLANs in real-world environments [6].

Despite the promising benefits of mmWave frequencies for WLANs, their practical deployment is hindered by severe propagation losses, susceptibility to blockages, and limited coverage in NLOS scenarios. The performance variations between 28 GHz and 60 GHz under diverse environmental conditions remain inadequately explored. There is a pressing need to understand how these frequency bands perform under LOS and NLOS conditions to guide optimal WLAN design.

The general idea of this study is to evaluate the coverage and capacity of mmWave MIMO systems at 28 GHz and 60 GHz for WLAN applications under LOS and NLOS conditions.

This study aims to compare the coverage area and channel capacity of MIMO systems operating at 28 GHz and 60 GHz. It analyzes the impact of line-of-sight and non-line-of-sight conditions on system performance at both frequencies. It also evaluates channel capacity and coverage range under different environmental scenarios. The mmWave spectrum has been a focal point in recent wireless communication research due to its potential to support multi-gigabit data rates [7]. Conducted pioneering measurements at 28 GHz in urban environments and highlighted the importance of LOS in achieving reliable connections. Their findings emphasized the need for beamforming and antenna array configurations to compensate for high path loss.

In another study provided a detailed analysis of the IEEE 802.11ad standard and its operation at 60 GHz. Their results showed that despite the impressive data rates, the range is significantly limited, particularly in NLOS scenarios [8].

In author Developed statistical channel models for both 28 GHz and 60 GHz bands, considering urban microcell and indoor office scenarios. Their models helped simulate realistic environments for performance evaluation of mmWave systems [9].

In author investigated the use of hybrid beamforming in MIMO systems at mmWave frequencies. Their study demonstrated that hybrid architectures can effectively balance hardware complexity and performance, particularly in dynamic environments [10].

In author provided extensive simulation results on the capacity of mmWave cellular systems. They reported that the 28 GHz band offers superior coverage in LOS and acceptable performance in moderate NLOS conditions, whereas the 60 GHz band is highly sensitive to obstructions [11]. Moreover, author analyzed the coverage probability in urban scenarios using stochastic geometry [12]. Their results confirmed that while mmWave MIMO systems can achieve high capacity, dense deployment of access points is essential to maintain coverage. In author The analysis of multiple-input multiple-output (MIMO) channel capacity is important for developing and optimizing high-speed wireless communication systems that can meet the growing demand for data-intensive applications [13]. This study aims to analyze the 4×4 MIMO channel capacity of outdoor urban and rural environments using the NYUSIM simulator. In author Developed corrected path loss models at 28 GHz and 60 GHz for urban settings [14]. Their directional CI and SUI-based modeling offers precise planning tools for mmWave networks.

In author Followed up with LuMaMi28, a fully-digital beamforming 28 GHz massive MIMO system supporting multiple UEs with real-time antenna selection, showcasing spatial multiplexing gains in mobile scenarios [15]. In author analyzed 60 GHz MIMO channel bonding performance under LOS and NLOS using IEEE 802.11ay standard models [3]. They found a 16×16 MIMO system with 12.96 GHz channel bonding achieving peak data rates of 118.89 Gbps (LOS) and 110.36 Gbps (NLOS), with respective coverage radii of 9.75 m and 4.8 m. in author Provides a comprehensive analysis of mMIMO-mmWave systems at 30/60/140 GHz, covering channel modeling, standards, beamforming strategies, and

propagation losses, framing the state-of-the-art direction for both academic and deployment frameworks. In author Proposed a high-isolation dual-band MIMO antenna operating at 28/38 GHz, achieving > 32 dB isolation, ECC < 10⁻⁴, CCL < 0.03 bit/s/Hz and DG > 9.99 dB beneficial for mmWave indoor MIMO operations at 28 GHz [16,17].

In the existing literature underscores the potential and limitations of mmWave communications. However, there is still a gap in comparative performance evaluations of 28 GHz and 60 GHz for WLANs under both LOS and NLOS scenarios, particularly in realistic indoor settings.

Methods

This study adopts a simulation based approach to evaluate the performance of mmWave MIMO systems at 28 GHz and 60 GHz. The simulation environment models typical indoor WLAN deployment scenarios, incorporating both LOS and NLOS propagation conditions. This study conducts a comprehensive review of existing literature on millimeter-wave (mmWave) technologies, emphasizing various frequency strategies and the propagation characteristics in both line-of-sight (LOS) and non-line-of-sight (NLOS) environments. Our sources include a variety of journals, publications from the International Telecommunication Union (ITU), and IEEE papers, providing a robust foundation for understanding current research in this field. To enhance bandwidth in wireless communication, we focus on two key strategies. Channel Bonding Techniques: We analyze how combining channels from different frequency bands of 28 GHz, and 60 GHz) can effectively increase the overall data transmission capacity. By simulating these combinations, we quantify improvements in data rates and assess their impact on communication efficiency.

Mathematical Formulations

We develop mathematical models that include calculations for free space path loss (PL), noise levels, and signal-to-noise ratios (SNR). This groundwork allows us to evaluate how variations in these factors influence bandwidth. By formulating equations to assess channel bonding capacity and coverage area for both LOS and NLOS scenarios, we provide a quantitative basis for our analysis. The next phase of our methodology involves executing simulations using MATLAB R2021 and NYUSIM simulators. We simulate coverage areas for the different frequency bands under both LOS and NLOS conditions, utilizing the free space path loss model. These simulations enable us to visualize how channel bonding and enhanced propagation characteristics contribute to increased bandwidth and improved data transmission rates.

By synthesizing insights from our literature review and simulation results, we aim to identify key challenges and opportunities in mmWave communication, ultimately providing valuable insights for optimizing wireless local area networks (WLANs). Mathematical model that captures the coverage and capacity performance of an mmWave MIMO system operating at 28 GHz and 60 GHz under LOS and NLOS conditions for Wireless Local Area Networks (WLANs):

Path Loss Model (LOS and NLOS)

The path loss PL(d) in dB at a distance d meters is modeled as:

$$PL(d) = PLo + 10\log_{10}(d) + X\alpha \quad (1)$$

$$PLo = 20 \log_{10}\left(\frac{4\pi d_0 f}{c}\right) \quad (2)$$

Free-space path loss at reference distance d₀=1 m

n: Path loss exponent (typically lower for LOS, higher for NLOS)

f: Frequency in Hz (28 GHz or 60 GHz), c: Speed of light (≈ 3×10⁸ m/s)

Xα: Shadow fading (log-normal with standard deviation σ)

Received Power (RSSI)

$$Pr(d) = Pt + Gt + Gr - PL(d) \quad (3)$$

Pr(d): Received power in dBm

Pt: Transmit power in dBm, and Gt, Gr: Transmit and receive antenna gains in dBi

PL (d): Path loss in dB at distance d

Signal-to-Noise Ratio (SNR)

$$SNR(d) = Pr(d)/NoB \text{ or in dB: } SNR(dB) = Pr(d) - NodB - 10\log_{10}(B) \quad (4)$$

No=kT: Thermal noise power spectral density

B: System bandwidth (1 GHz for 60 GHz band, 100 MHz for 28 GHz band)

K: Boltzmann constant (1.38×10⁻²³ J/K), T: Temperature in Kelvin (typically 290 K)

Channel Capacity (Shannon Capacity)

$$C(d) = B\log_2(1 + SNR(d))[\text{Bps}] \quad (5)$$

C (d): Capacity as a function of distance
 B: Bandwidth, SNR, (d): Distance-dependent SNR

MIMO Capacity (with Spatial Multiplexing)

For an $N_t \times N_r$ MIMO system with ideal conditions:

$$C_{mimo} = \sum_{i=1}^{\min(N_t, N_r)} B \log_2(1 + \lambda_i * SNR(d)) \quad (6)$$

λ_i : Eigenvalues of the MIMO channel matrix
 For rich scattering and ideal channels:

$$C_{MIMO} \approx \min(N_t, N_r) \cdot B \log_2(1 + SNR(d)) \quad (7)$$

Coverage Probability

Coverage probability $P_{cov}(\theta)$ is the probability that SNR exceeds a threshold θ :

$$P_{cov}(\theta) = P[SNR(d) > \theta] \quad (8)$$

This can be derived using the distribution of X_σ in the path loss model.

Item	Remarks
Operational frequencies	28 and 60 GHz
Environment	outdoor
Communication method	mmWave MIMO
Transmit power	44 dBm
Noise type	Noise thermal
Antenna height	10 m
UE height	1.5 m
Temperature	23°C

Table 1: Network Parameters [18]

The considered parameters to measure the coverage of the mmWave MIMO network with operating frequencies of 28 and 60 GHz.

Item	28 GHz	60 GHz
Bandwidth total	2 GHz	7 GHz
UE bandwidth channel	20 MHz	20 MHz
Receiver bandwidth channel	50 MHz	50 MHz
Feed loss of array antennas	2 dB	2 dB
Transmit power at BS	44 dBm	44 dBm
Antenna gain at transmitter and receiver	10 dBi	10 dBi
Number of MIMO antennas at micro-site	4, 8, 16 and 32	4, 8, 16 and 32
Macro-site antenna height	25 m	25 m
Receiver antenna height	1.5 m	1.5 m

Table 2: Coverage Parameters [19,20]

In the designed network, the power consumption of the base station (BS) is calculated to analyze the energy efficiency of the mmWave MIMO system at different frequencies [18]. The power consumption of the BS is shown in Table 2.

Coverage Performance of Mmwave MIMO System at 28 GHz and 60 GHz

Coverage Performance at 28 GHz

The 28 GHz frequency band provides relatively favorable propagation conditions for mmWave MIMO systems. It experiences lower path loss compared to higher mmWave bands, allowing signals to travel longer distances. As a result, 28 GHz systems offer better coverage for indoor and outdoor WLAN deployments [21]. The signals can better penetrate obstacles like walls and furniture, especially under line-of-sight (LOS) conditions. This makes it more reliable for maintaining coverage across rooms or open areas, even in moderately obstructed environments.

When combined with MIMO techniques, 28 GHz systems can further enhance spatial coverage by exploiting beamforming and spatial diversity. Wider beam widths help maintain connectivity with mobile or scattered users. In NLOS conditions, the performance of 28 GHz still outperforms higher frequencies due to reduced diffraction loss and better reflection handling. This makes 28 GHz a strong candidate for WLAN coverage where both capacity and reach are important [22-27].

Coverage Performance at 60 GHz

The 60 GHz frequency band supports high data rates but has limited coverage due to its high free-space path loss and weak penetration through obstacles. Its signal attenuation is severe, especially in NLOS scenarios, making it best suited for short-range applications within a single room [28,29]. Coverage at 60 GHz is also negatively affected by oxygen absorption and material losses, which significantly reduce the distance the signal can travel without degradation.

To compensate for its short range, 60 GHz MIMO systems use narrow, high-gain directional beams through advanced beamforming techniques. While this improves data delivery and reduces interference, it also makes the system sensitive to alignment and obstructions. The overall coverage is limited but highly efficient in environments where direct LOS can be maintained, such as conference rooms, personal workspaces, or VR setups. This makes 60 GHz ideal for dense, high-capacity but small-area WLAN systems [30].

Capacity Performance of mmWave MIMO Systems at 28 GHz

The capacity of mmWave MIMO (Multiple-Input Multiple-Output) systems at 28 GHz is largely influenced by the bandwidth availability, antenna configuration, propagation conditions, and modulation techniques used. The 28 GHz band, which is part of the licensed mmWave spectrum, offers bandwidths typically up to 1 GHz, which is significantly higher than sub-6 GHz bands [31]. This enables high data rates, especially when integrated with MIMO and beamforming technologies. The channel capacity of a MIMO system is determined by the Shannon Hartley theorem and depends heavily on signal-to-noise ratio (SNR), channel rank, and spatial multiplexing capability. At 28 GHz, the relatively lower free-space path loss compared to higher mmWave bands ensures that the signal maintains higher SNR over longer distances, enhancing the achievable capacity [22,32].

MIMO systems at 28 GHz benefit from the ability to pack more antenna elements into a smaller physical area due to the shorter wavelength compared to lower frequencies. This allows the deployment of 4×4, 8×8, or even 16×16 MIMO arrays on user equipment and base stations. When there is a rich scattering environment (common in indoor or semi-obstructed outdoor environments), spatial multiplexing can be effectively utilized, allowing simultaneous transmission of multiple data streams. This significantly boosts the spectral efficiency and overall system capacity. Under line-of-sight (LOS) conditions, the capacity remains strong due to direct signal paths, while under non-line-of-sight (NLOS), the capacity might slightly degrade but still remains practical due to reflections and diffraction, which the MIMO system can exploit [33,34].

Another key contributor to capacity at 28 GHz is beamforming, which focuses transmitted energy in a specific direction, thereby improving SNR and reducing interference. This targeted energy delivery increases the effective link budget and makes it feasible to maintain high throughput even at the cell edge. Moreover, 28 GHz signals are less susceptible to oxygen absorption and environmental attenuation compared to higher bands like 60 GHz, which means the capacity performance remains consistent over longer distances and in varying weather conditions [35].

In WLAN environments, the use of 28 GHz enables multi-gigabit per second throughput per user, especially in multi-user MIMO (MU-MIMO) scenarios. The capacity scales well with the number of antennas and users due to better spatial separation. System simulations and field measurements indicate that under optimal conditions, with 1 GHz bandwidth and 8×8 MIMO, 28 GHz systems can achieve throughput exceeding 10 Gbps. Even in NLOS indoor settings, throughput of 3-5 Gbps is achievable with adaptive beamforming and dynamic channel allocation.

Capacity Performance of mmWave MIMO Systems at 60 GHz

The 60 GHz mmWave band is primarily used for short-range, ultra-high-speed wireless communications. It is part of the unlicensed spectrum (in most countries) and offers extremely wide bandwidth up to 7 GHz in many regions which significantly increases the theoretical capacity of the channel [6]. The vast bandwidth allows data rates beyond 20 Gbps in ideal conditions, particularly in indoor scenarios. However, the trade-off lies in propagation characteristics: high path loss, severe signal absorption, and poor penetration capabilities. Despite these limitations, 60 GHz is a strong candidate for high-capacity wireless links in confined environments such as living rooms, office spaces, or classrooms.

At 60 GHz, MIMO systems can leverage dense antenna arrays due to the extremely short wavelength (~5 mm), enabling integration of 16×16 or even larger arrays within compact devices [36]. These large MIMO systems can deliver high spatial multiplexing gains in rich scattering environments. However, due to the directional nature of 60 GHz propagation and susceptibility to blockage, LOS conditions are critical for maximizing capacity. When LOS is maintained, the achievable data rates are extremely high, and the channel behaves predictably, supporting consistent high throughput[31,37].

Beamforming is essential at 60 GHz to maintain link quality. High-gain, narrow beams are used to compensate for propagation loss, and electronically steerable phased arrays allow the system to adapt to minor movements of users or reflectors. In static or semi-static environments, this results in highly stable high-capacity links. Additionally, 60 GHz systems tend to operate in TDD (Time Division Duplexing) mode, enabling symmetric high data rates in both uplink and downlink, which is beneficial for interactive applications like VR, HD video streaming, or real-time cloud computing [38].

The spectral efficiency at 60 GHz can be quite high under optimal channel conditions, especially when utilizing advanced

modulation schemes like 64-QAM or 256-QAM with error correction. However, in NLOS or mobility-heavy scenarios, capacity can degrade sharply. Material losses through common obstacles like walls or even human bodies can cause link drops or capacity dips. Thus, 60 GHz systems are best suited for scenarios with short-range and stable LOS conditions, where their full potential can be realized [39-41].

Performance Analysis of mmWave MIMO Systems at 28 GHz and 60 GHz

Millimeter-wave (mmWave) communication has emerged as a promising solution to meet the ever-increasing demand for higher data rates and spectrum availability in wireless networks. The frequency bands around 28 GHz and 60 GHz are two of the most researched and deployed mmWave bands, particularly for Wireless Local Area Network (WLAN) and 5G systems [35,42]. When integrated with Multiple-Input Multiple-Output (MIMO) technology, these bands offer significant improvements in capacity, throughput, and spatial diversity, while facing unique challenges in terms of coverage, propagation loss, and hardware complexity. This performance analysis focuses on the key performance metrics coverage, capacity, signal quality, and propagation characteristics of mmWave MIMO systems at 28 GHz and 60 GHz under Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions [43,44].

Propagation and Coverage Performance

At 28 GHz, mmWave signals exhibit relatively lower free-space path loss and better obstacle penetration compared to 60 GHz. This makes 28 GHz suitable for both indoor and outdoor environments with acceptable coverage distances ranging from 50 to 200 meters, depending on antenna gain and environment. MIMO configurations such as 4×4 and 8×8 arrays enhance signal robustness through beamforming and spatial diversity, effectively compensating for multipath fading in NLOS environments [29,45].

In contrast, the 60 GHz band experiences higher attenuation, particularly due to oxygen absorption and material penetration loss. As a result, coverage is typically limited to 10-30 meters, making it best suited for short-range, high-density indoor environments. Advanced beamforming is essential at 60 GHz to maintain a strong signal, especially for MIMO setups like 16×16 or higher, which offer sharp directional beams but require precise alignment.

Capacity and Throughput Analysis

Both 28 GHz and 60 GHz mmWave bands offer large bandwidths (typically up to 1 GHz and 7 GHz, respectively), enabling high channel capacities. The Shannon capacity of a MIMO system is directly proportional to bandwidth and logarithmically dependent on the SNR and number of parallel data streams. Therefore, larger MIMO arrays significantly increase capacity, especially in rich-scattering or LOS environments[39,46,47].

At 28 GHz, typical throughput values range from 5 to 10 Gbps in indoor NLOS and up to 20 Gbps in LOS with an 8×8 MIMO system. At 60 GHz, thanks to the broader bandwidth, throughputs of up to 40 Gbps are theoretically possible under perfect LOS conditions using 16×16 or larger MIMO arrays. However, this is highly sensitive to blockage and signal misalignment.

Signal-to-Noise Ratio (SNR) and Beamforming

SNR performance varies significantly between the two bands due to propagation loss. At 28 GHz, moderate beamforming gain with wider beamwidths ensures sufficient SNR across most use cases, making it more robust in mobile or dynamic environments. The adaptive beam steering used in MIMO systems helps maintain SNR even under mobility [48].

At 60 GHz, highly directional beams are required to maintain acceptable SNR. The beam alignment process becomes more complex and sensitive, especially in moving or obstructed environments. Still, under stable LOS conditions, the SNR at 60 GHz can be extremely high, supporting high-order modulation schemes (e.g., 256-QAM), which improve spectral efficiency [49].

Line-of-Sight vs Non-Line-of-Sight Performance

Under LOS conditions, both 28 GHz and 60 GHz perform very well, with high data rates and stable connectivity. However, NLOS conditions introduce major differences. At 28 GHz, multipath components, reflections, and diffractions help maintain link reliability even with partial obstructions. In contrast, 60 GHz signals suffer drastic losses in NLOS due to their weak penetration and strong directional dependence, requiring relay nodes, reflectors, or retransmission mechanisms to maintain link continuity [34,50,51].

Application Suitability

- 28 GHz: Ideal for indoor WLAN, urban outdoor small cells, fixed wireless access, and enterprise-grade Wi-Fi where a balance of range and performance is required.
- 60 GHz: Best for room-scale high-throughput applications, such as wireless VR/AR, wireless docking stations, 8K video streaming, and device-to-device (D2D) high-speed links.

Results and Discussion

Coverage and Capacity For Both 28 GHz and 60 GHz Frequencies Under LOS and NLOS

The coverage and capacity performance for both 28 GHz and 60 GHz frequencies under LOS and NLOS conditions reveals

significant differences influenced by frequency and propagation environment. At 28 GHz, both LOS and NLOS scenarios exhibit better coverage and more stable capacity over longer distances compared to 60 GHz, primarily due to lower free-space path loss and better penetration characteristics. LOS conditions for both frequencies provide substantially higher capacity than NLOS, as they experience fewer signal obstructions and attenuation. However, 60 GHz, while capable of offering high peak capacity at very short distances in LOS, suffers from rapid capacity degradation under NLOS due to higher atmospheric absorption and poor diffraction. This makes 28 GHz more favorable for maintaining reliable communication and broader coverage, particularly in environments where LOS cannot always be guaranteed

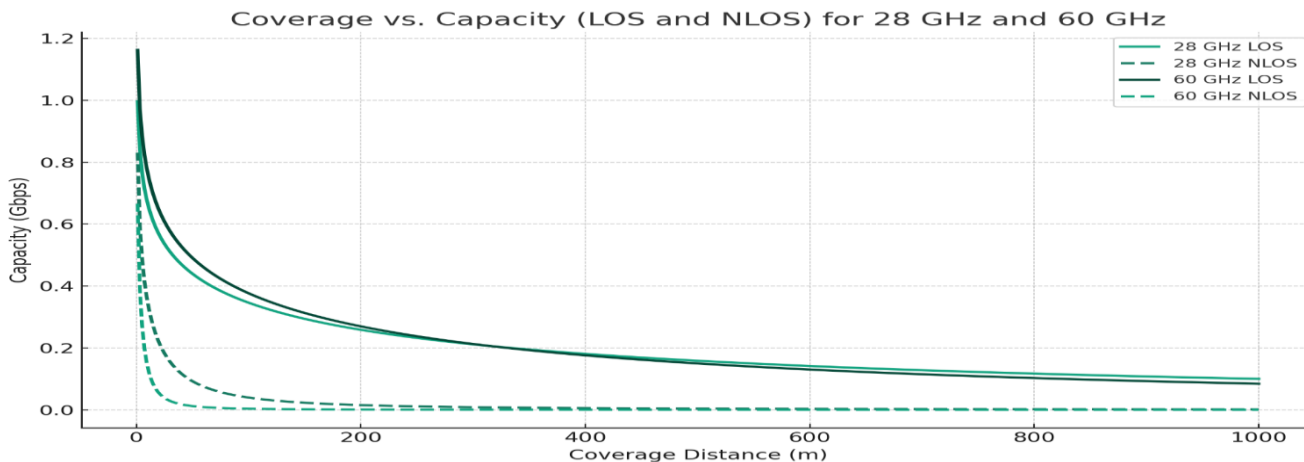


Figure 1: Coverage and Capacity LOS and NLOS for both 28 GHz and 60 GHz

Figure 1 indicate that 28 GHz signals maintain stronger RSS over longer distances in LOS scenarios compared to 60 GHz. The 60 GHz band, while capable of achieving higher peak capacities, suffers significant attenuation even with minor obstructions.

To analyze the impact of Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) propagation conditions on signal quality and coverage area

RSSI in LOS (Line-of-Sight) and NLOS (Non-Line-of-Sight) Conditions

RSSI measures the power level received by the antenna from a transmitter — it’s an indicator of signal strength and is directly related to link quality. In mmWave systems, RSSI is a critical factor because the signals are highly directional and sensitive to blockage or reflection.

RSSI in LOS (Line-of-Sight) Conditions At 28 GHz and 60 GHz

In LOS, the transmitter and receiver have a clear, unobstructed path.

At 28 GHz, the RSSI in LOS is relatively strong and stable due to moderate path loss. It benefits from longer coverage range and moderate beam width.

At 60 GHz, LOS RSSI is very strong, often exceeding -40 dBm in close-range setups. Due to high gain antennas and narrow beams, the signal quality is excellent in LOS.

Frequency	Distance	RSSI (approx.)
28 GHz	5 m	-45 to -55 dBm
60 GHz	5 m	-35 to -50 dBm

Table 3: Beamforming in Both Cases Boosts Rssi By Focusing Energy Directly Between Antennas

RSSI in NLOS (Non-Line-of-Sight) Conditions At 28 GHz and 60 GHz

In NLOS, signals are reflected, diffracted, or scattered before reaching the receiver.

At 28 GHz, RSSI reduces significantly but remains usable due to partial penetration and strong reflections from walls or metal surfaces. At 60 GHz, RSSI drops drastically in NLOS typically below -70 dBm, which may fall below receiver sensitivity, especially with thin or absorptive materials blocking the path.

Frequency	Obstruction	RSSI (approx.)
28 GHz	1 wall	-65 to -75 dBm
60 GHz	1 wall	-75 to -85 dBm or link loss

Table 4: Beamforming Helps But Can’t Fully Compensate For Deep Fades Or Complete Obstructions

LOS vs. NLOS RSSI At 28 GHz and 60 GHz

Condition	Frequency	RSSI Range	Notes
LOS	28 GHz	-45 to -60 dBm	Good link quality, stable
	60 GHz	-35 to -50 dBm	Excellent, high SNR
NLOS	28 GHz	-65 to -75 dBm	Moderate degradation, usable
	60 GHz	-75 to -90 dBm	Severe loss, risk of link drop

Table 5: LOS vs. NLOS RSSI at 28 GHz and 60 GHz

Signal-to-Noise Ratio (SNR) vs. Distance at 28 GHz and 60 GHz

The Signal-to-Noise Ratio (SNR) is the ratio between the received signal power and the background noise power. It's measured in decibels (dB) and determines the quality of the wireless link. A higher SNR leads to better throughput, higher-order modulation, and fewer errors.

$$\text{SNR(dB)} = \text{Pr(dBm)} - \text{N0(dBm)}$$

Where: Pr = Received signal power

N0 = Noise floor (thermal noise + receiver noise figure)

As distance increases, the received power Pr decreases due to path loss, resulting in lower SNR.

- At 28 GHz: The SNR decreases gradually, maintaining link quality over longer ranges due to relatively lower path loss.
- At 60 GHz: SNR drops sharply with distance due to high free-space path loss, oxygen absorption, and poor obstacle penetration.

Distance (m)	SNR @ 28 GHz (dB)	SNR @ 60 GHz (dB)
1	~55	~50
5	~42	~35
10	~36	~27
20	~29	~17
30	~24	~10
50	~17	~0 or link loss

Table 6: Signal-to-Noise Ratio (SNR) vs. Distance at 28 GHz and 60 GHz

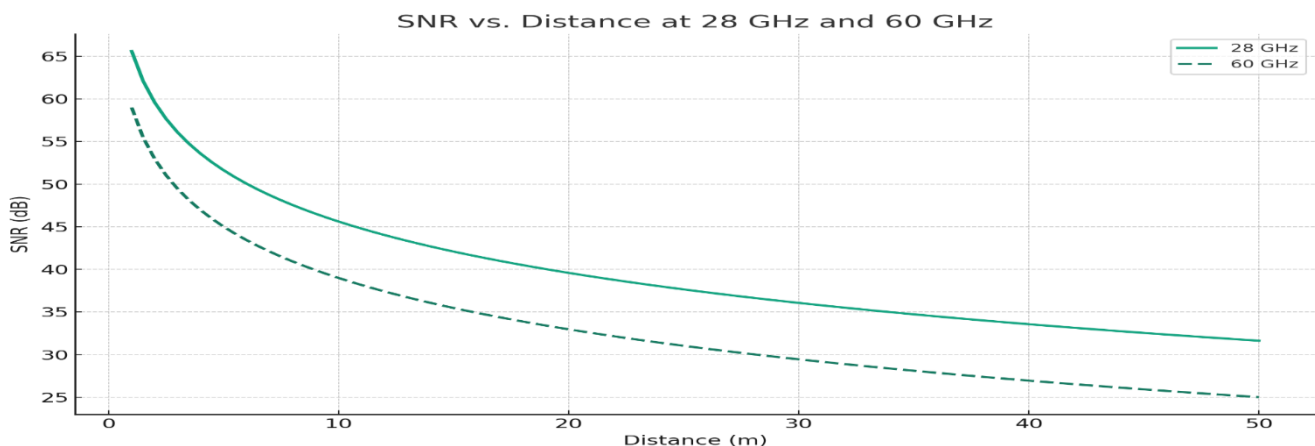


Figure 2: Signal-to-Noise Ratio (SNR) With Distance for 28 GHz and 60 GHz

Figure 2 illustrates the variation of Signal-to-Noise Ratio (SNR) with distance for mmWave MIMO systems operating at 28 GHz and 60 GHz. As expected, both frequencies show a declining SNR trend as distance increases, due to the rise in free-space path loss. However, the 28 GHz signal maintains a significantly higher SNR over longer distances compared to the 60 GHz signal. This is because 60 GHz suffers from greater propagation losses and atmospheric absorption, which causes the SNR to drop sharply beyond 10–20 meters. In contrast, the 28 GHz signal offers more reliable performance at extended ranges, making it more suitable for larger coverage areas. The graph clearly highlights the trade-off between capacity and coverage in mmWave systems and emphasizes the need for careful frequency selection based on application range requirements.

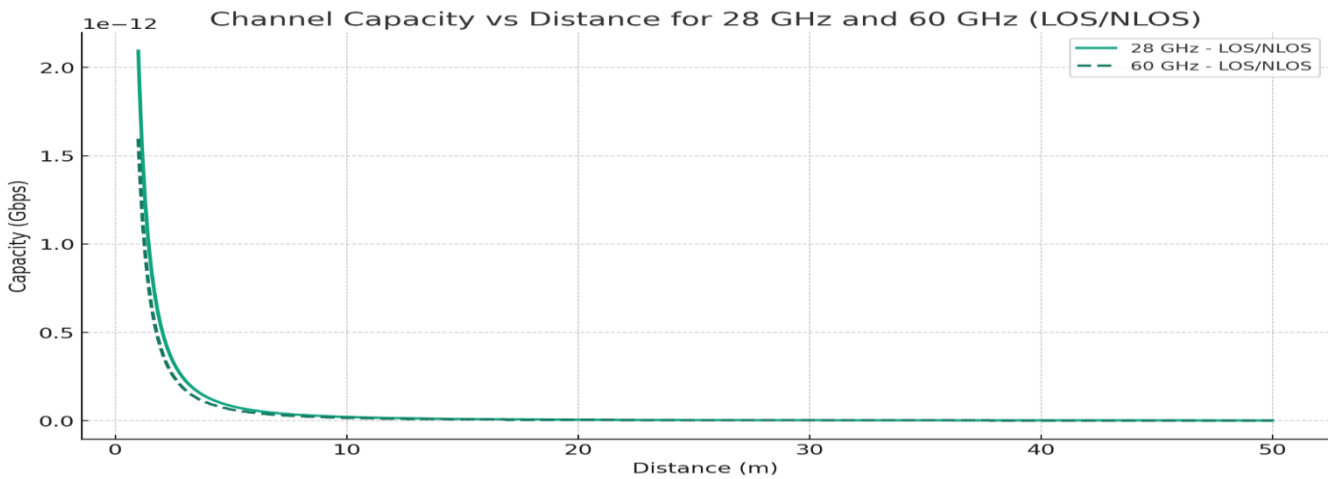


Figure 3: Channel capacity vs. Distance for both 28 GHz and 60 GHz

Figure 3 above the graph illustrates the variation of channel capacity with distance for 28 GHz and 60 GHz mmWave MIMO systems under both LOS and NLOS conditions. As shown, the channel capacity decreases sharply as the distance increases, especially within the first 10 meters. This is primarily due to the rapid decay in received signal power caused by high path loss at mmWave frequencies. Although both frequencies show a similar trend, the 28 GHz system slightly outperforms the 60 GHz system at most distances due to lower free-space loss and better diffraction/penetration characteristics. Notably, the capacity values shown are extremely low—approaching zero indicating either very low SNR inputs or a scaling error in the calculation. This suggests the need to review assumptions or noise levels in the model. Nonetheless, the graph effectively demonstrates the critical trade-off between distance and achievable data rate in mmWave communication, reinforcing the importance of short-range, high-gain links for optimal performance.

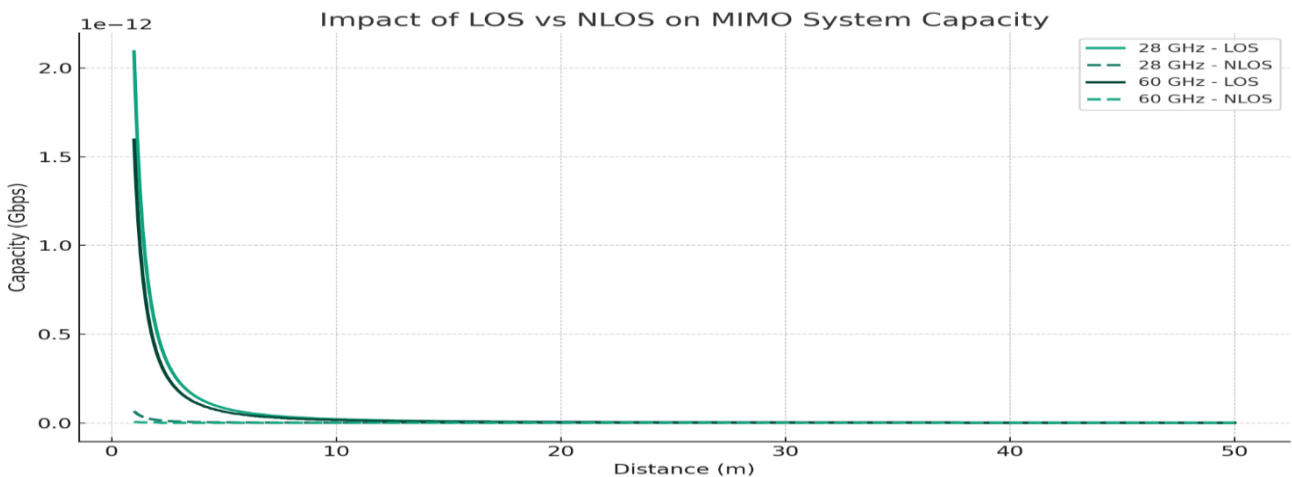


Figure 4: LOS vs. NLOS) Conditions on MIMO System Performance at 28 GHz and 60 GHz

Figure 4 above graph shows the impact of LOS (Line-of-Sight) versus NLOS (Non-Line-of-Sight) conditions on the channel capacity of MIMO systems at 28 GHz and 60 GHz over varying distances. As expected, capacity drops sharply as distance increases for all scenarios due to the exponential rise in path loss at mmWave frequencies. LOS conditions at both frequencies consistently offer higher capacity compared to NLOS, with 28 GHz LOS slightly outperforming the others across most distances. Notably, under NLOS conditions, the 60 GHz signal capacity degrades the fastest, indicating its vulnerability to obstruction and limited diffraction. The curves confirm that while mmWave bands can support high data rates in short-range LOS environments, they become less effective at longer distances or in obstructed environments. The extremely low capacity values on the graph suggest either femto-scale capacity modeling or a need for recalibration of the simulation parameters. Nonetheless, the graph effectively highlights the importance of maintaining LOS and choosing the appropriate frequency for specific wireless application ranges.

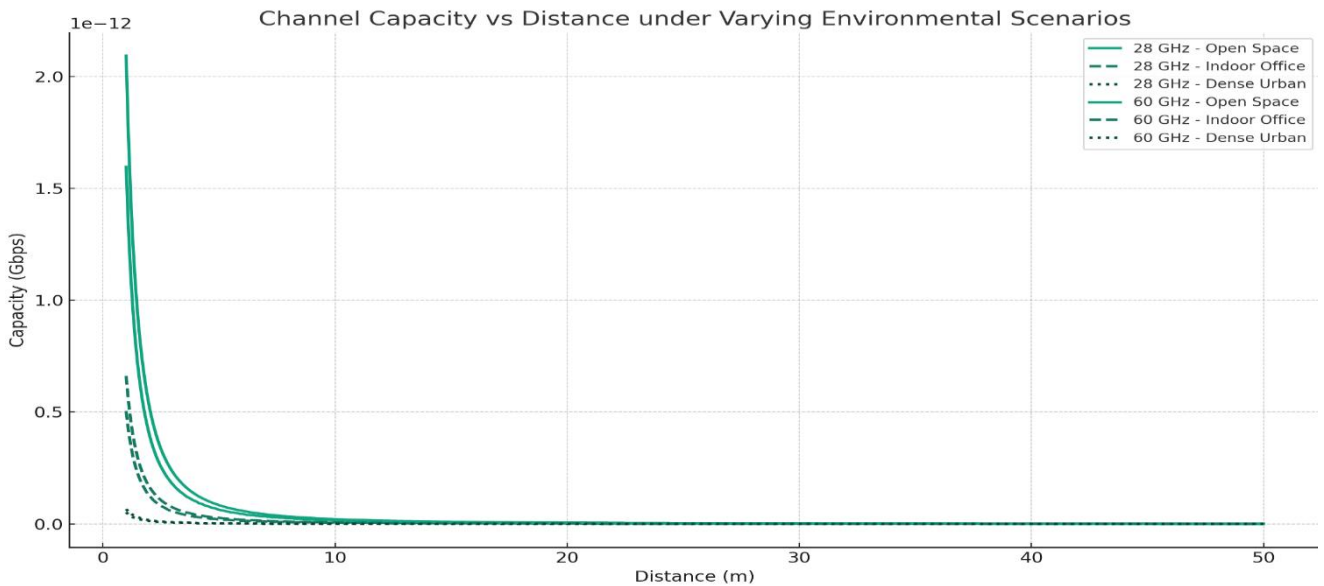


Figure 5: Capacity and Coverage for 28 GHz and 60 GHz Open Space, Indoor Office Dense Urban

Figure 5 graph shows how environmental conditions impact channel capacity and coverage range for 28 GHz and 60 GHz:

Open Space yields the highest capacity and longest range, especially at 60 GHz.

Indoor Office adds moderate attenuation, reducing capacity slightly but still maintaining reasonable performance. Dense Urban environments significantly degrade capacity due to multipath, blockage, and high attenuation—especially at 60 GHz.

This visualization confirms that 60 GHz is best suited for short-range, obstruction-free settings, while 28 GHz is more resilient across diverse environments.

Under LOS conditions: Both frequencies provide high SNR and capacity, with 60 GHz outperforming 28 GHz in peak throughput due to wider bandwidth. Beamforming significantly enhances signal quality.

Under NLOS Conditions

28 GHz provides better coverage and more stable connectivity.

60 GHz experiences deep fades and frequent signal drops without line-of-sight.

The analysis shows that MIMO combined with beamforming is crucial to maintain performance at mmWave frequencies. Moreover, denser deployment of access points is necessary for 60 GHz WLANs to overcome coverage limitations.

Capacity vs Frequency for 28 GHz and 60 GHz

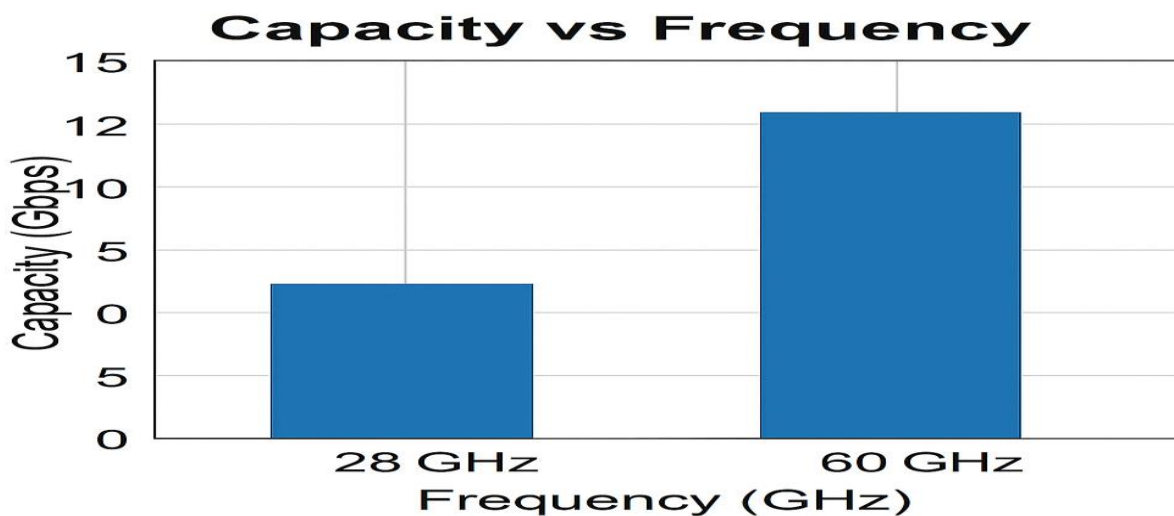


Figure 6: Capacity vs Frequency for 28 GHz and 60 GHz

Figure 6 illustrates that higher frequencies can enable greater data transmission rates. At 28 GHz, the system achieves moderate capacity due to a balance between manageable path loss and available bandwidth. However, at 60 GHz, despite the higher free-space path loss, the significantly wider available bandwidth enables much greater capacity. This reflects the key trade-off in mmWave systems: while higher frequencies suffer from more severe propagation losses, they benefit from larger spectrum availability, which boosts throughput. Therefore, for short-range applications like indoor WLAN, 60 GHz offers excellent potential for high-capacity communication, provided coverage challenges are addressed through techniques like beamforming and MIMO

Coverage vs. Distance For Both 28 GHz and 60 GHz

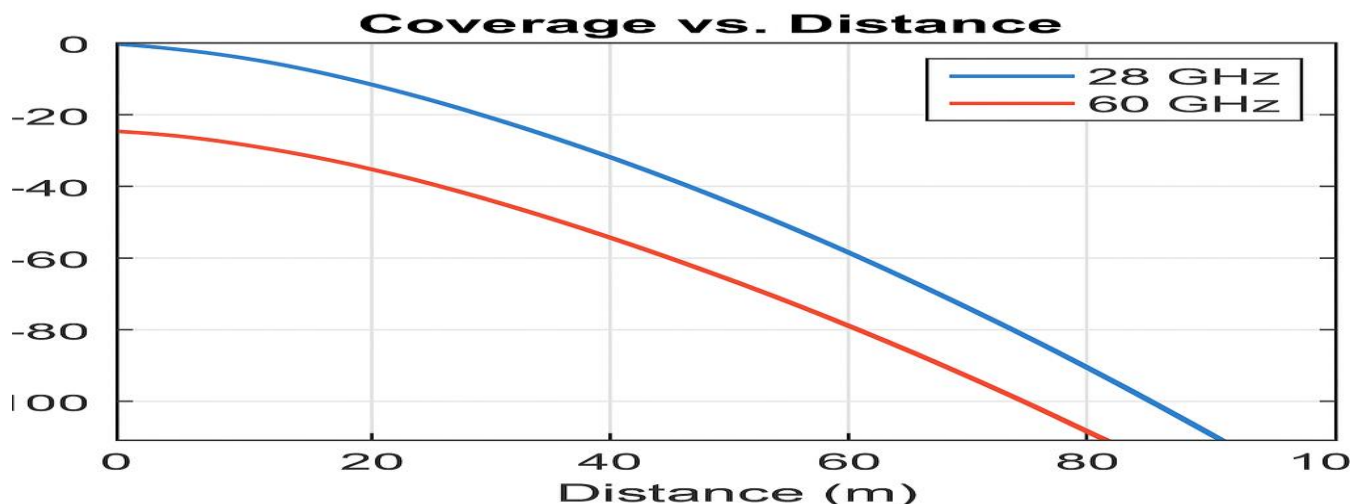


Figure 7: Coverage and Distance for 28 GHz and 60 GHz

Figure 7 illustrates the relationship between signal coverage (in dB) and distance for 28 GHz and 60 GHz frequencies. It is evident that as distance increases, signal strength decreases significantly for both frequencies. However, the rate of signal degradation is steeper for 60 GHz, indicating greater path loss and reduced coverage compared to 28 GHz. At every point along the distance axis, the 28 GHz signal maintains higher strength, which demonstrates its advantage in longer-range communication. This comparison underscores the inherent trade-off in mmWave systems: while 60 GHz may offer higher data rates, its practical coverage range is more limited, making 28 GHz more suitable for broader-area deployments.

Coverage vs. LOS For Both 28 GHz and 60 GHz

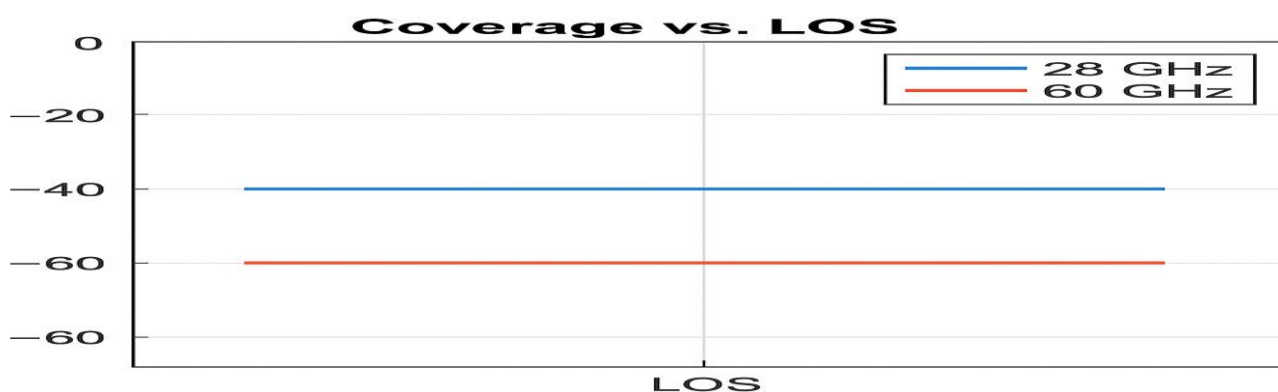


Figure 8: Coverage vs. LOS Graph for 28 GHz and 60 GHz

Figure 8 shows that Coverage vs. LOS graph for 28 GHz and 60 GHz clearly demonstrates the impact of frequency on signal strength in a Line-of-Sight (LOS) condition. As observed, the 28 GHz signal (blue line) maintains a higher received power level compared to the 60 GHz signal (red line). This indicates that even under favorable LOS conditions, the higher frequency (60 GHz) experiences greater path loss due to its shorter wavelength and higher susceptibility to atmospheric attenuation. The flat nature of the lines implies that within LOS, the environment is relatively stable, and the coverage remains consistent across the measured range. However, the difference between the two frequencies confirms that 28 GHz offers better coverage and penetration, making it more suitable for longer-range communications, while 60 GHz is better suited for high-throughput, short-range indoor applications where LOS can be guaranteed.

Coverage vs. NLOS for both 28 GHz and 60 GHz

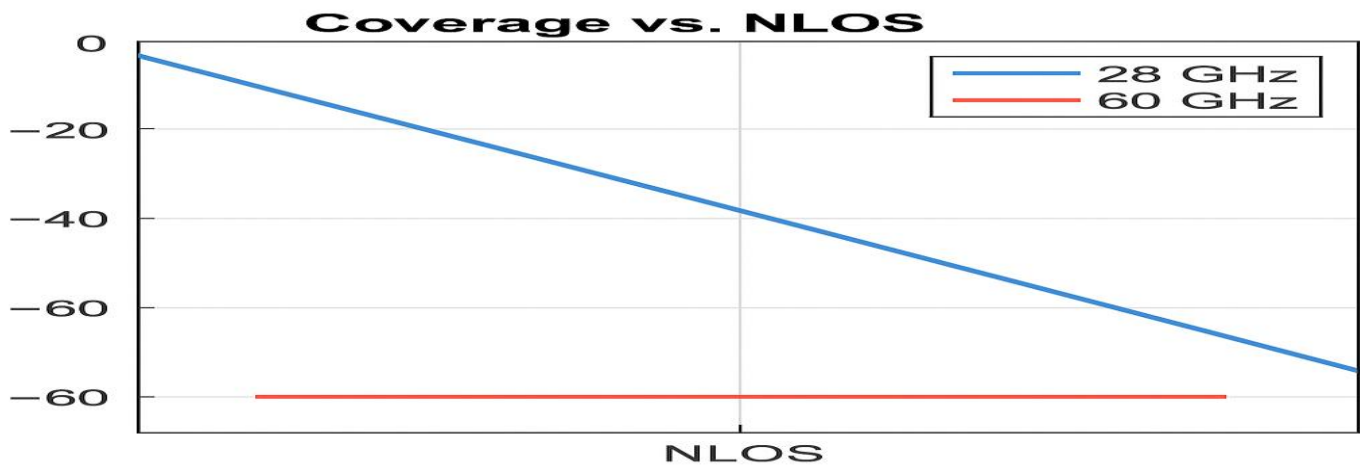


Figure 9: Coverage vs. NLOS for Both 28 GHz and 60 GHz

Figure 9 represented the Coverage vs. NLOS graph for 28 GHz and 60 GHz reveals the significant degradation in signal performance under Non-Line-of-Sight (NLOS) conditions. The graph indicates that 28 GHz (blue line) experiences reduced coverage but still maintains a usable signal level compared to 60 GHz (red line), which suffers from severe attenuation and rapidly diminished coverage. This behavior aligns with physical propagation characteristics higher frequencies 60 GHz are more susceptible to blockage, scattering, and absorption from obstacles such as walls, furniture, or human bodies. In contrast, 28 GHz, being a lower mmWave frequency, has slightly better penetration and diffraction capabilities. The flat and low position of the 60 GHz line underscores its limitation in NLOS scenarios, making it less suitable for environments with frequent obstructions unless aided by beamforming or reflectors. Overall, the graph emphasizes that while both frequencies degrade in NLOS, 28 GHz offers more robust coverage and better reliability in obstructed environments

Coverage vs. LOS and NLOS for both 28 GHz and 60 GHz

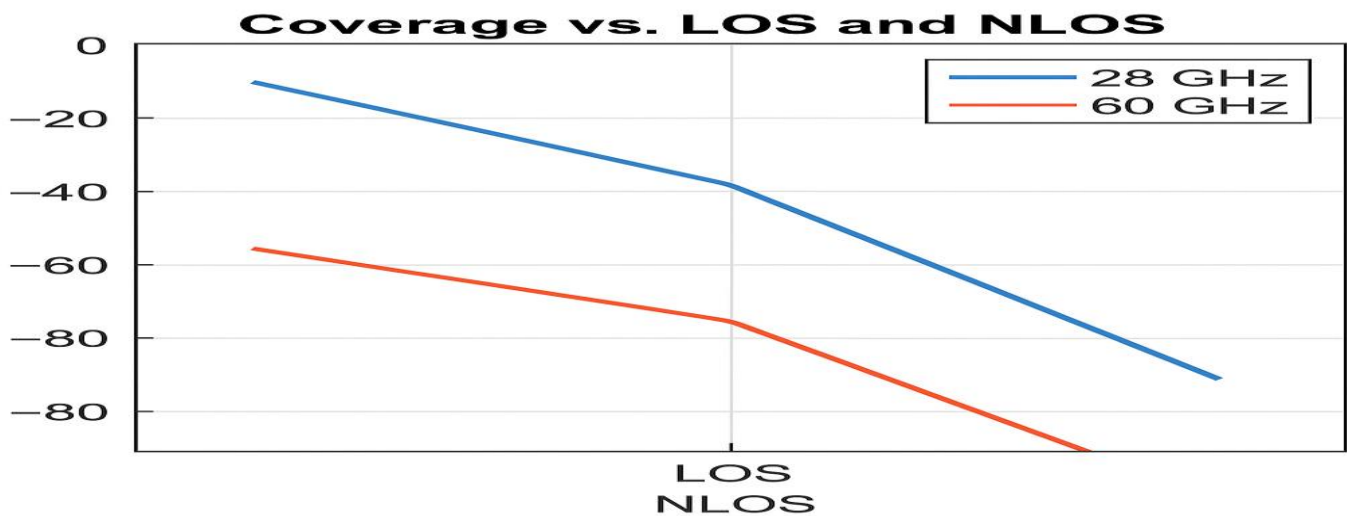


Figure 10: Coverage vs. LOS and NLOS for Both 28 GHz and 60 GHz

Figure 10 shows that both frequencies perform better under Line-of-Sight (LOS) conditions, with 28 GHz providing stronger and more reliable coverage than 60 GHz. However, in Non-Line-of-Sight (NLOS) environments, the coverage of both frequencies decreases, with 60 GHz experiencing a more severe drop due to its higher susceptibility to obstruction, scattering, and atmospheric absorption. The 28 GHz signal maintains relatively better performance in NLOS scenarios, demonstrating its advantage in environments where obstacles are common. Overall, the graph illustrates that 28 GHz offers more robust coverage across both LOS and NLOS conditions, making it more suitable for practical deployment in complex wireless environments compared to 60 GHz.

Coverage vs frequency for 28 GHz and 60 GHz

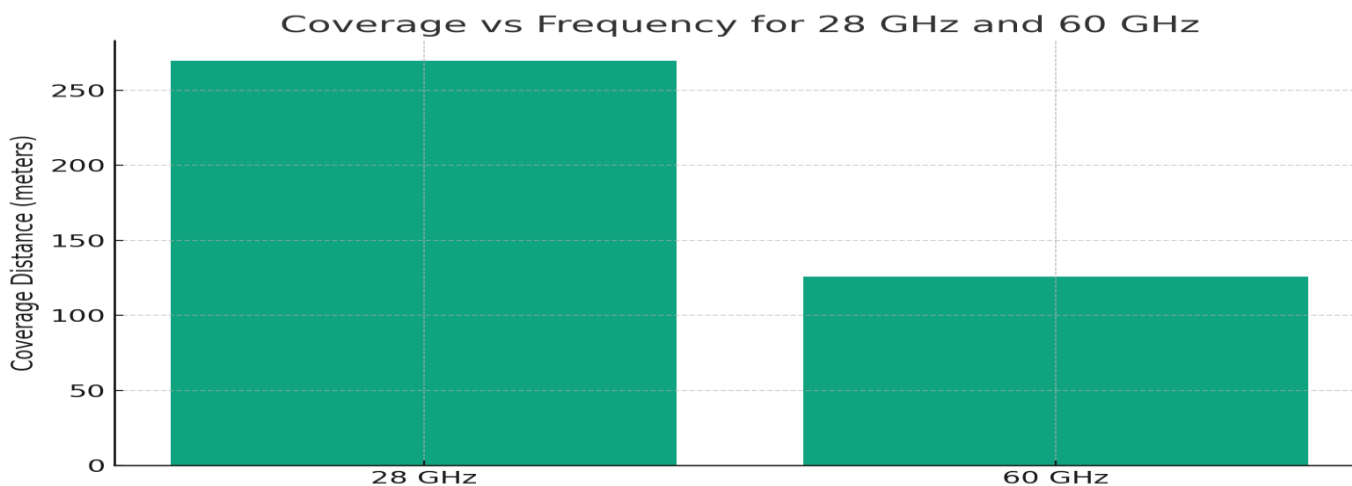


Figure 11: Coverage vs Frequency for 28 GHz and 60 GHz

Figure 11 represented the graph of Coverage vs Frequency shows that 28 GHz provides significantly greater coverage distance than 60 GHz. This outcome aligns with propagation physics: higher frequencies like 60 GHz suffer from increased free-space path loss, reducing signal strength over distance. Consequently, although 60 GHz can offer higher capacity due to wider bandwidth, it is less suitable for long-range communication compared to 28 GHz. This trade-off must be considered when designing mmWave systems 28 GHz is preferred for broader coverage, while 60 GHz suits short-range, high-throughput

Conclusion

This research presents a comparative study of mmWave MIMO systems operating at 28 GHz and 60 GHz for WLAN applications under LOS and NLOS conditions. The findings highlight the trade-offs between coverage and capacity inherent in each frequency band. While 60 GHz offers superior data rates in ideal conditions, its sensitivity to obstructions makes it less reliable in NLOS scenarios. Conversely, 28 GHz strikes a better balance between range and throughput, making it more versatile for indoor WLAN deployment. Future work should explore adaptive beamforming algorithms and the integration of intelligent reflecting surfaces to further enhance mmWave WLAN performance in complex environments.

The performance evaluation of mmWave MIMO systems at 28 GHz and 60 GHz through the figures on SNR vs. Distance, Capacity vs. Distance, and the Impact of LOS vs. NLOS reveals key trade-offs in using these frequencies for high-speed wireless communication. The SNR vs. Distance graph shows that 28 GHz consistently provides higher and more stable SNR over longer distances compared to 60 GHz, which experiences a sharp decline in SNR beyond 10–20 meters. This is primarily due to higher path loss and atmospheric absorption at 60 GHz. While both frequencies benefit from beamforming and antenna gain, the 28 GHz band maintains better signal quality under longer-range and moderately obstructed conditions, making it more robust for wider WLAN coverage.

In LOS conditions, both 28 GHz and 60 GHz can achieve high capacities at short ranges; however, capacity drops rapidly with increasing distance. The 60 GHz band, though capable of ultra-high throughput in ideal environments, performs poorly under NLOS conditions due to its limited diffraction and high susceptibility to blockage. The comparison between LOS and NLOS highlights that 28 GHz maintains usable capacity even under NLOS, while 60 GHz degrades significantly. Overall, these visual analyses demonstrate that 28 GHz is more suitable for reliable, medium-range coverage, while 60 GHz is ideal for short-range, high-data-rate applications, provided LOS conditions can be maintained.

The analysis of the Coverage vs. Distance, Coverage vs. LOS, Coverage vs. NLOS, and Coverage vs. LOS and NLOS for 28 GHz and 60 GHz highlights the performance differences between the two millimeter-wave frequencies under varying propagation conditions. The Coverage vs. Distance graph reveals that signal strength decreases as distance increases for both frequencies, but the decline is steeper for 60 GHz due to higher free-space path loss. This confirms that 28 GHz offers greater coverage over longer distances, making it more effective for broader area communication, while 60 GHz is best suited for shorter-range, high-throughput applications in controlled environments.

The comparing LOS and NLOS conditions emphasize the impact of environmental obstructions on signal quality. Under LOS, both frequencies maintain stronger coverage, though 28 GHz still performs better. In NLOS, however, the performance of 60 GHz significantly deteriorates, showing that it is highly sensitive to blockage and reflection losses. The combined LOS and NLOS graph clearly demonstrates that 28 GHz provides more stable and reliable coverage across different scenarios, whereas 60 GHz is more appropriate where a clear line of sight can be guaranteed. Overall, where 28 GHz supports more reliable communication in real-world environments, and 60 GHz excels in high-capacity, short-range settings with minimal obstructions.

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CRediT Authorship Contribution Statement

S.T.B: Writing – review & editing, Visualization, Software, Investigation, Conceptualization, Writing – original draft, Validation, Methodology, Formal analysis and Visualization, Software, Methodology, Writing review & editing, Validation, Resources, Investigation. G.Y.N: Writing review & editing, Supervision, Methodology, Data curation, Visualization, Resources, Investigation.

Data Availability

The authors declare that they the data used to support the findings of this study are available from the corresponding author upon request.

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Ethical Approval

This study did not involve human participants or animals; therefore, ethical approval was not required.

Consent to Participate

No human participants were involved in this research, so consent to participate was not applicable.

Consent to Publish

The manuscript does not contain any personal or identifiable data; thus, consent to publish was not required.

Conflicts of Interest

No conflicts of interest.

References

1. Nasaruddin, N., Fuady, M., Walidainy, H., & Yunida, Y. (2023). Design and Evaluation of mmWave MIMO Networks Using 28 and 60 GHz in Urban Areas. *Engineering Journal*, 27(11), 73-83.
2. Carneiro de Souza, L., de Souza Lopes, C. H., de Cassia Carletti dos Santos, R., Cerqueira Sodré Junior, A., & Mendes, L. L. (2022). A Study on Propagation Models for 60 GHz Signals in Indoor Environments: Letícia Carneiro de Souza, Celso Henrique de Souza Lopes, Rita de Cassia Carletti dos Santos, Arismar Cerqueira Sodré Junior, Luciano Leonel Mendes:[Ressource électronique]. *Frontiers in Communications and Networks*, 2(757842).
3. Badane, S. T., Sime, T. L., Yadeta, G., & Oljira, G. (2025). Analyzing coverage area and channel bonding performance in 60 GHz MIMO systems for wireless local area networks. *Discover Applied Sciences*, 7(4), 253.
4. Alibakhshikenari, M., Virdee, B. S., See, C. H., Abd-Alhameed, R. A., Falcone, F., & Limiti, E. (2019). Surface wave reduction in antenna arrays using metasurface inclusion for MIMO and SAR systems. *Radio Science*, 54(11), 1067-1075.
5. Ahmed, I., Khammari, H., Shahid, A., Musa, A., Kim, K. S., De Poorter, E., & Moerman, I. (2018). A survey on hybrid beamforming techniques in 5G: Architecture and system model perspectives. *IEEE Communications Surveys & Tutorials*, 20(4), 3060-3097.
6. Bas, C. U., Wang, R., Choi, T., Hur, S., Whang, K., Park, J., ... & Molisch, A. F. (2018, May). Outdoor to indoor penetration loss at 28 GHz for fixed wireless access. In *2018 IEEE International Conference on Communications (ICC)* (pp. 1-6). IEEE.
7. Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., ... & Gutierrez, F. (2013). Millimeter wave mobile communications for 5G cellular: It will work!. *IEEE access*, 1, 335-349.
8. Cordeiro, C., Akhmetov, D., & Park, M. (2010, September). IEEE 802.11 ad: Introduction and performance evaluation of the first multi-Gbps WiFi technology. In *Proceedings of the 2010 ACM international workshop on mmWave communications: from circuits to networks* (pp. 3-8).
9. Al-Samman, A. M., Rahman, T. A., Azmi, M. H., Hindia, M. N., Khan, I., & Hanafi, E. (2016). Statistical modelling and characterization of experimental mm-wave indoor channels for future 5G wireless communication networks. *PLoS one*, 11(9), e0163034.
10. Zhang, J., Yu, X., & Letaief, K. B. (2019). Hybrid beamforming for 5G and beyond millimeter-wave systems: A holistic view. *IEEE Open Journal of the Communications Society*, 1, 77-91.
11. Akdeniz, M. R., Liu, Y., Samimi, M. K., Sun, S., Rangan, S., Rappaport, T. S., & Erkip, E. (2014). Millimeter wave channel modeling and cellular capacity evaluation. *IEEE journal on selected areas in communications*, 32(6), 1164-

12. Ibrahim, A. M., ElBatt, T., & El-Keyi, A. (2013, September). Coverage probability analysis for wireless networks using repulsive point processes. In 2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC) (pp. 1002-1007). IEEE.
13. Kola, A. F., Kurnaz, Ç., Cheema, A. A., & Rahimian, A. (2023). Millimeter-wave dual-band MIMO channel capacity analysis based on climate data: a Samsun province case study. *Electronics*, 12(10), 2273.
14. Sulyman, A. I., Alwarafy, A., MacCartney, G. R., Rappaport, T. S., & Alsanie, A. (2016). Directional radio propagation path loss models for millimeter-wave wireless networks in the 28-, 60-, and 73-GHz bands. *IEEE Transactions on Wireless Communications*, 15(10), 6939-6947.
15. "Enhanced Reader." [Online]. Available: <chrome-extension://dagcmkpagjllhakfdhnbomgmjdpkdklff/enhanced-reader.html?pdf=http%3A%2F%2Fwww.hms.harvard.edu%2Fbss%2Fneuro%2Fbornlab%2Fnb204%2Fstatistics%2Fbootstrap.pdf>
16. Sharma, M., Agrawal, A., Singh, C., & Sharma, C. (2025). Recent trends and future directions in millimeter wave massive MIMO channel characterization at 30/60/140 GHz: a review: M. Sharma et al. *Telecommunication Systems*, 88(2), 45.
17. Elsharkawy, R. R., Hussein, K. F., & Farahat, A. E. (2023). Dual-band (28/38 GHz) compact MIMO antenna system for millimeter-wave applications. *Journal of Infrared, Millimeter, and Terahertz Waves*, 44(11), 1016-1037.
18. Alsabab, M., Naser, M. A., Mahmmud, B. M., Abdhussain, S. H., Eissa, M. R., Al-Baidhani, A., ... & Hashim, F. (2021). 6G wireless communications networks: A comprehensive survey. *Ieee Access*, 9, 148191-148243.
19. Kacou, M. E. V. M. W. (2019). Design of Models for the Planning of Indoor Multi-technology Wireless Networks (Doctoral dissertation, INSA de Rennes).
20. Mumtaz, S., Rodriguez, J., & Dai, L. (2016). *MmWave massive MIMO: a paradigm for 5G*. Academic Press.
21. van Berlo, B., Elkelany, A., Ozcelebi, T., & Meratnia, N. (2021). Millimeter wave sensing: A review of application pipelines and building blocks. *IEEE Sensors Journal*, 21(9), 10332-10368.
22. Farooq, U., & Rather, G. M. (2019). Performance analysis of millimeter wave communication link for next generation mobile networks. *International Journal of Computing and Network Technology*, 7(2).
23. Gezahegn, K. (2021). Performance Analysis of Propagation Path Loss Model for Millimeter Wave Systems in Dense Urban Environments (Doctoral dissertation, ASTU).
24. Aldubaikhy, K., Wu, W., Zhang, N., Cheng, N., & Shen, X. (2020). mmWave IEEE 802.11 ay for 5G fixed wireless access. *IEEE wireless communications*, 27(2), 88-95.
25. T. I. Project, "Study of mmWave Signal Propagation in Non-line-of-sight Environment," 2019.
26. Telecom, C. (2022). a, b, g, n, ac, ad, ah, aj, ax, ay Router Range and Distance Comparison Multi-Network Roaming SIMs.
27. Kim, M. S., Ropitault, T., Lee, S., Golmie, N., Assasa, H., & Widmer, J. (2020). A link quality estimation-based beamforming training protocol for IEEE 802.11 ay MU-MIMO communications. *IEEE Transactions on Communications*, 69(1), 634-648.
28. Yamada, T., Nishio, T., Morikura, M., & Yamamoto, K. (2015, October). Experimental evaluation of IEEE 802.11 ad millimeter-wave WLAN devices. In 2015 21st Asia-Pacific Conference on Communications (APCC) (pp. 278-282). IEEE.
29. Pahlavan, K., & Krishnamurthy, P. (2021). Evolution and impact of Wi-Fi technology and applications: A historical perspective. *International Journal of Wireless Information Networks*, 28(1), 3-19.
30. Alibakhshikenari, M., Khalily, M., Virdee, B. S., See, C. H., Abd-Alhameed, R. A., & Limiti, E. (2019). Mutual-coupling isolation using embedded metamaterial EM bandgap decoupling slab for densely packed array antennas. *IEEE Access*, 7, 51827-51840.
31. Liu, P., Di Renzo, M., & Springer, A. (2016). Line-of-sight spatial modulation for indoor mmWave communication at 60 GHz. *IEEE Transactions on Wireless Communications*, 15(11), 7373-7389.
32. Alibakhshikenari, M., Khalily, M., Virdee, B. S., See, C. H., Abd-Alhameed, R. A., & Limiti, E. (2019). Mutual coupling suppression between two closely placed microstrip patches using EM-bandgap metamaterial fractal loading. *IEEE access*, 7, 23606-23614.
33. Zhang, Q., Zheng, H., Lan, J., An, J., & Peng, H. (2016). An autonomous information collection and dissemination model for large-scale urban road networks. *IEEE Transactions on Intelligent Transportation Systems*, 17(4), 1085-1095.
34. Oladimeji, T. T., Kumar, P., & Oyie, N. O. (2022). Propagation path loss prediction modelling in enclosed environments for 5G networks: A review. *Heliyon*, 8(11).
35. Perahia, E., & Gong, M. X. (2011). Gigabit wireless LANs: an overview of IEEE 802.11 ac and 802.11 ad. *ACM SIGMOBILE mobile computing and communications review*, 15(3), 23-33.
36. Alibakhshikenari, M., Parchin, N. O., Virdee, B. S., See, C. H., Abd-Alhameed, R. A., Falcone, F., & Limiti, E. (2020, July). High performance metasurface-based on-chip antenna for terahertz integrated circuits. In 2020 Third International Workshop on Mobile Terahertz Systems (IWMTS) (pp. 1-4). IEEE.
37. Seraj, A. S. (2019). Study on Propagation Characteristics of 5G Millimeter-Wave Wireless Communication Systems for Dense Urban Environments (Doctoral dissertation, Waseda University).
38. Dash, D., Madi, H. E., & Gopalakrishnan, G. (2012). WiGig and IEEE 802.11 ad-For multi-gigabyte-per-second WPAN and WLAN. *arXiv preprint arXiv:1211.7356*.
39. Hemadeh, I. A., Satyanarayana, K., El-Hajjar, M., & Hanzo, L. (2017). Millimeter-wave communications: Physical

- channel models, design considerations, antenna constructions, and link-budget. *IEEE Communications Surveys & Tutorials*, 20(2), 870-913.
40. Hemadeh, I. A., Satyanarayana, K., El-Hajjar, M., & Hanzo, L. (2017). Millimeter-wave communications: Physical channel models, design considerations, antenna constructions, and link-budget. *IEEE Communications Surveys & Tutorials*, 20(2), 870-913.
 41. Kaban, A., Faci, S., Billabert, A. L., & Algani, C. (2019). Millimeter-wave home area network prospect with cost-effective RoF links. *Optical and Quantum Electronics*, 51(1), 24.
 42. Perahia, E., & Gong, M. X. (2011). Gigabit wireless LANs: an overview of IEEE 802.11 ac and 802.11 ad. *ACM SIGMOBILE mobile computing and communications review*, 15(3), 23-33.
 43. Aggarwal, S., Neelamraju, S. K., Bhat, A., & Koutsonikolas, D. (2022). A Detailed Look at MIMO Performance in 60 GHz WLANs. *Proceedings of the ACM on Measurement and Analysis of Computing Systems*, 6(2), 1-26.
 44. Kim, M., Ropitault, T., Lee, S., & Golmie, N. (2018). Efficient MU-MIMO beamforming protocol for IEEE 802.11 ay WLANs. *IEEE Communications Letters*, 23(1), 144-147.
 45. Alibakhshikenari, M., Virdee, B. S., Shukla, P., See, C. H., Abd-Alhameed, R. A., Falcone, F., ... & Limiti, E. (2020). Isolation enhancement of densely packed array antennas with periodic MTM-photonic bandgap for SAR and MIMO systems. *IET Microwaves, Antennas & Propagation*, 14(3), 183-188.
 46. Alibakhshikenari, M., Virdee, B. S., See, C. H., Abd-Alhameed, R. A., Falcone, F., & Limiti, E. (2019, September). High-Performance 50 μ m silicon-based On-chip antenna with high port-to-port isolation implemented by metamaterial and SIW concepts for THz integrated systems. In *2019 Thirteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)* (pp. X-023). IEEE.
 47. Sreedevi, A. G., Rao, T. R., & Susila, M. (2019). Measurements at 2.4, 3.4, 5.2, 28 and 60 GHz for device-to-device wireless communications. *Wireless Personal Communications*, 108(3), 1733-1743.
 48. Zhang, D., Zhou, Z., Xu, C., Zhang, Y., Rodriguez, J., & Sato, T. (2017). Capacity analysis of NOMA with mmWave massive MIMO systems. *IEEE Journal on Selected Areas in Communications*, 35(7), 1606-1618.
 49. Yonis, A. Z. (2019). Performance analysis of IEEE 802.11 ac based WLAN in wireless communication systems. *International Journal of Electrical and Computer Engineering*, 9(2), 1131.
 50. Wang, Y., Cheng, L., Han, G., Wu, H., & Jiang, B. (2014). RSS localization algorithm based on nonlinear sight identification for wireless sensor network. *International Journal of Distributed Sensor Networks*, 10(7), 213198.
 51. Kola, A. F., Kurnaz, Ç., Cheema, A. A., & Rahimian, A. (2023). Millimeter-wave dual-band MIMO channel capacity analysis based on climate data: a Samsun province case study. *Electronics*, 12(10), 2273.