Comprehensive Modeling and Evaluation of Carrier Aggregation Effects on Network Performance Across Diverse Applications

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***Abstract*—The exponential growth of connected devices in modern communication networks drives an increasing demand for higher data rates and ultra-low latency. This study addresses the challenge of maintaining reliable performance, especially at the network edges where signal degradation is most severe. Carrier Aggregation (CA) emerges as a key enabler to enhance network capacity and efficiency in fifth-generation (5G) systems. Utilizing the SIMU5G simulation framework, this research evaluates the impact of CA on critical performance metrics. The results demonstrate significant improvements, including increased throughput, enhanced Signal-to-Interference-plus-Noise Ratio (SINR), reduced latency, optimized Channel Quality Index (CQI), and improved efficiency of the Hybrid Automatic Repeat Request (HARQ) mechanism. These findings highlight the pivotal role of CA in overcoming network limitations and optimizing 5G performance, offering practical insights for real-world deployments and future network enhancements.**

***Index Terms*—Carrier Aggregation, 5G, SIMU5G, Signal-to-interference-plus-noise ratio, HARQ, CQI.**

I. Introduction

THE increasing reliance on wireless communication technologies has led to a substantial rise in the number of devices connected to modern networks. This growth places significant demands on communication systems to not only expand their capacity but also ensure secure and efficient services to users [1]. Over time, communication networks have evolved from providing basic voice services to offering diverse and advanced solutions, such as real-time video streaming, healthcare applications, and the Internet of Things (IoT), which enables seamless integration of devices and systems into a unified network [2-4].

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Fifth-generation (5G) communication technologies have marked a major breakthrough in addressing these challenges by delivering high-speed connectivity, reduced latency, and improved network capacity. This new generation of communication supports a wide range of advanced applications that drive technological and economic development. Key technologies, including carrier aggregation (CA), millimeter waves, massive MIMO, and non-orthogonal multiple access (NOMA), play an essential role in achieving these performance improvements [2-6].

To standardize 5G deployment, the Third Generation Partnership Project (3GPP) has defined two key configurations for integrating the New Radio (NR) with the 5G Core Network (5GC). The Standalone (SA) mode operates independently, allowing NR to function as a self-sufficient network. In contrast, the Non-Standalone (NSA) mode combines NR and LTE technologies to enhance network performance and flexibility. Each configuration has its specific advantages and is adopted based on user requirements and operational scenarios. Figure 1 illustrates the primary implementation options for these configurations [7-9].

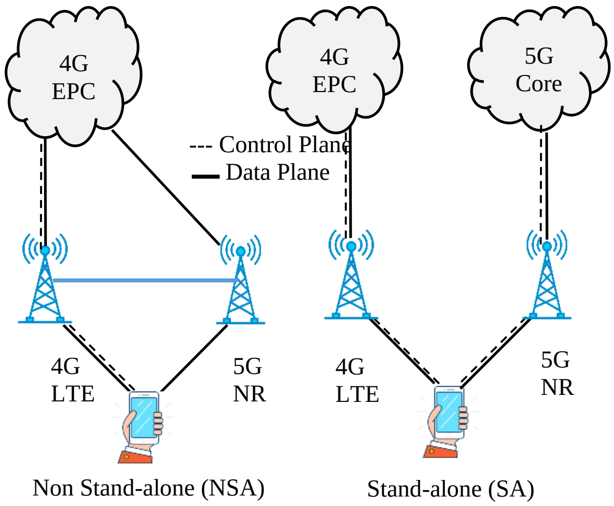

Fig.1. 4G and 5G implementation options.

There are numerous key features supported by the fifth generation (5G), including improved energy efficiency, reduced access times, and enhanced productivity. Carrier aggregation (CA) has emerged as a crucial technology in 5G, addressing these challenges by combining multiple spectrum bands. This integration has proven to significantly boost network capacity and efficiency, contributing to the overall performance improvements in 5G networks [10].

The main contributions of this manuscript can be summarized as follows:

1. Comprehensive modelling and simulation using SIMU5G to evaluate carrier aggregation (CA) technology and improve overall network performance (throughput, SINR, CQI).
2. Address user challenges at network edges by enhancing user performance, reducing latency, and improving call quality.
3. Analyze the impact of CA on different applications (VOIP, CBR, Burst applications).

In this study, we compare network performance with and without the application of Carrier Aggregation (CA), analyzing its effects through various metrics across three diverse applications. The paper is organized as follows: Section II reviews related works in the field. Section III provides an overview of the core technologies in 5G. Section IV outlines several key applications utilized in 5G. Section V develops a CA model for 5G. Section VI presents and discusses the results. Section VII concludes with the most significant findings of this study.

II. Related Work

A low-complexity traffic partitioning algorithm, utilizing the fuzzy relative integral derivative control method, was proposed for a network configuration. This network includes a single user connected to a new 5G radio base station (Next Generation NodeB - 5G Base Station (gNB)) and a secondary gNB station. Communication between the two stations occurs via X2. Following network parameter adjustments and enabling the network to operate with non-adjacent carrier aggregation (CA) technology across different bands, including sub-6 GHz and millimeter wave bands, the proposed algorithm used temporary stored information to manage local communications across these bands and minimize repeated feedback from the user. The algorithm achieved over 90% of the required resource utilization rate in various user transmissions, reflecting a 10% improvement compared to baseline results [11].

Additionally, monitoring was conducted in an industrial area in Karawang, where CA technology was utilized in an out-of-plane scenario with line of sight, monitoring multiple parameters. A significant increase in data rate was observed while maintaining wide coverage [12].

In this context, each user (UE) is assigned a primary cell (PCell) and multiple secondary cells (SCell). The primary cell remains active continuously, while secondary cells are activated or deactivated based on specific plans to select common component carriers and allocate resource blocks. This strategy aims to enhance user productivity, minimize energy consumption, and meet quality of service (QoS) requirements. The proposed plan has demonstrated superiority over comparable technologies [13].

Moreover, a comprehensive study identified key factors affecting the deployment of CA in 5G networks and analyzed the performance and impact on quality of experience (QoE) using the Prism5G deep learning framework [14].

The technology was applied in a Massive MIMO network with several cells and carrier waves, using alternating maximization algorithms to address two issues: balancing price trade-offs to solve energy consumption problems and increasing energy efficiency. The network demonstrated its effectiveness in improving energy efficiency (EE), fairness, and reducing energy consumption [15].

Overall, the study concluded that CA technology is not merely a method for increasing data rate and capacity through spectrum width expansion. Instead, it serves as a diversity technology to enhance mobile communication system performance. By dividing existing spectrum into sub-blocks, each treated as a component carrier, the data rate can be increased without additional spectrum, achieving high spectral efficiency through proposed mathematical models and analytical expressions that describe the technology's performance, considering ergodic and secrecy capacities [4].

III. Carrier Aggregation (CA) in 5G

Carrier Aggregation (CA) was first introduced in LTE-10 as one of the most important technologies that support high data rates. In this technology, unused spectrum is added to the basic carrier wave to benefit from it in increasing bandwidth and improving the overall performance of the network. Each carrier wave from the group of aggregated waves is called a component carrier (CC) and the group of aggregated waves is called Radio Frequency (RF). The user using the technology can aggregate up to 5 carrier waves for each carrier wave with a frequency range of up to 20 MHz, thus the frequency range becomes 100 MHz for LTE [16-17]. As for the 5G the capabilities of this technology have been expanded and the carrier waves CCs can operate at different frequencies and use more than 16 carriers and a bandwidth of up to 400 MHz [18]. In OFDM systems, windowing design is used to mitigate Inter-Carrier Interference (ICI) and Out-of-Band Emissions (OOBE), which are critical factors affecting Carrier Aggregation performance. The windowing technique addresses these issues by applying a smooth function to the time-domain signal to reduce sharp edges. Windowing reduces inter-carrier interference, leading to lower error rates [19]. Windowing enhances the signal-to-interference-plus-noise ratio, improving signal quality [20]. This allows more efficient carrier aggregation without causing harm to adjacent users [21].

The base station and user devices operate in different spectrum ranges in 5G. This depends on several factors, including the applications used in the network, the transmission range, and others. Table I below shows the spectrum divisions [22].

TABLE I
5G CHANNEL FREQUENCY

FREQUENCY RANGE	SPECTRUM
FR1	410 MHz -7125 MHz
FR2	24250 MHz – 52600 MHz

A. Implement Carrier Aggregation (CA)

There are three ways to implement carrier aggregation technology [23-24]:

A.1 Intra-band contiguous CA scheme: Includes the combination of the frequency of adjacent carriers that are adjacent to each other and belong to the same band as shown in Figure 2.

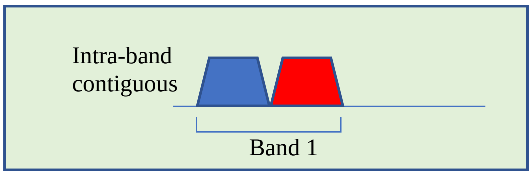

Fig. 2. Intra-band contiguous CA scheme.

A.2 Intra-band non-contiguous CA scheme: In which the frequency carriers belong to the same band are combined but are not adjacent and have a gap between them as shown in Figure 3.

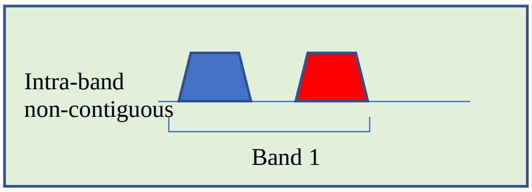

Fig. 3. Intra-band non-contiguous CA scheme.

A.3 Inter-band non-contiguous CA scheme: Refers to the collection of frequency carriers belonging to different frequency bands and distributed in a non-adjacent manner as shown in Figure 4.

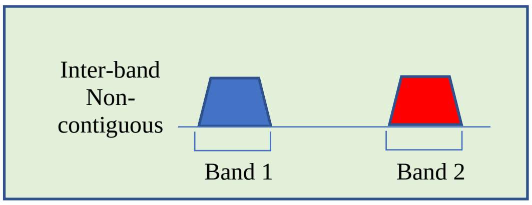

Fig. 4. Inter-band non-contiguous CA scheme.

IV. APPLICATIONS AND TECHNOLOGIES SUPPORTED BY 5G

5G supports many applications, including the following.

VOIP: Voice over Internet Protocol is one of the most important applications in fifth generation communication networks and provides many benefits to users. It enables the user to request a phone number and contact another party with a smartphone supporting the VOIP application. The connection is made by transferring data on IP packets via the data connection in the phone [25-26].

Burst: In 5G, this term refers to the user receiving a large batch of data at high speed within a short period and continuing to receive data in batches. This technology is used with applications that do not require a continuous flow of data and require high speeds, such as online games and high-resolution videos. For example, we have a high-quality video clip consisting of 60 frames per second, and each frame can be sent and processed within a period of 16.67 milliseconds. This is considered a continuous batch of data, and these batches continue to be sent until the video clip is complete. The user can be in a power-saving mode, and this was one of the solutions to address the problem of dealing with a limited battery. 5G can know the end of the transmission via the user's control level signals and inform him to enter power-saving mode immediately without affecting the data. The image below represents BURST, where the batch contains different groups of data called PDU Sets as shown in Figure 5 [27-28].

Constant bit rate (CBR): is a type of data transmission in networks in which all data is sent at a constant and continuous bit rate during a unit of time, where all units of time carry the same number of bits. It is used in applications that require data to be transmitted in a guaranteed and continuous manner, such as video transmission [29].

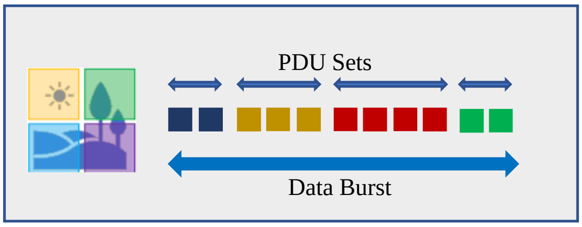

Fig. 5. PDU sets and data burst example.

V. MODELLING AND SIMULATION

There are several software tools available for simulating 5G networks. In this research, we utilized the Simu5G model library, which is based on the OMNeT++ simulator, to simulate a 5G network. OMNeT++ is renowned for its framework designed for discrete event simulation, allowing for the modeling of various network types, such as optical, wired, and wireless networks. This is achieved by programming communication layers and employing modules that range from simple to complex, interconnected by gateways and capable of exchanging messages. Users can create protocol layers, connect them, and develop intricate models. Furthermore, numerous other features can be leveraged during the design and implementation phases [30].

As for the Simu5G framework, it simulates the 5G New Radio RAN and CN data level. The most important elements in its library are the complex units gNodeB and NrUe, which represent the UE and gNB, including NR capabilities, and their internal structure is shown in Figure 6.

All nodes can be located and defined in a three-dimensional

Cartesian plane, which allows the distances between them to be calculated. The UE includes all protocol layers from the application layer to the physical layer and TCP/UDP vectors and IP protocols. Its functions are implemented in a network interface card called NrNicUe [31]-[33].

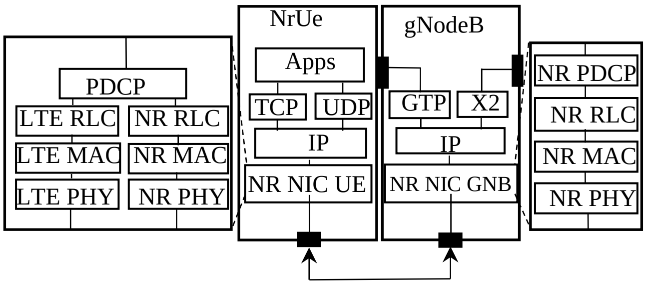

Fig. 6. High-level architecture of Simu5G's main modules.

A. System Model

The proposed model is based on a simulation of a 5G network to study the impact of carrier aggregation (CA) technology on three different 5G applications (VOIP, BURST, CBR) and its impact on user throughput, spectral efficiency, and other indicators. In addition, it compares the results before and after using the technology through a communications network consisting of one gNB and 6 users randomly distributed over an area of 1000 * 1000 connected to the gNB in the downlink transmission. Also, it compares the results after operating the network without adding the carrier aggregation technology and after adding it, noting that the number of carriers is 4 and the technology is type 2. Intra-band non-contiguous.

B. Model Assumptions

The proposed model is based on a set of assumptions, including the use of a Stand-Alone (SA) network type and homogeneous networks. The network dimensions are defined as 1000×1000 meters to cover a specific area. It consists of one gNB (Next Generation NodeB) and four background cells (bgCell) to support communication. Additionally, six users are distributed within the network to simulate system performance and analyze the impact of carrier aggregation on various performance metrics.

TABLE II
SIMULATION PARAMETER

PARAMETER	VALUE
gNB-tx-power	43dBm
app	CBR , VOIP , BURST
Number of CC's	4
Carrier-Frequency	(800MHz, 1.8 GHz, 2.3GHz, 3.5GHz)
Channel-delay	5e-08 s
SINR6	-1.9103 dB
Fading_type	JAKE
Propagation-Model	Free Space Model
Path-loss	2
ue_height	1.5 m
gNB-height	25 m
Building_height	20 m
User Status	Constant

C. Simulation Parameter

The simulation parameters of the network architecture adopted to describe this model are listed in Table II.

Figure 7 shows the network structure on which the study was conducted using SIMU5G, showing the location of the base station and users in addition to the locations of the bgCell.

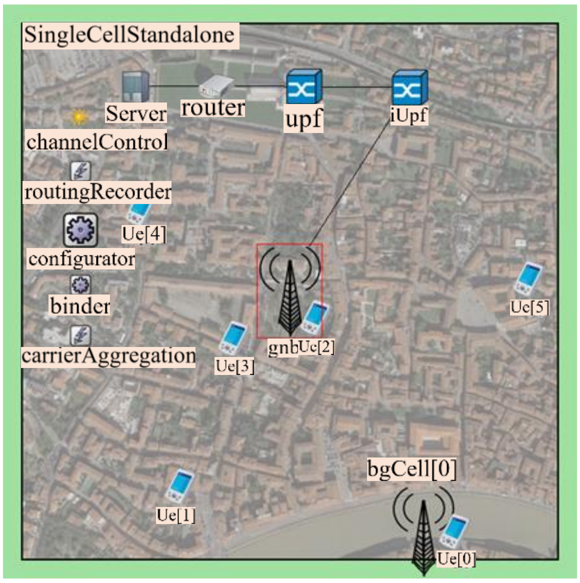

Fig. 7. The network structure using SIMU5G

VI. Results and Discussion

The simulation results are divided into two categories. The first category contains simulation results without using carrier aggregation technology and relying on a single primary carrier. Three different applications in the network are used to study the network efficiency and its impact on users.

The second category includes simulation results after applying the mentioned technology to the network (using four carriers) and using the same three applications to study the extent of the impact of this technology on the network through a set of results including (Delay, Received Pcket, SINR, Average Channel Quality Indicator (CQI) DL, Automatic Repeat Request (HARQ) Error Rate).

The results appeared as follows:

A. Frame Delay (mean)

It represents the time taken to process and transmit one data frame from the base station to the user. It includes the delay in sending and receiving, as well as the delay in the channel due to various conditions. Figures 8, and 9 show average users frame delay using CBR, VOIP applications without and with CA technique, respectively. The burst packet delay (mean) describes the time delay experienced by a packet as it travels from the sender to the recipient. It encompasses various types of delays, including those associated with transmission, propagation, and transport, among others.

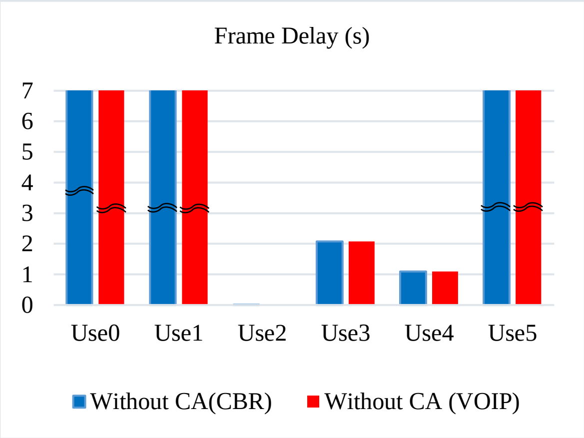

Fig. 8. Average users frame delay using CBR, VOIP applications without CA technique.

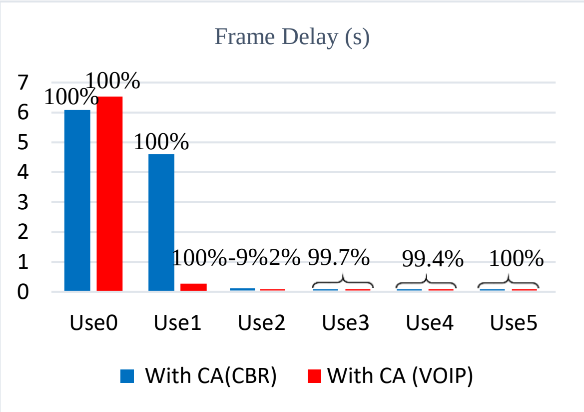

Fig. 9. Average users frame delay using CBR, VOIP applications with CA technique.

In Figures 8, 9, and 10, the broadcast was received by users at close and medium distances from the gNB, while the far users (Us0, Us1) could not receive it because the signal is exposed to different conditions in the channel during propagation, such as interference, diffraction, and refraction. As a result, the signal fades before reaching the user due to the long distances. When CA technology is applied, we notice that the reception delay is reduced for all users. Also, the users far from the base station started receiving the broadcast from it and showed the delay, despite its high value and improvement rate when using carrier aggregation technology for each user, as shown in Figures 8, and 9 for CBR and VOIP applications and Figure 10 for Burst application and the overall improvement rate for each application is as follows CBR (81.6%), VOIP (83.5%) and Burst (80.2%).

B. Received Packet

It is the packet that arrives or is received by the final receiver in the communication network after it is sent from the source and passes through the transmission channel. Figures 11 and 12 represent users received packet using CBR, VOIP, and burst applications without and with CA technique.

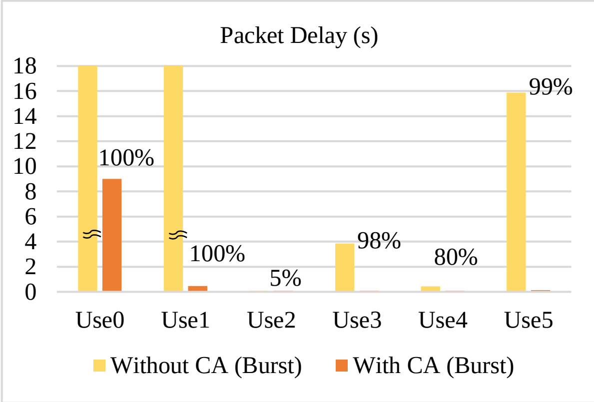

Fig. 10: Average users frame delay using Burst application without & with CA technique.

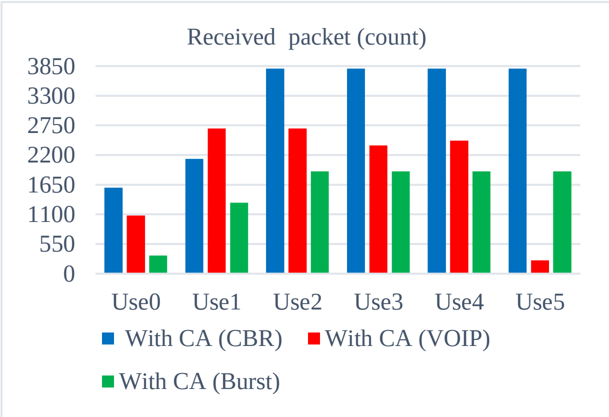

Fig. 11. Received packet using three applications without CA technique.

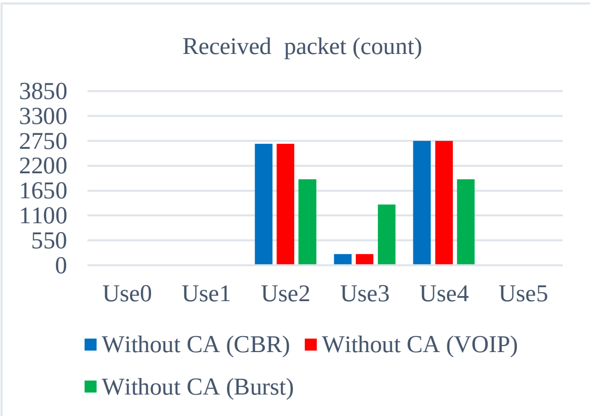

Fig. 12. Users received packet using three applications with CA technique.

In Figures 11 and 12, there was an improvement for all users after using the carrier aggregation technique, and its effect was clear for all users, especially those located at the edge of the cell (Us0, Us1). The results of the improvement percentage for each application were arranged as follows: CBR (75.1%), VOIP (63.1%), Burst (54.9%).

C. MAC throughput DL

It is the actual rate of data transfer over the downlink through the Medium Access Control (MAC) layer responsible for determining how resources are allocated to users connected to the network. For six users, MAC throughput DL using CBR, VOIP, burst applications without and with CA technique is shown in Figure 13 and 14, respectively.

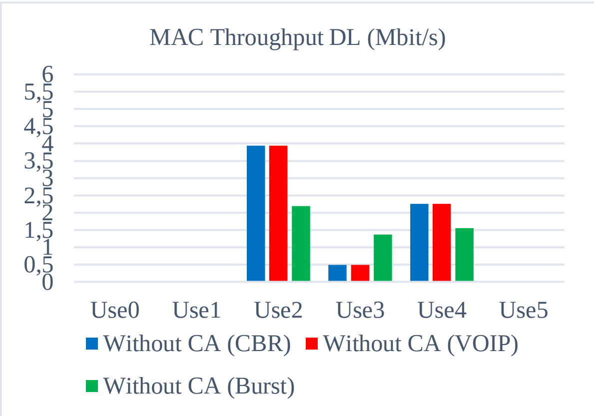

Fig. 13. MAC Throughput DL users using the same applications without CA technology.

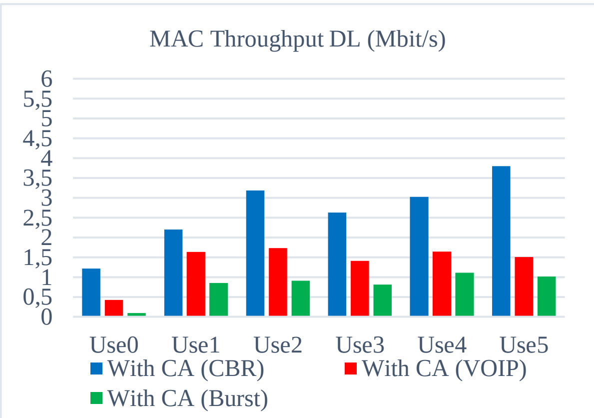

Fig. 14. MAC Throughput DL users using the same applications with CA technology.

Figures 13 and 14 illustrate the data transfer rate across the MAC layer in the downward direction. The impact of CA technology is clearly visible, as it significantly increases the amount of data transferred through the MAC layer from the gNB to the user in the CBR application. The improvement rate reached 63.8%, which is the highest improvement rate compared to other applications, with VOIP at 33.3% and burst at 7.8%. However, it appears that some users experienced a negative impact on their throughput rate in the MAC layer due to CA technology.

D. Received SINR DL

This term refers to the ratio of the received signal strength to the interference and noise in the downstream direction of the 5G network. It serves as a measure of the signal quality received by the final receiver. A higher ratio indicates better signal quality. It is simply clear by comparing Figures 15, and 16 that Received SINR improves after using CA technique for all applications.

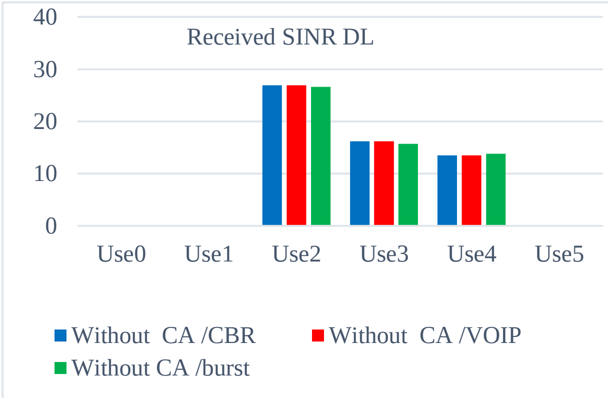

Fig. 15. Users Received SINR without CA technique.

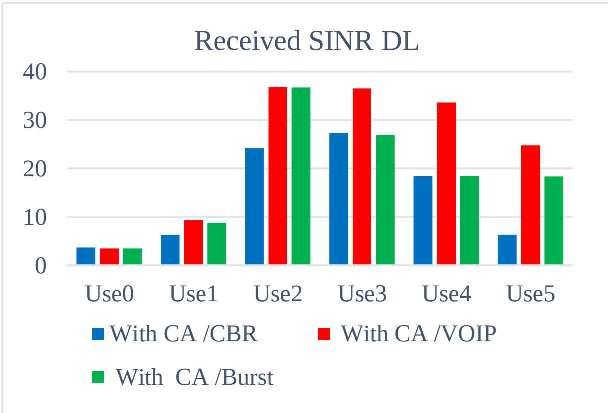

Fig. 16. Users Received SINR with CA technique.

Significant improvement in SINR is noted for most users, with the improvement percentage for each application being CBR (59.3%), VOIP (73.7%), and Burst (65.7%). This has improved the network capacity and stability of these applications, compared to the previous performance.

E. Average CQI DL

In 5G communications, this term refers to the arithmetic mean of the Channel Quality Index (CQI) in the downward direction over a specific period of time. The user's device measures the CQI and sends reports to the gNB to indicate the connection quality over the channel connecting them. The CQI value varies depending on the user's distance from the base station before using CA technology, as shown in Figure 17. For most users, it improves after implementing this technology, as illustrated in Figure 18 for all applications.

As for the signal quality measure in the channel (CQI) shown in Figures 17, and 18. it is clear that it is low without using CA technology. The implementation of this technology resulted in an increased connection quality and improved CQI measurements for all users, regardless of their distance from the gNB and across all applications. The improvement ratios were CBR (62.7%), VOIP (59.2%), and Burst (56.1%), thus enhancing the reliability of the connection.

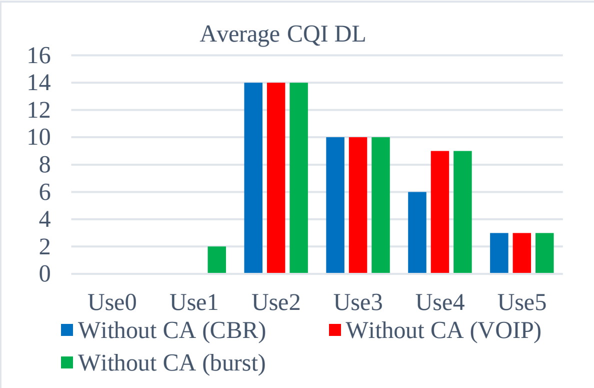

Fig. 17. Average CQI using CBR, VOIP, Burst applications without CA technique.

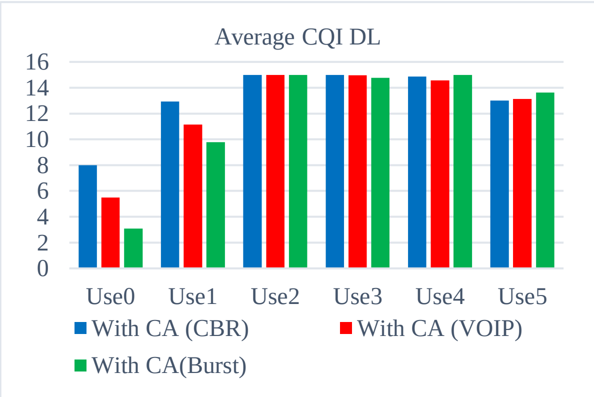

Fig. 18. Average CQI using CBR, VOIP, Burst applications with CA technique.

F. HARQ Error Rate (mean)

This term refers to a mechanism that consists of two technologies: Automatic Repeat Request (ARQ) and coding technology. This mechanism is used to enhance the reliability of data transmission in fifth-generation networks. When a packet received by the gNB or the user contains errors due to interference and noise, the user's device requests a retransmission. The retransmitted packet may include additional information to increase the likelihood of successful reception. Figure 19 shows HARQ before adding the technology and after adding it is shown in Figure 20 for all users and the three applications.

In Figures 19 and 20, we observe that CA technology has significantly and distinctly improved the system performance compared to its previous performance in Figure 19. It has reduced connection problems and the need for automatic data retransmissions. Consequently, the user will not have to request retransmissions from the gNB. Although user user0 encountered errors, they were not receiving data initially in the absence of the technology. When they began receiving data, errors appeared, and the improvement percentage for each user is shown in Figure 20.

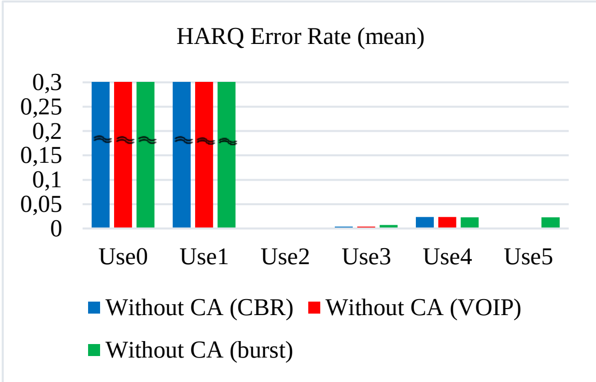

Fig.19. HARQ error rate without CA for three application users.

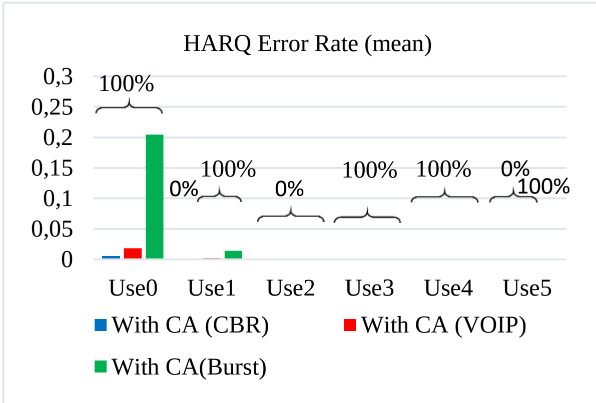

Fig. 20. HARQ error rate with CA for three application users.

G. Received throughput (Mbit/s)

This measure indicates the speed at which data is actually received by the user from the network. It is influenced by several factors, including network load, interference, and noise, among others. This metric differs from the MAC Throughput DL statistic, which is specific to the MAC layer. In the SIMU5G framework, there is no such statistic available for the Burst application. However, we obtained throughput data for the CBR and VOIP applications, and the results were as shown in two Figures 21 and 22.

Throughput demonstrated a significant improvement for all users when CA technology was implemented in the network. However, user 3 in the CBR application and user 2 in the VOIP application experienced a negative impact, as previously illustrated. The overall improvement rate for the CBR application was 54.5%, while the VOIP application saw an improvement rate of 51.8%.

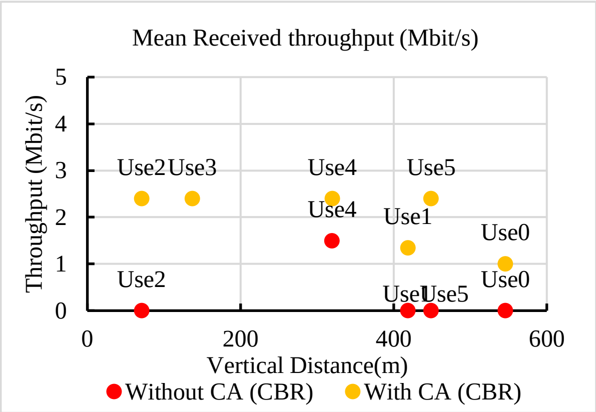

Fig. 21. Users mean received throughput using CBR application without & with CA technique.

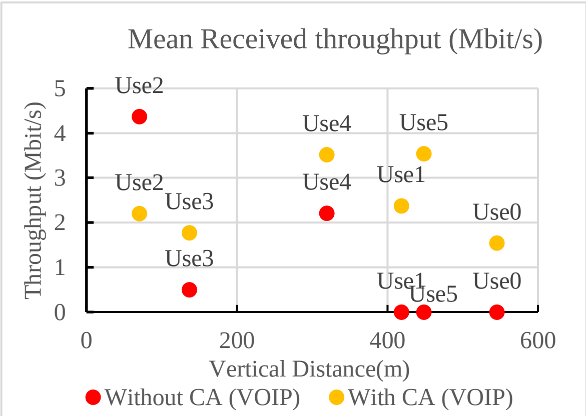

Fig. 22. Users mean received throughput using VOIP application without & with CA technique.

TABLE III
THE COMPARISON OF THIS PAPER WITH OTHER PAPERS.

Main contents		[6]	[10]	[13]	[24]	THIS WORK
Number of CC's	2	✔		✔		
	Upto two		✔		✔	4
Deployment	Single-user					
	Multi-user	✔	✔	✔	✔	6
Configurations options	SA		✔		✔	✔
	NSA	✔		✔		
Com. path	LOS					
	NLOS	✔	✔	✔	✔	✔
Environment	Out door	✔	✔	✔	✔	✔
Measurement and improvement ratio	SNR					
	SINR	--	--	--	--	CBR: 59.3% VOIP; 73.7% Burst; 65.7%

Table III provides a comprehensive analysis of various contents and characteristics related to wireless communication systems. We begin by detailing the main contents, ranging from [6] to [24], including the current work. Then, we move on to the number of CC's (Carrier Components), showing the distribution of different standards.

Next, we review deployment environments, starting from single-user to multi-user, and illustrate the different options for network configurations, whether SA (Standalone) or NSA (Non-Standalone). We also explore communication paths, focusing on both LOS (Line of Sight) and NLOS (Non-Line of Sight) paths, and the operating environments, whether indoor or outdoor.

Finally, we provide an overview of performance measures, such as SNR (Signal-to-Noise Ratio) and SINR (Signal-to-Interference-plus-Noise Ratio), and how they affect communication quality. This table aims to offer a precise and comprehensive understanding of these aspects to help us evaluate and improve the current system.

It is worth noting that applying the Kaiser window improves the OOBE by 20% more than the Hahn window [21].

VII. CONCLUSION

Carrier aggregation (CA) technology plays a pivotal role in improving network performance, especially in urban environments with heavy traffic. The results of this study, derived from simulations of a 5G standalone network (SA) with and without CA across three different downlink applications, demonstrate the significant benefits of this technology. CA significantly improved overall network efficiency, improving connection quality for all users. Specifically, the average frame delay decreased for most users, while those with favorable channel conditions experienced little impact from the introduction of CA as shown in Figures 9, 10 above. The number of received packets increased across all user groups by (64.3%) as an average increase for all applications. Several key performance metrics, including DL MAC throughput, SINR, and average DL CQI, showed significant improvements of (34.9%), (66.3%), and (59.3%), respectively, as an average increase for all applications. In addition, the retransmission error rate decreased for most users after implementing CA, and the improvement rates appeared as we explained previously. As for throughput, users showed a clear improvement in it with an overall rate of (53.1%), except for User 3 and User 2, who were negatively affected by the technology and affected the overall rate. Among the applications tested, VOIP and CBR applications benefited the most from CA, followed by Burst applications, which witnessed more significant performance improvements due to irregular data flow, which is characterized by sudden spikes and drops at specific periods. In the future, we will discuss the impact of speed on users and network performance and how the negative effects can be improved. In addition to increasing the number of carriers to 13 carriers, a study of the effect of Doppler on these carriers.

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