Multi-Connectivity using NR-DC for High Throughput and Ultra-reliable Low Latency Communication in 5G Networks

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***Abstract*—The next generation of cellular networks needs paradigm shifts to realize the exponentially increasing demands for high throughputs, low latencies, and reliable communication. These networks will be required to address the requirements of a number of applications and services as well as industry verticals such as intelligent transportation, industrial Internet of Things (IoT), e-Health, augmented reality/virtual reality (AR/VR), and other future networks-based services. Millimeter wave (mmWave) communication is a promising technology for 5G systems due to its potential for multi-gigabit throughput. However, mmWave links suffer from high path loss and blockage. We propose an approach using New Radio Dual Connectivity (NR-DC) to maximize the throughput while ensuring ultra-reliable low latency communication. The performance evaluation conducted using Simu5G, which is an OMNeT++ based network simulator, demonstrates that this multi-connectivity technique can improve the performance of next generation 5G networks. Simulation results show that NR-DC improves the performance significantly in terms of throughput, latency, and reliability by up to 14%, 33%, and 11%, respectively, compared to a single connectivity system.**

***Index Terms*—5G, Multi-Connectivity, New Radio Dual Connectivity, enhanced Mobile Broadband, Ultra-Reliable Low Latency Communication, Network Simulator, Simu5G.**

I. Introduction

The fifth generation (5G) standards developed by the 3rd Generation Partnership Project (3GPP) aim to meet the diverse and demanding performance requirements of new services generated by a wide variety of applications. 3GPP categorizes the applications in three different classes of services: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (URLLC), and massive Machine Type Communication (mMTC). The 5G New Radio (NR) [1] is a new air interface developed by 3GPP that can operate over two frequency ranges, FR1 (sub-6 GHz) and FR2 (above 24 GHz). Each frequency range has certain propagation characteristics. For example, millimeter wave (mmWave) can cover densely populated areas but only over short distances. Sub-6 GHz can be coupled with technologies such as massive multiple-input/multiple-output (MIMO) antennas to deliver reliable, cost-effective, and highly scalable mobile broadband access. However, a significant increase in the number of users and the surge in mobile data traffic required for high bandwidth applications have led to a shortage of sub-6 GHz band availability. The mmWave bands are thus of prime importance for next generation cellular network systems. The massive data rates provided by mmWave bands are primarily due to a large amount of spectrum available in these bands. However, mmWave links have a lower transmission range and are subject to blockage.

Multi-connectivity is one of the key approaches to address these issues. It is defined as the system architecture where each user equipment (UE) is simultaneously connected to multiple base stations and is a key feature of the 3GPP NR specifications. Simultaneous connectivity to multiple radio access technologies represents an important solution for ongoing 5G deployments. Multi-connectivity enhances the system performance by providing multiple connections.

Initial 5G deployment used the non-standalone architecture [2] where E-UTRA-NR Dual Connectivity (EN-DC) was used to improve the user throughput while maintaining good coverage. It did so by leveraging the already existing LTE infrastructure with innovative technologies deployed in 5G-NR. Multi-connectivity, specifically EN-DC, thus played an important role in ensuring that the high throughput benefits of 5G are available to a maximum number of users while ensuring connectivity during mobility scenarios. However, rapid 5G deployment is expected in the upcoming years, with more base stations having mmWave capabilities and the development of 5G core services. Moving towards a standalone 5G architecture enables us to leverage attributes of 5G such as high throughput, ultra-reliable low latency communication, and massive machine type communication. However, using the FR2 band alone could significantly impact the reliability of the network. Thus, the 3GPP standards propose the New Radio Dual Connectivity (NR-DC) feature [2] containing high band NR small cells overlaid by sub-6 GHz FR1 band 5G macro cells for effective deployment.

In this work, we study a 5G system with NR-DC capabilities to provide a UE with both low-band and high-band channels simultaneously. NR-DC can assure higher data rates, higher reliability, and lower delays, which are critical for emerging applications such as augmented reality/virtual reality (AR/VR) or mission-critical applications such as autonomous vehicles, which demand ultra-reliable low latency communication. To study the performance of such a system, we use Simu5G [3], a 5G simulation library based on the OMNeT++ framework [4]. Using Simu5G, we simulate the data plane of an end-to-end

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standalone 5G network that transmits packets from a remote server via the User Plane Function (UPF) in the 5G core to a UE that is connected to a gNB. Throughput, latency, and packet loss were used as metrics to evaluate the performance of the system. Performance of a network using a single gNB operating at 28 GHz was compared to a network with NR-DC deployment where the master gNB is operating at 28 GHz, and the secondary gNB is operating at 2 GHz. Two use cases are considered for this study, the first being an eMBB type of application and the second one is an ultra-reliable low latency type of application. Also, the impact of mobility and varying numerologies was investigated for these networks.

The major contributions of this paper are summarized as follows:

- We propose a novel system for NR-DC deployment using Simu5G network simulator, which has not been addressed by any prior work.
- We present a method to systematically evaluate and make improvements to the system, which increases the performance of the 5G system.
- We demonstrate the effectiveness of our approach for realistic applications and mission critical scenarios and achieve significant improvements.

The remainder of the paper is organized as follows. Section II reviews the related work done in the areas of multi-connectivity and 5G network simulators. We present the novel NR-DC deployment and the details of the simulation environment in Section III. Section IV evaluates the performance of our NR-DC deployment for high throughput and ultra-reliable low latency applications. Section V concludes the paper.

II. Related Work

Multi-connectivity has been widely recognized as one of the key features for improving the resiliency of next generation wireless networks that operate at mmWave bands. It is defined as the system architecture where each UE is simultaneously connected to multiple base stations to achieve high throughputs along with high reliability and low latency. In [5], the authors discussed specific architecture options for integrating multi-connectivity into 5G networks. More recently, in [6], the authors studied the impact of using multi-connectivity in a realistic ultra-dense network scenario. They also discussed the EN-DC deployment employing non-standalone 5G. However, with the continued evolution of 5G services, more and more standalone 5G architectures are being deployed. Hence, it is critical to study and analyze NR-DC deployment strategies for standalone 5G. The authors in [7], and [8] have proposed and evaluated an EN-DC simulation model using the mmWave library based on ns-3 simulator [9] but the model is not fully 3GPP standard compliant.

Given the wide range of services and performance offered by 5G networks, it is integral to use a platform capable of performing an end-to-end analysis. There are many infrastructure complexities associated with building a real-world cellular network for testing. The POWDER platform [10] built at the University of Utah in Salt Lake City offers a remotely accessible end-to-end software-defined platform to conduct such wireless research. However, discrete-event network simulators offer a better and more scalable alternative for the analysis of complex networks and the development of new protocols. In this paper, we use the Simu5G tool that provides a 3GPP compliant 5G simulation model library based on the OMNeT++ framework.

Wireless network simulators include physical-level simulators which are only suitable for physical-layer measurements, such as the signal-to-interference-plus-noise ratio (SINR) or spectral efficiency. On the other hand, link-level simulators many times do not even consider modeling layers above the MAC. Thus, to analyze system properties like end-to-end latency, throughput, packet loss rates, etc., application-level performance must be considered, which is only possible through *end-to-end simulators*. End-to-end network simulators can perform full-stack simulations using models for all layers of the protocol stack, network equipment, and application logic. This ability to simulate the whole network stack plays a crucial role in understanding many new features of 5G networks.

The two most widely used network simulation frameworks are OMNeT++ and ns-3 that allow users to develop their own model libraries. Apart from Simu5G, which is based on the OMNeT++ framework and discussed in more detail in the next section, the other popular end-to-end simulation tools for 5G networks are based on ns-3. The 5G-LENA [11] model library uses the ns-3 framework and builds upon the LENA (LTE-EPC Network Simulator) 4G LTE library [12]. The 5G-LENA library mainly focuses on implementing the MAC (Medium Access Control) and PHY layers of the 5G network stack. The ns-3 mmWave module was developed before 3GPP 5G standards were finalized and thus remains non-compliant to current standards. Both 5G-LENA and mmWave modules only support the Time Division Duplexing (TDD) mode. In this work, we used Simu5G, which is a 3GPP compliant 5G network simulator, to develop a novel NR-DC architecture.

III. Simu5G Simulation Environment

This section discusses the OMNeT++ framework and how Simu5G libraries are used to simulate the data plane of a 5G network. We then provide the specifics of the NR-DC architecture and the simulation environment.

Simu5G is built upon OMNeT++, which is a widely used discrete-event simulation framework that can be used to model wired and wireless networks, among others. The basic building blocks in the OMNeT++ framework are called *modules*. Modules can be simple, or they can be combined to create more complex compound modules. Modules can be linked through their interfaces called *gates* with links known as *connections*. Modules communicate among each other using *messages* and simple modules are programmed to exhibit a specific behavior on receipt of these messages. The OMNeT++ model behavior is programmed in C++. It uses Network Description language (NED) to define the modules along with their gates and connections definitions. The parameter values

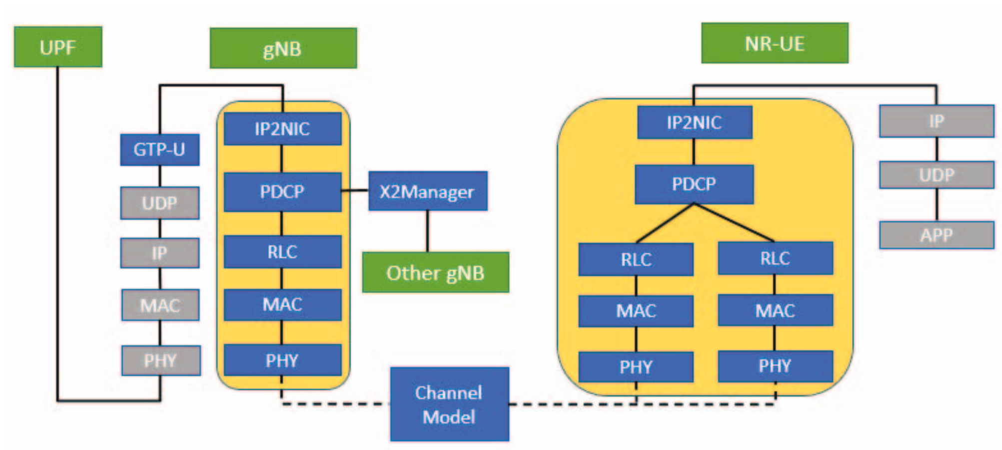

Fig. 1. Submodule structure of gNB and NR-UE modules in Simu5G NR-DC Deployment

needed to initialize a model are defined in an initialization (INI) file. It also provides an Eclipse-based Integrated Development Environment (IDE) to facilitate editing and debugging. Simu5G also uses the INET model library in OMNeT++, which implements models for various communication protocols, network nodes, connections, etc. This allows Simu5G to simulate end-to-end scenarios involving complex networks, including 5G NR interfaces. In Simu5G, the functionalities of layer 1 and layer 2 of the RAN are implemented as a stack of four protocols, which are Packet Data Convergence Protocol (PDCP) layer, Radio Link Control (RLC) layer, Media Access Control (MAC) layer, and Physical (PHY) layer, all combined to form the Network Interface Card.

Simu5G simulates the NR capabilities of the 5G RAN through two main compound modules, NrUe and gNodeB. Fig. 1 shows the submodule structure of the two modules. The gNodeB module consists of four submodules (NrPdcp, NrRlc, NrMac, NrPhy), each representing a layer in the protocol stack along with an Ip2Nic submodule that deals with the IP (Internet Protocol) packets between the UPF and the PDCP layer. The gNodeB module also contains an X2Manager module responsible for forwarding IP packets on the X2 link towards the secondary node when multi-connectivity is implemented. The PDCP layer on the master gNB is responsible for deciding if a packet will be sent to the lower RLC layer on the local stack or forwarded through the X2 link. The forwarded packet is then received by the RLC layer of the secondary gNB, after which the packet continues to flow through the lower layers towards the UE.

The NrUe module, on the other hand, implements all the layers of the protocol stack from the physical layer up to the application layer. It uses the INET library to implement the UDP and IP protocol layers in the stack. To implement dual connectivity, the NrUe has a dual stack with two PHY, two MAC, and two RLC layer submodules. NrUe has a single NrPdcp module responsible for reordering the incoming RLC PDUs (Protocol Data Units) from the dual stack and sending them to the higher layers.

In Simu5G, physical transmission is modeled via realistic and customizable channel models. Simu5G also offers a carrierAggregation module that can be used for communication on multiple carrier component frequencies. Using the parameters in the NED and INI files, we can choose the carrier frequencies, bandwidths, number of resource blocks, etc. Through this module, we can also adjust the numerology that varies the subcarrier spacing and the slot duration of 5G signals.

As part of the 5G core implementation, Simu5G provides a UPF module responsible for handling IP packet flow between the data network and the gNBs through GTP (GPRS Tunnelling Protocol) tunnels. The UPF module can be directly connected to a gNB resulting in the standalone architecture deployment scenario. The standalone deployment scenario was extended to implement the NR-DC deployment in this paper. The master gNB operates at a carrier frequency of 28 GHz with a bandwidth of 100 MHz, thus providing a high bandwidth link. However, for mobile UEs or stationary UEs far away from the master gNB, the reliability of the connection with the master gNB decreases, and the secondary gNB operating at a carrier frequency of 2 GHz is used to provide a reliable connection.

IV. Evaluation

The performance of the system using NR-DC was compared to a system using single connectivity. An example of the NR-DC simulation scenario using Simu5G is shown in Fig. 2. Systematic evaluation of the system was conducted for two different packet sizes of 3000 B and 4096 B. Throughput, latency, and packet loss were used as metrics to evaluate the performance of the system. Experiments were conducted for both stationary and mobile UEs. For the mobile UE, the speed is kept at 10 m/s along the x-axis, with the initial and final coordinates being (200m, 300m) and (800m, 300m), respectively. In the experiments with stationary UE, the location is fixed at (800m, 300m). The coordinates for the

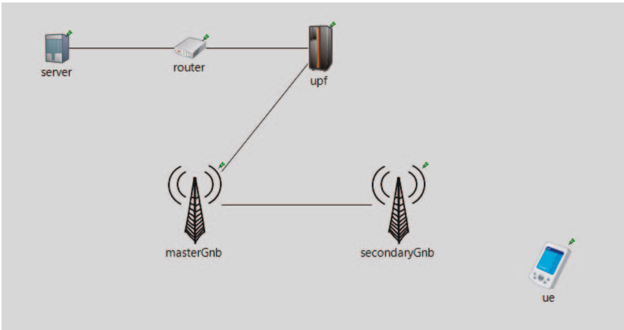

Fig. 2. Simu5G NR-DC Simulation Scenario

master and secondary gNBs are (400m, 200m) and (600m, 200m), respectively. Additional simulation parameters used in our experiments are shown in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
mmWave Carrier Frequency	28 GHz
mmWave Bandwidth	100 MHz
Carrier frequency	2 GHz
Bandwidth	20 MHz
UDP Packet Size	3000 B, 4096 B
UDP Packet Interarrival Time	0.125 ms

A. eMBB application

The experimental results shown in Tables II and III indicate that the proposed NR-DC system outperforms the single connectivity system for all the packet sizes and mobility scenarios. For a stationary UE, multi-connectivity increases the throughput to 191.62 Mbps for a packet size of 4096 B, as shown in Table II, which will enable it to meet the requirements of eMBB applications. It improves the throughput by 13.55% and the latency by 30.44%, compared to a single connectivity system. Similar improvements are also seen for a packet size of 3000 B.

NR-DC also increases the throughput of a mobile UE to 112.08 Mbps for a packet size of 4096 B, as shown in Table III. It improves the throughput by 14.07% and the latency by 32.94% compared to a single connectivity system. The packet loss of the system also improves by 11.11%. Similar improvements are also observed for a packet size of 3000 B. Thus, NR-DC improves the performance of the 5G system significantly. In addition, it is observed that throughput increases with an increase in packet size, whereas latency and packet loss improves with a decrease in packet size. This is because, with larger packet sizes, we can transmit more data in a given period, but it also results in buffer overflow and packet drop issues in the system.

The above experiments were conducted with a fixed numerology value of 0. Simulations were also conducted to study the effects of varying numerology values in an NR-DC configuration for a mobile UE, as shown in Table IV. This

TABLE II
THROUGHPUT, LATENCY, AND PACKET LOSS FOR NR-DC AND SINGLE CONNECTIVITY WITH VARYING PACKET SIZES FOR A STATIONARY UE

	Throughput (Mbit/s)	Latency (ms)	Packet Loss (Ratio)
Packet Size: 3000 B			
Multi-connectivity	**140.35**	**4.57**	**0**
Single connectivity	123.61	6.47	0
Packet Size: 4096 B			
Multi-connectivity	**191.62**	**4.57**	**0**
Single connectivity	168.75	6.57	0

TABLE III
THROUGHPUT, LATENCY, AND PACKET LOSS FOR NR-DC AND SINGLE CONNECTIVITY WITH VARYING PACKET SIZES FOR A MOBILE UE MOVING AT A SPEED OF 10 M/S

	Throughput (Mbit/s)	Latency (ms)	Packet Loss (Ratio)
Packet Size: 3000 B			
Multi-connectivity	**97.88**	**7.53**	**0.001**
Single connectivity	90.62	12.34	0.003
Packet Size: 4096 B			
Multi-connectivity	**112.08**	**10.89**	**0.008**
Single connectivity	98.26	16.24	0.009

experiment considers a split bearer scenario where packets are split equally between the master and the secondary gNB for transmission. Table IV compares the throughput, latency, and packet loss results for the master gNB, secondary gNB, and their average. Experiments were conducted with numerology values varying from 0 to 3 with a packet size of 4096 B. The numerology values were chosen to be 0, 1, 2, and 3, corresponding to subcarrier spacings of 15 kHz, 30 kHz, 60 kHz, and 120 kHz, respectively. It is observed that an increase in numerology increases the throughput and reliability while decreasing the latency. The latency and reliability of the secondary gNB are better than the master gNB, as the master gNB uses mmWave bands, which are subject to higher path loss and blockage. For a numerology value of 3, the throughput increases to 112.33 Mbps with a latency of 1.06 ms and a packet loss of 0.0004. This enables the system to meet the requirements for eMBB applications, which require a user data rate of 100 Mbps with a user plane latency of 4 ms.

TABLE IV
THROUGHPUT, LATENCY, AND PACKET LOSS USING NR-DC FOR A PACKET SIZE OF 4096 B WITH A MOBILE UE AND VARYING NUMEROLOGY

	Numerology			
	0	**1**	**2**	**3**
Throughput (Mbit/s)				
Master	112.73	112.84	112.93	112.99
Secondary	111.42	111.56	111.63	111.66
Average	112.08	112.20	112.28	112.33
Latency (ms)				
Master	16.64	5.69	2.09	1.52
Secondary	5.14	2.57	1.22	0.59
Average	10.89	4.13	1.65	1.06
Packet Loss (Ratio)				
Master	0.015	0.007	0.002	0.0008
Secondary	0	0	0	0
Average	0.008	0.004	0.001	0.0004

B. URLLC application

The NR-DC deployment was also tested for a URLLC type of application and was evaluated for varying numerologies as shown in Figure 3 for a packet size of 32 B. For all the scenarios, we observe zero packet loss. The system using NR-DC gives better performance than the single connectivity system. Additionally, the performance improves with an increase in numerology. It is shown that NR-DC can address the stringent requirements for URLLC, which needs reliability of 10^{-5} in terms of packet loss rate for a 32 B packet with a user plane latency of 1 ms. For NR-DC with a numerology value of 3, the latency is shown to be 0.56 ms with zero packet loss, which meets the URLLC requirements. Additionally, NR-DC outperforms single connectivity for all the numerology values.

Simulations were also conducted with up to 40 UEs as shown in Table V. The latency increases with an increase in the number of UEs. The system performs well with scalability, with zero packet loss and very low latency for all the scenarios.

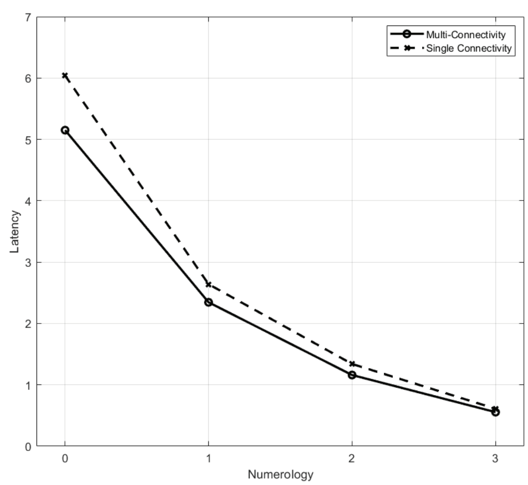

Fig. 3. Latency (ms) for NR-DC and Single Connectivity with varying numerology for a packet size of 32 B

TABLE V
LATENCY AND PACKET LOSS WITH VARYING NUMBER OF UES FOR A NUMEROLOGY VALUE OF 3 WITH A PACKET SIZE OF 32 B

Number of UEs	Latency (ms)	Packet Loss (Ratio)
10	0.732	0
20	0.820	0
30	0.938	0
40	1.033	0

Thus, NR-DC significantly improves the performance of next generation 5G networks and shows great potential for achieving high throughput and ultra-reliable low latency communication, which are critical for emerging applications.

V. CONCLUSION

In this paper, we present and evaluate solutions using Simu5G to improve the performance of next generation mobile networks using NR-DC, which to the best of our knowledge, has not been addressed in any prior work. NR-DC enables the integration of multiple radio resources, thereby improving throughput, latency, and reliability simultaneously. The performance of the designed 5G system was examined using the Simu5G network simulator. The proposed techniques were shown to significantly increase the throughput and reliability of the system while simultaneously decreasing the latency. Our work focuses on developing novel real-world solutions for addressing the challenges involved in building next generation cellular networks. As part of the next steps, we are also looking into enhancing our system by leveraging multi-connectivity and extending it to the core network with support for more than two links. In the future, we plan to further develop our system for deployment in smart city environments.

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