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Original Article

Analysis of Uplink Performance of 5G mm-Wave Networks in Contrast to 4G Networks

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Abstract *- 5G, the latest wireless communication network, offers high-speed data transmission capabilities and is known as New Radio (NR). It serves as an extension of 4G technology. The main objective of this research is to analyze the physical layer of 5G NR and 4G Long Term Evolution (LTE) using MATLAB 2020a. In this context, the study evaluates the performance of 4G and 5G in the uplink cell, focusing on metrics such as Throughput, Spectral Efficiency, Latency, and Block Error Rate (BLER). It also highlights the differences between 4G LTE and 5G NR. Notably, 5G outperforms 4G in various aspects: it achieves a spectral efficiency of 25 bps/Hz, while 4G only manages 2.52 bps/Hz. Throughput for 5G shows a 5% improvement over 4G (considering 300 frames). The latency in 5G is reduced to less than 0.1ms compared to 4G, and the Block Error Rate has decreased from 0.02 to 0.01. These findings illustrate that 5G offers a wide range of services with high data rates, extensive coverage, reduced latency, increased system capacity, and enhanced user connectivity across the board.*

Keywords *- Block error rate, Latency, Physical layer, Spectral efficiency, Throughput, Uplink cell.*

1. Introduction

In the past few years, there have been notable progressions in mobile networks, and wireless communication standards have become a crucial aspect of our everyday experiences. The development of communication networks has been continuous, with each successive generation aiming to provide "mobile broadband." The enhancement of cellular network design has been a constant effort to adapt to the rising number of users and escalating data traffic. Engineers have been actively seeking improved solutions in their quest for increased bandwidth, quicker connection times, and smooth handovers. [1].

Within this framework, the objectives of 4G encompass ambitious goals [2], including the provision of exceptionally high data rates for users in motion and the assurance of seamless handovers. Consequently, there has been a substantial focus on research endeavors aimed at defining a future standard capable of improving Quality of Service (QoS) with regard to throughput, mobility, and other relevant factors [3].

Moreover, the increasing prominence of high-resolution real-time applications in future wireless communication systems necessitates low latency. Present communication systems face challenges in efficiently meeting these crucial requirements. As a result, the wireless communication industry is actively working towards supporting approximately 1000 times more data traffic than the current capacity, which is around 10 gigabits per second (Gbps). This expanded capacity aims to facilitate the connection of a multitude of devices, enable high-resolution applications with minimal delay, and promote continuous communication within the upcoming Fifth Generation (5G) wireless communication systems.

The 3GPP New Radio (NR) serves as a unified and adaptable air interface designed to accommodate the three primary categories of 5G communications [4], as defined by the ITU:

- Enhanced Mobile Broadband
- Ultra-Reliable Low-Latency Communication
- Massive Internet of Things

Beyond these fundamental categories, NR is also equipped to support various 5G vertical applications, extending its functionality to industries such as automotive and healthcare.

In the realm of 5G connectivity, a diverse spectrum of frequencies is employed, broadly categorized into two main groups:

- Sub-6 GHz
- Millimeter wave (MM Wave)

Frequencies categorized as Sub-6 GHz, spanning from 410 MHz to 7 GHz (FR1), are predominantly utilized for traditional cellular mobile communications and traffic, covering longer distances. Conversely, mm-wave frequencies, ranging from 24 GHz to 52 GHz (FR2), are optimized for short-range communication with high data rate capabilities. While these higher frequencies enable faster data transmission, they come with the trade-off of having a more limited coverage area.

To enhance data rates, the 5G architecture employs the Multiple-Input-Multiple-Output (MIMO) concept. Each cell is equipped with multiple antennas that communicate with wireless devices, facilitating the simultaneous transmission of multiple data streams in parallel. The 5G system is structured around three main channels: transport, logical, and physical channels, with further subdivisions for both downlink and uplink channels [5]. For uplink communication, key 5G NR physical channels include the Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH), and Physical Random Access Channel (PRACH).

Additionally, 5G utilizes a New Radio interface and advanced technologies that operate at significantly higher radio frequencies (e.g., 28 GHz instead of 2.5 GHz in 4G). This enables the transfer of larger volumes of data at faster speeds, reducing congestion and latency [6]. Using a millimeter wave spectrum in this new interface allows a greater number of devices to operate within the same geographic area. In contrast, while 4G can support approximately 4,000 devices per square kilometer, 5G is anticipated to support around one million, allowing more users to stream data without interruptions, even in densely populated areas with limited available air space.

2. Literature Review

The primary focus of this paper [7] is to provide an in-depth understanding of spectral efficiency in fourth-generation wireless LTE networks. It aims to explore the various factors that impact this metric and examine potential methods for enhancing it. The study and analysis conducted reveal that Signal-to-Interference-Plus-Noise Ratio (SINR) is a crucial measurement that directly influences spectral efficiency. In the LTE network, User Equipment (UE) calculates the Channel Quality Indicator (CQI) value based on SINR, which is then reported back to the LTE base station. Subsequently, the link adaptation entity within the eNB (Evolved Node B) selects an appropriate Modulation and Coding Scheme (MCS) index. This MCS index is then mapped to a corresponding Transport Block Size (TBS) index, which determines the size of the transport block, or in other words, the number of transmitted bits on the downlink (DL) path. It is worth noting that the greater the number of bits transmitted within a given Transmission Time Interval (TTI), the higher the system's throughput and, consequently, the better the spectral efficiency achieved.

In paper [8] an analysis of the LTE transceiver in both downlink (PDSCH) and uplink (PUSCH) transmissions has been conducted. The analysis involved using the LTE System Toolbox to perform simulations, and the obtained results were used to assess the performance of the LTE transceiver. The paper presents measured throughput and Bit Error Rate (BER) graphs, which offer insights into the expected performance for different Signal-to-Noise Ratio (SNR) values. These results clearly depict the throughput and BER under varying SNR conditions. Future research can expand on this by conducting additional end-to-end simulations and modelling for both downlink and uplink scenarios using the LTE System Toolbox.

In [9], the study aimed to assess the performance of the 5G New Radio (NR) Physical Uplink Shared Channel (PUSCH). The primary objective was to analyse throughput with respect to Signal-to-Noise Ratio (SNR) while varying various system parameters, such as Subcarrier Spacing (SCS), modulation schemes, the number of antennas at both the Base Station (BS) and User Equipment (UE), and different propagation channel models (CDL and TDL). The extensive simulations conducted in this study have confirmed that increasing the SCS is an effective way to maximize throughput. Furthermore, the research suggests that using a larger number of antennas at the BS is advantageous for achieving maximum throughput, even in situations with very poor SNR conditions. Finally, the study analysed the behaviour of different propagation channel models. It concluded that the 5G NR PUSCH performs well in terms of throughput concerning SNR when compared to its counterpart, especially over the CDL channel model.

In this paper, the primary goal is to analyze the parameters of 5G and compare them with those of 4G. These parameters encompass spectral efficiency, block error rate, latency, and throughput.

3. System Analysis

In the realm of wireless communication, the term "uplink" pertains to the process of transmitting data, signals, or information from a user's device, such as a mobile phone or computer, to a base station or access point within a wireless network, as depicted in Figure 1. It constitutes the pathway employed for conveying data from the user's device to the network infrastructure, where the data undergoes further processing, routing, or distribution. In a typical mobile network, the uplink functions as the channel through which users upload data, participate in voice calls, send messages, or execute any actions involving data transmission from their devices to the network or the internet.

3.1. Physical Uplink Shared Channel

PUSCH, which stands for "Physical Uplink Shared Channel," is a crucial component in cellular communication systems, especially notable in 4G LTE and 5G networks. Its primary function is transmitting user data and control signals from user equipment (UE) to the base station (eNodeB or gNodeB) through the uplink pathway.

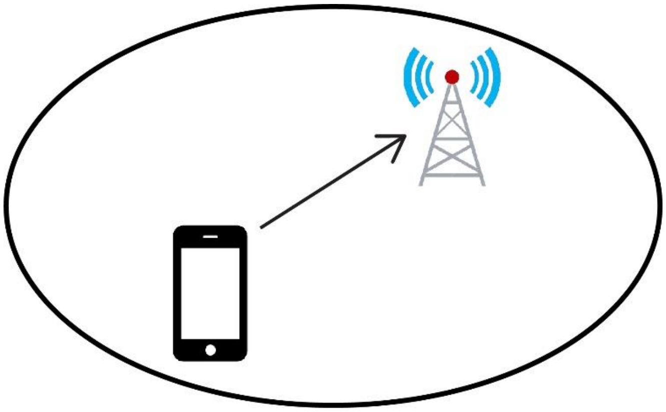

Fig. 1 Uplink transmission in wireless Communications

The essential attributes of the PUSCH comprise the following:

1. PUSCH's core function is transporting user data and controlling information from the UE to the base station.
2. It operates as a shared channel, allowing multiple UEs to simultaneously use it for transmitting their data.
3. Typically, data on the PUSCH undergoes modulation techniques like SC-FDMA (Single Carrier Frequency Division Multiple Access) to adapt to the dynamic conditions of the wireless channel.
4. The base station determines the allocation of specific subcarriers, time slots, and other resources for PUSCH transmission, tailored to network requirements and individual user needs.
5. PUSCH functions within the uplink frequency band, facilitating the transmission of data and information from UEs to the base station.

In conclusion, PUSCH plays a crucial role in facilitating bidirectional communication between user devices and the network infrastructure in contemporary cellular networks. Its significance lies in ensuring the efficient and reliable transmission of uplink data.

3.2. PUSCH Key Components

A block diagram depicting the Physical Uplink Shared Channel (PUSCH) illustrates the sequence of activities and signal processing steps involved in the uplink transmission of shared data within a wireless communication system. Common elements typically found in a PUSCH block diagram include the following, as depicted in Figure 2:

3.2.1. Data Source

The procedure initiates with the existence of a data source, which may consist of diverse types of information or content intended for transmission through the uplink channel. This content could include user data, control information, or acknowledgments, depending on the particular communication context.

3.2.2. Data Processing

Subsequently, the data undergoes processing to prepare it for modulation and subsequent transmission. This processing phase may involve encoding, the application of error correction coding, and other data manipulation steps aligned with the communication protocol in use.

3.2.3. Modulation

The processed data then undergoes modulation using the selected modulation technique. For PUSCH, the commonly chosen modulation technique is often SC-FDMA (Single Carrier Frequency Division Multiple Access).

3.2.4. IFFT (Inverse Fast Fourier Transform)

After modulation, the signal undergoes an Inverse Fast Fourier Transform (IFFT) operation, converting the signal from the frequency domain to the time domain. This transformation prepares the signal for transmission within the time domain.

3.2.5. Subcarrier Mapping

The result of the IFFT is then mapped onto specific subcarriers within the available bandwidth, aligning with the allocated resources and the overall system configuration.

3.2.6. Channel Coding

The signal may undergo Forward Error Correction (FEC) coding, a process that improves its resilience against noise and interference.

3.2.7. Resource Allocation

Resource allocation [10] is the process that determines how the PUSCH signal is distributed across the frequency and time domains. It specifies which subcarriers and time slots are designated for transmission.

3.2.8. Antenna Mapping

In scenarios with multiple antennas, the signal is distributed among various antennas, considering factors such as antenna configurations, diversity techniques, and spatial processing.

3.2.9. Channel Estimation

At the receiving end, channel estimation may occur to assess the characteristics of the wireless channel. This information is valuable for the subsequent demodulation and decoding processes at the receiver.

3.2.10. Transmission

The signal is transmitted from the user equipment (UE) to the base station (BS) or access point.

3.2.11. Reception and Demodulation

At the recipient's end (BS or access point), the received signal undergoes demodulation and is subjected to channel decoding to recover the transmitted data.

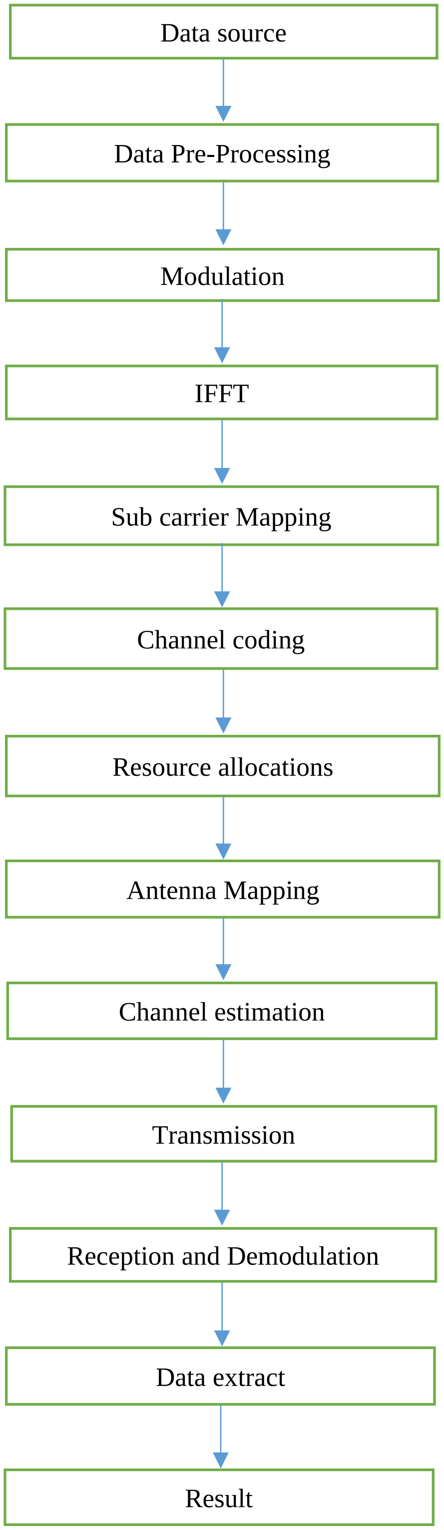

Fig. 2 Key components of PUSCH

3.2.12. Data Extraction

The original data is extracted from the received signal, and any required error correction or decoding processes are applied to ensure the integrity of the data.

3.2.13. Result

The final result is the successfully received data, acknowledgments, or control information, which can then be utilized for further processing within the communication system.

In brief, PUSCH channels are crucial for enabling uplink communication in both 4G LTE and 5G, ensuring the effective and dependable transmission of user data and control signals. The shift to 5G introduces improvements in spectrum utilization, frequency bands, and the ability to support various vertical applications, thereby elevating the overall capabilities of PUSCH channels.

3.3. System Parameters

The advent of 5G technology represents a substantial advancement in wireless communication. However, it is crucial to recognize that 4G technology, while widely used, has certain limitations when compared to 5G. In the following section, we will delve into the shortcomings of 4G in comparison to 5G, covering aspects such as throughput, latency, block error rate, spectral efficiency, and more. With the continued expansion of 5G networks [11], these limitations are becoming more evident, providing a compelling rationale for the transition to 5G technology.

3.3.1. Throughput

Throughput is the measure of the speed at which data is effectively transmitted from one location to another within a communication system. It quantifies the amount of data or information that can be sent over a network, channel, or system within a specific time frame. In the context of 4G and 5G, throughput refers to the data transfer speeds or the volume of data that can be transmitted across the network within a defined period. It is important to note that throughput can fluctuate due to various factors, including network conditions, device capabilities, and the specific network configuration.

In 4G (LTE) networks, peak throughput typically ranges from 100 Mbps to 1 Gbps. This means that, under optimal conditions, users can experience data transfer speeds of up to 1 gigabit per second. However, actual user throughput may be significantly lower due to issues like network congestion and signal strength. 5G networks are designed to offer significantly higher throughput compared to 4G. Depending on the network setup and the frequency bands in use, 5G networks can provide peak data rates ranging from 1 Gbps to 10 Gbps or more. These advancements are facilitated by the utilization of higher frequency bands (millimeter wave) and advanced technologies such as massive MIMO (Multiple Input, Multiple Output) and beamforming.

It is essential to understand that real-world throughput for users in both 4G and 5G networks can vary significantly based on actual network conditions and a user's proximity to cell towers. Peak throughput values represent the theoretical maximum data rates achievable under optimal circumstances, but the actual user experience may be less than these peak values.

3.3.2. Spectral Efficiency

Spectral efficiency, both in 4G and 5G networks, quantifies the amount of data that can be transmitted over a given frequency range or spectrum. It is often measured in bits per second per Hertz (bps/Hz) and serves as a crucial metric for evaluating the efficiency of wireless communication systems. The formulae to calculate spectral efficiency are given as

$$spectral\ efficiency\ = \frac{Data\ Rate}{Bandwidth} \quad (1)$$

In 4G LTE networks, spectral efficiency typically ranges from 0.1 bps/Hz to 2.5 bps/Hz. The specific value depends on factors such as the LTE release version, network setup, and the application of modulation and coding schemes. Advanced LTE technologies, like LTE Advanced Pro, can achieve higher spectral efficiency values, approaching 2.5 bps/Hz. LTE networks employ various modulation schemes, including QPSK, 16-QAM, and 64-QAM, alongside adaptive modulation to optimize spectral efficiency under varying conditions.

5G networks are designed to enhance spectral efficiency significantly compared to 4G. Spectral efficiency values within 5G can range from 2 bps/Hz to 10 bps/Hz or potentially higher, influenced by factors such as frequency bands and network deployment strategies. Higher spectral efficiency in 5G is achieved through various technologies, including using higher frequency bands like millimeter waves, massive MIMO (Multiple Input, Multiple Output), advanced modulation schemes, and beamforming. The flexibility in numerology and subcarrier spacing in 5G enables efficient spectrum utilization and adaptation to diverse usage scenarios.

In essence, 5G networks are engineered to achieve superior spectral efficiency when compared to 4G, signifying their capability to transmit more data for a given unit of available spectrum. This advantage positions 5G to support a wide array of applications with varying data rate requirements.

3.3.3. Latency

Latency, within the framework of 4G and 5G networks, denotes the duration it takes for data to travel round trip from its origin (such as a user's device) to its destination (such as a server). Measured in milliseconds (ms), latency is pivotal in assessing a network's responsiveness and real-time capabilities. The formula for calculating latency is provided as

$$\begin{aligned} Total\ Latency = Trasmission\ delay\ + \\ Propagation\ delay + Processing\ delay \\ + Queueing\ delay \end{aligned} \quad (2)$$

4G networks, such as LTE, typically demonstrate latency ranging from 30 to 50 milliseconds (ms) for the user plane (data transfer) and around 50 to 100 ms for the control plane (signaling). While 4G effectively supports services like voice calls and video streaming with acceptable latency, applications requiring ultra-low latency, such as real-time gaming or critical machine-to-machine communication, may encounter certain limitations.

In contrast, 5G networks are specifically designed to reduce latency significantly. The latency target for 5G is often set at less than 1 millisecond (ms) for ultra-reliable low-latency communication (URLLC) services. 5G achieves this lower latency by integrating technologies like edge computing, network slicing, and advanced air interfaces. The ultra-low latency capabilities of 5G pave the way for applications that demand real-time responsiveness, including autonomous vehicles, remote surgery, augmented reality, and industrial automation.

5G networks are intentionally engineered to provide substantially reduced latency compared to 4G, making them suitable for a broad range of real-time and low-latency applications. Ultra-reliable low-latency communication emerges as a defining feature of 5G, enabling innovative use cases that depend on almost instantaneous data transfer.

3.3.4. Block Error Rate

The Block Error Rate (BLER) in 4G and 5G networks gauge the probability of encountering errors or block failures during data transmission, providing insights into the system's reliability and quality. BLER can vary due to factors like modulation schemes, channel conditions, and error correction methods.

In 4G LTE networks, BLER is influenced by factors such as the selected modulation and coding scheme (MCS), signal-to-noise ratio (SNR), and channel conditions. Lower BLER values indicate more reliable transmission, while higher BLER values suggest a greater likelihood of data errors or loss. In 5G networks, BLER is also impacted by modulation schemes, SNR, and channel conditions.

The introduction of more advanced modulation schemes in 5G, such as 256-QAM, can enhance data rates but may lead to increased BLER in challenging situations. BLER is particularly significant for applications requiring low latency and high reliability, such as ultra-reliable low-latency communication (URLLC) services in 5G.

In summary, 4G and 5G networks prioritize monitoring BLER to ensure trustworthy data transmission. While 5G introduces advanced modulation schemes and error correction techniques, both generations strive to minimize BLER to provide high-quality and dependable communication services.

4. Simulation Results

A performance evaluation of 4G and 5G networks concerning various system parameters has been conducted using MATLAB 2020a. The corresponding 5G and 4G system configurations are detailed in Table 1 and Table 2.

Table 1. Simulation Configuration for 4G

Simulation Configuration	
Parameters Used	Values
Number of frames	300
SNR range	-5,0,5
Total number of sub-frames	1
Cell Identity	10
Number of Layers	1
Number of transmit antennas	1
Number of receive antennas	2
Doppler frequency	5

Table 2. Simulation configuration for 5G

Simulation Configuration	
Parameters Used	**Values**
Number of frames	300
SNR range	-5,0,5
Bandwidth in the number of resource blocks	52
Subcarrier Spacing	15KHz
Cyclic prefix	Normal
Cell Identity	0
Number of PUSCH transmission layers	1
Modulation	QPSK
Code rate	193/1024
Number of transmit antennas	1
Number of receive antennas	2
Doppler shift	10
Transform precoding	disable
Number of antenna ports	1

Figures 3 and 4 visually represent the data throughput for 4G and 5G systems, respectively.

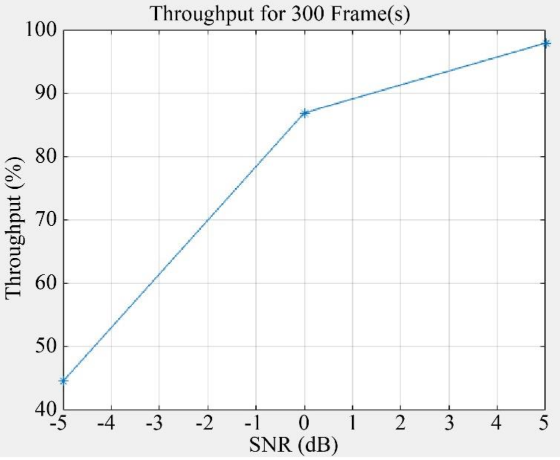

Fig. 3 Throughput of 4G system for 300 frames

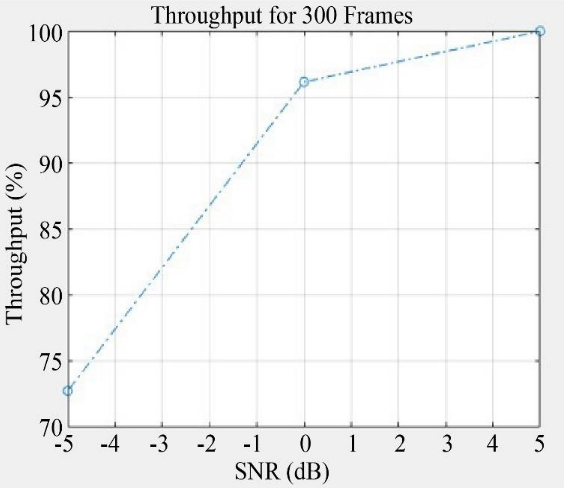

Fig. 4 Throughput of 5G system for 300 frames

It is evident that the 5G system outperforms the 4G system in terms of throughput during uplink data transmission.

Figure 5 demonstrates the spectral efficiency of both 4G and 5G systems.

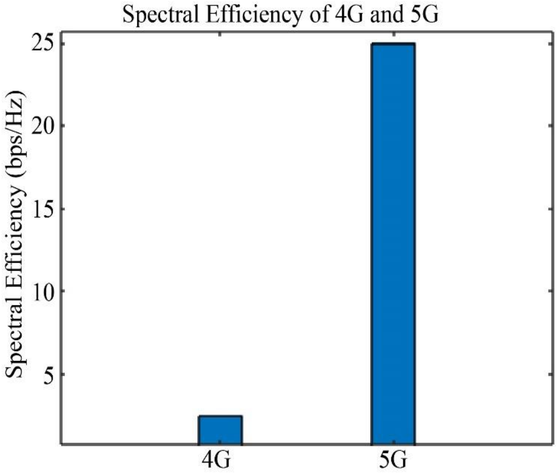

Fig. 5 Spectral efficiency of 4G and 5G systems

Indeed, the 5G system clearly demonstrates superior spectral efficiency in comparison to the 4G system during uplink data transmission.

Figure-6 illustrates the latency of both 4G and 5G systems.

Certainly, the 5G system prominently showcases reduced latency when contrasted with the 4G system during uplink data transmission.

Figures 7 and 8 offer graphical depictions of the block error rate for 4G and 5G systems, correspondingly.

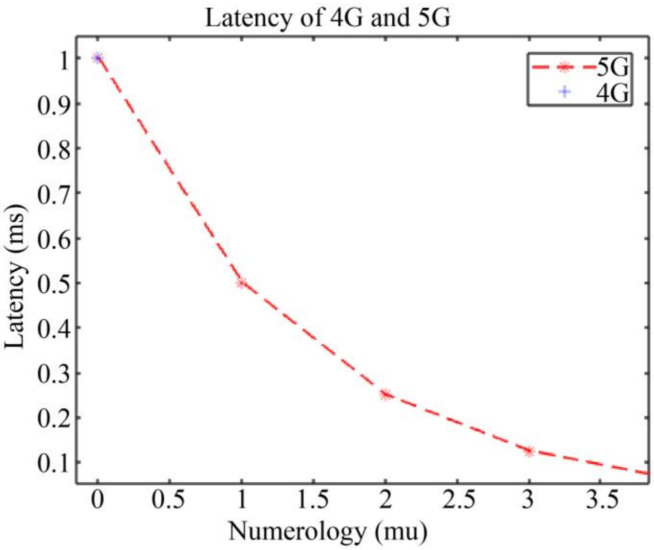

Fig. 6 Latency of 4G and 5G systems

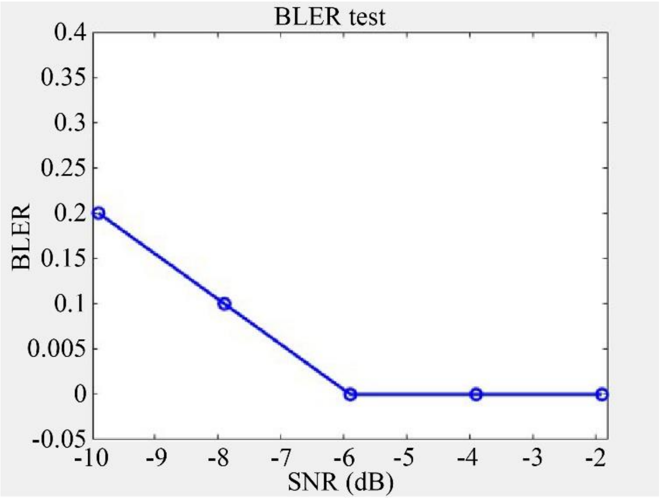

Fig. 7 Block error rate of 4G system

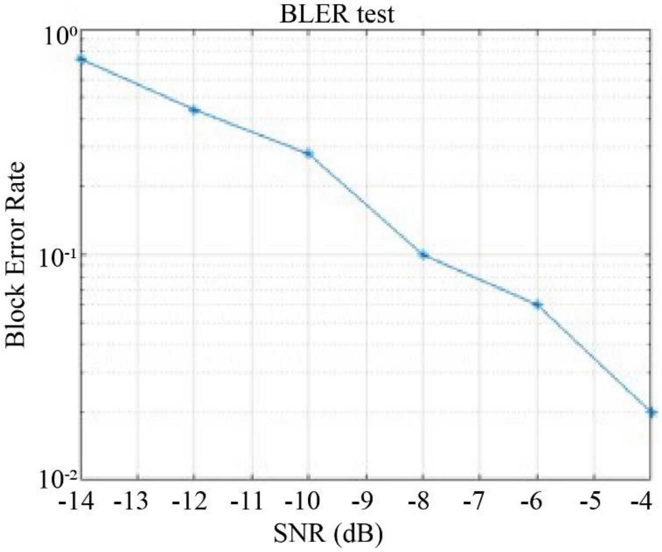

Fig. 8 Block error rate of 5G system

Indeed, the 5G system clearly demonstrates a lower Block Error Rate (BLER) when compared to the 4G system during uplink data transmission.

Here are the analyzed system parameters for both 4G and 5G networks, presented in the table below.

Table 3. Comparison of various parameters of 4G and 5G systems

System Parameters	4G System	5G System
Throughput	95%	100%
Spectral Efficiency(bps/Hz)	2.52	25
Latency(ms)	1	< 0.1
Block error rate	0.02	0.01

From the above-tabulated values, it is evident that 5G surpasses 4G in terms of performance.

5. Conclusion

Effective communication is a vital element of our daily lives, intricately woven into the human experience. Its importance cannot be overstated. Ensuring top-notch telecom services, attracting customers, and enhancing user satisfaction are critical facets of this communication ecosystem. The conclusions drawn from this paper, rooted in a case study, reveal that the 5G NR uplink surpasses the 4G LTE uplink in terms of throughput. Furthermore, the study illustrates that as throughput increases, the Block Error Rate (BLER) decreases. The spectral efficiency of 5G NR stands notably superior, approximately ten times that of 4G LTE. While 4G LTE employs a fixed Subcarrier Spacing (SCS), 5G utilizes a variable SCS. A higher SCS value leads to more slots per frame and shorter symbol durations, contributing to lower latency. Consequently, it can be inferred that 5G holds advantages over 4G concerning latency, spectral efficiency, throughput, and BLER.

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