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Performance Evaluatıon of Beamformıng in 5G OFDM Systems and Advantages over 4G

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ABSTRACT

This paper investigates the performance of 5G networks. It focuses on the implementation and advantages of Orthogonal Frequency Division Multiplexing (OFDM) and beamforming compared to 4G LTE systems. Through MATLAB simulations, it examines critical performance metrics, including signal-to-noise ratio (SNR), throughput, and latency, highlighting the benefits of 5G in enhancing data transmission rates, reducing latency, and supporting higher user density. Beamforming, a core component in 5G, enables directional signal transmission, significantly improving signal quality and reducing interference, especially in dense and urban environments. The results indicate that 5G, with its advanced technologies, outperforms 4G by delivering improved connectivity, increased network capacity, and low-latency communication, which are essential for emerging applications like IoT, autonomous vehicles, and augmented reality. Limitations related to frequency bands, simulation constraints, and scalability are acknowledged, with recommendations for future research focused on diverse testing conditions, higher frequency bands, and optimization techniques. This study underscores the transformative potential of 5G technology in modern wireless communications, setting the stage for future advancements as we transit toward 6G.

1. INTRODUCTION

The fifth-generation (5G) wireless network is a major step forward in telecommunications. It offers faster speeds, better reliability, and improved connectivity. Unlike earlier generations, 5G goes beyond simply speeding up mobile internet. By using advanced techniques like Orthogonal Frequency Division Multiplexing (OFDM) and beamforming, it supports high-demand technologies such as the Internet of Things (IoT), self-driving cars, and real-time services in various settings like cities, industries, and rural areas (Dixit, S., and Katiyar, H., 2018). These advancements position 5G as a key tool for future innovations in fields like healthcare and smart cities. The shift from 4G LTE to 5G addresses a growing need for faster data speeds, reduced latency, and support for a massive number of connected devices (Thota, et al., 2015). This need has driven 5G to introduce significant advancements in signal processing, particularly through technologies like Orthogonal Frequency Division

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Multiplexing (OFDM) and beamforming. These enhancements work together to improve data transfer rates, signal quality, and energy efficiency, allowing 5G to adapt to a wide range of use cases with flexibility and reliability.

OFDM, originally implemented in 4G LTE, has been refined in 5G New Radio (NR) to include flexible frequency use and seamless integration with massive MIMO (Multiple-Input, Multiple-Output) systems. This evolution allows 5G to operate across a broader frequency range, including higher frequencies like millimeter waves (mmWave), which are essential for high-capacity applications. With this adaptable structure, OFDM in 5G supports efficient use of frequency resources, making it versatile enough to meet the demands of various environments and network conditions (Baybakov et al., 2004).

Beamforming, another core innovation in 5G, directs radio signals precisely toward individual users, reducing interference and enhancing connectivity, especially in high-density areas. This targeted approach to signal transmission is crucial in urban environments, where managing interference is vital for maintaining stable connections. Additionally, beamforming supports ultra-reliable, low-latency communication (URLLC), making it ideal for applications that require quick response times, such as autonomous driving and remote healthcare. Together, these advancements position 5G as a powerful tool for enabling future technological growth across numerous fields, from smart cities to industrial automation (Hasneen and Sadique, 2021)

In summary, 5G represents a significant leap in wireless technology, addressing the growing need for faster, more reliable, and highly connected networks. With advancements in OFDM and beamforming, 5G not only enhances data speeds and connectivity but also supports a wider range of applications in diverse environments. These improvements lay a strong foundation for future innovations and provide critical support for technologies like IoT, smart cities, and real-time services. This study will further investigate 5G's potential by examining its key features in comparison to 4G LTE.

This study aims to conduct a Performance Evaluation of Beamforming in 5G OFDM Systems and Advantages Over 4G. The main objectives of this research is to:

1. Compare the performance of 5G's beamforming feature to that of 4G LTE, specifically Simulate 4G and 5G OFDM systems in MATLAB.
2. Create a channel model for 4G and 5G simulations.
3. Compare SNR and throughput in 4G and 5G scenarios.
4. Analyze time series data to quantify 5G beamforming advantages.

This research literature review highlights key advancements in 5G technology and its benefits compared to 4G LTE. The review organizes findings into themes to establish a foundation for this study and identify areas that need further research. Starting with the evolution of Wireless Technologies. Shukla and Sawarkar (2022) provided a comprehensive analysis of the transition from 4G to 5G, focusing on deployment architectures. Their research emphasizes the importance of both standalone (SA) and non-standalone (NSA) implementations, suggesting a gradual transition approach to optimize network performance. Gavric et al., (2019) complement this by detailing technical differences between 4G LTE and 5G NR, underscoring 5G's advanced capabilities.

Thereafter, review on the advancements in OFDM revealed that the evolution of OFDM technology has been central to 5G's enhanced capabilities. Liu, (2023) presents advanced OFDM techniques like Flexible Configured OFDM (FC-OFDM) and Generalized DFT-s-OFDM (G-DFT-s-OFDM), which improve spectral efficiency and adaptability. Bi et al., (2017) explore Filtered-OFDM (F-OFDM) in 5G networks, demonstrating its effectiveness in achieving seamless carrier aggregation and improved data rates. Similarly, in the area of beamforming techniques, Ahmed et al., (2018) analyze hybrid beamforming in 5G, showing that hybrid approaches balance performance and cost effectively. This is crucial for practical deployments, especially in high-density urban settings.

Following the studies on the OFDM Performance Analysis, Gupta and Nagaich (2017) establish performance baselines for OFDM under different channel conditions, while Manusha, (2019) examines F-OFDM's scalability in 5G, showing its ability to reduce complexity without sacrificing data rates. Balint and Budura (2018) confirm that 5G's multi-carrier waveforms offer superior spectral efficiency compared to 4G. While research on integration challenges highlights critical insights for deployment. Yli-Kaakinen et al., (2021) demonstrate improvements in spectral efficiency and flexibility through frequency-domain signal processing in 5G.

In the cause of literature review, some research gaps were identified. The review highlights several areas needing further investigation. These includes limited studies that offer direct and quantitative comparisons of 4G and 5G performance in varied environments. Insufficient data on beamforming's impact specifically in dense urban settings. Lack of standardized methods for comparing 4G and 5G performance metrics consistently.

2. METHODOLOGY

This study compares the performance of 5G's beamforming and OFDM systems to those of 4G LTE. MATLAB simulations was used to measure key factors like SNR (Signal Quality), Throughput (Data Speed), and Latency (Delay).

The 4G model is based on standard OFDM with Quadrature Phase Shift Keying (QPSK) modulation. It uses a 1.4 MHz bandwidth and a fixed 15 kHz subcarrier spacing in a 2x2 MIMO (Multiple-Input, Multiple-Output) setup. This setup, chosen for its simplicity, represents traditional 4G systems with basic processes like subcarrier allocation, Inverse Fast Fourier Transform (IFFT), and adding a cyclic prefix. Figure 1 shows the 4G LTE OFDM system, detailing the signal generation steps, including subcarrier allocation and IFFT processing.

The 5G model builds on the 4G model, adding advanced features for better performance. These features include flexible Subcarrier Spacing in which 30 kHz spacing is used to lower delay and improve performance. Beamforming, where by 8x8 antenna array with Maximum Ratio Transmission (MRT) beamforming is applied to focus signal energy toward the receiver, which helps reduce interference and improve signal quality. MIMO Setup using 8x8 array that allows both horizontal and vertical beamforming, giving 5G systems better control over signal direction.

Some key parameters for 5G are bandwidth which is 100 MHz, typical for mid-range 5G frequencies (sub-6 GHz) and modulation which is 16-QAM for higher data speeds. Figure 2 provides an overview of the 5G NR OFDM system, illustrating the flexible subcarrier spacing, MIMO setup, and beamforming.

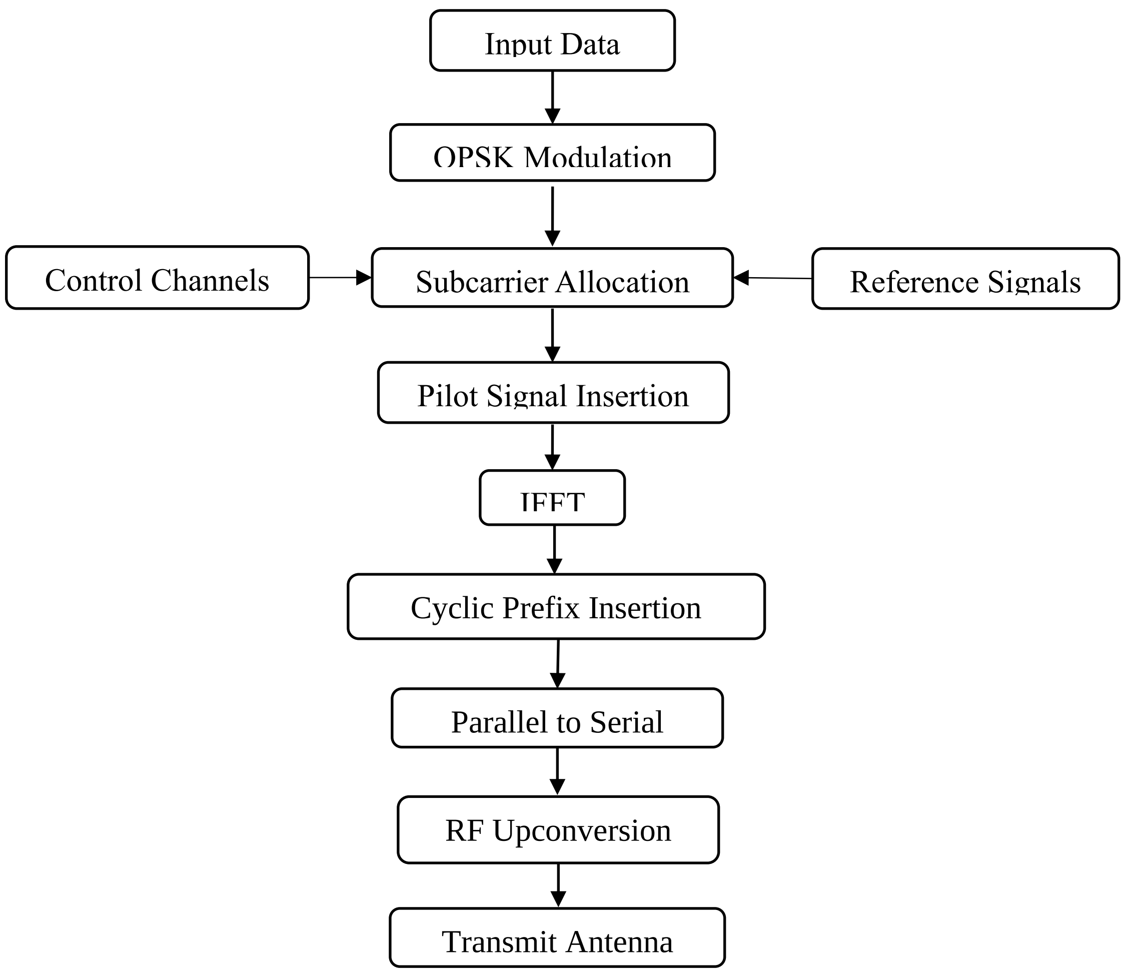

Figure 1: Block Diagram of the 4G LTE OFDM System Model

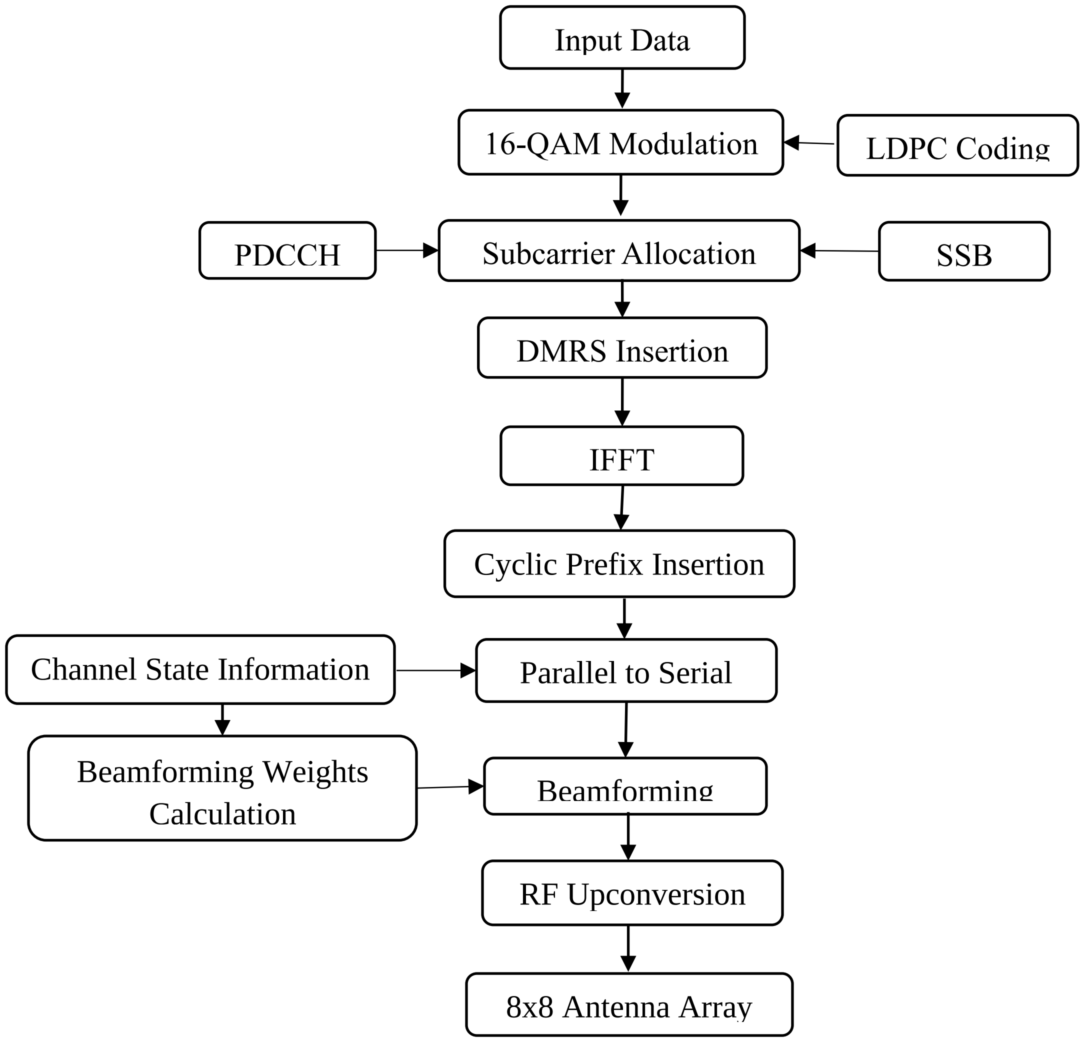

Figure 2: Block Diagram of the 5G OFDM System Model with Beamforming Model

Channel modeling is a critical component in evaluating the performance of wireless communication systems. For this study, simplified yet effective models were used to capture the main factors impacting signal propagation, attenuation, and interference in both 4G LTE and 5G NR systems under urban conditions. These conditions are path loss model, multipath fading and noise modelling as subsequently discussed.

Path Loss Model: The 3GPP Urban Macro (Uma) path loss model is chosen to represent a realistic urban environment, which is common for both 4G and 5G deployments. This model accounts for signal attenuation over distance and reflects the additional challenges posed by urban structures and environmental factors.

Multipath Fading: This is simulated based on conditions of Multipath Fading, Rayleigh Fading, Rician Fading and implemented the fading. The Multipath fading caused by reflections, scattering, and diffraction, is incorporated to simulate urban environments where signals can take multiple paths to the receiver. Also, Rayleigh Fading was applied for non-line-of-sight (NLOS) conditions where multiple reflected paths interfere, representing dense urban areas with significant obstacles. Similarly, Rician Fading was used for line-of-sight (LOS) conditions where a dominant direct path exists, alongside reflected paths. This is typical in open urban areas with fewer obstacles. For the fading implementation**,** MATLAB functions are utilized to generate Rayleigh and Rician fading profiles, allowing for realistic modeling of the signal variations that impact performance in 4G and 5G systems.

Noise Modeling: Additive White Gaussian Noise (AWGN) is added to represent thermal noise and minor interference sources within the urban environment.

Performance Metrics Calculation was carried out to evaluate and compare the performance of 4G LTE and 5G NR systems, we focused on key metrics: Signal-to-Noise Ratio (SNR), Throughput, and Latency. These metrics offer insights into system quality, efficiency, and overall user experience.

SNR computation indicates the quality of the received signal in relation to the background noise, directly impacting data rates and signal reliability. While throughput estimation reflects the actual data rate achieved by the system, providing a measure of network efficiency and capacity. Whereas latency measures the delay between data transmission and reception, a critical factor for real-time applications.

Simulation Scenarios were formulated to ensure the evaluation is thorough, several scenarios were simulated such as single-user scenario, multi-user scenario and environmental conditions. In a single-user scenario, a Static User with a stationary user at various distances (10m to 500m) was modelled from the base station to compare signal quality and speed between 4G and 5G. Also, Multi-User Scenarios with distributed ten users spread out within a 120-degree sector were simulated to evaluate how well 5G and 4G manage resources and interference. Thereafter, Environmental Conditions, Line-of-Sight (LOS) vs. Non-Line-of-Sight (NLOS) were examined on how beamforming performs with and without clear visibility to the base station, especially important in urban areas with obstacles.

3. RESULTS AND ANALYSIS

The simulations show clear performance improvements in 5G over 4G in terms of signal quality, speed, and delay.

SNR (Signal Quality)

The results show a significant improvement in signal quality (measured as SNR) in 5G compared to 4G, across both clear and obstructed conditions:

In obstructed (NLOS) conditions, 4G's SNR peaks at around 30 dB, while 5G reaches up to 60 dB, thanks to advanced signal processing. With clear line-of-sight (LOS) and beamforming, 5G achieves about 80 dB, more than doubling the signal quality of 4G. Figure 3 compares SNR levels for 4G and 5G in both LOS and NLOS conditions, showing 5G's strong improvement.

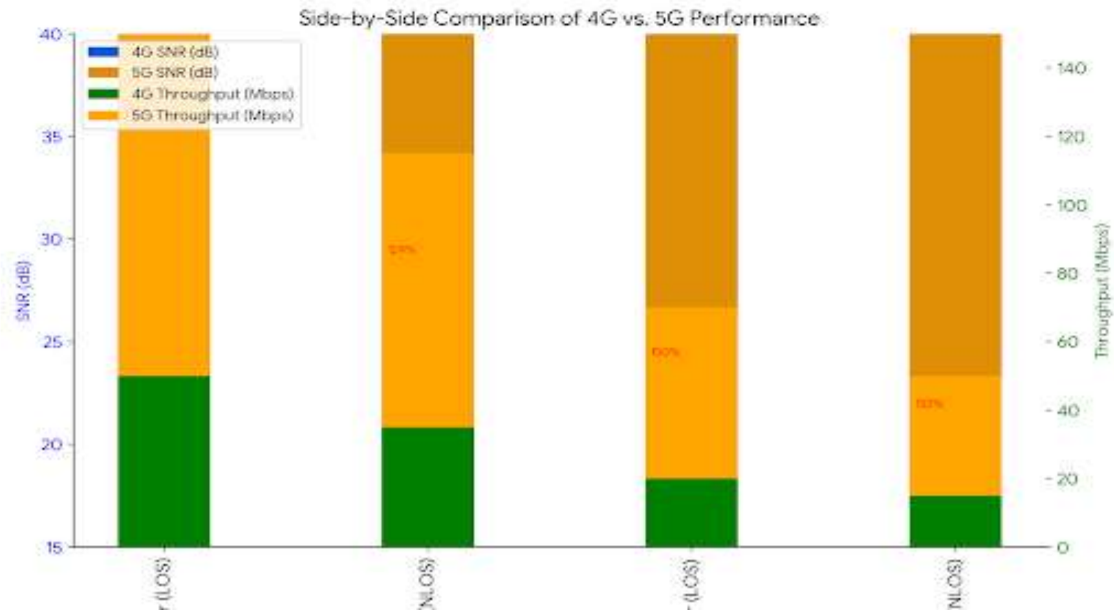

Figure 3: Comparison of 4G vs 5G Performance based on throughput and SNR

Throughput (Data Speed)
5G shows substantial gains in data speed over 4G. In obstructed (NLOS) conditions, 4G peaks at around 25 Mbps, while 5G achieves up to 60 Mbps, an improvement of 140%. With beamforming in clear conditions, 5G reaches over 100 Mbps, compared to 40 Mbps for 4G. The Figure 3 shows data speed levels for 4G and 5G at different SNRs, highlighting the improvement that 5G's beamforming provides.

Latency (Delay)
5G dramatically reduces delay compared to 4G, with latency as low as 1 ms in ideal conditions. This reduction makes it possible to support real-time applications like augmented reality (AR), virtual reality (VR), and industrial automation. Figure 4 compares latency between 4G and 5G, showing the lower delays that make 5G suitable for real-time applications.

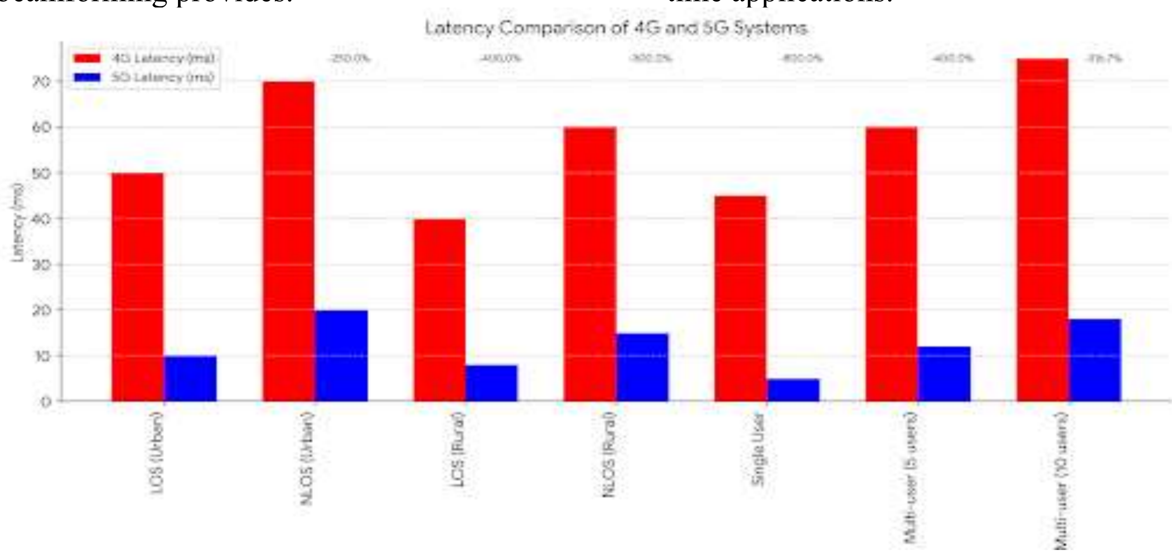

Figure 4: Latency Comparison of 4G and 5G Systems

Network Capacity and Scalability
Network capacity in 5G is significantly enhanced compared to 4G, owing to several technological innovations. These include Massive MIMO (Multiple Input Multiple Output), the use of higher frequency spectrum (such as mmWave), and advanced techniques like beamforming. Figure 5 provides a clear visual comparison, showing the distinct advantages that 5G holds over 4G in terms of handling more users and data traffic simultaneously.

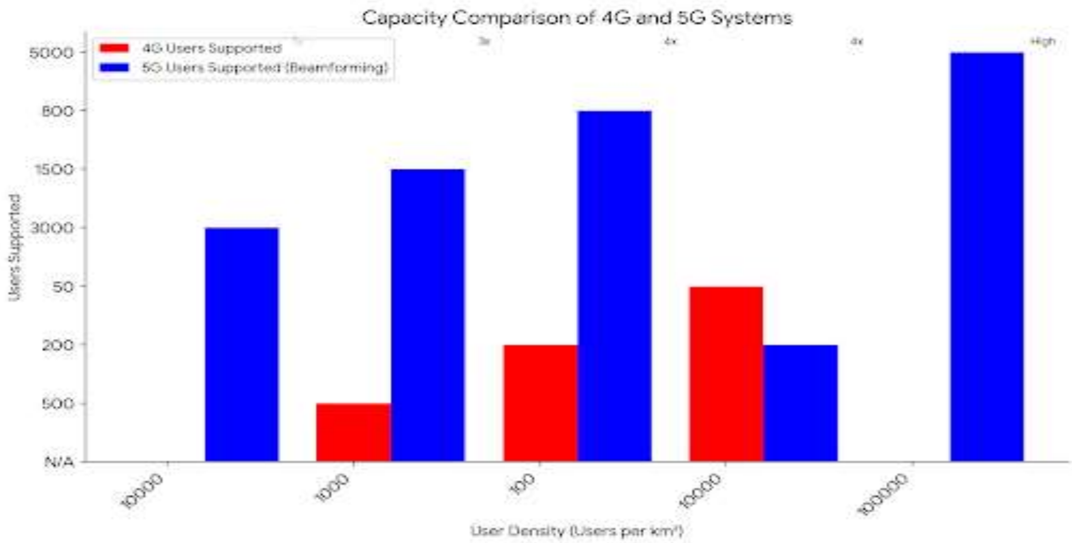

Figure 5: Capacity Comparison of 4G and 5G Systems

4G Network Capacity
In 4G networks, capacity is limited by the available spectrum and the number of antennas used for communication (MIMO configuration). The typical spectrum bandwidth used in 4G ranges from 10 MHz to 20 MHz, with support for up to 4x4 MIMO in some advanced deployments. The capacity of a 4G network, depending on the configuration, ranges from 100 Mbps to 1 Gbps under optimal conditions. However, this capacity decreases significantly as more users join the network or as they move further away from the base station.

5G Network Capacity Without Beamforming
Even without beamforming, 5G networks show a substantial increase in capacity compared to 4G due to wider spectrum usage and higher MIMO configurations. 5G can utilize up to 100 MHz of spectrum in sub-6 GHz bands, which is five times more than typical 4G deployments. Massive MIMO configurations, such as 32x32 or even 64x64, further increase the number of simultaneous connections, allowing the network to handle more users. As a result, 5G can achieve a capacity of up to 10 Gbps, which is 10 times higher than 4G in ideal conditions.

Discussion
The analysis of 4G and 5G networks presented in the previous sections highlights key advancements in 5G technology, particularly in terms of throughput, latency, signal-to-noise ratio (SNR), and beamforming capabilities. In this section, we synthesize the results and discussed their broader implications for network performance, user experience, and future applications.

4. CONCLUSION

This study has evaluated the performance of 5G's beamforming and OFDM technologies, comparing them to 4G LTE in key areas like signal quality, data speed, latency, and network capacity. Using MATLAB simulations, we found that 5G offers substantial improvements across these metrics, largely due to its advanced signal processing and beamforming capabilities.

Comparison between 4G and 5G systems, based on the presented images and data, provides several notable insights. 5G significantly outperforms 4G in terms of throughput, both for static and mobile users. Static users in 5G can experience speeds up to 10 Gbps, while mobile users benefit from throughput ranging from 100 Mbps to 1 Gbps, 5G's beamforming and Massive MIMO technologies are the major improvement compared to 4G, where throughput for mobile users often drops to 10 Mbps or lower. The latency in 5G networks is substantially lower than that of 4G, with average latency ranging from 1 ms to 10 ms in 5G, compared to 40 ms to 60 ms in 4G. The reduced latency in 5G opens up opportunities for real-time applications such as autonomous vehicles, remote surgery, and immersive augmented/virtual reality experiences.

5G exhibits better SNR performance at greater distances compared to 4G, particularly due to its use of beamforming. Beamforming helps maintain higher SNR even in mobile scenarios, which in turn sustains higher throughput levels over longer distances. This is particularly beneficial in urban and suburban environments where users are frequently in motion. Beamforming is a key feature of 5G, particularly in mobile scenarios. By directing the signal toward the user, beamforming mitigates signal loss and interference, ensuring that mobile users experience more consistent and higher throughput compared to 4G, which lacks such advanced signal optimization. 5G offers significantly higher network capacity than 4G, enabled by the use of wider spectrum bands, especially in the mmWave range, and the adoption of advanced MIMO configurations. This increased capacity allows 5G to handle more users simultaneously while providing higher data rates, addressing issues of congestion that are common in 4G networks during peak times.

These improvements in 5G have major implications for network performance and user experience. Higher speeds and lower delays in 5G greatly enhance the experience for data-heavy applications, like HD streaming and gaming. Lower delays and faster speeds allow 5G to support cutting-edge applications like autonomous Vehicles, AR and VR and industrial IoT /Automation: Reliable, quick data transfer is crucial for process control in industries. These findings highlight 5G's transformative potential for modern communication and high-demand applications. As 5G technology continues to develop, further research should focus on testing its scalability, efficiency, and real-world performance in various environments, ensuring it meets the demands of future applications.

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