IMPROVEMENT OF THROUGHPUT USING DUAL CONNECTIVITY IN NON-STANDALONE 5G NR NETWORKS

A Dissertation (Major Project-II) submitted in partial fulfillment of the requirement for the award of the degree of

Master of Technology

in

Information Systems

by

Sakshi Dubey

2K18/ISY/10

Under the Supervision of

Mr. Jasraj Meena
(Assistant Professor, Department of Information Technology)

Department of Information Technology
Delhi Technological University
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Bawana Road, Delhi – 110042 (India)
August-2020

DECLARATION

I, Sakshi Dubey, hereby declare that the work which is being presented in the dissertation (Major Project-II) entitled "**IMPROVEMENT OF THROUGHPUT USING DUAL CONNECTIVITY IN NON-STANDALONE 5G NR NETWORKS**" by me in partial fulfillment of requirements for the award of the degree of Master of Technology (Information System) from Delhi Technological University, is an authentic record of my work carried out under the supervision of **Mr. Jasraj Meena**, Assistant Professor, Information Technology Department. The material contained in the report has not been submitted to any university or institution for the award of any degree.

Sakshi Dubey.

Place: Delhi **SAKSHI DUBEY**

Date: 08/08/2020 **2K18/ISY/10**

CERTIFICATE

This is to certify that Major Project report-2 entitled "**IMPROVEMENT OF THROUGHPUT USING DUAL CONNECTIVITY IN NON-STANDALONE 5G NR NETWORKS**" submitted by **SAKSHI DUBEY (Roll No. 2K18/ISY/10)** for partial fulfillment of the requirement for the award of degree Master of Technology (Information System) is a record of the candidate work carried out by her under my supervision.

08/08/2020

Place: Delhi
Date: 08/08/2020

Mr. Jasraj Meena
Supervisor,
Assistant Professor
Department of Information Technology
Delhi Technological University, Delhi

ACKNOWLEDGMENT

First and foremost, I would like to express my sincere gratitude to **Mr. Jasraj Meena,** Assistant Professor, Information Technology Department, DTU, for his continuous support during this thesis. He has not only been my supervisor but also a very inspirational figure during my master's studies. This is my heartfelt thanks for his motivational lectures which have helped me to improve as a computer science student and pursue the field of machine learning.

Secondly, I am grateful to **Prof. Kapil Sharma**, HOD, Information Technology Department, DTU, for his immense support. I would also like to acknowledge the Delhi Technological University faculty for providing the right academic resources and environment for this work to be carried out. Last but not least I would like to express sincere gratitude to my parents and friends for constantly encouraging me during the completion of work.

Sakshi Dubey

SAKSHI DUBEY

2K18/ISY/10

ABSTRACT

Wireless communications are constantly evolving to facilitate better access to information for the improvement of business, education, and technology around the world. Hence to overcome the lack of spectrum new bands like millimeter wave (mmWave) bands are needed to be utilized. The mmWave bands offer a huge spectrum due to which substantial attention is being given to exploit this frequency range for deploying 5G cellular systems. 5G wireless technology is anticipated to deliver multi-Gbps data rates, vast network capacity, low latency, and more reliability. Despite the provision of the spectrum, the new mmWave bands are prone to blockages and obstacles. Hence, these bands must be deployed with the help of an architecture that can overcome this drawback and can prevent any disruption of service in case of blockage. This work will present the non-standalone architecture of the mmWave module of ns-3 or network simulator 3 by modifying the dual connectivity of user equipment (UE) to Long Term Evolution (LTE) module and mmWave module of ns-3 for improved simulation of 5G New Radio (NR) networks. It also includes a detailed discussion upon the design and functioning of 5G wireless technology in NSA mode with the help of simulation setup. Finally, the performance of the 5G network in standalone (SA) and non-standalone mode are compared graphically and numerically.

Keywords: 5G, cellular, dual connectivity, millimeter-wave, non-standalone, ns-3, standalone

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

S.No.	Abbreviated Name	Full Name
1	mmWave	Millimeter-Wave
2	NR	New Radio
3	UE	User Equipment
4	LTE	Long Term Evolution
6	NSA	Non-Standalone
7	SA	Standalone
8	DC	Dual Connectivity
9	3GPP	3rd Generation Partnership Project
10	RRC	Radio Resource Control
11	EPC	Evolved Packet Core
12	MME	Mobility Management Entity
13	gNB	Next Generation Node Base
14	eNB	Evolved Node Base
15	NS-3	Network Simulator 3
16	MAC	Media Access Control layer
17	PHY	Physical layer
18	RLC	Radio Linc Control layer
19	PDCP	Packet Data Convergence Protocol
20	NAS	Non-Access Stratum
21	S-GW	Serving Gateway
22	P-GW	Packet Data Network Gateway
23	TDD	Time Division Duplex
24	SINR	Signal to Interference plus Noise Ratio
25	UP	User Plane
26	CP	Control Plane

LIST OF EQUATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Introduction to mmWave Bands

The constant evolution of wireless communication and shortage of spectrum in the existing wireless services has led to the study of millimeter-wave (mmWave) bands as a frequency range that can provide a huge spectrum and multi-Gbps wireless services [1]. Because of this ability, mmWave bands have gained major heed in the deployment of 5G wireless technology. Despite this potential, the susceptibility of mmWave bands towards obstacles and weak radio propagation at high frequency makes these new bands require several layer-wise improvements and advancements in the protocol stack to get deployed adequately. Some of these advancements have already been implemented in the previous studies like modified channel models and adaptive antenna in the physical layer [2], [3]. Latency challenges are tackled to implement to provide the mmWave cellular system with ultra-low latency [4]. And these advancements are implemented and tested with the help of ns-3. The network simulator-3 or ns-3 [5] already supports various network protocols and implements modules for simulating networks like 3GPP-LTE. It also has a millimeter-wave (mmWave) module first implemented in [6]. So, this work aims to utilize this module and develop a non-standalone architecture for 5G networks.

To overcome the challenges faced by a typical standalone mmWave system and improve the overall throughput achieved, this work suggests the design of non-standalone architecture (NSA) for 5G cellular networks. Hence, the existing mmWave and LTE modules of ns-3 are integrated with the help of the dual connectivity technique introduced in [7] with some modifications to implement an NSA architecture. Also, this study presents the evolution of the mmWave module by describing the related work done in previous years for the advancement of the mmWave module. It discusses snd compares the previous studies that led to the expansion of the existing module and enhancements presented by each of these studies in tabular form. This work imparts information about the design and functioning of the proposed non-standalone framework at the Radio Resource Control (RRC) layer. And addresses the evaluation of the functioning of the proposed architecture and compares it to the typical standalone architecture.

1.2 5G NR Networks

5G NR Networks refers to the fifth generation new radio networks [8]. These networks are expected to deliver multi-Gbps peak data rates. Since mmWave bands offer a broad spectrum so recent interest has been developed in deploying 5G NR networks with the help of mmWave bands. 5G cellular systems are being thoroughly studied all over the world [9]–[16]. 5G cellular networks are anticipated to provide peak data rates of 20 Gbps i.e. 100 times faster than LTE (Long Term Evolution). Other than this 5G cellular networks are projected to achieve the following targets:

- Data rates as high as 50 Mbps at the edges of cells
- Peak data rates of about 1 Gbps
- Latency lower than 10 ms for end-to-end-support
- Super reliable communications
- Enormous Machine Type Communication (MTC) by utilizing low power

5G networks are in an evolving phase whereas we have a fully established infrastructure for 4G LTE. A contrast in the deployment of 4G LTE and 5G NR is shown in Figure 1.1. The base stations used in LTE are described as eNBs or evolved Node Base while in the case of 5G networks base stations are termed as gNBs or Next Generation Node Base. AMF/UPF are the Access and Mobility Management Functions and User Plane Functions respectively. The UPF is the evolution of the data plane [17]. It was implemented as an extended version of the Evolved Packet Core (EPC). It interconnects data network and mobile infrastructure and provides encapsulation and decapsulation of GTP-U (GPRS Tunneling Protocol for user plane) [18].

The functioning of the Mobility Management Entity (MME) of 4G is decomposed in 5G and the Access and Mobility Management Function (AMF) conducts the mobility management and connection setup tasks only [19]. AMF manages the handover between the gNBs. All the session management related tasks are dispatched to the Session Management Function (SMF). Hence, the data from the UE reaches the UPF of 5G core via the source gNB and the RRC signaling performs continuous checks the signal strength of the source gNB. And if the signal quality degrades a switch is performed. The switching process is initiated with the help of the handover to the target gNB which is managed by AMF. And now UE can again transmit data through the target gNB to the UPF.

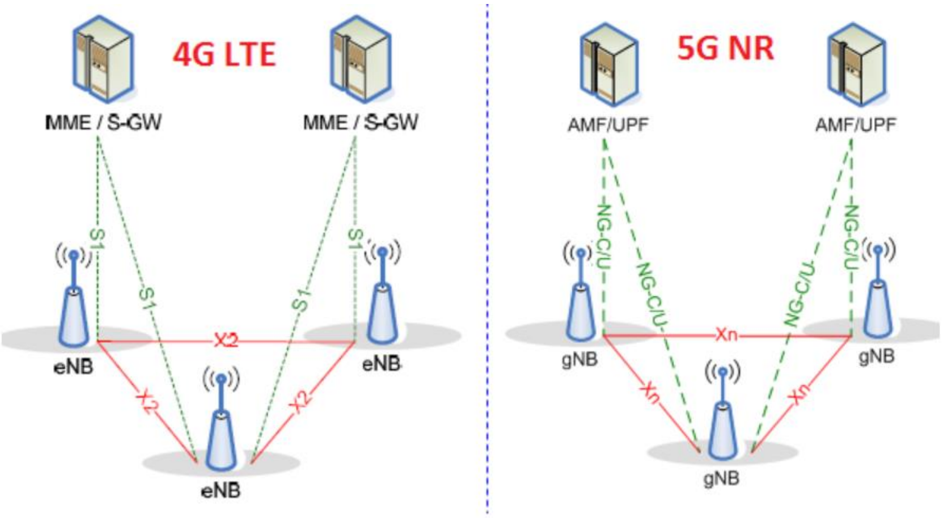

Figure 1.1: Comparison of system models of 4G LTE and 5G NR

1.3 Standalone (SA) and Non-standalone (NSA) modes

Standalone mode refers to the execution of 5G cellular systems such that only 5G cells manage the data transfer as well as signaling messages. Hence, both control and user planes are managed by the 5G cellular systems. Whereas in non-standalone mode 5G cellular systems take the leverage of pre-existing 4G LTE systems for operating control plane tasks and the user plane is managed by 5G systems. NSA architecture helps in the faster deployment of 5G NR networks as the already existing LTE infrastructure can be modified to 5G services. It is a better alternative to SA architecture until an improved and established end-to-end SA architecture can be deployed.

1.4 Network Simulator 3 or NS-3

NS-3 [5] is an open-source simulator that provides a platform for network simulation to develop and assess protocols, mechanisms, and technologies for research and scholastic purposes. NS-3 is designed with the libraries of software programs that implement various network protocols and modules to simulate communication standards like 3GPP-LTE, WiMAX, etc [20]. Hence, ns-3 helps in the research and evaluation of new mechanisms and techniques introduced in these communication standards by simulating a real-life scenario for the assessment of such techniques. And ns-3 simulator is used in this work for the assessment of performances of the standalone and non-standalone mode.

CHAPTER 2

LITERATURE REVIEW

2.1 Evolution of mmWave Module

This module is inspired by the LTE-LENA module [21] of ns-3 and designed similarly. It has a customizable design and is entirely developed in C++. The functioning and the architecture of the module can be understood through its UML diagram provided in [6]. An entire framework of mmWave module is can be studied in [6] including channel models. Propagation schemes and the configuration for the MAC and PHY layer. The PHY layer of mmWave module consists of a time division duplex (TDD) frame structure and supports multiple-input-multiple-output (MIMO) techniques. For modeling, the PHY layer for UE and eNB there exist functions namely, *mmWaveUePhy* and *mmWaveEnbPhy* in the ns-3 mmWave module. It is also responsible for the calculation of signal-to-interference-plus-noise-ratio (SINR) which will be needed later while describing the proposed work. The mmWave module also models the propagation loss model with three states as stated in [3]. These states are outage, non-line-of-sight (NLOS), line-of-sight (LOS). The MAC layer of this module manages the transfer of data packets to and from the upper layers. It also looks into the resource allocation and initially implemented a round-robin algorithm for allocation of resources.

2.2 Inspiration from LTE

2.2.1 LTE architecture

LTE architecture consists of three key modules:

1) User Equipment (UE)
2) Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) [22]
3) Evolved Packet Core (EPC) [23]

The user equipment or UE is a wireless mobile device in LTE and other wireless communication systems that seeks connection with a base station or evolved Node Base (eNB) in the case of 4G LTE. It forms the first module. E-UTRAN consists of a single component that is eNB. It manages the interaction between the UE and eNB. The eNBs are connected to mobile devices, EPC, and also to the other eNBs with the help of interfaces. S1 interfaces connect eNB to EPC and X2 interfaces connect an eNB to another eNB. EPC consists of memory management entity (MME), home subscriber server (HSS), packet data network gateway (P-GW), the serving gateway (S-GW). MME manages the tasks on mobile devices with the help of signaling and HSS. HSS serves as a central database that keeps information regarding network subscribers and user profiles that can be utilized for authentication purposes. P-GW assigns UE with an IP address to provide access to the outside world that is to the Packet Data Network or PDN. And the S-GW transmits data from E-UTRAN to P-GW.

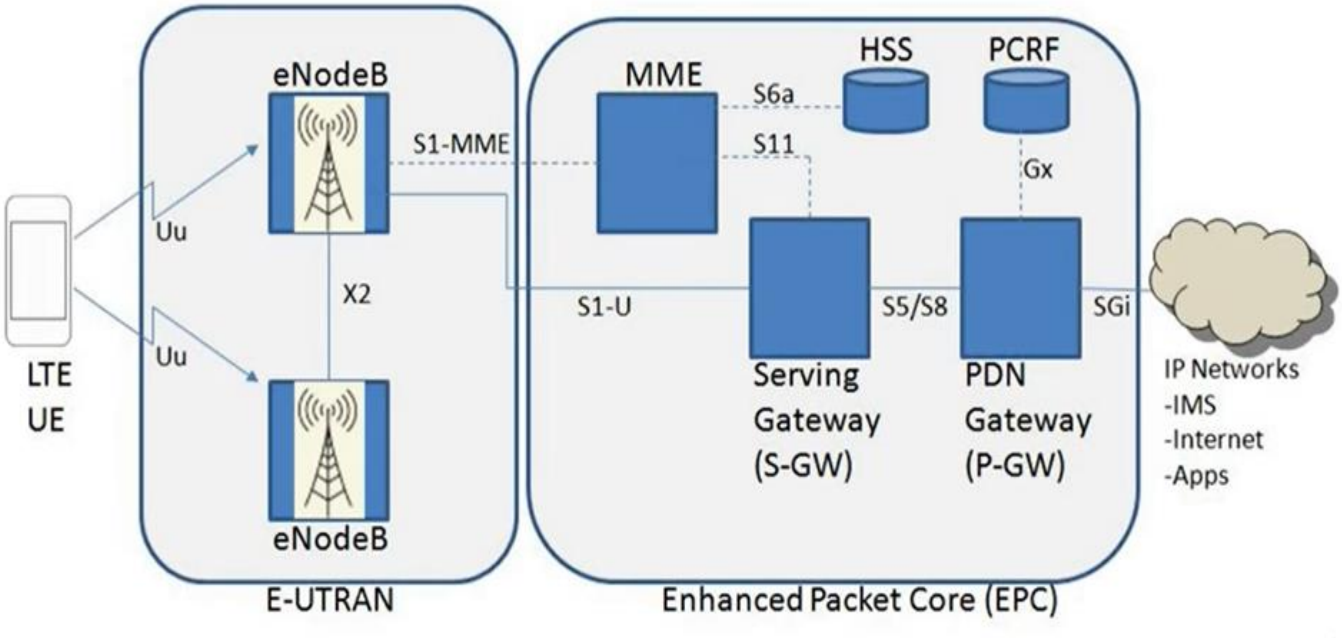

Figure 2.1: Components of LTE architecture

2.2.2 LTE Protocol Stack

The protocol stack for LTE is shown in Figure 2.2. This is a layer-wise presentation of the E-UTRAN protocol stack [24]. The working of all the layers is described as follows:

- **Physical Layer:** The main purpose of this layer is to transfer data and control signals between eNB and UE. MAC layer obtains data from layers above it and transfers the data to the PHY layer [25] which then transmits that data towards the required entity. It also takes care of adaptive modulation and coding (AMC) [26] schemes and cell search for handover purposes.

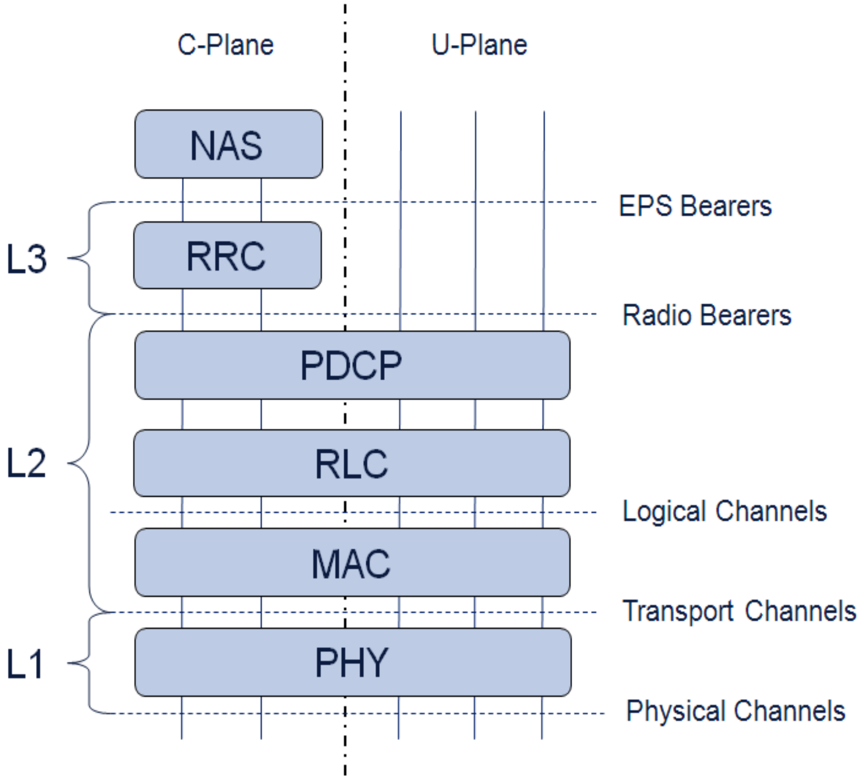

Figure 2.2: LTE protocol stack layers

- **MAC Layer:** MAC layer or Media Acces Control protocol is a radio network protocol that is present in both E-UTRAN and UE [27]. It is also present in the user plane as well as the control plane. It performs multiplexing/ demultiplexing of data. It also consists of the HARQ entity and control entity.

- **RLC Layer:** Radio Link Control layer or RLC operates in three modes, i.e., Acknowledged Mode (AM), Unacknowledged Mode (UM), and Transparent Mode (TM) [28]. It also transfers the upper layer Protocol Data Units (PDUs), carries out error correction in AM only. And operates segmentation, concatenation, and reassembly in UM and AM only.

- **RRC Layer:** Radio Resource Control layer broadcasts system information regarding Access Stratum (AS), Non-Access Stratum (NAS) [29]. It manages the radio bearer establishment, paging, and operates RRC connection establishment, release, and maintenance between UE and E-UTRAN. It also manages the functioning of the lower layers. Figure 2.3 shows the state diagram representing the procedure involved in the RRC connection. The proposed work in this article modifies the functioning of this layer for accessing 5G services.

- **PDCP Layer:** The Packet Data Convergence Protocol (PDCP) layer sits at the top of

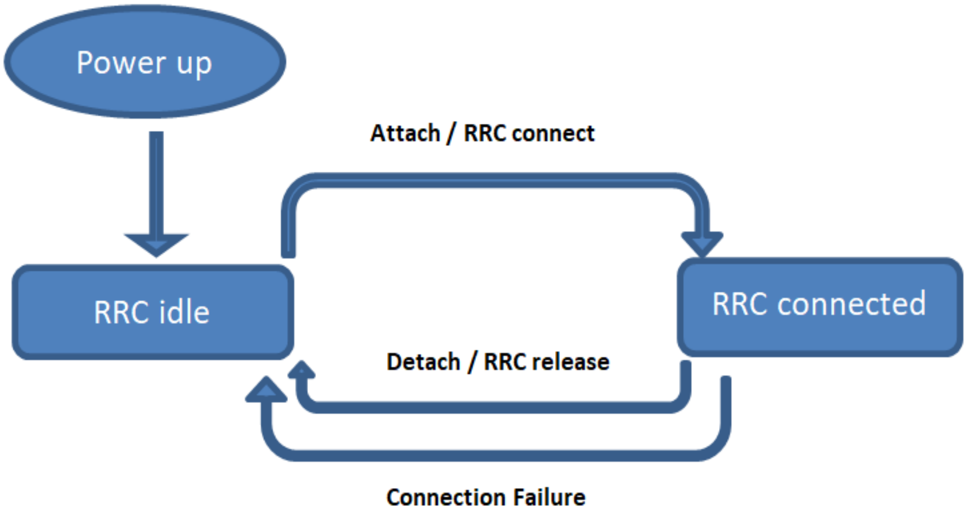

Figure 2.3: RRC connection for LTE

the RLC in the protocol stack. It ciphers and deciphers of control plane and user plane data. Performs compression and decompression of IP header, integrity protection of the data related to the control plane. And also discards duplicate Service Data Units (SDUs).

- **NAS:** Non-Access Stratum is the topmost protocol of the control plane [30]. It supports UE mobility and manages a communication session establishment to provide an IP connection between P-GW and UE. The working of NAS is opposite to AS (Access Stratum).

2.3 Integration of LTE and 5G mmWave

The mmWave bands are expected to provide approximately 10 GHz of frequency due to which a lot of attention is being paid for exploiting this frequency range for the deployment of 5G cellular systems. And the fastest mode to deploy the 5G mmWave system is through the help of already established LTE architecture. And to provide reliable connections and to stabilize the channel quality some of the improvements were implemented as multi-connectivity of user equipment (UE) to more than one cell and fast handover methods between cells [31]. Multi-connectivity refers to the connection of a single eNB to many cells. These can be either 4G or 5G cells. Different layers of the protocol stack are also studied to find an efficient integration point of the protocol stacks of the two Radio Access Technologies (RATs) [32].

In [7] a new protocol is proposed that integrates LTE and mmWave module of ns-3 which is termed as Dual Connectivity (DC) protocol. This protocol is later modified in this article so that non-standalone architecture can be developed. The integration of the LTE and mmWave module is carried out with the help of DC protocol and by taking care of the following guidelines.

- From both the architectures that are LTE and mmWave an integration layer is selected above which the protocol stack of both the architectures will have common layers [33].

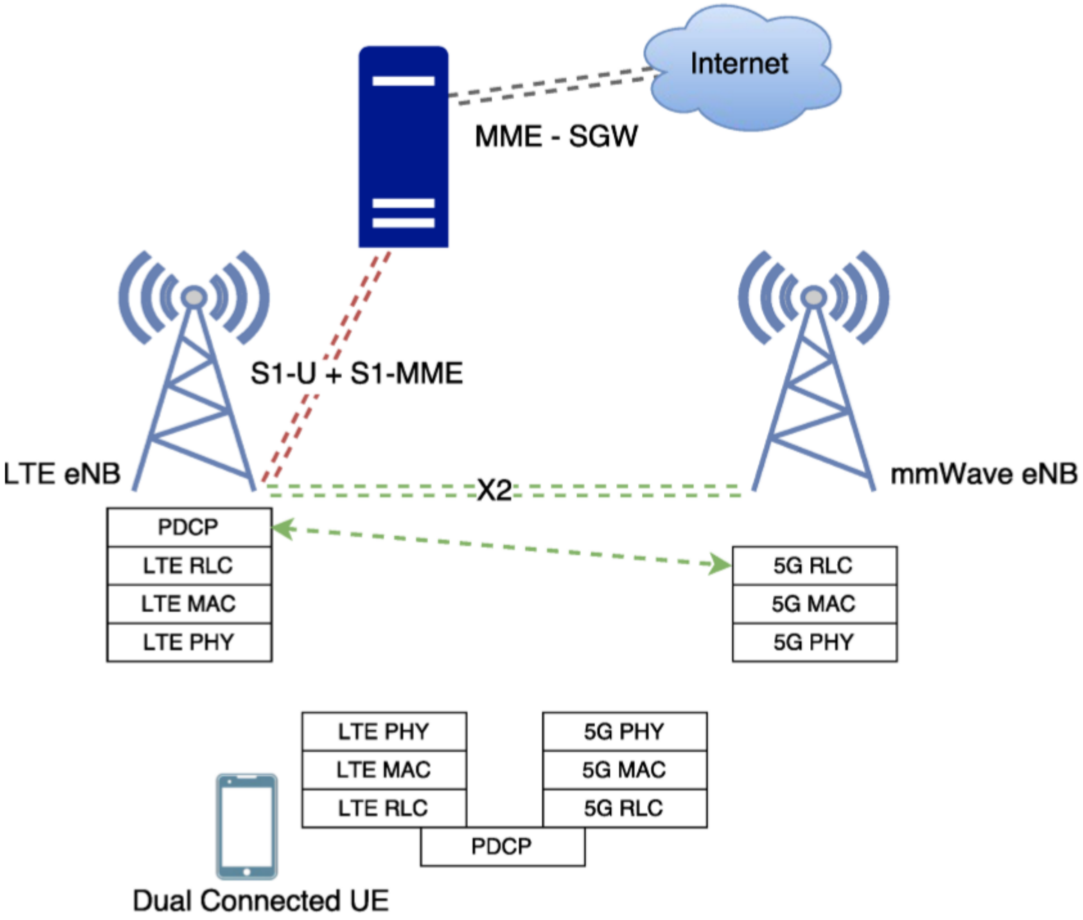

Figure 2.4: LTE-5G tight integration architecture [7]

- The integration layer will form a point of interference and below this layer, the working and implementation of protocol stack layers might differ.
- Since the PDCP layer is quite independent of the lower layer functionalities this layer is chosen as an integration layer.
- To switch from one radio network to another inter Radio Access Technology (RAT) is required.
- Hence, some inter-RAT handover mechanisms are needed to be designed which are fast and prevent delay while switching.
- While switching any possibility of contention must be checked and a random access procedure must be designed accordingly.
- An exchange of messages needs to be carried out with the MME so that the path

can be switched from the S-GW to that particular BS to which the handover is going to be performed by the UE.

- The delay interval due to processing at MME should be as low as 10 ms (one-way).
- The BS that is initiating the handover must transmit packets in this interval to the targeted BS.
- The handover from one BS to the other BS is initiated only when the former BS is out of service, i.e., a mmWave gNB will initiate the handover to the LTE eNB only if the mmWave gNB suffers an outage.
- The block diagram shown in Figure 2.4 represents the implementation of the DC scheme for tight integration of LTE and mmWave module.
- A Dual Connected device is shown in Figure 2.4 accommodating protocol stack for both LTE as well as mmWave technology.
- The DC device is connected to the LTE eNB that maintains a solitary connection to the EPC using the S1 interface.
- LTE eNB is linked to the mmWave eNB (gNB) through the X2 interface.
- The eNB acts as the backup cell to which the connection falls whenever mmWave eNB suffers an outage or the quality of the link deteriorates.
- Hence, the LTE eNB acts as a coordinator and selects a potential mmWave with the help of a sounding reference signal (SRS) [32] which is broadcasted in all the angular directions of the coordinator cell (eNB).
- The centralized selecting BS nominates the best candidate mmWave BS that is having the best SINR metrics in the report table.
- Since DC mobile device already maintains protocol stacks for both mmWave and LTE technologies so a complete handover is no longer required rather an RRC control message will accomplish the purpose.

Hence, by considering the above guidelines an integration of LTE and mmWave technology is performed to form a more robust system.

2.4 Comparative Analysis of Relevant Studies

Some significant work is done towards the development and evolution of mmWave module beginning from the inspiration from LTE module [34] to the implementation of a mmWave module in ns-3 which exhibits a similar design and functioning with an additional advantage of better results in channel capacity, data rates, broader spectrum, and many other metrics. A detailed evolution and enhancements in the module are formulated in Table 2.1. It also compares some previous works based on the parameters like their novel aspects, modifications made in the existing module, results of these modifications, and their benefits.

Table 2.1: Comparison of relevant works done for the evolution of mmWave module

	Proposed Model	Novel Aspects	Configurational Enhancements	Results	Advantages
[34]	Simulation module of LTE networks for the ns-3 simulator	The module supports 1) Radio Resource Management, 2) Inter-cell Interference Management, 3) QoS -aware Packet Scheduling and 4) Dynamic Spectrum Access	MAC implements: 1) Resource Allocation Module, 2) modified Adaptive Modulation and Coding (AMC), 3) Round Robin scheduler, 4) Proportional Fair Scheduler	Developed simulation module evaluates the performances of Self Organised Networks (SON) algorithms for LTE	RRM/SON algorithms for LTE can be evaluated with the help of simulation prior to real-world applications.
[6]	The first mmWave module for the ns-3 simulator is developed	The module comprises of 1) PHY layer, 2) MAC layer and 3) propagation and channel models	PHY consists of 1) TDD frame structure, 2) Radio characterization with channel variation supporting MIMO techniques, 3) Error model at receiver, 4) Interference model.	A new & customizable simulation module for mmWave 5G cellular networks is introduced	1) Spectrum scarcity can be eliminated by introducing new bands, 2) Researchers can flexibly analyze

			MAC transfers the upper layer data to the PHY layer. Also conveys resource allocation & scheduling decisions	consisting of fundamental implementation of PHY, MAC & mmWave devices	various setups using the different configuration of the simulation
[35]	A module for simulation and evaluation of end-to-end connectivity is developed for 5G mmWave cellular networks in ns-3	The module consists of MAC and PHY-layer configurations which can be interoperated with the core network unit of the ns-3 LTE model with the help of SAPs and higher layer protocols for end-to-end simulation	PHY layer implements 1) TDD frame which allows flexible allocation of data and control channels for variable Transmission Time Interval (TTI), 2) Path loss model is merged with building obstacle model for realistic hindering MAC layer now contains 1) modified AMC, 2) two scheduler classes, 3) multi-process stop-and-wait HARQ	A customizable simulation module is introduced for the provision of evaluation of new 5G protocols custom mmWave MAC/PHY layer protocols can also be analyzed over the implementations of mmWave eNB, mmWave stack & channels	1) Millimeter-wave provides a huge amount of spectrum, low latency links, 2) the developed module provides an easy evaluation of new 5G protocols
[36]	3GPP channel	1) 3GPP channel model for ns-3	Propagation Loss Model is extended to implement	An enhanced and improved	1)The channel model covers

	model is presented for 6-100 GHz band for end-to-end 5G mmWave framework of ns-3	mmWave framework is introduced that can be further utilized for simulating NR technologies, and 2) MIMO beamforming architecture is introduced	the 3GPP guidelines for calculating path loss and an alternative model is provided which uses the ns-3 Building model to position buildings in the simulation in a random or deterministic manner MIMO based beamforming calculation is implemented	channel model is introduced to accurately access and analyze 5G NR technology	broader frequency range, 2) Eliminates channel inconsistency due to random obstacles and mobility
[7]	The model consists of a dual connectivity framework and improved mechanisms for handover and path switching	1) Implementation of dual connectivity for better mobility management & faster handover process, 2) evaluation of the handover process for mmWave systems	In the dual connectivity (DC) architecture UE performs secondary cell handover (SCH) rather than performing hard handover (HH). The upper layers of mmWave & LTE DC frameworks are extended from the same layers of the ns-3 LTE module. PHY & MAC layers of mmWave module and LTE classes are modified for the proper functioning of framework and PDCP is the integration layer	The dual connectivity model performs better concerning packet loss, latency, and throughput.	1) Improved end-to-end network performance, 2) reduction in latency due to fast switching with the help of SCH, and 3) multi-connectivity framework enhances the quality of service

[37]	Two integration alternatives are proposed to come up with a reliable mmWave and LTE integration system	1) Dual Connectivity mechanism is used to perform tight integration, 2) implementation of faster switching mechanism than Hard Handover	Architecture with the PDCP layer as an integration layer of two Radio Acces Technology is implemented with DC mobile device having protocol stacks of both the RATs to establish the connection to both the technologies. So, this integration module could be implemented with a fast switching mechanism. Another alternative for the integration is also suggested with Hard Handover as the switching mechanism.	1)The dual connectivity module with switching procedure performs better than the traditional Hard Handover module, 2) A simulation framework is presented to analyze such schemes.	1) Improved through and latency, 2) a faster switching mechanism will result in a more robust system

The studies described in this section demonstrate how the path is paved towards the evolution of the mmWave module. The mmWave module was initially implemented as an idea to leverage the mmWave bands for the provision of 5G wireless technology. Later the layer-wise improvements, integration of channel models, and multi-connectivity framework led to the customization of the pre-existing module. The development of this module of ns-3 has sped up the process of research and assessment of 5G wireless technology. The upcoming advancements in the 5G NR networks can be indisputably evaluated with the help of simulation setups employed with the support of the mmWave module of ns-3.

2.5 Problem Identification

This section presents the conclusion derived by comparing some standard works formulated over the mmWave module of ns-3. It also identifies the problems faced by the existing framework and the modifications needed to implement a more robust architecture for 5G NR networks. The framework presented in [6] is the introduction of the mmWave module in ns-3. This is the initial stage of the mmWave module which was unable to handle the susceptibility towards obstructions and hindrances. Later dual connectivity [7], multi-connectivity [31], and tight integration [37] of mmWave module are presented for the interoperability of 5G and other wireless technologies like LTE. The inducement of these advancements in the mmWave module led to the idea of a non-standalone (NSA) architecture proposed in this work. The NSA architecture can result in better performance of 5G NR by providing the support of LTE technology to eliminate any service disruption that occurred due to the vulnerable nature of mmWave technology towards obstacles.

CHAPTER 3

THE PROPOSED WORK

3.1 Objective

This work intends to implement a non-standalone (NSA) architecture by modifying the existing dual connectivity (DC) mechanism. In this architecture, the user device will be able to access 5G data services with the help of LTE base stations. This will provide the improved and robust services of the 5G cellular system with the help of well-established LTE infrastructure. It also aims at the better deployment of mmWave technology. It eliminates the susceptibility of these bands towards blockages and hindrances by providing an architecture that can extract maximum performance advantages from this frequency range.

This study will provide a thorough exploration of the performances of the NSA and SA architectures. In SA mode UE will have direct access to the mmWave eNBs (or gNBs). Whereas in NSA mode UE will form dual connectivity to LTE eNB and mmWave eNB (or gNB) and will utilize the 5G data services with the help of LTE eNBs. Later a comparison of performances of both the architecture is carried out to provide an improved and reliable environment for the deployment of 5G cellular systems. It will also check the variation of performances of both the architecture with the mobility of the user device. And how the two architectures will change their courses of action if the link to the serving gNB gets disrupted.

3.2 Modified Dual Connectivity Mechanism

The existing DC mechanism that was implemented in [7] is used to improve the handover mechanism and to replace the traditional Hard Handover with fast switching with the help of dual connected UE. Dual connectivity allowed the UE to maintain a simultaneous connection with the mmWave as well as the LTE module of ns-3. Since there exists a connection between UE and LTE eNB, there is no requirement of performing a complete traditional handover and a sole RRC message can operate a switch between two radio technologies.

Here in this work, a modified DC mechanism is presented that is inspired by the pre-existing mechanism of dual connected UE. In this mechanism, the UE maintains a dual protocol stack for LTE as well as mmWave modules of ns-3 and also maintains a permanent connection to the LTE module as shown in Figure 3.1. The LTE module is the centralized coordination system that performs all the necessary tasks including gNB selection, gNB switching, and gNB config. The procedure for **gNB selection** is stated below:

- It searches the most suitable gNB for the UE.
- It transmits the sound referencing signals (SRS) in all the directions sweeping the annular space around it.
- These signals are decoded by C-RNTI (Cell Radio Network Temporary Identifier) [38] and then used by gNBs to estimate the channel.

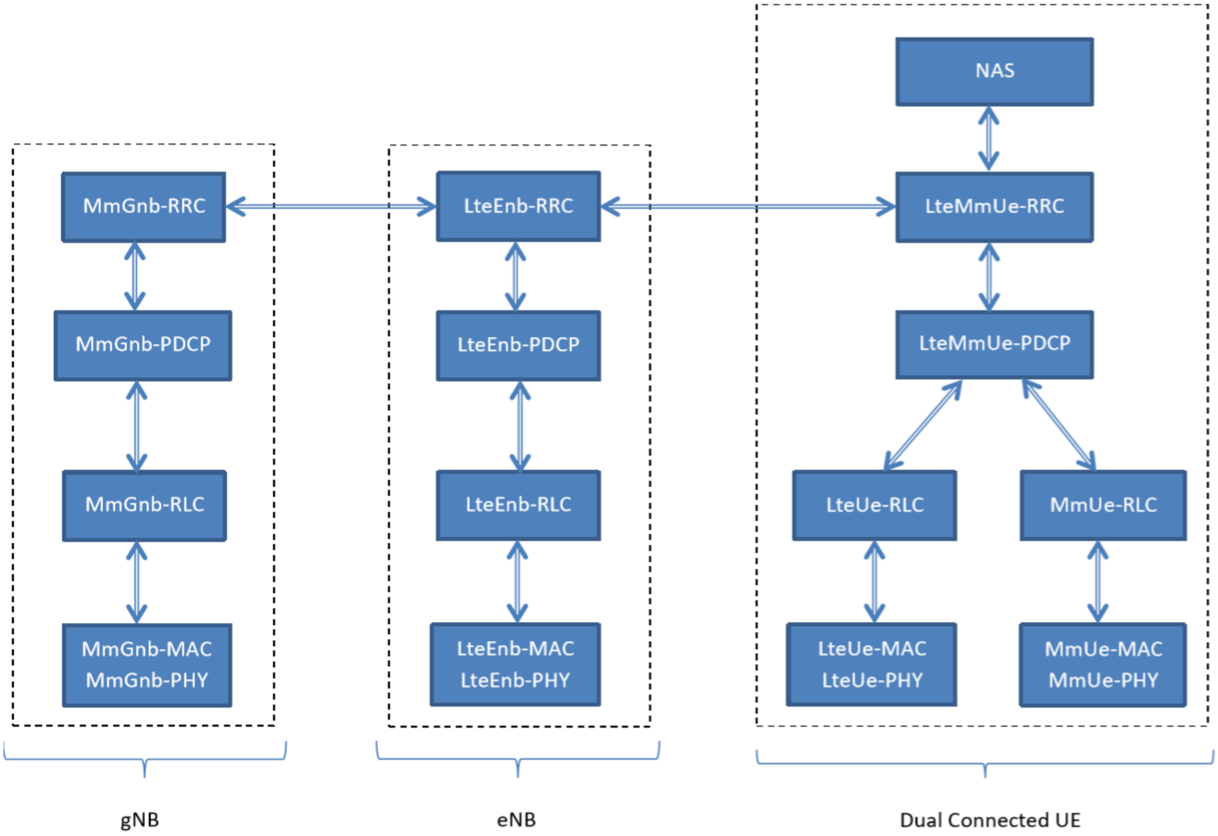

Figure 3.1: Protocol stack of modified DC

- The gNBs collect all these signals by scanning through their directions.
- Now each gNB fills a record table mentioning its best SINR value for every UE that it can get by selecting the best direction to transmit.
- The coordinator eNB collects all these tables that it received via the X2 link to the gNBs and merges them into one table.
- After going through the entire table it selects the best gNB candidate based on the SINR of each entry.
- Hence, a connection to the most eligible gNB candidate of the table can be commenced.

Figure 3.1 shows a dual connected UE, a coordinator eNB, and a gNB. Since the UE is dual connectivity enabled it contains protocol stack to communicate with both the RATs. PDCP layer is the integration layer of the dual connected stack. LTE is the coordinating entity and controls the gNB connection establishment through its RRC layer. The UE always maintains a permanent connection to the LTE eNB in its vicinity and appoints it as a master node for the selection and communication commencement with mmWave gNB.

3.3 Proposed NSA Architecture

The non-standalone or NSA architecture proposed here involves the key role of the modified DC mechanism stated above. As to implement a DC architecture DC enabled UE is required that can form simultaneous connections to both LTE and 5G NR networks. In the NSA architecture of 5G NR technology, all the control plane tasks of the mmWave BS are managed by the LTE BS and the mmWave BS indulges only in the user plane tasks as shown in Figure 3.2. The UE establishes an uninterrupted connection to LTE eNB so that it can support the mmWave gNBs in performing control signaling while switching between the gNBs when required. The switching of a mmWave gNB with the other is required when the current gNB results in zero throughput or the link between the coordinator eNB and the gNB deteriorate due to UE mobility. The switching between two gNBs or **gNB switching** is initiated according to the following guidelines. Let us suppose there exists three potential gNBs in the vicinity of the UE-eNB pair, $gNB_{i,}$ $gNB_{j,}$ gNB_k with $SINR_{i,}$ $SINR_{j,}$ $SINR_{k,}$ then:

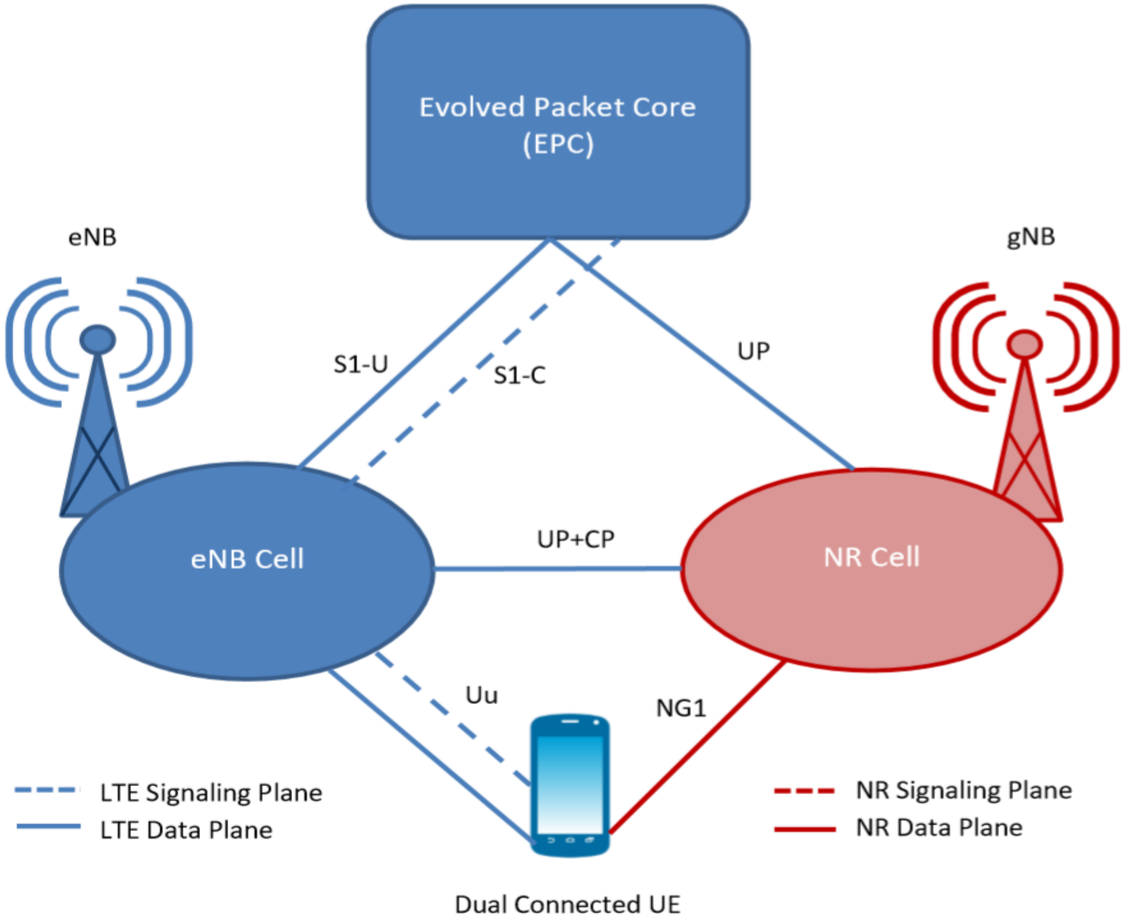

Figure 3.2: NR addition and NR removal process at RRC

- Selected gNB should have maximum SINR, i.e.,

$$\boldsymbol{max}(\boldsymbol{SINR_i}, \boldsymbol{SINR_j}, \boldsymbol{SINR_k}) \tag{1}$$

- If after a certain time interval the SINR of the selected gNB degrades, suppose gNB_i is the selected gNB and $SINR_i$ becomes less than the SINR of other gNBs which are not in an outage at that timestamp, i.e.,

$$\left((\boldsymbol{SINR_i} < \boldsymbol{SINR_j}) \wedge (\boldsymbol{SINR_j} > \boldsymbol{Outage_{th}})\right) \vee \left((\boldsymbol{SINR_i} < \boldsymbol{SINR_k}) \vee (\boldsymbol{SINR_k} > \boldsymbol{Outage_{th}})\right) \tag{2}$$

- Here $Outage_{th}$ is the SINR value which is set as a threshold to check whether the certain gNB has suffered an outage or is still in the vicinity. So if the serving gNB is still in the vicinity of the UE-eNB pair then its SINR should be greater than the $Outage_{th}$, i.e.,

$$\boldsymbol{SINR_i > Outage_{th}} \tag{3}$$

- And if the SINR degrades and becomes lesser than the set threshold due to which gNB config failure occurs then a switch is performed to next potential gNB, i.e.,

$$\boldsymbol{SINR_i < Outage_{th}} \tag{4}$$

3.3.1 gNB config

This entire procedure for the selection of the most suitable gNB candidate is termed as **gNB config**. The gNB configuration covers two essential processes that have been stated in the above two sections:

1) **gNB Selection**: Selection of a potential gNB based on the SINR entries from the record table maintained by the coordinator eNB.
2) **gNB Switching**: Switching between gNBs if the SINR of the serving gNB degrades due to user mobility or outage, i.e., **gNB config failure** occurs.

3.4 Framework Illustration

The deployment of 5G NR network in non-standalone (NSA) mode describes the system where 5G networks rely on the control plane of the pre-existing LTE module for control functions whereas the 5G networks manage the user plane tasks only. In this work, the functioning of the NSA mode is designed with the help of dual connectivity technology. The dual connectivity (DC) mechanism is implemented in [7]. This mechanism is used to improve the process of handover in the mmWave module of ns-3 by the provision of the simultaneous connection of UE to the LTE base station as well as mmWave base station.

The DC protocol is implemented by extending the NetDevice module of ns-3 and developing the McUeNetDevice function. A layer-wise configuration of the DC protocol with PDCP (Packet Data Convergence Protocol) layer as the integration point of dual connectivity architecture can be studied in [37]. As a result, the mechanism eliminated the delay caused by carrying out the traditional hard handover (HH) between the LTE evolved Node Base (eNodeB or eNB) and mmWave eNB or gNB, in case if the mmWave eNB suffered an outage.

As required by this framework UE can maintain a simultaneous physical layer link with LTE and 5G networks with the help of the DC mechanism. This helps LTE to handle the control plane functions for 5G networks while 5G exclusively operating the user plane tasks and thus creating a non-standalone design for the execution of 5G networks. So, every LTE enB acts as a coordinator and manages all the gNBs that fall into its vicinity. The eNB also functions as a selector and selects the best gNB with potential signal-to-interference-plus-noise-ratio or SINR. The process of selecting the best gNB is termed as **gNB config** which is performed according to the guidelines stated above. The process of NR addition and removal is executed at the Radio Resource Control (RRC) layer which is shown in Figure 3.3.

3.4.1 Attach or RRC connect

Since the Radio Resource Control (RRC) layer of LTE module administers the functioning of the user plane of LTE as well as mmWave module so the addition and removal of gNB are initiated by this layer. RRC connection establishment takes place when UE sends *attach request* to the eNB. The *attach request* signals that UE is ready for the dual connectivity mechanism. And the Evolved Packet Core (EPC) checks if UE is authorized to connect to LTE eNB and mmWave gNB.

3.4.2 Detach or RRC idle

The state before the RRC connection establishment is *RRC idle* state. As the name signifies in this state RRC layer is idle and eNB does not serve any connection with any UE. When connection establishment encounters any failure or the purpose is accomplished the eNB releases the connection

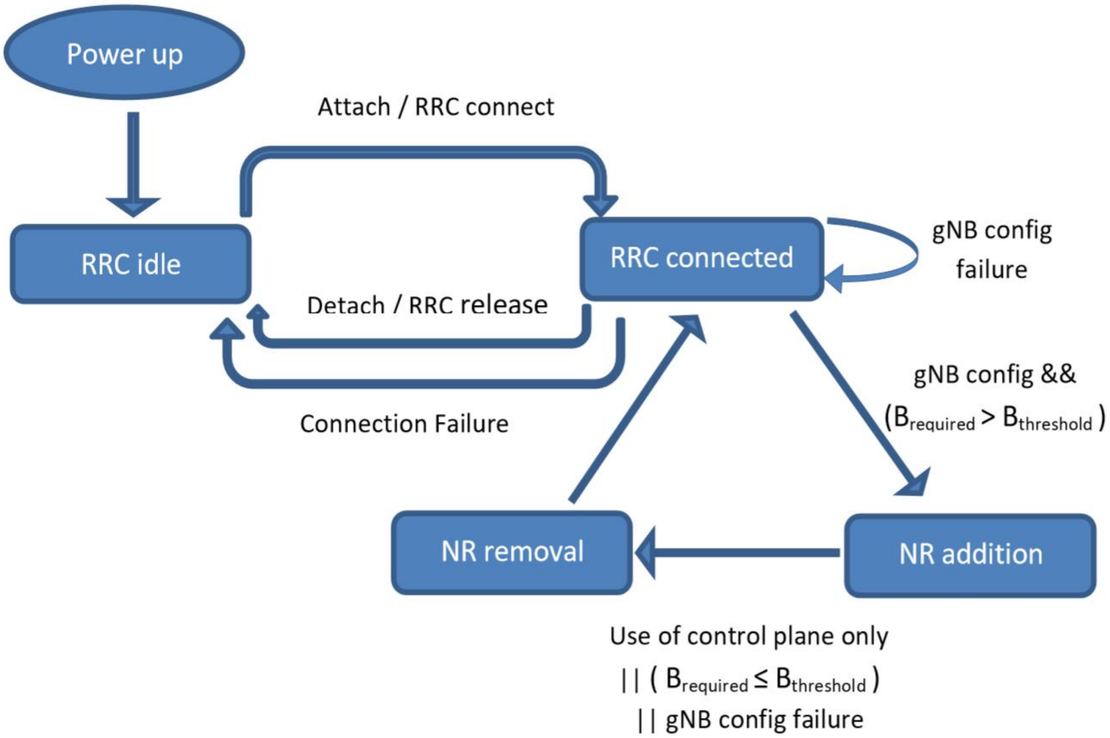

Figure 3.3: NR addition and NR removal process at RRC

and returns to the *RRC idle* state.

3.4.3 NR Addition

When eNB enters *RRC connected* state it decides to set up a connection with the appropriate gNB which is termed as ***NR addition*** which is needed when any one of the two situations is satisfied: 1) if user-plane functions or transmission of data packets is required or 2) if the bandwidth requirement exceeds the set threshold, i.e.,

$$\boldsymbol{B_{required} > B_{threshold}} \tag{5}$$

Here, $\mathbf{B_{required}}$ is the bandwidth required by UE and $\mathbf{B_{threshold}}$ is the threshold bandwidth based on which **Enb-RRC** decides that the addition of NR is needed. If any of the two conditions are met the next step is to find a potential gNB. The potential of each gNB is measured based on the SINR of each gNB. The process begins by scanning the vicinity of UE-eNB pair and storing the

SINR of each gNB encountered in the vicinity into a table. The gNB with the highest SINR is selected as the potential candidate. This process of configuration of the best gNB is termed as **gNB config.** Once the **gNB config** is successful and the bandwidth requirements are met, the LTE RRC communicates with the selected gNB to set up a connection.

3.4.4 NR Removal

NR removal takes place if any of these conditions hold: 1) when the purpose of NR addition is fulfilled and user plane functions are no longer required, 2) SINR of the connected gNB drops and switching to another gNB with better SINR is required, i.e., **gNB config failure** has occurred due to user mobility or link quality degradation, or 3) Bandwidth requirements can be accomplished with the help of LTE, i.e.,

$$\boldsymbol{B_{required}} \leq \boldsymbol{B_{threshold}} \tag{6}$$

Here, $\mathbf{B_{required}}$ is the bandwidth required by UE and $\mathbf{B_{threshold}}$ is the threshold bandwidth based on which **Enb-RRC** decides the removal of NR. After this state eNB returns to RRC connected state as it still serves the connection to UE but the connection to gNB is terminated.

CHAPTER 4

EXPERIMENTAL WORK AND RESULT

4.1 Overview

The primary motive of this work is to evaluate the performance of NSA architecture for 5G NR networks which relies on the LTE EPC to perform control plane tasks. This section simulates two scenarios one is SA and the other is the NSA 5G network. The simulation aims to compare the performance of the two architectures numerically and graphically. For numeric evaluations, throughput is used as a metric based on which the performance of the SA and NSA architectures is compared. For graphical comparison two plots: 1)Throughput v/s Time and 2) SINR v/s Time, are retrieved from the simulation results of the two scenarios with the help of ns-3. This chapter is arranged as follows: Section 4.2 covers the explanation of the simulation scenario of 5G NR in standalone mode. Section 4.3 discusses the simulation of 5G NR in NSA mode. Later the simulation outcomes from these scenarios are discussed in both the sections with respective simulation parameters.

4.2 Simulation of Standalone Mode

The SA architecture contains a gNB that serves the direct connection to a UE to deliver 5G services as shown in Figure 4.1. Here, the gNB performs user (or data) plane as well as control (or signaling) plane functions. UE and gNB are assigned with the *Constant Position Mobility Model* [39] to simulate user mobility. The distance between the gNB and UE is updated with time. The parameters for the simulation are given in Table 4.1. The distance of UE is updated after every 100 ms. Since the UE constantly moves away from the connected gNB, the overall throughput decreases with time as shown in Figure 4.2. And the SINR also reduces gradually as the distance between UE and gNB increases as shown in Figure 4.3. The channel state allotted to the simulation is non-line-of-sight (NLOS) which is a type of radio transmission required in partially obstructed propagation conditions. The simulation of NLOS and LOS can be reviewed in the adaptive and advanced beamforming section of [40].

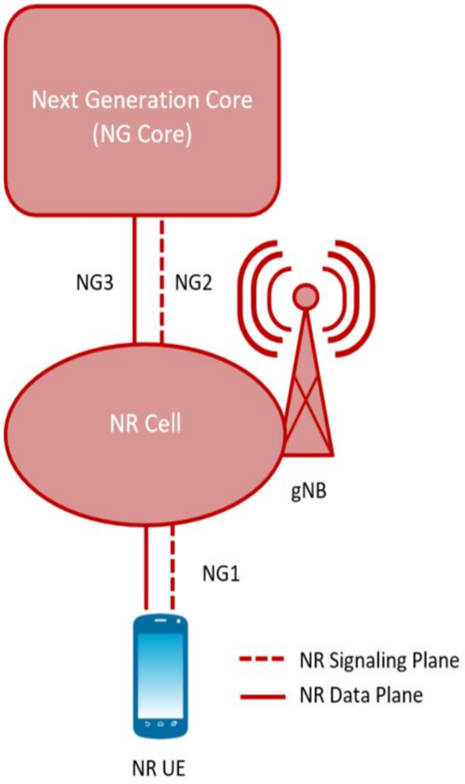

Figure 4.1: Simulation model of 5G NR in SA mode

4.2.1 Simulation Outcomes

The plot given in Figure 4.2 shows a gradual decrease in the throughput of 5G NR in SA mode as the distance between the UE and gNB increases by 10 meters in 100 ms. This is because the SA architecture does not possess any supporting NR base station (BS) whenever the serving BS suffers an outage. Here, user mobility is the reason for the poor performance of standalone architecture. As UE moves away from the serving gNB, the SINR of the gNB suffers a gradual diminution due to the this the required data transfer rates remain unfulfilled.

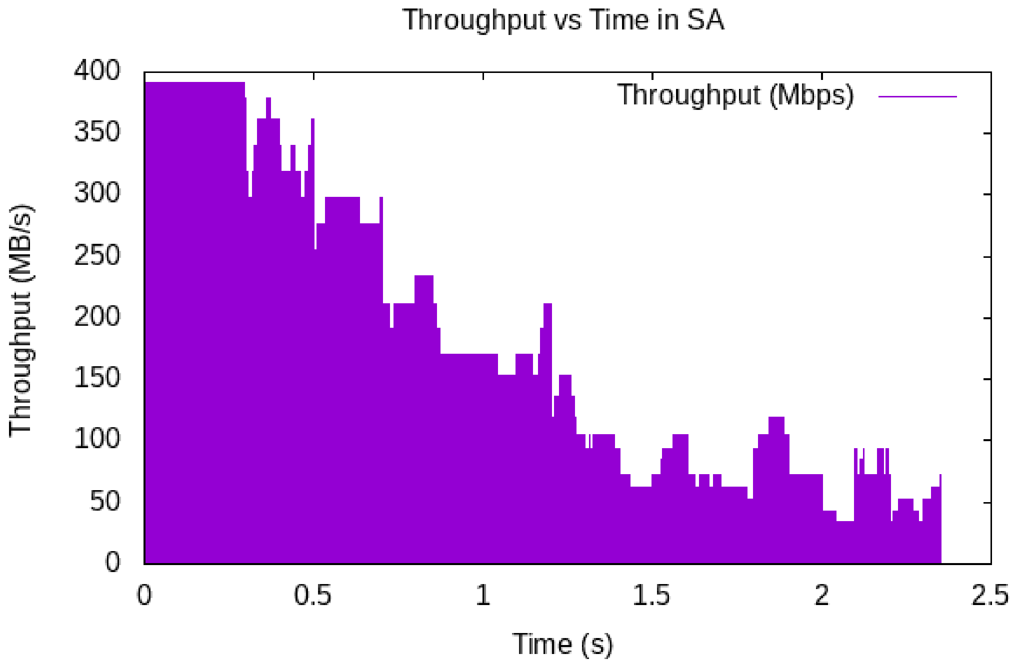

Figure 4.2: Plot for throughput vs time in SA mode

Another plot for SINR v/s Time is shown in Figure 4.3. This plot depicts the reduction in SINR strength with time due to the movement of UE away from the serving gNB.

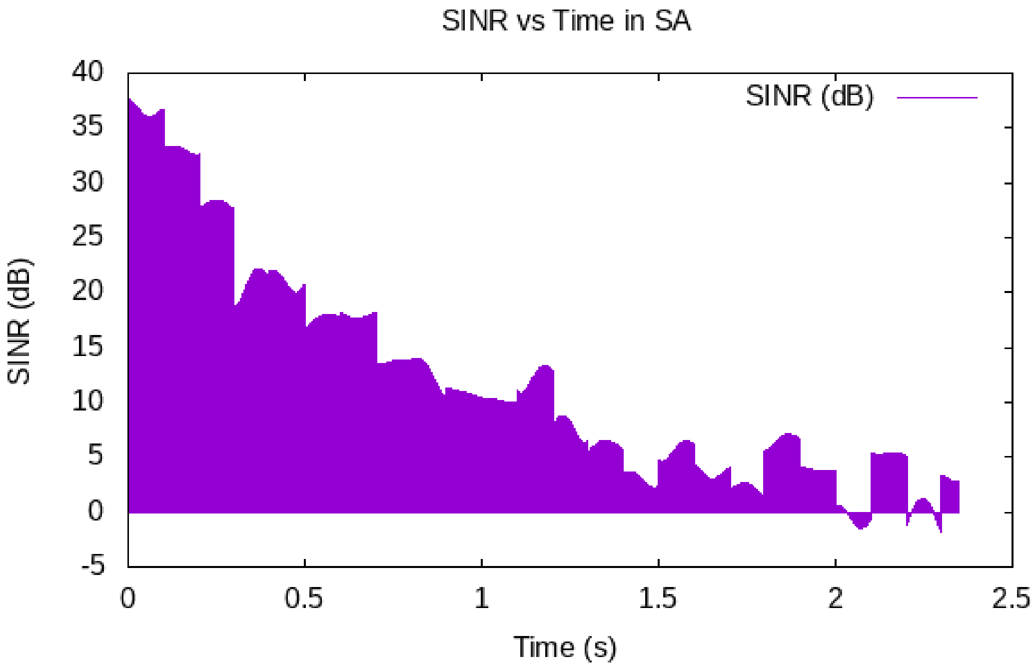

Figure 4.3: Plot for SINR vs time in SA mode

The parameters for the simulation of 5G NR networks in SA mode are given in Table 4.1 along with the description and the value of those parameters.

Table 4.1: Simulation parameters for SA mode

Parameters	**Values**	**Description**
distUpdateInterval	100.0 ms	Distance updation time
distInc	10 metres	Increment in UE-eNB distance
numGnb	1	No. of gNBs
numUe	1	No. of user equipments
distMin	15.0 metres	Minimum eNB-UE distance
distMax	250.0 metres	Maximum eNB-UE distance
channelState	NLOS	Non-Line-of-Sight path

4.3 Simulation of Non-Standalone Mode

The simulation scenario of NSA architecture is deployed with one LTE eNB, two gNBs in its vicinity, and a UE. The UE seeks an enduring connection with the eNB to access 5G services from the best gNB in its vicinity with the help of dual connectivity between LTE and mmWave module as shown in Fig. 4. Hence, the eNB acts as a coordinator and selects the data best gNB between the two to access 5G data services. Here the LTE cell performs all the signaling functions to manage the user plane of 5G NR cell. The switching judgment between the gNBs depends upon two factors: 1) the superiority of SINR among the gNBs and 2) if the serving gNB suffers an outage. The superiority of SINR decides which gNB should be added for the provision of better data transfer rates. And threshold bandwidth determines when to initiate dual connectivity among LTE and 5G NR to proceed to the NR addition state from the RRC connected state as presented in Fig. 2. The eNB manages the state of the user plane of the linked gNB and both of them communicate for establishing the radio bearer and the UE is reported about the bearer by the RRC Reconfiguration message. The simulation parameters are stated in Table III. For simulating user mobility Constant Velocity Mobility Model of ns-3 is assigned to the simulation.

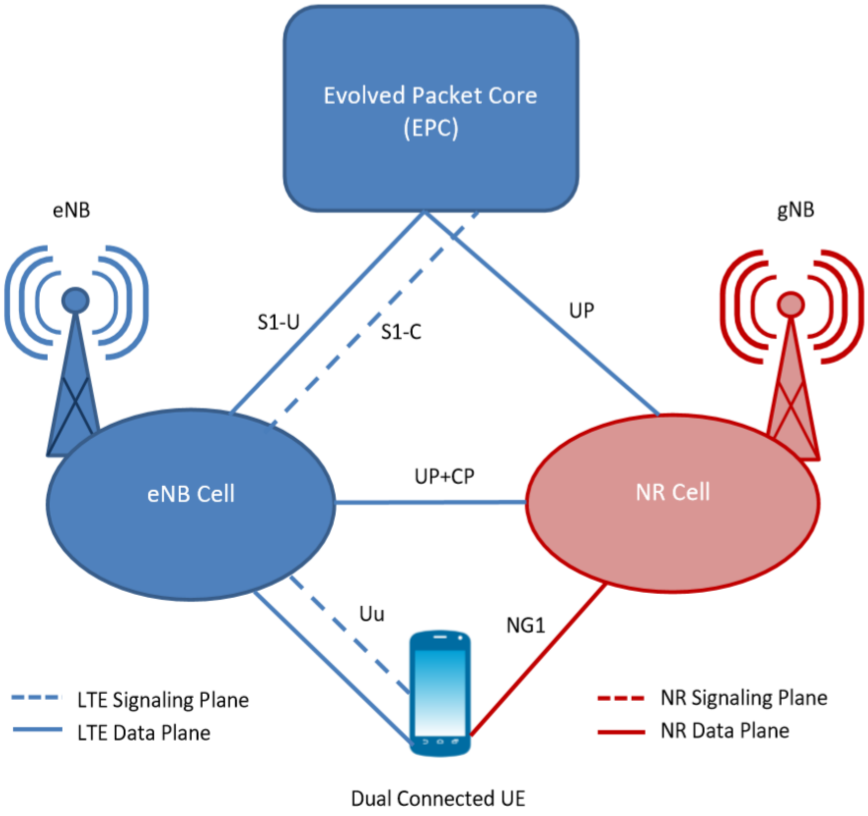

Figure 4.4: Simulation model of 5G NR in NSA mode

4.3.1 Simulation Outcomes

The plot shown in Figure 4.5 represents the throughput versus time curve for the 5G NR networks in NSA mode. The NSA architecture maintains an enduring connection between UE and the LTE eNB irrespective of the addition and removal of the NR base station (BS). Due to this attribute of the NSA mode of 5G NR, the data transfer can be maintained at a constant rate even if the serving gNB suffers an outage.

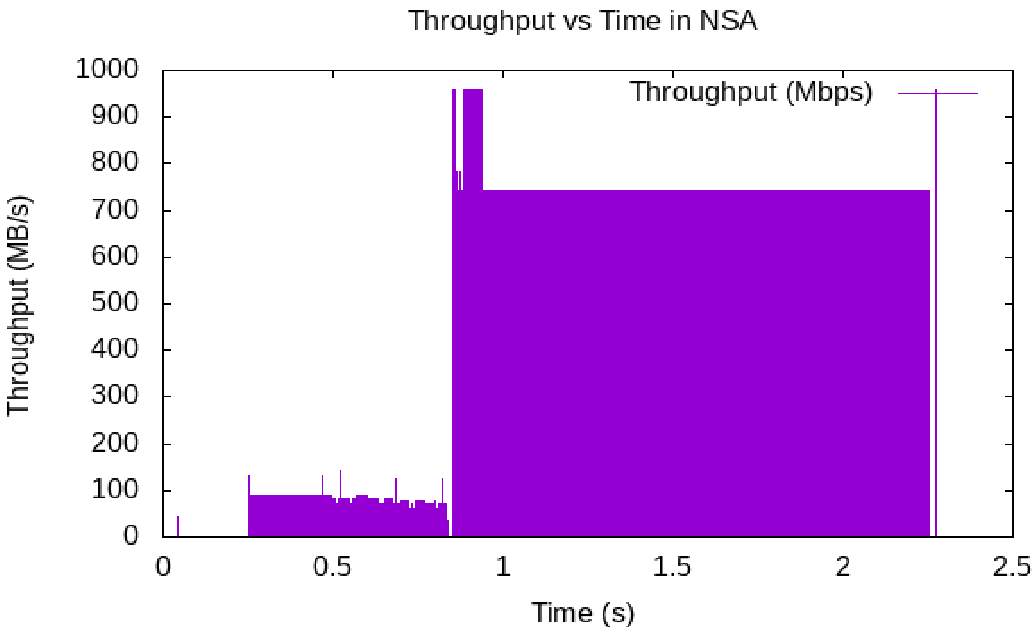

Figure 4.5: Plot for throughput vs time in NSA mode

Figure 4.6 represents the plot for SINR versus Time for 5G NR networks in NSA mode. Whenever the SINR becomes less than the set threshold, i.e., -5 dB, a switch is made between the gNBs.

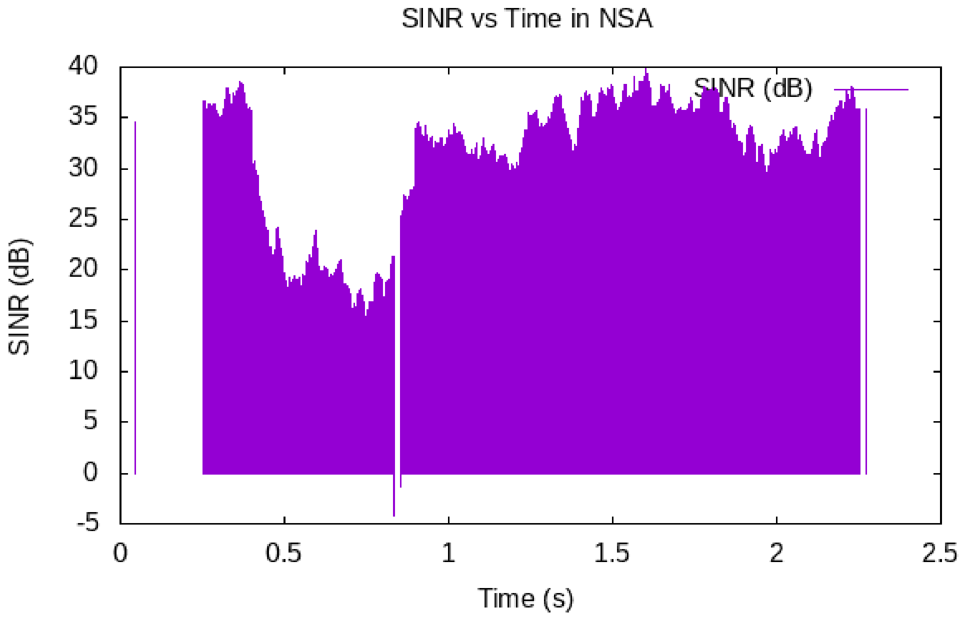

Figure 4.6: Plot for SINR vs time in NSA mode

The parameters for the simulation of 5G NR networks in NSA mode are stated in Table 4.2 along with their description and value.

Table 4.2: Simulation parameters for NSA mode

Parameters	**Values**	**Description**
gnbDist	200 metres	Distance between gNB 1 and 2
x2Latency	50	Latency on X2 interface (µs)
mmeLatency	100	Latency on MME interface (µs)
ueSpeed	10 m/s	Speed of UE
ueInitialPosition	80	Starting position of UE
ueFinalPosition	180	Final position of UE
symPerSf	24	Symbols per subframe
gnb1PosVector	(50,70,3)	Position of first gnb
gnb2PosVector	(150,70,3)	Position of second gnb
outageThreshold	-5	Outage threshold for gNBs
$B_{threshold}$	80 Mb/s	Threshold bandwidth

4.4 Performance Evaluation

By carrying out the above simulations, the performance of both architectures can be compared and their characteristics can be formulated. In standalone architecture, the variation of throughput with time can be witnessed with the help of the plot shown in Figure 4.2. As the distance between UE and the serving gNB increases, the plot depicts a gradual diminution in throughput. The drop in throughput is because of the standalone characteristics of the architecture, i.e., no supporting base station to serve the UE if the current serving UE suffers an outage. The disruption in the connection is prominent due to the susceptibility of mmWave bands towards obstacles. The plot in Figure 4.3 depicts the reduction in SINR with increasing time as well as distance due to which the serving gNB suffers an outage and disruption in service occurs.

The proposed non-standalone architecture is a provisioning solution for the susceptible nature of mmWave bands. It provides an enduring connection between UE and LTE eNB overcoming the drawbacks of mmWave bands and thus supporting the data rates when the UE-gNB connection is disrupted. Hence the throughput curve of the NSA architecture is more stable and results in better throughput. Also, the SINR curve for NSA architecture demonstrates better SINR levels during the whole simulation. This can be accomplished because the LTE eNB acts as a coordinator in NSA mode and selects the appropriate gNB and can perform the switch when the SINR of connected gNB drops. Figure 4.6 shows the drop in SINR to -5 dB which is the outage threshold for the simulation and it depicts the outage of the serving gNB that is when the switch between the gNBs occurs. Once the switch is performed the SINR levels are improved.

The plots in Figure 4.2 and Figure 4.5 validate the performance improvement achieved by the proposed architecture. The plot in Figure 4.2 depicts gradual decrement in throughput as UE travels away from the serving gNB. This happens due to the lack of any supporting connection to UE when the serving gNB suffers an outage. While the plot in Fig. 6 demonstrates a constant curve for throughput after a certain interval of time. This is achieved due to the enduring connection of UE with the LTE module of ns-3 when gNB suffers an outage, preventing any disruption of data service. It also performs gNB switching

Table 4.3: Outcomes

Architecture	**Average Throughput**	**Peak Throughput**	**Average SINR**
Standalone	180 Mbps	400 Mbps	11.85 dB
Non-Standalone	512.6 Mbps	1 Gbps	30.76 dB

for better data transfer rates. For numerical assessment of the performances of the two architectures the rate at which data is transferred at the PHY layer is recorded. On simulating the two scenarios over ns-3 two trace files are generated depicting the traces of bytes transferred at the PHY layer with respect to the time in seconds. This helps in the average throughput calculation of the two simulation scenarios. The average throughput of NSA architecture is 512.6 Mbps while that of the SA architecture is 180 Mbps. And the peak data rates achieved can be approximated as 400 Mbps in SA whereas 1 Gbps in NSA. So, this demonstration illustrates the better performance of the proposed NSA architecture with the modification of the DC protocol.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The non-standalone architecture for 5G NR networks presented in this work is implemented with the help of the DC mechanism and mmWave module of ns-3. The proposed architecture has appropriately used mmWave technology to produce improved outputs in terms of data rates. It overcomes the highly susceptible nature of mmWave technology by taking leverage of DC protocol and customizing it accordingly. This architecture provides the dual connectivity of UE to 5G NR and LTE to avoid any interruption in connectivity. Hence the proposed NSA architecture is able to deliver the data rate that is approximately three times the data rate provided by the traditional SA architecture. Also, there is no major disruption in connection while switching of gNBs due to the assistance provided by LTE eNB, so the latency of the system is minimal and the system maintains an average SINR of 30 dB that is better than SA system. Thus, the NSA architecture is more efficient as compared to the typical SA architecture. Also, the deployment of 5G NR in the real world overwhelms the deployment of SA mode because NSA architecture is deployed with the support of fully established LTE architecture whereas a lot of effort is still needed for the provision of the end to end support for the 5G SA network.

6.2 Future Work

The full-stack model of proposed architecture can be used for additional layer-wise innovations. For forthcoming interests, this model needs to get evaluated for the implementation of novel and highly computational augmented and virtual reality applications. Though the NSA architecture is a better alternative right now in comparison to partially developed SA architecture of 5G NR, a lot of improvement is needed to develop a better mobility module that accurately simulates real-life user mobility scenarios. So that the performance of simulation can be assessed more accurately. More advanced mobility management for sustainable data rates needs to be developed in the impending times. And the evolution of the standalone mode of 5G NR network for the provision of end to end support remains an upcoming interest.

REFERENCES

[1] A. M. Hamed and R. K. Rao, “Evaluation of capacity and power efficiency in millimeter-wave bands,” *Simul. Ser.*, vol. 48, no. 8, pp. 32–37, 2016.

[2] S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” *Proc. IEEE*, vol. 102, no. 3, pp. 366–385, 2014, doi: 10.1109/JPROC.2014.2299397.

[3] M. R. Akdeniz *et al.*, “Millimeter wave channel modeling and cellular capacity evaluation,” *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1164–1179, 2014, doi: 10.1109/JSAC.2014.2328154.

[4] R. Ford, M. Zhang, M. Mezzavilla, S. Dutta, S. Rangan, and M. Zorzi, “Achieving Ultra-Low Latency in 5G Millimeter Wave Cellular Networks,” *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 196–203, Mar. 2017, doi: 10.1109/MCOM.2017.1600407CM.

[5] “ns-3 | a discrete-event network simulator for internet systems.” [Online]. Available: https://www.nsnam.org/. [Accessed: 13-May-2020].

[6] M. Mezzavilla, S. Dutta, M. Zhang, M. R. Akdeniz, and S. Rangan, “5G MmWave module for the ns-3 network simulator,” *MSWiM 2015 - Proc. 18th ACM Int. Conf. Model. Anal. Simul. Wirel. Mob. Syst.*, pp. 283–290, 2015, doi: 10.1145/2811587.2811619.

[7] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, “Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks,” *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 2069–2084, 2017, doi: 10.1109/JSAC.2017.2720338.

[8] C. A. Professor, “COMPREHENSIVE SURVEY OF WIRELESS COGNITIVE AND 5G NETWORKS,” *J. Ubiquitous Comput. Commun. Technol. (UCCT*, 2019, doi: 10.36548/jucct.2019.1.003.

[9] K. S. Kim, S. L. Ju, and H. R. Choi, “Performance Evaluation for 5G NR based Uplink Millimeter-wave MIMO Systems under Urban Micro Cell,” *2019 2nd Int.*

Conf. Commun. Eng. Technol. ICCET 2019, pp. 121–124, 2019, doi: 10.1109/ICCET.2019.8726917.

[10] A. Swindlehurst, E. Ayanoglu, P. Heydari, and F. Capolino, “Millimeter-wave massive MIMO: The next wireless revolution?,” *IEEE Commun. Mag.*, vol. 52, no. 9, pp. 56–62, Sep. 2014, doi: 10.1109/MCOM.2014.6894453.

[11] A. Alkhateeb, G. Leus, and R. W. Heath, “Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems,” *IEEE Trans. Wirel. Commun.*, vol. 14, no. 11, pp. 6481–6494, Nov. 2015, doi: 10.1109/TWC.2015.2455980.

[12] J. Noh, T. Kim, J. Y. Seol, and C. Lee, “Zero-Forcing Based Hybrid Beamforming for Multi-User Millimeter Wave Systems,” *IET Commun.*, vol. 10, no. 18, pp. 2670–2677, Dec. 2016, doi: 10.1049/iet-com.2016.0769.

[13] E. Bjornson, L. Van Der Perre, S. Buzzi, and E. G. Larsson, “Massive MIMO in sub-6 GHz and mmWave: Physical, practical, and use-case differences,” *IEEE Wirel. Commun.*, vol. 26, no. 2, pp. 100–108, Apr. 2019, doi: 10.1109/MWC.2018.1800140.

[14] “TS 38.211 (1Q20, 130 p.) – 5G NR Physical Channels and Modulation.” [Online]. Available: https://www.tech-invite.com/3m38/tinv-3gpp-38-211.html. [Accessed: 26-Jun-2020].

[15] X. Chen, J. Lu, P. Fan, and K. Ben Letaief, “Massive MIMO Beamforming with Transmit Diversity for High Mobility Wireless Communications,” *IEEE Access*, vol. 5, pp. 23032–23045, Oct. 2017, doi: 10.1109/ACCESS.2017.2766157.

[16] H. Ji *et al.*, “Overview of Full-Dimension MIMO in LTE-Advanced Pro,” *IEEE Communications Magazine*, vol. 55, no. 2. Institute of Electrical and Electronics Engineers Inc., pp. 176–184, 01-Feb-2017, doi: 10.1109/MCOM.2016.1500743RP.

[17] P. Sebastian and M. A. Khan, “Anticipatory user plane management for 5G,” in *Proceedings - 8th IEEE International Symposium on Cloud and Services Computing, SC2 2018*, 2018, pp. 9–15, doi: 10.1109/SC2.2018.00009.

[18] C. Lee, K. Ebisawa, H. Kuwata, M. Kohno, and S. Matsushima, “Performance Evaluation of GTP-U and SRv6 Stateless Translation,” in *15th International Conference on Network and Service Management, CNSM 2019*, 2019, doi: 10.23919/CNSM46954.2019.9012725.

[19] I. Alawe, Y. Hadjadj-Aoul, A. Ksentini, P. Bertin, and D. Darche, “On the scalability

of 5G core network: The AMF case," in *CCNC 2018 - 2018 15th IEEE Annual Consumer Communications and Networking Conference*, 2018, vol. 2018-January, pp. 1–6, doi: 10.1109/CCNC.2018.8319194.

[20] S. R. Nikhale, C. M. Mankar, and D. S. Auti, "Implementation of 802.16 using Ns-3 simulator," in *Proceedings of 2015 IEEE 9th International Conference on Intelligent Systems and Control, ISCO 2015*, 2015, doi: 10.1109/ISCO.2015.7282325.

[21] "The LTE-EPC Network Simulator: LENA." [Online]. Available: http://networks.cttc.es/mobile-networks/software-tools/lena/. [Accessed: 10-May-2020].

[22] A. E. I. Pastrav, A. Bara, T. Palade, and E. Puschita, "Assessing VoLTE performances for fundamental E-UTRAN technologies," in *2015 38th International Conference on Telecommunications and Signal Processing, TSP 2015*, 2015, doi: 10.1109/TSP.2015.7296442.

[23] S. Oh, B. Ryu, and Y. Shin, "EPC signaling load impact over S1 and X2 handover on LTE-Advanced system," in *2013 3rd World Congress on Information and Communication Technologies, WICT 2013*, 2014, pp. 183–188, doi: 10.1109/WICT.2013.7113132.

[24] W. Qiong and L. Yi, "Design and realization of PDN connectivity procedure in LTE radio protocol stack," in *2011 IEEE 3rd International Conference on Communication Software and Networks, ICCSN 2011*, 2011, pp. 110–113, doi: 10.1109/ICCSN.2011.6014400.

[25] J. Zyren and W. Mccoy, "Overview of the 3GPP Long Term Evolution Physical Layer," 2007.

[26] F. T. Chen and G. L. Tao, "A novel MCS selection criterion for supporting AMC in LTE system," in *ICCASM 2010 - 2010 International Conference on Computer Application and System Modeling, Proceedings*, 2010, vol. 6, doi: 10.1109/ICCASM.2010.5620840.

[27] "LTE MAC Layer - Medium Access Control | 3GLTEInfo." [Online]. Available: http://www.3glteinfo.com/lte-mac-layer-medium-access-control/. [Accessed: 27-Jun-2020].

[28] A. R. Reserved, "3GPP LTE Radio Link Control (RLC) Sub Layer All Rights

Reserved . LTE RLC Sub Layer Functions," *Control*, 2009.

[29] S. Yi, S. Chun, Y. Lee, S. Park, and S. Jung, "Radio Resource Control (RRC)," in *Radio Protocols for LTE and LTE-Advanced*, John Wiley & Sons, Ltd, 2012, pp. 47–85.

[30] "NAS-3GPP." [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/96-nas. [Accessed: 27-Jun-2020].

[31] M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "An efficient uplink multi-connectivity scheme for 5G millimeter-wave control plane applications," *IEEE Trans. Wirel. Commun.*, vol. 17, no. 10, pp. 6806–6821, 2018, doi: 10.1109/TWC.2018.2864650.

[32] M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "Multi-connectivity in 5G mmWave cellular networks," *2016 Mediterr. Ad Hoc Netw. Work. Med-Hoc-Net 2016 - 15th IFIP MEDHOCNET 2016*, no. Dl, 2016, doi: 10.1109/MedHocNet.2016.7528494.

[33] I. Da Silva, G. Mildh, and J. Rune, "Tight Integration of New 5G Air Interface and LTE to Fulfill 5G Requirements," 2015.

[34] N. Baldo, M. Miozzo, M. Requena-Esteso, and J. Nin-Guerrero, "An open source product-oriented LTE network simulator based on ns-3," *MSWiM'11 - Proc. 14th ACM Int. Conf. Model. Anal. Simul. Wirel. Mob. Syst.*, pp. 293–297, 2011, doi: 10.1145/2068897.2068948.

[35] R. Ford, M. Zhang, S. Dutta, M. Mezzavilla, S. Rangan, and M. Zorzi, "A framework for end-to-end evaluation of 5G mmWave cellular networks in ns-3," *ACM Int. Conf. Proceeding Ser.*, vol. Part F1321, pp. 85–92, 2016, doi: 10.1145/2915371.2915380.

[36] M. Zhang, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Ns-3 implementation of the 3GPP MIMO channel model for frequency spectrum above 6 GHz," *ACM Int. Conf. Proceeding Ser.*, vol. Part F1283, pp. 71–78, 2017, doi: 10.1145/3067665.3067678.

[37] M. Polese, M. Mezzavilla, and M. Zorzi, "Performance comparison of dual connectivity and hard handover for LTE-5G tight integration," *Proc. 9th EAI Int. Conf. Simul. Tools Tech. SIMUTools 2016*, vol. 3, pp. 118–123, 2016.

[38] S. Kucera and D. Lopez-Perez, "C-RNTI management for orthogonally-filled

subframes in LTE heterogeneous networks," in *IEEE International Conference on Communications*, 2015, vol. 2015-September, pp. 1483–1488, doi: 10.1109/ICC.2015.7248533.

[39] "ns-3: ns3::Constant Position Mobility Model Class Reference." [Online]. Available: https://www.nsnam.org/doxygen/classns3_1_1_constant_position_mobility_model.html#a6c5b0c0e334ffa40cc3480a94c8bd526. [Accessed: 02-May-2020].

[40] M. Mezzavilla *et al.*, "End-to-end simulation of 5G mmWave networks," *IEEE Commun. Surv. Tutorials*, vol. 20, no. 3, pp. 2237–2263, 2018, doi: 10.1109/COMST.2018.2828880.

LIST OF PUBLICATIONS BY CANDIDATE

[1] Sakshi Dubey and Jasraj Meena, “Computation Offloading Techniques for Mobile Edge Computing Environment: A Review,” in *IEEE International Conference of Communication and Signal Processing*, 2020 [Presented].

[2] Sakshi Dubey and Jasraj Meena, “Improvement of Throughput using Dual Connectivity in Non-standalone 5G NR Networks,” in *IEEE International Conference on Smart Systems and Inventive Technology*, 2020 [Accepted].