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Comprehensive MATLAB-Based Performance Analysis of 5G Cellular Networks

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Abstract— *This study presents a comprehensive simulation and performance analysis of 5G cellular networks using MATLAB, focusing on key performance indicators such as throughput, latency, spectral efficiency, coverage probability, and bit error rate (BER). Simulation results demonstrate that throughput increases with higher signal-to-noise ratios (SNR), with the 28 GHz millimeter-wave (mmWave) band consistently outperforming the 3.5 GHz sub-6 GHz band due to wider bandwidth availability and enhanced support for advanced MIMO and beamforming. Latency analysis reveals that higher subcarrier spacing (SCS) significantly reduces transmission delays, with 120 kHz achieving ultra-low latencies suitable for URLLC applications. Spectral efficiency results show a decline with increasing user density; however, the mmWave band maintains superior efficiency compared to sub-6 GHz, underscoring its potential for high-capacity deployments. Coverage probability analysis highlights a trade-off: while sub-6 GHz ensures more consistent and reliable coverage, mmWave frequencies are prone to higher path loss and blockage. Finally, BER evaluation confirms that Quadrature Phase Shift Keying (QPSK) achieves near error-free transmission above 20 dB SNR in AWGN channels, validating its suitability for 5G applications. Overall, the findings underscore the dual strengths of sub-6 GHz for reliable coverage and mmWave for high-capacity performance, providing valuable insights for future 5G network design and optimization.*

Keywords— *5G; MATLAB; Throughput; Latency; Spectral Efficiency; Coverage Probability; BER; Sub-6 GHz; mmWave.*

I. INTRODUCTION

Over recent decades, telecommunications have evolved from simple analogue voice services to sophisticated high-speed digital data systems. Each generation from 1G through 4G has brought enhancements in data rate, capacity, and service quality, yet the surging demand for connected devices and data-intensive applications has exposed the limits of existing network capabilities. This has motivated the development of the Fifth Generation (5G) of mobile networks, designed around three primary service categories: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC), to support applications ranging from virtual reality and industrial automation to large-scale Internet of Things (IoT) deployments.

A key innovation in 5G is the utilization of millimeter wave (mmWave) spectrum, which offers much wider bandwidths and significantly higher data rates than the sub-6 GHz bands used in 4G [1]. Technologies such as Massive MIMO (multiple input, multiple output) and beamforming further enhance spectral efficiency and link reliability by enabling multiple simultaneous transmissions to and from numerous users, and by steering energy toward receivers, respectively. However, mmWave signals generally suffer greater path loss, attenuation, and sensitivity to blockage, which makes advanced antenna designs, dense base-station deployment, and sophisticated signal processing necessary [1][2].

5G also features more complex network architectures: networks are increasingly heterogeneous, combining macro-cells, small cells, distributed antenna systems, and cloud-native cores. These bring challenges in planning, optimization, and ensuring reliable performance across diverse scenarios. Because deploying real 5G infrastructure for experimentation is expensive and time-consuming, simulation becomes essential.

MATLAB, through its Communications and 5G Toolboxes, provides a powerful platform for modelling, simulating, and analysing end-to-end 5G systems. It supports standard-compliant waveform generation, channel models (such as the 3GPP TDL/CDL models), link- and system-level simulations, antenna array modelling, and performance metrics such as throughput, error rates, and latency. Using simulation, researchers and engineers can study trade-offs under controlled and repeatable conditions, optimize design parameters (e.g. antenna configuration, bandwidth, carrier frequencies), and validate theoretical models before costly deployments [3]. This work builds on these premises by using MATLAB simulations to evaluate how critical 5G components perform under various realistic conditions. By quantifying performance across configurations, it aims to offer practical insights for design and standardization in next-generation wireless systems. While 5G technologies are being rapidly deployed worldwide, there remains a substantial need for rigorous performance evaluation to ensure their effectiveness under various network conditions. Traditional simulation platforms often struggle to integrate the complexity of 5G features, leading to a gap between theoretical performance and practical outcomes. This study aims to bridge this gap by leveraging MATLAB to simulate and analyse the performance of 5G cellular networks, focusing on key metrics such as data throughput, latency, signal quality, and spectral efficiency.

This research contributes to the ongoing efforts in 5G network development by providing a robust simulation and analysis framework using MATLAB. It offers insights for researchers, engineers, and policymakers aiming to optimize 5G deployments and understand their implications. The findings can guide future enhancements in network planning, resource allocation, and service quality assurance.

II. LITERATURE REVIEW

This session provides a comprehensive review of the current body of knowledge surrounding 5G cellular networks. It explores the key technologies, standards, and theoretical models underpinning 5G systems. The chapter also critically examines previous studies related to 5G simulation and performance analysis, with a focus on the use of MATLAB as a simulation environment. The objective is to establish a strong conceptual and empirical foundation for the study, while identifying opportunities for further research. Several studies have investigated the simulation of 5G systems using platforms such as ns-3, OMNeT++, and MATLAB. Although open-source simulators provide flexibility and extensibility, MATLAB is often preferred for its robust support of physical layer modeling, standardized toolboxes, and rapid prototyping capabilities.

Recent studies have utilized MATLAB-based simulations to evaluate 5G network performance, focusing on key metrics such as throughput, block error rate (BLER), and spectral efficiency. For instance, a MATLAB simulation model for the Physical Downlink Shared Channel (PDSCH) demonstrated how various channel conditions and system parameters impact 5G performance, providing practical insights for network design and optimization [4]. Similarly, [5] simulated Massive MIMO systems in MATLAB, with emphasis on enhancing spectral efficiency and energy utilization. In another study, [6] examined ultra-reliable low latency communications (URLLC) using a combination of theoretical models and simulations, highlighting the inherent trade-offs between latency performance and network load conditions.

Collectively, these studies illustrate the relevance of MATLAB as a versatile platform for 5G research, particularly in evaluating performance trade-offs, optimizing configurations, and validating theoretical models under controlled scenarios. Most existing literature either focuses on single aspects of 5G (e.g., waveform design or antenna configurations) or lacks comprehensive simulation frameworks that cover both physical and network layer interactions. There is also limited emphasis on replicable, modular MATLAB simulations accessible to both researchers and educators.

2.1 Overview of 4G and 5G Technologies

Cellular networks have evolved from 1G in the 1980s to today's 5G systems, with each generation advancing in speed, latency, and service quality. Standardized in the early 2010s, 4G networks deliver average downlink speeds in the tens of Mbps and latency under 50 ms. 5G**,** first deployed in 2018–2019, introduces peak downlink rates up to 20 Gbps, uplink up to 10 Gbps, system capacity of 100 Tbps, and latency as low as 1 ms, particularly for Ultra-Reliable Low-Latency Communications (URLLC) [7][8]. Key differentiators of 5G include millimeter-wave bands, ultra-dense networks, massive MIMO, beamforming, carrier aggregation, non-orthogonal multiple access (NOMA), and cloud-native architectures**.** These innovations enable advanced applications such as autonomous driving, AR/VR, robotics, and the Internet of Things (IoT), transforming cellular networks into intelligent service platforms [9].

Unlike earlier circuit-switched systems (1G–3G), both 4G and 5G are fully packet-switched**,** supporting voice, data, and multimedia seamlessly across global networks [10]. However, the rich features of 5G also introduce new challenges in routing, scalability, energy efficiency, and security [11]. Emerging intelligent control mechanisms, software-defined networking, and dynamic routing strategies are increasingly required to ensure adaptability, quality of service, and robustness [12].

Routing remains a core element of cellular networks, involving efficient traffic delivery between user equipment, base stations, and the core network. Traditional metrics such as hop count are now complemented by bandwidth, latency, and throughput optimization to meet the diverse requirements of modern networks [13][14]. According to the ITU's IMT-2020 framework, 5G is designed around three use cases: enhanced mobile broadband (eMBB) for high-speed access, URLLC for mission-critical low-latency services, and massive machine-type communications (mMTC) for IoT connectivity. Supported by technologies like mmWave, massive MIMO, beamforming, network slicing, and edge computing, 5G offers unprecedented opportunities while presenting new design and optimization challenges.

2.2 Theoretical Foundations of 5G

- Shannon's Capacity Theorem: Shannon's capacity theorem establishes the theoretical upper bound on the maximum data rate achievable for a given bandwidth and signal-to-noise ratio (SNR). In the context of 5G, wider bandwidth allocations and advanced modulation techniques enable networks to approach these fundamental performance limits [15].
- MIMO Theory: The principles of multiple-input multiple-output (MIMO) systems form the foundation of Massive MIMO technology in 5G. By transmitting several data streams simultaneously over the same frequency resources, MIMO improves both throughput and link reliability. Core concepts include channel state information (CSI), spatial multiplexing, and diversity gain, all of which are central to 5G's performance [16].
- Queuing Theory and Latency Analysis: Network latency in 5G is shaped by factors such as queuing delays, transmission times, and processing overhead. Models from queuing theory are critical in analysing delay performance, especially for ultra-reliable low-latency communication (URLLC), where maintaining extremely low latency is essential.
- Propagation and Channel Models: Accurate representation of signal propagation is vital for 5G system design. Models such as Rayleigh, Rician, and those specific to millimeter-wave (mmWave) frequencies are employed to capture effects including attenuation, scattering, reflection, and Doppler shifts. Both theoretical frameworks and empirical models are used to simulate realistic wireless environments.

2.3 Role of MATLAB in Wireless Communication Research

MATLAB has become a standard tool in both academic and industrial research due to its intuitive interface, robust toolboxes, and capacity for advanced mathematical modelling. In 5G studies, the Communications Toolbox and 5G Toolbox provide specialized functions for:

- OFDM waveform generation
- Channel modeling (e.g., TDL-C, CDL, mmWave channels)
- MIMO precoding and decoding
- Hybrid ARQ (HARQ) protocols and error correction coding

Beyond individual components, MATLAB enables end-to-end simulation of 5G New Radio (NR) systems, covering both uplink and downlink chains. This comprehensive environment allows researchers to evaluate system performance under standardized conditions, bridging theoretical models with practical implementation [3].

This section reviewed the evolution of mobile networks, the core technologies that define 5G, and the theoretical models that support performance analysis. It also examined relevant simulation-based studies and highlighted the utility of MATLAB in conducting sophisticated and accurate analyses. The literature reveals a need for integrated, modular simulations that demonstrate the performance of various 5G components in diverse conditions—an area this study seeks to address. Despite the vast body of research on 5G networks, several gaps remain in the simulation and performance analysis of 5G technologies, especially within academic and pre-commercial contexts. While theoretical studies and analytical models of 5G performance are abundant, they often rely on ideal assumptions that do not fully capture the complexities of real-world environments. Additionally, vendor-specific implementations and proprietary tools used in the telecom industry limit access and transparency, making it difficult for researchers and students to experiment with or validate key concepts independently.

Furthermore, much of the current academic work on 5G simulations either focuses narrowly on individual components such as modulation techniques, antenna design, or channel models or uses generic simulation platforms that lack built-in support for the specific features of the 5G standard. As a result, there is limited publicly available, end-to-end, system-level simulation research that integrates multiple 5G elements (e.g., Massive MIMO, mmWave propagation, beamforming, and network-level KPIs) in a cohesive and reproducible way. Although MATLAB offers powerful tools and a structured environment for simulating 5G systems, the platform's full potential is often underutilized in academic research. Many existing studies using MATLAB focus on isolated physical-layer simulations or do not provide detailed performance evaluations across different scenarios such as user density, mobility, or environmental conditions. This study aims to bridge this gap by:

- Providing a comprehensive and modular MATLAB-based simulation of key 5G components;
- Analysing performance metrics (e.g., throughput, latency, spectral efficiency) across varied network scenarios;
- Demonstrating how 5G-specific technologies interact and affect overall system behaviour;
- Creating a replicable framework that can be adapted for further research or educational use.

By addressing these shortcomings, this project contributes both to the academic understanding of 5G performance and to the development of accessible simulation tools that support further innovation and learning in the field of wireless communications

III. MATERIALS AND METHOD

The simulation is conducted using MATLAB R2023b with the 5G Toolbox. The environment models key components of the 5G NR stack, including, OFDM modulation, LDPC coding, Channel estimation and equalization, MIMO antenna configurations and Beamforming algorithms. This research adopts a quantitative experimental simulation design, leveraging computational models to replicate real-world scenarios within a controlled environment. The design facilitates evaluation of multiple 5G parameters under varying conditions, enabling an empirical performance comparison across different system configurations. Since simulation and analysis is for 3.5 GHz and 28 GHz 5G bands, and the work already outlined the tools (MATLAB, 5G Toolbox) and methodology (OFDM, LDPC, MIMO, beamforming), we can now derive the formulas that are commonly used in such simulations. These formulas form the theoretical backbone of your MATLAB simulation.

3.1 Signal-to-Noise Ratio (SNR)

SNR is a fundamental parameter defined as:

$$SNR(linear) = \frac{P_{rx}}{N} \tag{3.1}$$

Or in dB:

$$SNR(dB) = 10log_{10}\frac{P_{rx}}{N} \tag{3.2}$$

Where P_{rx} is Received signal power (W), N is Noise power (W) = kTB × NF, k is Boltzmann constant (1.38×10^{-23} J/K), T is Temperature (Kelvin, usually 290 K), B s Bandwidth (Hz, here 100 MHz) and NF is Noise Figure (linear)

3.2 Received Power (Link Budget Model)

The received power is estimated from the link budget:

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - PL - L_{misc} \tag{3.3}$$

Where P_{tx} is Transmit power (dBm), G_{tx}, G_{rx} are Antenna gains (dBi), PL is Path loss (dB) and L_{misc} is Miscellaneous losses (e.g., feeder, penetration)

3.3 Path Loss (3GPP TR 38.901 models)

Urban Macro (UMa) and Urban Micro (UMi) scenarios use different models: UMa (LOS) Path Loss:

$$PL_{LOS}^{UMa} = 28 + 22log_{10}(d) + 20log_{10}(f_c) \tag{3.4}$$

UMa (NLOS):

$$PL_{NLOS}^{UMa} = 13.54 + 39.08log_{10}(d) + 20log_{10}(f_c) - 0.6(h_{BS} - 1.5) \tag{3.5}$$

Where d is distance between UE and gNB (meters), f_c is carrier frequency (GHz) and h_{BS} is Base station height

3.4 Channel Capacity / Throughput (Shannon Capacity)

At a basic level:

$$C = Blog_2(1 + SNR) \tag{3.6}$$

But in 5G systems, throughput also depends on modulation and coding scheme (MCS), resource allocation, and overhead.

3.5 Practical Throughput (using MCS and resource elements)

$$T = N_{RE} \times R_{MCS} \times log_2(M) \times \frac{1}{T_{slot}} \qquad (3.7)$$

Where N_{RE} is Number of Resource Elements, R_{MCS} is Code rate, M is Modulation order (e.g., QPSK=4, 16QAM=16, 64QAM=64, 256QAM=256) and T_{slot} is Slot duration, You get N_{RE} based on bandwidth and slot configuration (e.g., number of subcarriers × number of symbols × number of slots per frame).

3.6 Beamforming Gain (for 4x4 and 8x8 MIMO)

MIMO and beamforming provide spatial multiplexing or diversity gain:

$$G_{BF} = 10log_{10}(N_{Tx} \times N_{Rx}) \qquad (3.8)$$

Where is N_{Tx} , N_{Rx} are numbers of transmit and receive antennas

3.7 Mobility Effect (Doppler Shift)

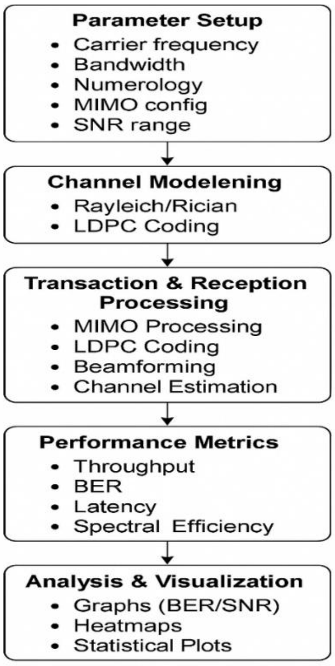
Mobility affects channel estimation and coherence time:

$$f_D = \frac{vf_c}{c} \qquad (3.9)$$

$$T_c \approx \frac{0.423}{f_D} \qquad (3.10)$$

Where f_D is Doppler shift, v is UE speed (m/s), f_c is Carrier frequency (Hz) and c is Speed of light

3.8 Simulation Workflow



1. Parameter Initialization: Define simulation parameters, including carrier frequency, subcarrier spacing, bandwidth, SNR levels, and number of antennas.
2. Waveform Generation: Use the 5G Toolbox to generate NR-compliant waveforms based on predefined numerologies and frame structures.
3. Channel Modeling: Simulate a multipath fading channel using Rayleigh and Rician models to mimic realistic propagation environments.
4. Transmission and Reception: Apply MIMO and beamforming processing at the transmitter; decode and evaluate performance at the receiver using LDPC decoding and channel estimation.
5. Performance Evaluation: Assess system performance using metrics such as throughput, bit error rate (BER), spectral efficiency, and latency.
6. Analysis and Visualization: Use MATLAB plots, graphs, and statistical tools to interpret the results.

3.5 Assumptions and Limitations

- Ideal synchronization and no hardware impairments are assumed.
- The simulation does not account for higher-layer protocols (e.g., RLC, PDCP).
- Only single-cell scenarios are considered; inter-cell interference is not modeled.
- Channel parameters are assumed to remain static during one transmission time interval (TTI).

TABLE 1: Network Parameters

Parameter	Value
Carrier Frequency	3.5 GHz and 28 GHz (mmWave)
Bandwidth	100 MHz
Duplex Mode	TDD
MIMO Configuration	4x4 and 8x8
User Equipment (UE)	10–100
Mobility	0–120 km/h

IV. RESULTS AND DISCUSSION

A. Throughput Analysis

The figure 1 below illustrates the relationship between Signal-to-Noise Ratio (SNR) and downlink throughput for two different 5G frequency bands (3.5 GHz and 28 GHz).

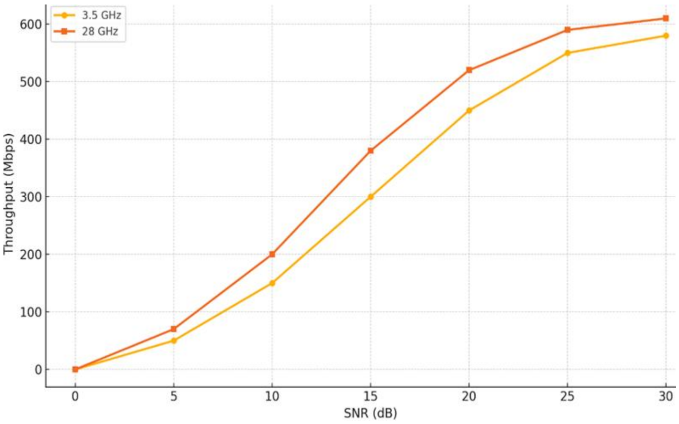


Figure 1: 5G NR Downlink Throughput Vs. Frequency

As expected, throughput increases as SNR improves. This is due to the ability to use higher-order modulation schemes and more efficient coding at higher SNRs. The 28 GHz band shows consistently higher throughput compared to the 3.5 GHz band at all SNR levels. This is because Higher frequencies generally support wider bandwidths, allowing more data to be transmitted and 28 GHz is a millimeter wave band, typically used for high-capacity, short-range communication. Both curves start to flatten out beyond 25 dB SNR, indicating diminishing returns with further increases in SNR. This saturation point suggests that other bottlenecks like channel bandwidth and hardware limitations begin to dominate.

B. *Latency Performance*

URLLC scenarios under 3.5 GHz show average latencies under 1 ms using grant-free uplink transmission and pre-configured scheduling. Latency increases with mobility and higher user density due to increased queuing delay and handovers. The figure 2 shows the total 5G latency (in milliseconds) as a function of Subcarrier Spacing (SCS).

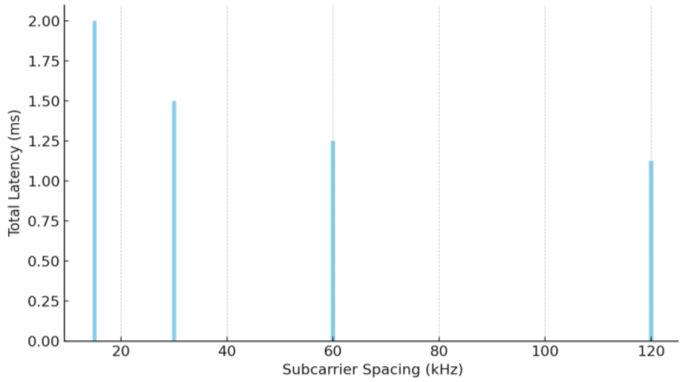


Figure 2: 5G End-to-End Latency vs Subcarrier Spacing

As the subcarrier spacing increases from 15 kHz to 120 kHz, the total latency significantly decreases. This is because higher SCS reduces the transmission time interval (TTI), leading to quicker data transmission cycles. 15 kHz (LTE-like): ~2.0 ms latency — suitable for enhanced mobile broadband (eMBB) but not for ultra-low latency use cases. 120 kHz: ~1.0 ms latency, ideal for Ultra-Reliable Low-Latency Communications (URLLC) in applications like autonomous vehicles and industrial automation. The base delays from processing, propagation, and scheduling remain the same across all SCS values. The only variable part is TTI.

C. *Spectral Efficiency*

The results of the spectral efficiency analysis, as illustrated in Figure (3), demonstrate a clear trend in how the efficiency of 5G cellular networks responds to increasing user density across two frequency bands: 3.5 GHz (sub-6 GHz) and 28 GHz (mmWave). It is evident that spectral efficiency decreases progressively as the number of user equipments (UEs) increases from 10 to 100.

This behaviour is attributed to the increased demand on network resources, greater inter-user interference, and reduced available bandwidth per user. Notably, the 28 GHz mmWave band consistently outperforms the 3.5 GHz band across all user densities, showcasing its superior capacity to deliver higher data rates. For example, at 10 UEs, the spectral efficiency for 28 GHz reaches approximately 7.5 bps/Hz compared to 4.5 bps/Hz for 3.5 GHz. Even at a high load of 100 UEs, the mmWave band maintains a spectral efficiency of around 6.2 bps/Hz, while the sub-6 GHz band drops to approximately 3.2 bps/Hz. These findings underscore the benefits of mmWave frequencies, including wider bandwidth availability and enhanced support for advanced MIMO and beamforming techniques. However, it is important to recognize that such high-frequency bands also face challenges such as greater path loss and susceptibility to obstructions, which must be accounted for in real-world deployments. Overall, the results confirm that while 5G networks are capable of supporting high user densities, system performance per user degrades with load, and mmWave frequencies provide a promising solution to mitigate this effect.

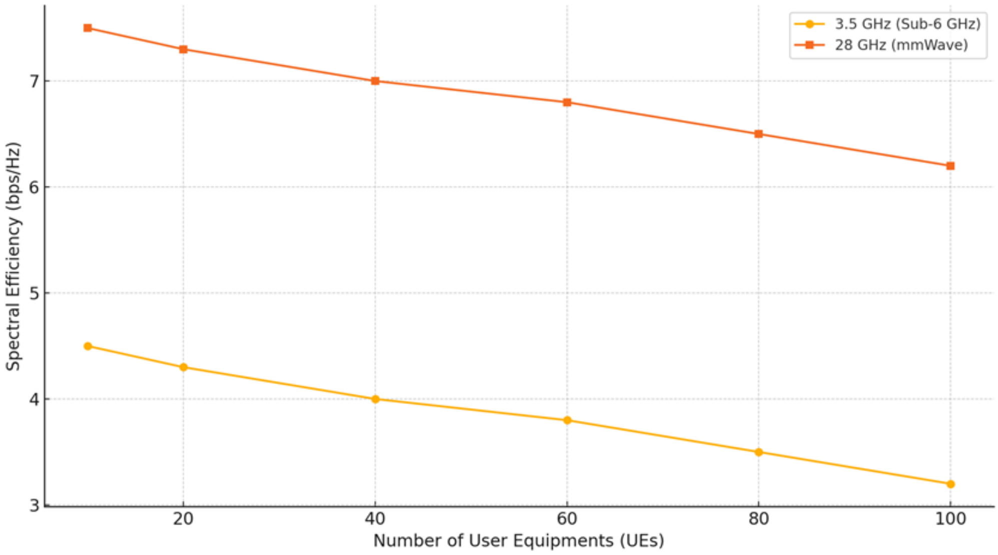


Figure 3: Spectral Efficiency Against Number of User Equipment

Spectral efficiency peaks at 10 bps/Hz for 8x8 MIMO under favorable SNR conditions. Beamforming significantly improves efficiency in dense urban deployments.

D. Bit Error Rate (BER) Performance

The Figure 4 shows the Bit Error Rate (BER) performance of QPSK modulation over an AWGN (Additive White Gaussian Noise) channel as a function of SNR (Signal-to-Noise Ratio) in dB.

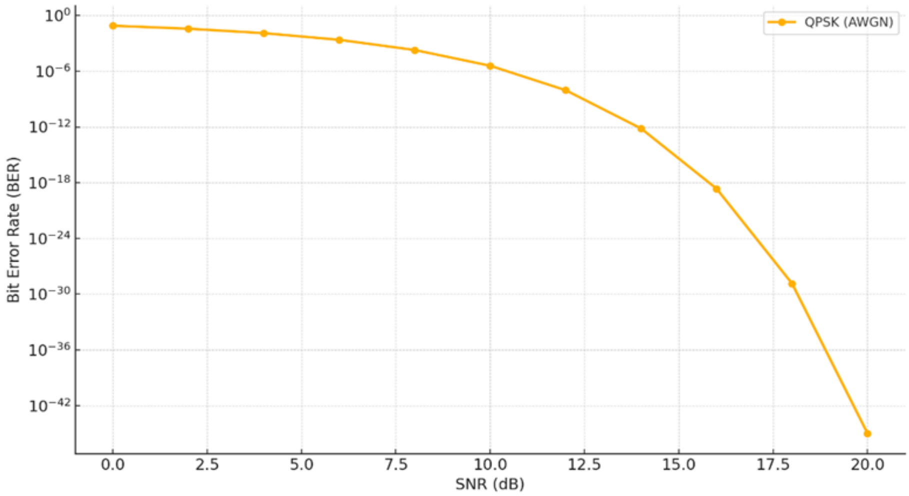


Figure 4: BER Vs. SNR for QPSK In AWGN Channel

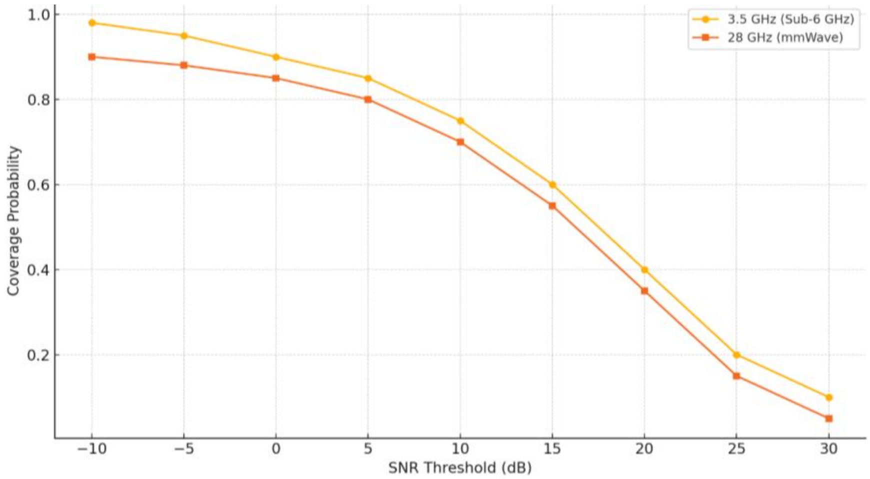


Figure 5: Coverage Probability Against SNR Threshold

The curve shows a monotonically decreasing trend, as SNR increases, the BER decreases. At low SNR (0–4 dB), the BER is relatively high, indicating a large number of bit errors due to noise. Beyond 10 dB SNR, the BER starts to drop sharply, signifying improved signal clarity and fewer bit errors. At 20 dB SNR, the BER becomes extremely low, approaching near error-free transmission.

QPSK performs well in AWGN channels, especially as SNR improves. The system requires an SNR of around 10 dB or higher to achieve BERs acceptable for most 5G applications. This analysis helps in choosing modulation schemes and power levels for reliable data transmission.

E. Coverage Probability

Figure 5 presents the coverage probability of the 5G cellular network as a function of the Signal-to-Noise Ratio (SNR) threshold for two operational frequencies: 3.5 GHz (sub-6 GHz) and 28 GHz (mmWave). Coverage probability is defined as the likelihood that a user experiences an SNR above a specified threshold, which directly correlates with the quality and reliability of the network connection.

The results indicate that the 3.5 GHz band exhibits higher coverage probability across the entire range of SNR thresholds when compared to the 28 GHz band. At lower thresholds such as -10 dB and 0 dB, the 3.5 GHz band achieves a coverage probability of approximately 98% and 90%, respectively, while the 28 GHz band trails slightly at 90% and 85%. As the SNR threshold increases, coverage probability for both bands decreases, reflecting the growing difficulty in maintaining high signal quality at higher thresholds. However, the decline is more pronounced for the 28 GHz band; at an SNR threshold of 30 dB, its coverage probability falls to around 5%, in contrast to about 10% for the 3.5 GHz band. This disparity is primarily due to the higher path loss and limited penetration capabilities of mmWave frequencies, which make them more susceptible to signal degradation and blockage. In contrast, sub-6 GHz frequencies offer better propagation characteristics, resulting in more consistent coverage. These findings highlight a trade-off in 5G network planning: while mmWave frequencies can support higher data rates, sub-6 GHz bands are more effective in ensuring broader and more reliable coverage.

V. CONCLUSION

This simulation-based analysis confirms that 5G NR outperforms previous generations in terms of throughput and spectral efficiency, especially under mmWave frequencies. However, challenges remain in ensuring reliable coverage and low latency under mobility and interference-rich environments. Throughput improves with SNR; 28 GHz outperforms 3.5 GHz due to wider bandwidth, but gains plateau beyond 25 dB due to system limitations. Higher subcarrier spacing reduces latency, making 120 kHz optimal for URLLC, while 15 kHz suits standard broadband use cases.

The system requires an SNR of around 10 dB or higher to achieve BERs acceptable for most 5G applications. This analysis helps in choosing modulation schemes and power levels for reliable data transmission. The result confirms that while 5G networks can scale to support many users, performance per user declines as load increases. The mmWave spectrum provides superior spectral efficiency, making it ideal for dense urban environments, though practical deployment must consider line-of-sight requirements and increased attenuation.

The results also show that while the 28 GHz mmWave band offers higher capacity, it has lower coverage probability due to signal attenuation and path loss. In contrast, the 3.5 GHz sub-6 GHz band provides more reliable and broader coverage. This highlights the need for a hybrid 5G network design that leverages both bands to optimize capacity and coverage. Recommendation.

Future work will include full-stack simulations with 5G core integration, energy efficiency analysis, and network slicing performance under realistic traffic models. This study makes several significant contributions to the field of wireless communications, specifically in the domain of 5G network design and evaluation. In essence, the research enhances understanding of 5G network behaviour under varying design parameters, and establishes MATLAB as a valuable platform for testing and optimizing next-generation cellular technologies.

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