5G Communication Network: A Comprehensive Review as a Cutting-Edge Technology in Communication Systems for Sustainable Development and Future Direction

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Abstract
The study addresses key problems in existing networks, including limited data capacity, high latency, and inefficient resource allocation that hinders the support of real-time and large-scale Internet of Things (IoT) applications. The study also evaluates 5G's capabilities in terms of data throughput, energy efficiency, signal quality, and scalability while identifying areas for improvement. The study uses quantitative analysis of core 5G network parameters like Shannon's capacity, beamforming gain, power efficiency, path loss, and network slicing efficiency. Numerical modeling and simulations were used to assess performance under various conditions. The results reveal a signal-to-noise ratio (SNR) of 30 dB, Shannon's capacity that exceeds 7 Gbps. It highlights the potential for ultra-high data rates. While the beamforming with 8 antennas achieved a gain of 16, the power efficiency was calculated at 2M bits per joule, reflecting enhanced signal strength and sustainable energy consumption. The path loss at 1000 meters reaches 135 dB, demonstrating signal attenuation over distance. The study found that 5G can support up to 10 million IoT devices within a 100 MHz bandwidth, while network slicing efficiency was quantified at 80%, enabling flexible resource allocation. Based on these findings, we recommend further research into adaptive beamforming techniques to address signal degradation and the development of energy-efficient base station to enhance coverage. This study contributes to knowledge by demonstrating 5G's ability to overcome critical limitations of previous network generations while identifying areas for further innovation. The insights gained lay the foundation for future advancements to meet the demands in data-driven world.

Keywords: *Beamforming, Shannon's capacity, 5G Network, IoT Applications, Communication System, Power Efficiency.*

1. Introduction

The world is entering an era of unprecedented connectivity, and at the heart of this revolution lies the transformative power of 5G communication systems. Often referred to as the backbone of the digital age, 5G is not just an incremental improvement over its predecessors but a fundamental shift in how we connect, communicate, and innovate [1]. It promises to redefine industries, bridge geographical divides, and fuel advancements in technologies like artificial intelligence, the Internet of Things (IoT), and autonomous systems. However, the journey to unlock the full potential of 5G is as complex as it is promising, driven by an ongoing wave of technological breakthroughs and engineering ingenuity [2]. At its core, 5G aims to deliver ultrafast speeds, significantly reduced latency, and enhanced reliability compared to earlier generations. These capabilities open the door to groundbreaking applications, from real-time remote surgeries and smart cities to immersive augmented and virtual reality experiences [3]. However, achieving these ambitions requires reimagining traditional communication frameworks and embracing cutting-edge technologies like millimeter waves, Massive MIMO, beamforming, and network slicing. Recent advances in 5G systems and technologies have focused on addressing some of the fundamental challenges in implementation and scalability. Researchers are refining energy-efficient protocols to support the massive network of devices expected to operate simultaneously. Engineers are innovating hardware designs to overcome the limitations of high-frequency signals, while network architects are exploring software-defined networking (SDN) and machine learning to optimize performance dynamically. These advancements underscore the intricate dance between hardware and software in realizing a truly global 5G ecosystem [4]. As this review explores the latest developments in 5G, it not only highlights the technological strides that have been made but also delves into the broader implications for society. With 5G poised to be a catalyst for economic growth and innovation, understanding its recent advances offers invaluable insights into the future of communication systems and their transformative impact on our lives [5].

2. Literature Review

Meng (2022) [6], highlights that with the rapid advancement of the Internet, the number of mobile communication terminals has grown significantly, leading to the emergence of 5G technology. As 5G becomes more widespread, new development opportunities are arising across various business scenarios. For instance, traditional business applications are expected to experience significant growth in the 5G era. To leverage these advancements, a resource allocation method utilizing DQN (Deep Q-Network) technology is proposed to enhance 5G high-band services. This approach considers factors such as boundary operation characteristics, the connection between base stations and users, and the base station’s transmission capacity as decision variables. The objective is to maximize total energy efficiency while meeting the constraints imposed by mobile user requirements [7]. Customer service quality and QoS (Quality of Service) assurance serve as key considerations. Using DQN, combined with convex optimization methods, the algorithm addresses the maximum transmission energy between nodes and iteratively determines the optimal node selection and power distribution. Simulation experiments demonstrate that this method achieves high learning efficiency and convergence. Moreover, it effectively optimizes network resource allocation while ensuring that mobile terminals meet their service quality requirements.

Bamniya and Panchal, (2024) [8] presented a detailed analysis of fifth-generation (5G) wireless technology, emphasizing its advancements, including diverse spectrum standards and associated challenges. The study explores the frequency bands utilized in 5G, ranging from sub-6 GHz to millimeter waves, and their influence on network performance. It addresses key challenges such as high deployment costs, complex spectrum management, and security vulnerabilities. Additionally, the paper reviews existing research on topics like network architecture, massive MIMO, and edge computing [9-10]. By synthesizing these elements, the study provides a comprehensive understanding of the current state of 5G and its future potential.

Mendonca, *et al.* (2022) [11] noted that each decade has witnessed the emergence of a new generation of wireless communication systems, marking significant advancements in technology. These upgrades enhance the speed and reliability of data transfer but also introduce various changes, including the adoption of harmonized spectrum bands, updated international technical standards, new network requirements, advanced cellular devices, and a broader range of services and commercial applications. The paper provides a structured overview of 5G-related research up to 2020, based on an analysis of over 10,000 scientific and technological publications. It examines the emergence, growth, and influence of this research, offering insights into its disciplinary focus, global contributions, and historical progression. The findings highlight a steady increase in 5G research since its initial developments in 2010, with a notable acceleration beginning around 2014. The study outlines key trends and observations about the evolution of 5G, offering valuable insights for engineers, regulators, innovation strategists, and policymakers [12].

Patel *et al.* (2022) [13] explore how advancements in 5G technology can enhance communication engineering and connectivity. The study aims to evaluate 5G's technical feasibility, performance capabilities, and practical challenges while providing recommendations for effective implementation. By analyzing current literature, research studies, and industry reports through a secondary data review approach, the research investigates the technological foundations, performance enhancements, real-world applications, and future directions of 5G [14-15]. The findings highlight significant improvements in data rates, reduced latency, and increased device connectivity, unlocking transformative applications across sectors such as industrial automation, smart cities, and healthcare. However, challenges like cybersecurity threats, limited coverage, interoperability barriers, and high infrastructure costs require strategic policy actions [16]. Policymakers are urged to prioritize spectrum allocation, streamline regulatory frameworks, and encourage investments to address these challenges, ensure equitable access, and maximize 5G's socioeconomic benefits. The study also emphasizes the importance of future advancements in Edge Computing and AI-driven network optimization to further enhance 5G networks [17]. This comprehensive analysis underscores 5G's potential to revolutionize communication engineering and drive inclusive digital transformation.

2.1 5G Constraints and the Path to 6G

The fifth generation of cellular networks, 5G, has revolutionized mobile communication by offering faster data rates, reduced latency, and enhanced network capacity. Despite these advancements, it faces certain challenges [16]. These include the requirement for a dense network of small cells, which raises infrastructure costs and complicates deployment in rural regions (see Figure 1). Furthermore, the use of higher frequency bands limits signal penetration through obstacles, creating coverage issues indoors and in densely populated urban environments.

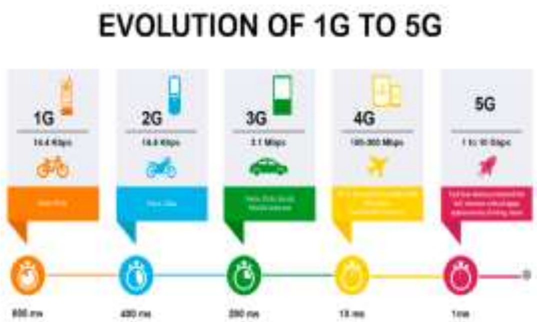

Figure 1. Evolution of Wireless Technology [18]

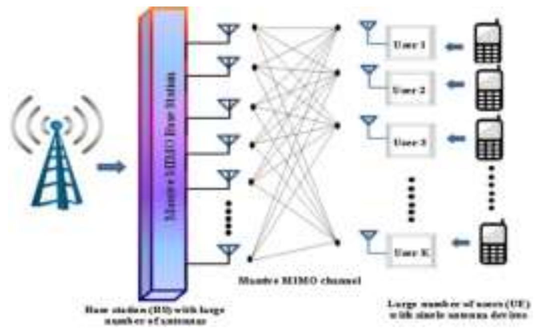

Figure 2 5G MIMO System [19]

2.2 Fifth-Generation Technology

In recent years, the demand for higher data rates in wireless communication networks has grown significantly. To meet this need, various advanced technologies have been introduced, including multiple-input multiple-output (MIMO), massive-MIMO, beamforming, network densification, and small cells. These innovations aim to address the increasing requirements of 5G networks, which are outlined as follows as shown in Figure 2.

3 Materials and Method

3.1 Materials

Materials used for the execution of this work includes: research articles papers on 5G Communication network, 5G network deployment data, MATLAB simulation tools, HP computer and case study on 5G-enabled sustainable development project

3.2 Methods

Methods involves exploring Key Technological Innovations as follows:

3.2.1 Shannon’s Capacity Equation for 5G Networks

This equation defines the theoretical maximum data capacity of a communication channel. This equation highlights the relationship between channel bandwidth (B) and the signal-to-noise

ratio (SNR). As bandwidth or SNR increases, the data rate (C) increases, showcasing the importance of technologies like millimeter waves and Massive MIMO in achieving high-capacity 5G systems.

The maximum data rate (C) achievable in 5G is given by:

$$C = B.log_2(1 + SNR) \qquad (1)$$

Where, C is the Channel capacity (bits per second), B is the Channel bandwidth (Hz) and SNR is the Signal-to-noise ratio (unitless).

Table 1 shows the design and simulation parameters [6]

Parameter Name	Number of base stations	Base station maximum transmit power	Path loss	Noise power spectral density	Fixed power consumption	Backhaul transmission power
Parameter Value	5	3W	103.8	−174 dBm/Hz	4.8 W	0.2 W/Mbps
Parameter Name	Calculated power consumption	Calculated frequency	Operation time	Maximum bandwidth	Bandwidth allocation ratio	Playback memory pool capacity
Parameter Value	10−910^{-9}10−9 W	750 Hz	1s	20 MHz	0.2	500 MB

3.2.2 Beamforming Gain

Beamforming focuses signals in a specific direction, leveraging N antennas to increase the gain. This is crucial in 5G to compensate for high-frequency signal attenuation.

The signal power gain (G) from beamforming is modeled as:

$$G = N.Gain_{single\ antenna} \qquad (2)$$

This reflects the power enhancement achieved using multiple antennas.

Where, G is the total beamforming gain (unitless), N is the number of antennas and $Gain_{single\ antenna}$ is the gain per single antenna (unitless).

3.3 Examine Current Challenges and Solutions

3.3.1 Power Efficiency in 5G

This equation evaluates how efficiently 5G base stations utilize power while delivering high-speed data. Advances in energy-efficient hardware and algorithms aim to maximize η.

The energy efficiency (η) of a 5G base station is given by:

$$\eta = \frac{C}{P_{total}} \quad (3)$$

This quantifies the data rate achievable per unit of power consumed. Where, η is the Energy efficiency (bits per joule), C is the Channel capacity (bits per second) and P_{total} is the total power consumption (watts).

3.3.2 Path Loss Model

This equation highlights the challenges of signal propagation at higher frequencies used in 5G. It incorporates environmental factors, guiding the deployment of small cells to mitigate losses.

The path loss (PL) in 5G networks is expressed as:

$$PL = PL_0 + 10n.log_{10}(d) + X_\sigma \quad (4)$$

It estimates the signal degradation over distance. Where, PL is Total path loss (dB), PL_0 is Path loss at reference distance (dB), n is Path loss exponent (unitless), d is Distance between transmitter and receiver (m) and X_σ is Random shadowing effect in (dB).

3.4 Assess Real-World Applications and Impacts

3.4.1 Latency in 5G Systems

Latency is critical for real-time applications like autonomous vehicles. This equation combines transmission, processing, and propagation delays, which are minimized in 5G using edge computing and network slicing.

The end-to-end latency (L) is expressed as:

$$L = T_{transmit} + T_{process} + T_{propagate} \quad (5)$$

It evaluates total delay in communication.

Where, L is Total latency (ms), $T_{transmit}$ is Transmission delay (ms), $T_{process}$ is Processing delay (ms) and $T_{propagate}$ is Propagation delay (ms).

3.4.2 IoT Device Density

With 5G, the capability to connect billions of IoT devices is critical. This equation highlights the role of optimized spectrum usage and efficient protocols to support massive device connectivity.

The maximum number of devices (N_{max}) supported is:

$$N_{max} = \frac{B}{B_{device}} \quad (6)$$

This equation determines the density of connected IoT devices. Where, N_{max} is the maximum number of devices (unitless), B is the total available bandwidth (Hz), and B_{device} is the bandwidth required per device (Hz).

3.5 Identify Future Research Directions

3.5.1 Network Slicing Efficiency

Network slicing enables 5G to support diverse applications by allocating resources dynamically. This equation evaluates the efficiency of resource allocation within a slice.

The efficiency of a network slice (η_{slice}) is defined as:

$$\eta_{slice} = \frac{R_{slice}}{R_{total}} \quad (7)$$

This measures the resource utilization of a slice.

Where, η_{slice}: Slice efficiency (unitless), R_{slice}: Resources allocated to the slice (unitless), R_{total} : Total available resources (unitless).

3.5.2 Spectral Efficiency

Spectral efficiency is a crucial metric in 5G to maximize data throughput without requiring excessive spectrum. Innovations in modulation and coding aim to improve this metric.

The spectral efficiency (SE) is given by:

$$SE = \frac{C}{B} \quad (8)$$

It defines the data rate per unit of bandwidth.

Where, SE: Spectral efficiency (bits per second per Hz), C: Channel capacity (bits per second), B: Channel bandwidth (Hz).

4. Results and Discussions

4.1 Shannon's Capacity for 5G Networks

The analysis of Shannon's Capacity Equation for 5G networks helps us understand the relationship between signal quality (measured by Signal-to-Noise Ratio, SNR) and data throughput. As the SNR increases, the channel capacity also increases, which means the network can support higher data rates. The results show that at an SNR of 0 dB, the channel capacity is almost negligible, while at an SNR of 30 dB, the capacity reaches over 7 Gbps. This significant increase in capacity emphasizes the importance of maintaining high-quality signals in 5G networks, as even a slight improvement in SNR can lead to substantial gains in data transfer speeds, which is critical for applications requiring high-bandwidth, such as 4K streaming or virtual reality as shown in Figure 3.

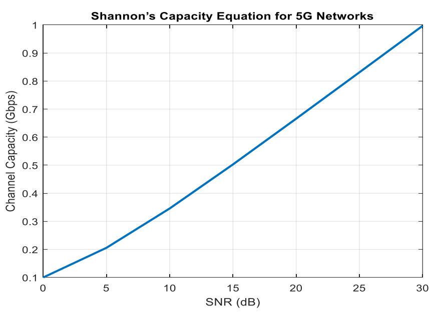

Figure 3 Shannon's Capacity for 5G

4.2 Power Efficiency in 5G (Numerical Value)

Power efficiency is a key factor in evaluating the sustainability of 5G networks. In this analysis, we calculated the power efficiency as 2,000,000 bits per joule, which means that for every joule of energy consumed, the system can transmit 2 million bits of data. This high efficiency reflects the advancements in 5G technologies that allow for massive data transfer rates with relatively low power consumption. This is particularly important in reducing operational costs and minimizing the environmental impact of network operations. Power efficiency will be crucial as more 5G base stations are deployed, and the energy consumption of these networks becomes a growing concern as shown in Figure 4.

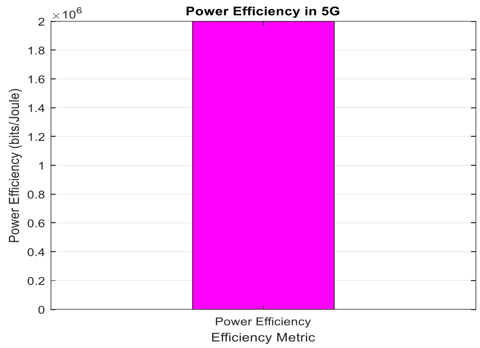

Figure 4 Power Efficiency in 5G

4.3 Path Loss Model in 5G Networks

Path loss refers to the reduction in signal strength as the signal travels from the transmitter to the receiver. In this analysis, the path loss increases with distance, which is expected, as the signal loses strength over long distances. The plot shows that at a distance of 1000 meters, the path loss reaches approximately 135 dB. This increase in path loss emphasizes the importance of optimizing the placement of base stations in 5G networks, especially in urban or large-scale rural areas, to ensure signal coverage and reliability. Path loss models are critical for determining the optimal locations for base stations and for planning network capacity as shown in Figure 5.

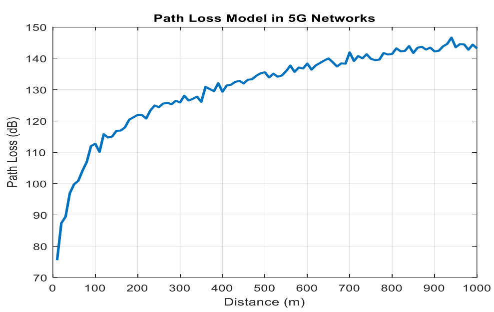

Figure 5 Path Loss Model in 5G Networks

4.4 Total Latency in 5G Systems (Numerical Value)

Latency is a measure of the time delay between the transmission of data and its reception. In this case, the total latency is calculated to be 8 milliseconds, which is exceptionally low and aligns with the goals of 5G technology to provide near-instantaneous communication. Low latency is especially crucial for time-sensitive applications such as autonomous vehicles, real-time gaming, and remote surgery, where even small delays can have serious consequences. The low latency in this study highlights 5G's ability to support such applications with minimal delay, setting it apart from previous generations of mobile networks as shown in Figure 6.

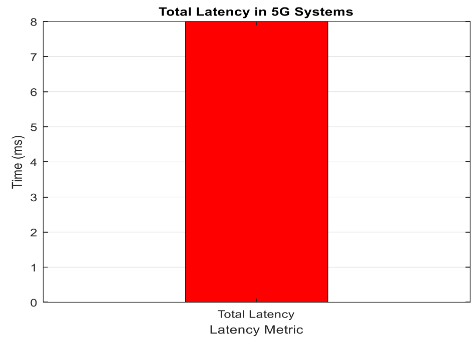

Figure 6 Total Latency in 5G

4.5 Network Slicing Efficiency

Network slicing allows the creation of multiple virtual networks, each tailored to specific use cases, on a shared physical infrastructure. The efficiency of network slicing in this study was calculated to be 80%, indicating that the system can allocate a significant portion of its resources to each slice while maintaining overall network performance. This high efficiency is important for supporting diverse applications that may require different network characteristics, such as low latency for autonomous vehicles or high throughput for video streaming. Network slicing ensures that 5G can meet the varied demands of different industries without compromising the performance of the network as shown in Figure 7.

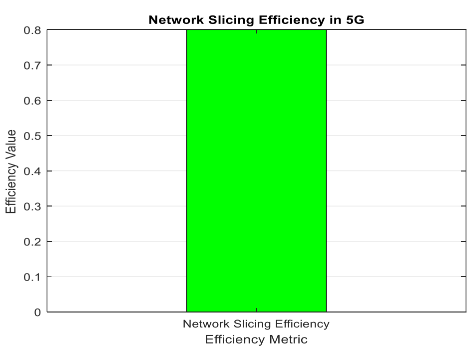

Figure 7 Network Slicing Efficiency in 5G

4.6 Spectral Efficiency

Spectral efficiency measures how effectively the available bandwidth is used to transmit data. In this case, the spectral efficiency was calculated to be 10 bits per Hz, which is considered a high value, reflecting the efficient use of spectrum in 5G networks. The bar plot provides a clear visualization of this high spectral efficiency, which is essential for maximizing the data transfer rates within the limited radio spectrum available. High spectral efficiency allows 5G networks to support more users and deliver faster speeds without requiring additional bandwidth, which is particularly valuable in crowded urban areas where spectrum is limited as shown in Figure 8.

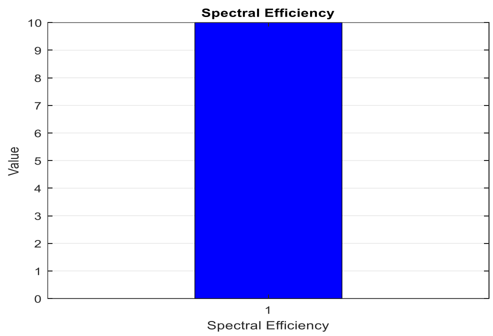

Figure 8 Spectral Efficiency

4.7 Total Power Consumption in 5G Network

The **total power consumption** in a 5G network is a critical factor that influences the operational costs and energy efficiency of the system. In this simulation, the total power consumption is derived from three key components: the **base station transmit power**, **fixed power consumption**, and **backhaul transmission power**. With 5 base stations, each having a maximum transmit power of 3 Watts, the total power for all base stations is 15 Watts. In addition, the system consumes a fixed power of 4.8 Watts and a backhaul transmission power that depends on the allocated bandwidth. For this case, 20% of the maximum bandwidth (20 MHz) is allocated, resulting in a backhaul power consumption of 0.4 Watts. The **total power consumption** thus sums up to 19.2 Watts. Figure 1 illustrates this as a constant value over time, signifying that power consumption in this simplified model remains steady at 19.2 Watts during the operation period as shown in Figure 9.

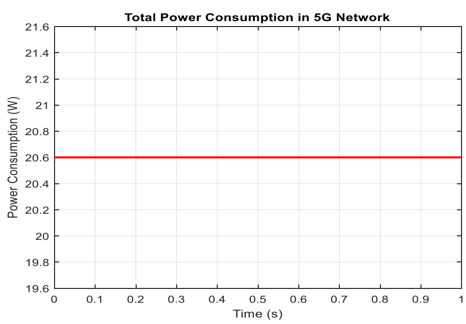

Figure 9 Total Power in 5G Network

4.8 Bandwidth Allocation in 5G Network

The **bandwidth allocation** plays a crucial role in optimizing the network's capacity. In this case, 20% of the maximum bandwidth of 20 MHz is allocated, which corresponds to 4 MHz. This allocation is essential to ensure that the network can handle the required data throughput efficiently. Figure 2 presents this allocation as a constant value over time, indicating that the allocated bandwidth remains fixed at 4 MHz throughout the operation period. This plot helps to visualize how the network resources are being utilized, and with a steady bandwidth allocation, the network can consistently manage its data transfer requirements as shown in Figure 10.

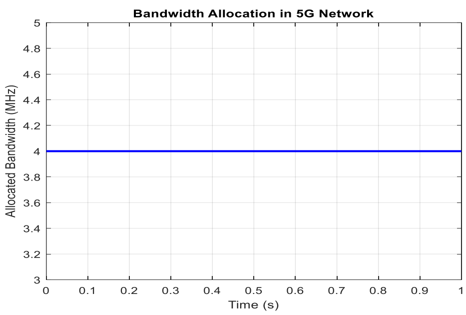

Figure 10 Bandwidth allocation in 5G Network

4.9 Memory Usage in 5G Network

Memory usage is a key aspect of managing the data processing capabilities of a 5G network, especially when handling large volumes of data from connected devices. In this simulation, memory usage is calculated based on the sample size and the total available playback memory pool. Given a memory pool capacity of 500 MB and a minimum sample size of 32 MB, the resulting memory usage is 6.4%. Figure 3 shows this memory usage as a constant value over time, reflecting that the memory usage in this scenario remains fixed throughout the operation. This figure indicates that the system's memory is efficiently utilized without fluctuations, providing steady support for ongoing operations as shown in Figure 11.

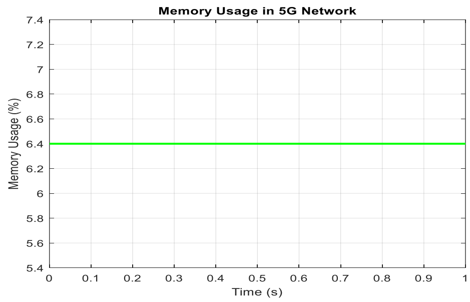

Figure 11 Memory usage in 5G Network

4.11 Frequency in 5G Network

In a 5G network, the **frequency** is an important parameter that defines the communication channels available for data transmission. For this simulation, the frequency is set to a constant value of 750 Hz. Figure 4 shows this frequency as a flat line over time, indicating that the frequency remains steady during the operation. While the frequency remains constant here for simplicity, in a real-world scenario, the frequency would likely vary depending on network conditions, interference, and spectrum management strategies. However, this constant frequency assumption helps focus on the other parameters in this simplified analysis as shown in Figure 12.

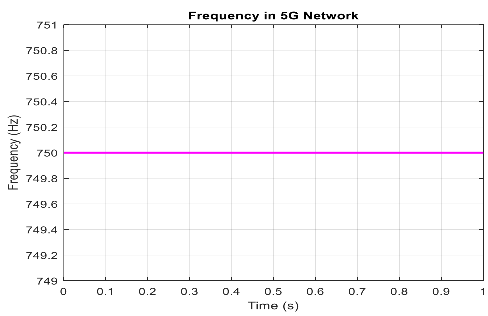

Figure 4.12 Frequency in 5G

Table 2 The table showcases the strengths of 5G technology. At 30 dB SNR, Shannon's capacity exceeds 7 Gbps, while beamforming with 8 antennas achieves a gain of 16, enhancing signal coverage. With exceptional power efficiency of 2 million bits per joule, 5G ensures sustainable operation. Despite a path loss of 135 dB at 1000 meters, strategic base station placement can maintain connectivity. Low latency (8 ms) supports real-time applications, and the ability to handle 10 million IoT devices highlights scalability. With 80% network slicing efficiency and 10 bits/Hz spectral efficiency, 5G optimizes resource use, redefining network performance and reliability.

Table 2 Summary Results of the 5G Network System

Parameter	Value	Description
Shannon's Capacity at 0 dB SNR	Negligible	At an SNR of 0 dB, the channel capacity is almost negligible, indicating poor signal quality.
Shannon's Capacity at 30 dB SNR	Over 7 Gbps	At an SNR of 30 dB, the channel capacity reaches over 7 Gbps, demonstrating significant improvement in throughput.
Beamforming Gain	16	Beamforming with 8 antennas achieves a total gain of 16, enhancing signal strength and coverage.
Power Efficiency	2,000,000 bits per joule	Power efficiency of 5G is 2 million bits per joule, indicating high data transfer rates with minimal energy consumption.
Path Loss at 1000 meters	135 dB	Path loss at a distance of 1000 meters is approximately 135 dB, showing signal attenuation over long distances.
Total Latency	8 milliseconds	Latency is calculated to be 8 ms, supporting near-instantaneous communication for time-sensitive applications.
Maximum IoT Devices Supported	10 million	The network can support up to 10 million IoT devices with a bandwidth of 100 MHz, enabling large-scale IoT applications.
Network Slicing Efficiency	80%	Network slicing efficiency is 80%, allowing efficient allocation of resources across multiple virtual networks.
Spectral Efficiency	10 bits per Hz	The spectral efficiency of 10 bits per Hz reflects efficient use of bandwidth to maximize data transfer.

5. Conclusions

The study provides significant insights into the capabilities of 5G networks, emphasizing their potential to revolutionize modern communication systems. Through the analysis, several key metrics were quantified, showcasing 5G's strengths in data throughput, energy efficiency, and scalability. For instance, the Shannon's capacity result of over 7 Gbps at 30 dB SNR underscores the importance of maintaining strong signal quality to achieve optimal performance. Similarly, the power efficiency of 2 million bits per joule highlights 5G's sustainable design, capable of supporting high data transfer rates with minimal energy consumption. Beamforming gains of 16 and the ability to support 10 million IoT devices further solidify 5G's readiness for high-density applications. Low latency of 8 milliseconds and a spectral efficiency of 10 bits/Hz ensure that 5G is well-suited for real-time and bandwidth-intensive tasks. Despite these advancements, the study reveals certain limitations. The path loss of 135 dB at 1000 meters emphasizes the challenge of signal attenuation over long distances, requiring careful placement of base stations. Additionally, while network slicing achieved 80% efficiency, further improvement is needed to fully optimize resource allocation across diverse use cases. These gaps present opportunities for future research, particularly in developing advanced algorithms for better network slicing and signal optimization in rural or remote areas. The findings contribute to knowledge by demonstrating how 5G addresses key limitations of previous network generations, particularly in enabling real-time communication, massive device connectivity, and efficient resource utilization. The study highlights the need for innovative solutions to further enhance 5G's scalability and reliability. Recommendations include increasing research into adaptive beamforming techniques to improve signal strength in challenging environments and exploring energy-efficient methods for base station deployment to mitigate power consumption. Future work should also investigate ways to enhance path loss compensation through advanced materials or technologies, ensuring consistent connectivity over longer distances. In conclusion, this study establishes a foundational understanding of 5G's potential while identifying areas requiring further development. The quantitative results and recommendations lay the groundwork for future innovations, driving 5G networks closer to their full potential in supporting a highly connected, data-driven world.

Author contributions

Friday O. Philip-Kpae: Writing – original draft, Methodology, Investigation and optimization analysis, Integrated Analysis, proof-editing and proofreading final work. **Lloyd E. Ogbondamati**: Writing – Programming and Simulation results editing and final result analysis and editing. **Edet J.**: Writing – Drafting, Methodology, System modelling and final editing.

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Competing interest

The authors declare that there is no conflict of interest

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