NetSim®

Accelerate Network R & D

5G NR

A Network Simulation & Emulation Software

By

TETCOS LLP

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Table of Contents

1 Introduction

NetSim 5G NR library allows for end-to-end simulation of all layers of the protocol stack as well as applications running over the network. 5G devices available are the 5G core devices: AMF, SMF and UPF, gNBs and UEs. Simulation is discrete event and done at a packet level abstraction. This 5G library is architected to connect to the base component of NetSim (and in turn to other components), which provides functionalities such as the TCP/IP network stack, Wireless protocols, Routing algorithms, Mobility, Output Metrics, Animation, Traces etc. The 5G library is based on Rel 15 / 3GPP 38.xxx series.

NetSim's protocol source C code shipped along with (standard / pro versions) is modular and customizable to help researchers to design and test their own 5G protocols.

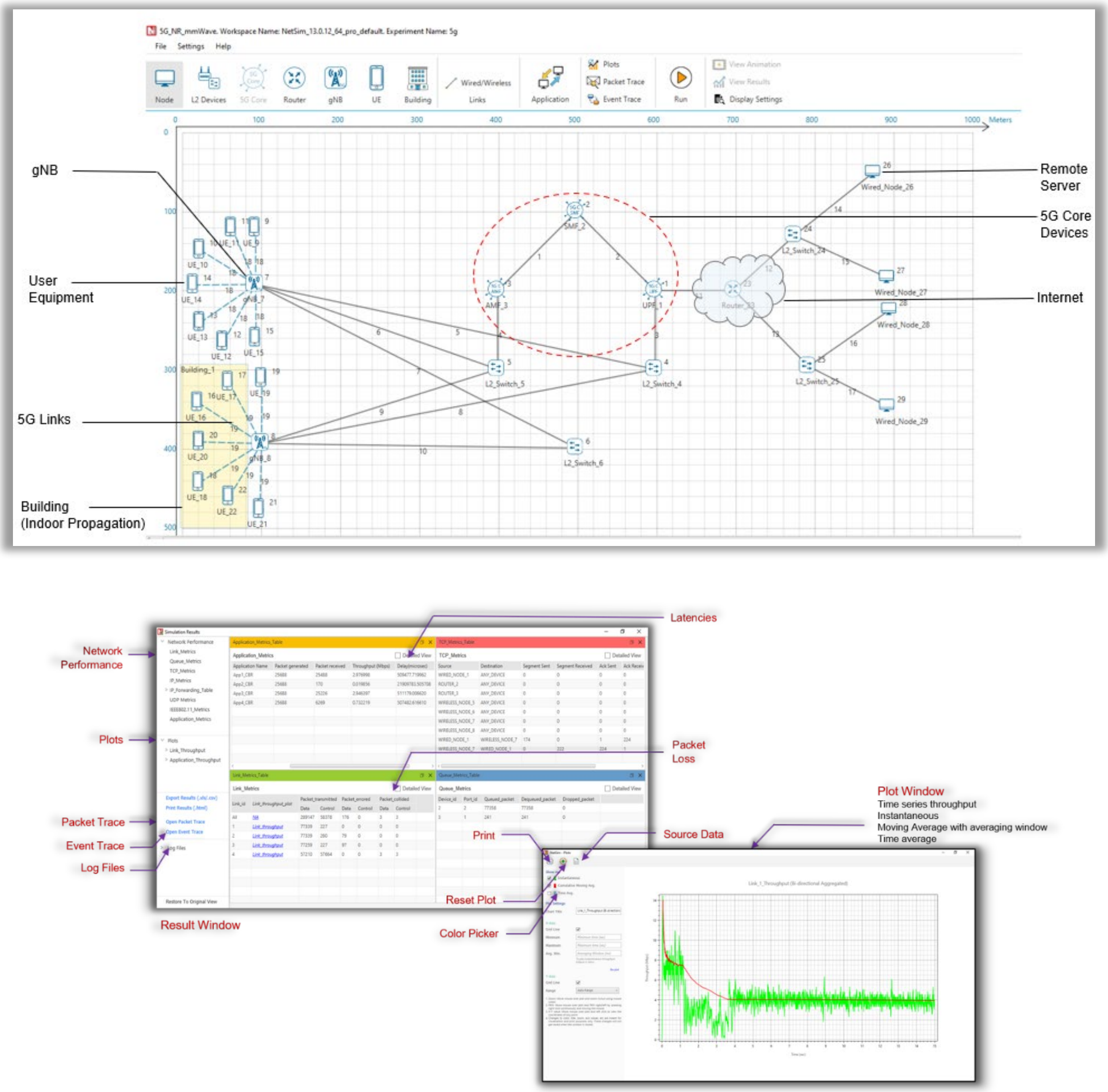


Figure 1-1: NetSim's 5G NR design window, the results dashboard and the plots window

2 Simulation GUI

Open NetSim, Go to **New Simulation → 5G NR**.

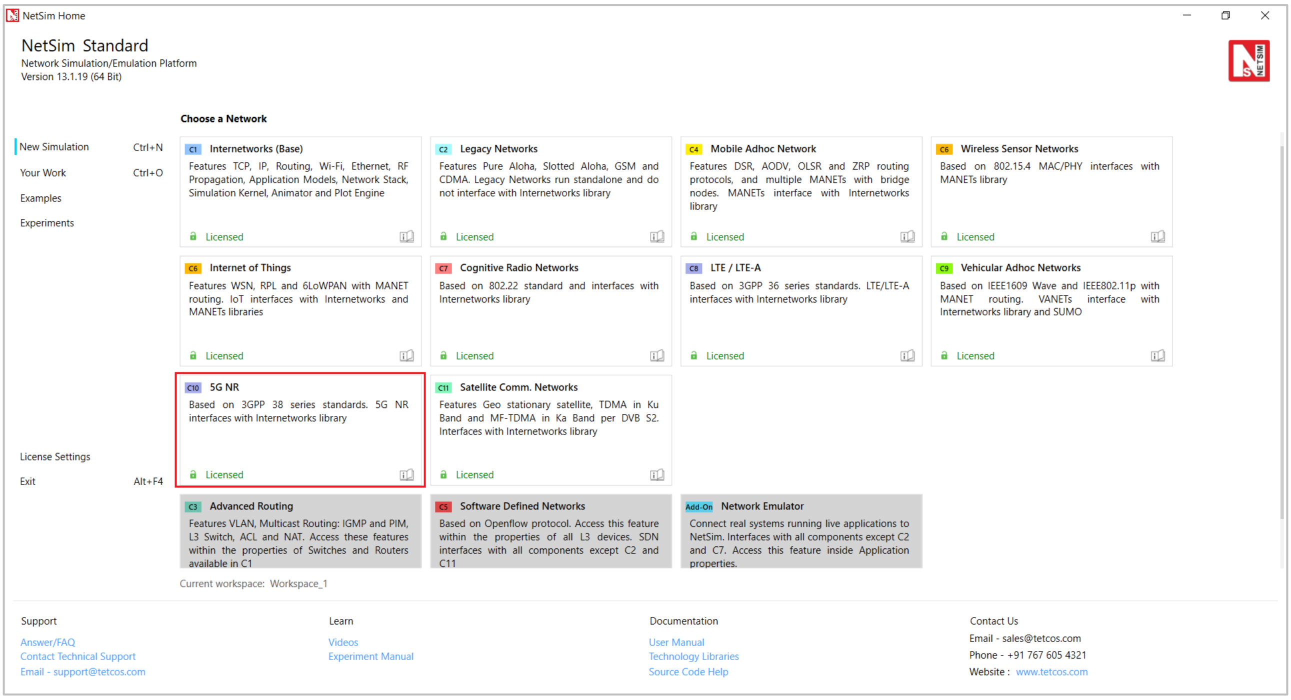


Figure 2-1: NetSim Home Screen

2.1 NetSim 5G Network Setup

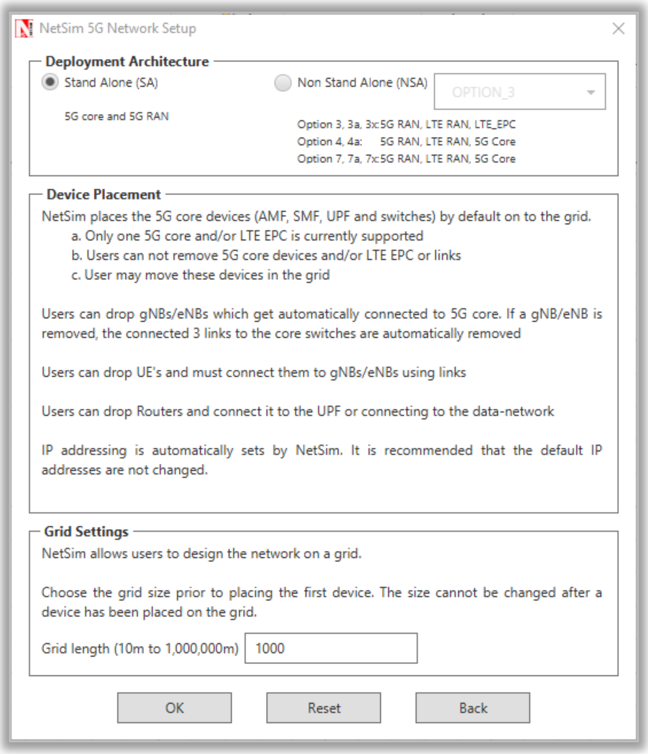


Figure 2-2: NetSim 5G Network Setup window

2.1.1 Deployment Architecture

The deployment options have been primarily grouped into 2 categories. Standalone (SA) option where there is only one independent access network (LTE or 5G NR) that is connected to either the EPC or the 5G Core and the Non-Standalone options where both LTE and 5G NR radio access technologies are present, where one of the access networks assist the other in connecting to either an EPC or a 5GC.

Stand Alone

In 5G Stand-alone mode of operation in NetSim, the network can be created using the 5G Core devices which includes a single AMF, SMF and UPF to which the gNB can be connected via Layer 2 Switches. The RAN part consists of gNBs and UEs and the UEs can handle both Uplink and Downlink data transfer to and from the Data Network (DN) via the UPF.

Non-Stand Alone

In the Non-Stand-alone mode of operation in NetSim, the users can design the network scenario using different deployment options.

The NSA modes in NetSim's 5G module includes:

1. Option 3 where only LTE core/ EPC is present and no 5G Core devices are present. Option 3 is categorized into:
    a. **Option 3:** Only eNB connects to EPC and eNB and gNB connects to the XN interface.
    b. **Option 3a:** Both eNB and gNB connects to the EPC. gNB connects to the XN interface and eNB does not XN interface.
    c. **Option 3x:** Both eNB and gNB connects to the EPC. eNB and gNB connects to the XN interface.
2. Option 4 where only 5G Core devices are present, and EPC is not available. Option 4 is categorized into:
    a. **Option 4:** Only gNB connects to all the 5G Core interfaces. eNB connects to the XN interface.
    b. **Option 4a:** gNB connects to all 5G Core interfaces and eNB connects to AMF and UPF through respective interfaces.
3. Option 7 where only 5G Core devices are present, and EPC is not available. Option 7 is categorized into:
    a. **Option 7:** eNB connects to all 5G Core interfaces. gNB connects only to the XN interface.
    b. **Option 7a:** gNB connects to all the 5G Core interfaces. eNB connects to AMF and UPF through the respective interfaces.
    c. **Option 7x:** gNB and eNB connects to all the 5G Core interfaces.

2.1.2 Device Placement

NetSim places the 5G core devices (AMF, SMF, UPF and Switches) / LTE EPC by default on to the grid.

a. Only one 5G Core and/or LTE EPC is currently supported.
b. Users cannot remove 5G Core devices and/or LTE EPC, or their interconnecting links.
c. User may move these devices in the grid.
   - Users can drop gNBs/eNBs which get automatically connected to 5G Core. If a gNB/eNB is removed, the connected links to the core switches are automatically removed.
   - Users can drop UEs and must connect them to gNBs/eNBs via links.
   - Users can drop Routers and connect them to the UPF/EPC for connectivity to the data-network (DN).
   - IP addressing is automatically set by NetSim. It is recommended not to change the default IP addresses.

2.1.3 NSA Deployment Device Connectivity

The device connectivity rules are explained below. Example screen shots are available in 5G- Non-Stand-alone (NSA)

2.1.3.1 Option 3 / 3a / 3x

- UE should mandatorily be connected to the master node (MN) first. In option 3, the MN is eNB
- UE should mandatorily be connected to the secondary node (SN) next. In option 3, the SN is the gNB
- UE cannot be connected to any other device.
- The data (external) network connects to the EPC. This is achieved by first connecting a router (let's call it R1) to the EPC.
- Switches, nodes, APs and other routers can now be connected to R1
- Connectivity rules for the devices within the data network is per the Internetwork library document.

2.1.3.2 Option 4 / 4a

- UE should mandatorily be connected to the master node (MN) first. In option 4, the MN is gNB
- UE should mandatorily be connected to the secondary node (SN) next. In option 4, the SN is the eNB
- UE cannot be connected to any other device.
- The data (external) network connects to the 5G core through the UPF. This is achieved by first connecting a router (let's call it R1) to the UPF.
- Switches, nodes, APs and other routers can now be connected to R1

- Connectivity rules for the devices within the data network is per the Internetwork library document.

2.1.3.3 Option 7 / 7 / 7x

- UE should mandatorily be connected to the master node (MN) first. In option 7, the MN is eNB
- UE should mandatorily be connected to the secondary node (SN) next. In option 7, the SN is the gNB
- UE cannot be connected to any other device.
- The data (external) network connects to the 5G core through the UPF. This is achieved by first connecting a router (let's call it R1) to the UPF.
- Switches, nodes, APs and other routers can now be connected to R1.
- Connectivity rules for the devices within the data network is per the Internetwork library document.

2.1.4 Grid Settings

- NetSim allows users to design the network on a square grid. The major and minor grid lines are displayed; major grid line values along X and Y co-ordinate is displayed. Each device's X, Y co-ordinate is determined by its location on the grid.
- Users can choose the grid size prior to placement of the first device. The grid size cannot be changed after the first device has been placed on the grid.
- The grid length can be in the range of 10m to 1,000,000m.

2.2 Create Scenario

5G NR comes with a palette of various devices like Wired & Wireless Nodes, L2 Switch & Access Point, AMF (Access and Mobility Management Function), UPF (User Plane Function), SMF (Session Management Function) & Router, gNB (Equivalent of eNB in LTE), UE (User Equipment), and Building.

2.3 Devices Specific to NetSim 5G NR Library

- **UE**: User Equipment. Each UE has a single LTE NR interface with an infinite buffer. A UE can be stationary or mobile. The UE's location is determined by its (X, Y) co-ordinate on the grid or by its (Lat, Lon) when using a map background.
- **gNB:** This represents a base station with all the components i.e., antennas, radio, baseband, and the protocol stack. NetSim currently does not allow for the gNB to be split.
    - It has a 5G RAN interface for wireless connectivity to UEs,
    - 5G_N3 interface for wired connectivity to UPF through L2_Switch,
    - 5G_N1_N2 interface for wired connectivity to AMF through L2_Switch, and

- 5G_XN interface for wired connectivity between the gNB's though L2_Switch. gNB has an infinite buffer.

- **UPF (User Plane Function)**: User Plane Function has 5G_N4 interface for wired connectivity to SMF, 5G_N3 interface for wired connectivity to gNB through L2_Switch, and 5G_N6 interface for wired connectivity to Routers in NG core which in turn can connect to Switches, APs, Servers etc.
- **SMF (Session Management Function)**: Session Management Function has 5G_N11 interface for wired connectivity to AMF and 5G_N4 interface for wired connectivity to UPF.
- **AMF (Access and Mobility Management Function)**: Access and Mobility Management Function has 5G_N11 interface for wired connectivity to SMF and 5G_N1_N2 interface for wired connectivity to gNB's through L2_Switch.
- **Building:** Users can place gNBs, UEs inside buildings to simulate indoor RF propagation effects.

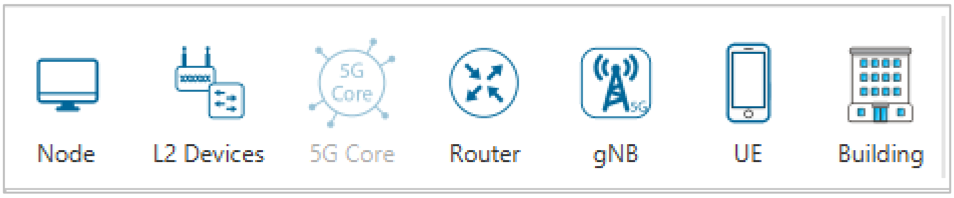


Figure 2-3: 5G NR Device Palette in GUI

2.3.1 Devices: Click and drop into environment

a. AMF, UPF, and SMF:

- Exactly one set of these devices are automatically placed by NetSim into the environment and connected appropriately to switches.
- These devices are part of the 5G core.
- These devices which are placed onto the environment cannot be deleted by the user.

b. Add a gNB:

- Click the **gNB** icon on the toolbar and place the gNB in the grid it will automatically connect to the L2_Switches connected to the AMF and UPF. The logical connectivity of the different interfaces (Xn, N1-N2, and N3) are broken out into different physical links.
- gNBs can also be placed inside the building based on the network scenario created.
- Every gNB should be connected to at least one UE.

c. Add a User Equipment (UE):

- Click the **UE** icon on the toolbar and place the UE in the grid.
- UE's can also be placed inside the building based on the network scenario created. The UE's are always assumed to be connected to one gNB.
- A UE can never be connected to more than one gNB, and neither can it be out-of-range of all gNBs.

d. Add a Router: Click on **Router** and drop it onto the environment. At least one Router should be connected to a **UPF.** A router is not a mandatory requirement.
e. Add a L2 Switch or Access Point: Click the **L2 Devices > L2_Switch** icon or **L2 Devices > Access_Point** icon on the toolbar and place the device in the grid.
f. Add a Wired Node and Wireless Node: Click the **Node > Wired_Node** icon or **Node > Wireless_Node** icon on the toolbar and place the device in the grid.
g. Add a Building: Click the **Building** icon on the toolbar and place the building in the grid.
   - Buildings will have an impact on RF propagation losses if Pathloss_Shadowfading_O2I is selected
   - A building occupies a minimum 1 cell on the grid and a maximum size equal to the complete grid. The default size is 10 cells * 10 cells.
   - An empty space of 10 cells * 10 cells within the grid is required to place a building.
   - Two buildings cannot be overlap one another.
   - The resizing corners of a building includes South and East edges and South-East corner.
   - The maximum number of buildings supported in NetSim is ten (10)
h. Connect the devices in 5G NR network by using Wired/Wireless Links present in the top ribbon/toolbar. While connecting gNB and UE, the following connections are allowed:
   - Outdoor gNB to Outdoor UE.
   - Outdoor gNB to Indoor UE.
   - Indoor gNB to Indoor UE.
   - Connecting Indoor gNB to Outdoor UE is not allowed in NetSim.
   - Based on gNBs/UEs placed inside or outside of the buildings NetSim automatically chooses the indoor/outdoor propagation models during simulation.
i. Configure an application as follows:
   - Click the application icon on the top ribbon/toolbar.
   - Specify the source and destination devices in the network.
   - Specify other parameters as per the user requirement.
j. Set the properties of UPF, AMF, SMF, gNB, UE, and other devices as follows:
   - Right-click an UPF, AMF, and SMF click Properties and modify the interface and layer-wise properties to your requirement.
   - Right-click a gNB or UE, click Properties and specify the parameters.
     - The TX_Power_per_layer (dBm) parameter (Interface 5G_RAN - Physical_Layer) is local and if you change this parameter in gNB or UE, manually update the parameter for the other devices.
     - The PDCP_Header_Compression, PDCP_Discard_Delay_Timer,

and PDCP_Out_of_Order_Delivery parameters (Interface 5G_RAN - DataLink_Layer) are local and if you change any of these parameters in gNB or UE, manually update the parameter for the other devices.

- Right-click an Access_Point, L2_Switch, Wireless_Node or Wired_Node and specify the parameters.
  - The Interface_Wireless > Physical Layer and Interface_Wireless > DataLink Layer parameters are local and if you change any of these parameters in Access_Point or Wireless_Node, manually update the parameter for the other devices.

2.4 GUI Parameters in 5G NR

The 5G NR parameters can be accessed by right clicking on a gNB or UE and selecting Interface Wireless (5G RAN) Properties → Datalink and Physical Layers.

gNB Properties			
Interface (5G RAN) – Datalink Layer			
Parameter	Type	Range	Description
Scheduling Type	Local	Round Robin	The scheduler serves equal portion to each queue in circular order, handling all processes without priority.
	Local	Proportional Fair	Schedules in proportional to the CQI of the UEs
	Local	Max Throughput	Schedules to maximize the total throughput of the network by giving scheduling priority accordingly
	Local	Fair Scheduling	Fair scheduling is a method of assigning resources to job such that all jobs get, on average, an equal share of resources over time.
UE Measurement Report Interval	Local	120 ms - 40960 ms	It is a time interval between UE Measurement Report
PDCP Header Compression	Link Global	True / False	Header compression of IP data flows using the ROHC protocol, Compresses all the static and dynamic fields.
PDCP Discard Delay Timer	Link Global	50/150/300/500/750/1500	The discard Timer expires for a PDCP SDU, or the successful delivery of a PDCP SDU is confirmed by PDCP status report, the transmitting PDCP entity shall discard the PDCP SDU along with the corresponding PDCP Data PDU.
PDCP Out of Order Delivery	Link Global	True / False	Complete PDCP PDUs can be delivered out-of-order from RLC to PDCP. RLC delivers PDCP PDUs to PDCP after the PDU reassembling.
PDCP T Reordering Timer	Link Global	0-500ms	This timer is used by the receiving side of an AM RLC entity and receiving AM RLC entity in order to detect loss of RLC PDUs at lower layer.
RLC T Status Prohibit	Link Global	0-2400ms	This timer is used by the receiving side of an AM RLC entity in order to prohibit transmission of a STATUS PDU.
RLC T Reassembly	Link Global	0-200ms	This timer is used by the receiving side of an AM RLC entity and receiving UM RLC entity in order to detect loss of RLC PDUs at lower

			layer. If t-Reassembly is running, t-Reassembly shall not be started additionally, i.e. only one t-Reassembly per RLC entity is running at a given time.
RLC T Poll Retransmit	Link Global	5-4000ms	This is used by the transmitting side of an AM RLC entity in order to retransmit a poll.
RLC Poll Byte	Link Global	1kB-40mB	This parameter is used by the transmitting side of each AM RLC entity to trigger a poll for every pollByte bytes.
RLC Poll PDU	Link Global	p4-p65536 (In multiples of 8)	This parameter is used by the transmitting side of each AM RLC entity to trigger a poll for every pollPDU PDUs.
RLC Max Retx Threshold	Link Global	t1, t2, t3, t4, t6, t8, t16, t32	This parameter is used by the transmitting side of each AM RLC entity to limit the number of retransmissions of an AMD PDU.

Note: For detailed information on RLC, please refer RLC (Based on specification 38.322)

Interface (5G_RAN) – Physical Layer			
Parameter	**Type**	**Range**	**Description**
Frame Duration (ms)	Fixed	10ms	Length of the frame.
Sub Frame Duration (ms)	Fixed	1ms	Length of the Sub-frame.
Subcarrier Number Per PRB	Fixed	12	NR defines physical resource block (PRB) where the number of subcarriers per PRB is the same for all numerologies.
gNB Height	Local	10-150m	It is the height of the gNB.
TX Power (dBM)	Local	-40dBm to 50dBm	It is the signal intensity of the transmitter.
CA_Type	Local	INTER_BAND_CA INTRA_BAND_CONTIGUOUS_CA INTRA_BAND_NONCONTIGUOUS_CA SINGLE_BAND	Carrier Aggregation (CA) is used in LTE/5G in order to increase the bandwidth, and thereby increase the bitrate. CA options are intra-band (contiguous and non-contiguous) and inter-band
CA_Configuration	Local	Depends on CA Type	Drop down provides the various bands available for the selected CA type (Eg: n78, n258, n261 etc)
CA_Count	Fixed	Depends on CA Type	Single or multiple carriers depending on the CA_Type chosen
Duplex Mode	Local	TDD, FDD	In TDD, the upstream and downstream transmissions occur at different times and share the same channel. In FDD, there are different frequency bands used uplink and downlink, The UL and DL transmission an occur simultaneously
Note: For detailed information to Frequency Range (FR1 & FR2), Please, refer PHY Layer			
Slot Type	Local	Mixed, Downlink, Uplink,	Mixed supports DL and UL traffic Downlink supports only DL traffic Uplink supports only UL traffic
Frequency Range	Local	FR1 & FR2	Frequency band for 5G NR is separated into two frequency ranges. First, is Frequency Range 1 (FR1) that includes sub-6 GHz and Frequency Range 2 (FR2) that includes frequency bands in the mmWave range.
DL/UL Ratio	Local	a:b	Represents the ratio in which slots are assigned to downlink and uplink transmissions. The value is in the form of a:b::DL:UL. Note that the ratio

			1:0 or 0:1 might lead to NIL data transmissions since the initial attachment procedures require both UL and DL control packet transmissions.
Operating Band	Fixed	n34, n38, n39, n40, n41, n50, n51, n77, n78, n79, n257, n258, n259, n260, n261	The 5G-NR operates in different operating bands corresponding to Frequency Ranges FR1 and FR2 respectively.
F_Low (MHz)	Fixed	2010-4400 MHz	Lowest frequency of the Uplink/Downlink operating band.
F_High (MHz)	Fixed	2025-5000 MHz	Highest frequency of the Uplink/Downlink operating band.
Numerology	Local	μ = 0, 1, 2, 3	It is the numerology value which represents the subcarrier spacing.
Channel Bandwidth (MHz)	Local	5-400 MHz	The frequency range that constitutes the channel.
PRB Count	Local	11-264	PRB stands for physical resource block. The PRB count is determined automatically by NetSim as per the other inputs and cannot be edited in the GUI.
Guard Band (KHz)	Local	242.5-9860 KHz	Guard band is the unused part of the radio spectrum between radio bands, for the purpose of preventing interference.
Subcarrier Spacing	Local	15-120 KHz	Subcarriers are mapped on the subset/superset of the PRB grid for subcarrier spacing of 15kHz in a nested manner in the frequency domain. The value for Subcarrier Spacing is set to 15 kHz.
Bandwidth PRB	Local	180-1440 KHz	Physical Resource Block Bandwidth is a range of frequencies occupied by the radio communication signal to carry most of PRB energy.
Slot per Frame	Local	10, 20, 40, 80	Slot within a frame is depending on the slot configuration.
Slot per Subframe	Local	1, 2, 4, 8	Slot within a Subframe is depending on the slot configuration.
Slot Duration (ms)	Local	125, 250, 500, 1000 ms	Slot duration gets different depending on numerology. The general tendency is that slot duration gets shorter as subcarrier spacing gets wider.
Cyclic Prefix	Local	Normal, Extended	Cyclic prefix is used to reduce ISI (Inter Symbol Interference), If you completely turn off the signal during the gap, it would cause issues for an amplifier. To reduce this issue, we copy a part of a signal from the end and paste it into this gap. This copied portion prepended at the beginning is called 'Cyclic Prefix'.
Symbol per Slot	Local	12, 14	The number of OFDM symbols within a slot is 14 for all slot configurations.
Symbol Duration (ms)	Local	71.43, 35.71, 17.86, 8.93, 20.83	Symbol duration is depending on the subcarrier spacing.
ANTENNA			
TX_Antenna_Count	Local	1, 2, 4, 8, 16, 32, 64, 128 in gNB (1, 2, 4, 8, 16 in UE)	The number of transmit antennas. Power is split equally among the transmit antennas.
RX_Antenna_Count	Local	1, 2, 4, 8, 16, 32, 64, 128 in gNB (1, 2, 4, 8, 16 in UE)	The number of receive antennas
PDSCH CONFIG			

MCS Table	Local	QAM64LOWSE, QAM64, QAM256	MCS (Modulation Coding Scheme) is related to Modulation Order.
X Overhead	Local	XOH0, XOH6, XOH12, XOH18	Accounts for overhead from CSI-RS, CORESET, etc. If the xOverhead in PDSCH-ServingCellconfig is not configured (a value from 0, 6, 12, or 18), N_oh^PRB the is set to 0.
PUSCH CONFIG			
MCS Table	Local	QAM64LOWSE, QAM64, QAM256	MCS (Modulation Coding Scheme) is related to Modulation Order.
Transform Precoding	Local	Enable/Disable	Transform Precoding is the first step to create DFT-s-OFDM waveform. Transform Precoding is to spread UL data in a special way to reduce PAPR (Peak-to-Average Power Ratio) of the waveform. In terms of mathematics, Transform Precoding is just a form of DFT (Digital Fourier Transform).
CSIREPORT CONFIG			
CQI Table	Local	Table1, Table2, Table3	The CQI indices and their interpretations are chosen from Table 1 or Table 3 for reporting CQI based on QPSK, 16QAM, and 64QAM. The CQI indices and their interpretations are chosen from Table 2 for reporting CQI based on QPSK, 16QAM, 64QAM and 256QAM.
CHANNEL MODEL			
Pathloss Model	Local	3GPPTR38.901-7.4.1 NONE	None represents an ideal channel with no pathloss. TR 38.901_Standard Table 7.4.2-1 means pathloss will be calculated per the formulas in this standard
Outdoor Scenario	Local	Rural Macro (RMa)	For RMa, we need to specify the Building Height and Street Width. Buildings can be used in the scenario. UEs can be inside/outside buildings but gNBs can only be outside buildings.
	Local	Urban Macro (UMa)	Buildings can be used in the scenario. UEs can be inside/outside buildings but gNBs can only be outside buildings.
	Local	Urban Micro (UMi)	Buildings can be used in the scenario. UEs can be inside/outside buildings but gNBs can only be outside buildings.
Building Height	Local	5-50m	It is the height of the building in meters. The building-height parameter shown in gNB, eNB Physical layer is for the Rural Macro environment. However, the properties won't be available when users choose other environments like Urban Macro or Urban Micro. Note: This Building-height parameter is an input parameter to the stochastic pathloss model and is not related to the “building” that can dragged and dropped into the environment. Buildings in the GUI are present to differentiate between indoor and outdoor propagation. They do not have height as a parameter.
Street Width	Local	5-50m	It is the width of the street in meters.
Indoor Scenario	Fixed	Indoor Office	Automatically chosen by NetSim in case the UE is within an indoor building. The Indoor Office parameter will be automatically chosen by NetSim depending on

			the scenario (whether the device is inside the building or outside). In the case of LTE, this parameter will be automatically chosen as Outdoor since buildings are not present.
Indoor Office Type	Local	Mixed-Office Open-Office	The pathloss will be per the chosen option when the UE is within a building
LOS_NLOS Selection	Fixed	3GPPTR38.901-Table 7.4.2-1 USER_DEFINED	This choice determines how NetSim decides if the gNB-UE communication is Line-of-sight or Non-Line-of-Sight. In case of USER_DEFINED the LOS probability is user defined. Else it is standards defined.
LOS Probability	Local	0 to 1	If LOS Probability =1, the LOS mode is set to Line-of-Sight and if the LOS Probability =0, the LOS mode as set to Non-Line-of-Sight. For a value in between the LOS is determined probabilistically. By default, value is set to 1.
Shadow Fading Model	Local	NONE LOG_NORMAL	Select NONE to Disable Shadowing Select LOG_NORMAL to Enable Shadowing Model, and the Std dev would be per 3GPP TR38.901-Table 7.4.1-1
Fading and Beamforming	Local	NO_FADING, RAYLEIGH_WITH_EIGEN_BEAMFORMING	See section 3.9.2
O2I_Building_Penetration_Model	Local	None, Low Loss Model, High Loss Model,	The composition of low and high loss is a simulation parameter that should be determined by the user of the channel models and is dependent on the buildings and the deployment scenarios. None to disable O2I Loss. Low-loss model is applicable to RMa. High-loss model is applicable to UMa and UMi.
Additional Loss Model	Local	NONE, MATLAB	Additional Loss model can be set to None or MATLAB, if set to MATLAB then MATLAB will be automatically called by NetSim during execution.
Propagation Model: Refer **mmWave Propagation Models (Per 3GPPTR38.900 Channel Model)** for technical information.			
UE Properties			
Interface (5G_RAN) – Physical Layer			
Parameter	**Type**	**Range**	**Description**
UE Height (m)	Local	1-22.5	It is the height of the UE in meters
TX Power (dBM)	Local	-40dBM to 50dBM	It is the signal intensity of the transmitter. The higher the power radiated by the transmitter's antenna the greater the reliability of the communications system.
ANTENNA			
TX_Antenna_Count	Local	1,2,4,8,16	Number of transmit antennas. NetSim uses this parameter in MIMO operations.
RX_Antenna_Count	Local	1,2,4,8,16	Number of receive antennas. NetSim uses this parameter in MIMO operations.
Beamforming Gain (dB)	Local	0dB to 100dB	The antenna gain provided by signal processing techniques for directional transmissions

3 Model Features

3.1 The 5G Frame Structure

5G uses Orthogonal Frequency Domain Multiplexing (OFDM) as the multiple access scheme for both downlink and uplink transmissions with the flexibility of multiple subcarrier spacing that supports diverse application scenarios. The smallest physical resource, known as the resource element (RE), comprises one subcarrier and one OFDM symbol. 5G NR supports a flexible OFDM numerology to support diverse spectrum bands/types and deployment models. The numerology, μ, can take values from 0 to 4 and specifies the Sub-Carrier-Spacing (SCS) as $15 \times 2^{\mu}$ kHz and a slot length of $\frac{1}{2^{\mu}}$ ms. With μ varying from 0 to 4, SCS varies from 15 to 240 kHz. NetSim supports μ = 0, 1, 2 for FR1 and μ = 2, 3 for FR2. The setting $\mu = 0$ corresponds to the LTE (4G) system configuration.

In the time domain (to support backwards compatibility with LTE) the frame length in 5G NR is set to 10 ms, and each frame is composed of 10 subframes of 1 ms each. The 1 ms subframe is then divided into one or more slots in 5G, whereas LTE had exactly two slots in a subframe. The slot size depends on the numerology, μ, and is equal to $\frac{1}{2^{\mu}}$ ms. The number of OFDM symbols per slot is 14 for a configuration using normal cyclic prefix. For extended cyclic prefix, the number of OFDM symbols per slot is 12. See section 3.9.7.2 - Numerologies, for more information.

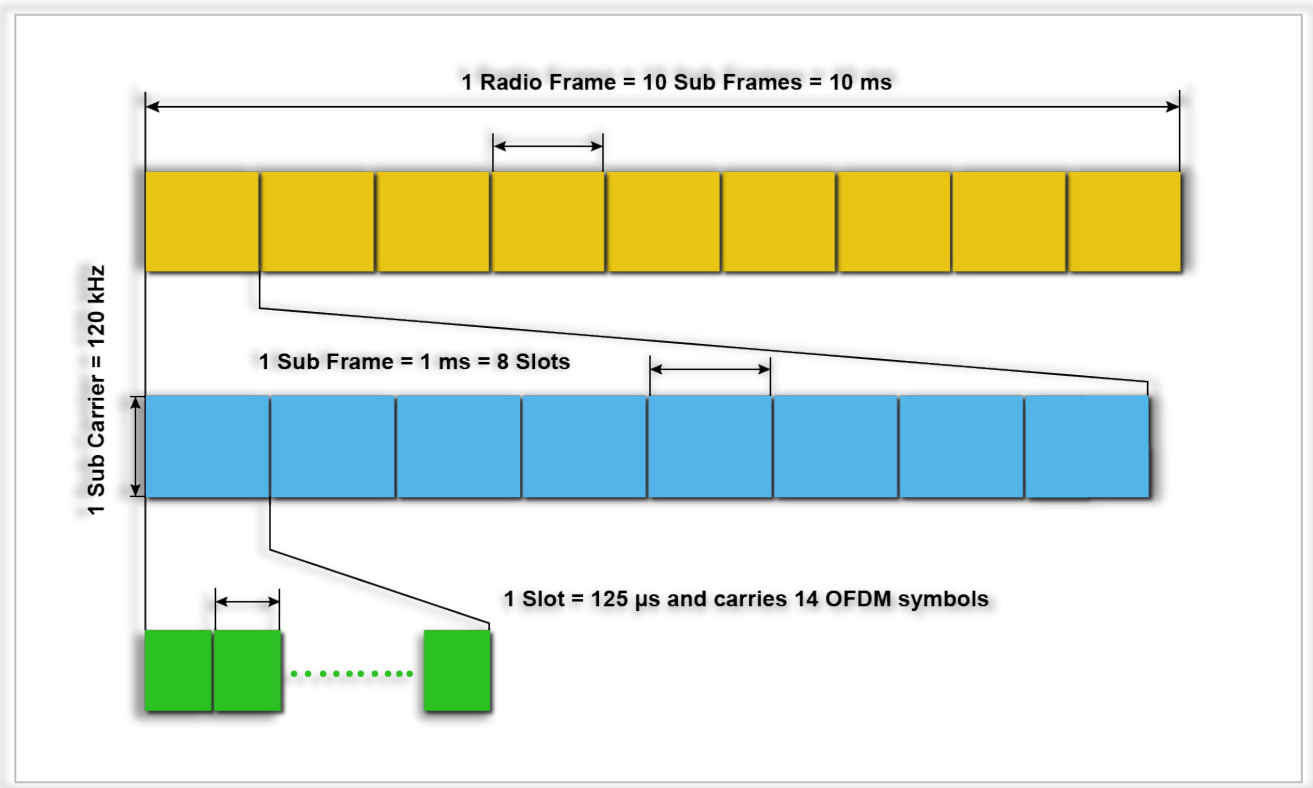


Figure 3-1: NR Frame Structure when numerology μ is set to 3

In the frequency domain, the number of subcarriers per physical resource block (PRB) is fixed to 12, and the Sub-Carrier-Spacing (SCS) is $15 \times 2^{\mu}$ kHz.

PRB: The physical resource block is the minimum unit of resource allocation in the frequency domain, i.e., the width of a resource block, 180 kHz. It is a system-level constant. For example, a PRB can either contain 12 subcarriers of 15 kHz each

Resource Block: It is the minimum unit of resource allocation, i.e., 1 PRB by 1 slot. NetSim's scheduler performs resource allocation every subframe (TTI, transmission time interval), however, the granularity of resource allocation 1 slot in time, i.e., the duration of a resource block, and 1 PRB in frequency.

3.2 Data Transmission Overview

- In NetSim only the DL and UL traffic channels (PDSCH and PUSCH) are modelled. The control signals and control channels are abstracted; these abstractions are explained is various parts of this document.
- In TDD operation the UL and DL transmissions are separated in the time-domain over different frames/subframes/slots/symbols and use the same carrier frequency. In FDD operation UL and DL transmissions are separated in the frequency domain, with different frequencies used for UL and for DL transmission.
- Higher layer packets arrive at the RLC buffer for each UE and each gNB.
- The MAC scheduler in the gNB determines which user to allocate the PRB (PHY resources) to, during transmission. In this module the Transport block size (TBS) (explained in 3.9.12) based on the channel quality index (CQI). The CQI is determined by the Adaptive Modulation and Coding (AMC) function based on the SNR.
- Now, the received SNR is determined from a) large scale pathloss and shadowing calculated per the 3GPP's stochastic propagation models, and b) the small-scale fading which leads to beamforming gains when using MIMO[1]. These models provide signal attenuation as an output. Several parameters are used in the model, including the distance between the transmitter and the receiver. These computations are executed each associated UE-gNB pair, in DL and UL, at the start of simulation and again at every mobility event. In calculating SNR, the noise power is obtained from $N = k \times T \times B$.
- Note that the SNR/CQI is not computed/fed-back using reference signals/control channels but is computed on the data channel (PDSCH and PUSCH). Then it is assumed to be instantaneously known to the transmitter and receiver. This assumption is known as perfect

[1] MIMO and beamforming are explained in section 3.9

CSIT and CSIR. With perfect CSIT the transmitter can adapt its transmission rate (MCS) relative to the instantaneous channel state (SNR).

- Based on this SNR the AMC determines a wideband CQI which indicates the highest rate Modulation and coding scheme (MCS), that it can reliably decode, if the entire system bandwidth were allocated to that user. The modulation scheme defines the number of bits, that can be carried by a single RE. Modulation scheme supported by 5G include QPSK (2 bits), 16 QAM (4 bits), 64 QAM (6 bits), and 256 QAM (8 bits). The code rate defines the proportion of bits transmitted that are useful. It is computed as the ratio of useful bits by total bits that are transmitted. The modulation order Q_m, which denotes the number of bits per RE, and the code rate denoted by R are jointly encoded as modulation and coding scheme (MCS) index. These values of Q_m and R are then passed to the TBS determination function.
- At each gNB a frame of length 10ms is started. Each frame in turn starts 10 sub frames each of length 1ms. Each sub frame then starts a certain number of slots based on numerology.
- The PHY layer in NetSim then notifies the MAC about the slot start. The MAC sub layer in turn seeks a buffer status report from the RLC layer and invokes the MAC scheduler. It then notifies the RLC of the transmission. The RLC then transmits the transport block to the PHY layer. The downlink and uplink data channels (PDSCH, PUSCH) receive this transport block as its service data unit (SDU), which is then processed and transmitted over the radio interface.

3.3 5G NR Stack

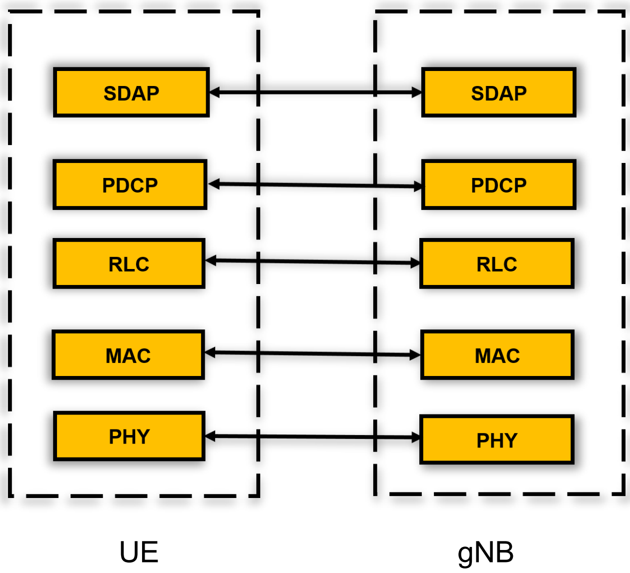


Figure 3-2: User Plane Protocol Stack

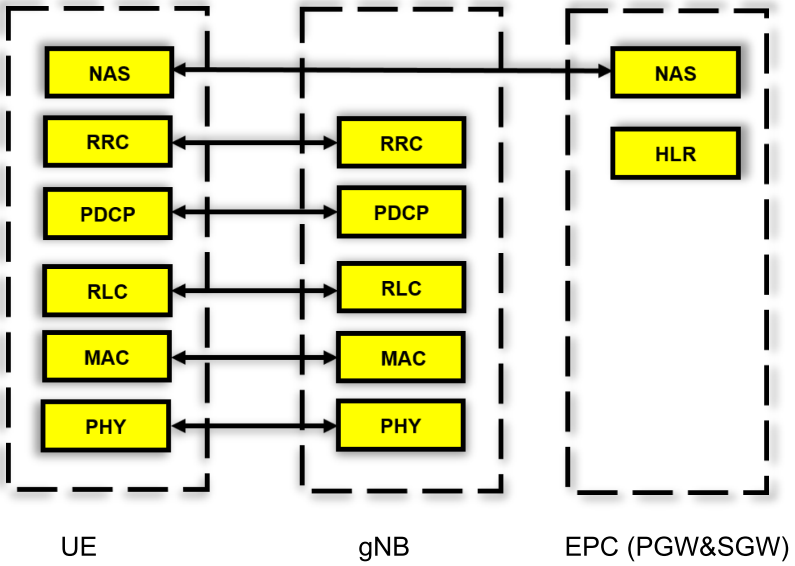


Figure 3-3: Control Plane Protocol Stack

3.4 SDAP (Specification: 37.324)

5G-NR User contains PHY, MAC, RLC, and PDCP same as LTE and has introduced a new layer named as SDAP (Service Data Adaptation Protocol). The features in NetSim SDAP are:

- Mapping between a QoS flow and a data radio bearer (DRB) (Due to new QoS framework)
- Marking QoS flow ID (QFI) in both DL and UL packets (DL: due to reflective QoS and UL: due to new QoS framework)

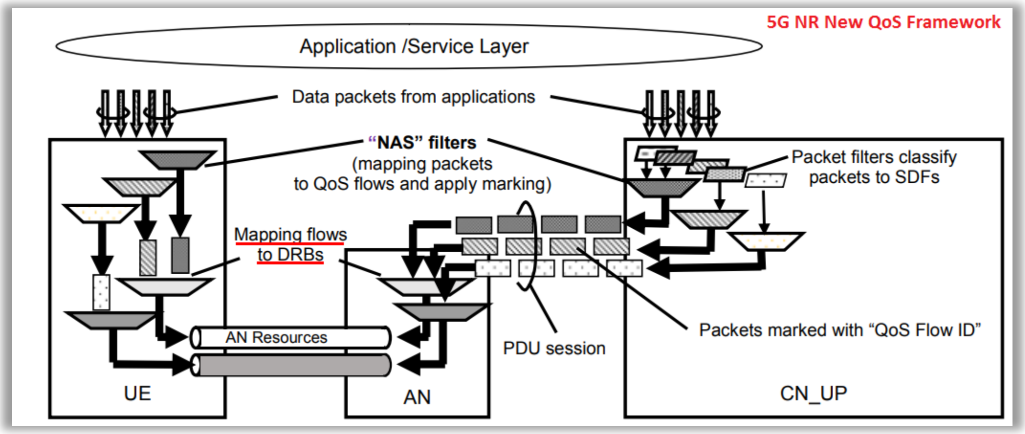


Figure 3-4: 5G Quality of Services (QoS)

In NetSim the SDAP module's SetMode function maps the Application QoS Type (which can be set in NetSim's GUI) to RLC mode

Application QoS (Set in NetSim GUI)	RLC Mode	Priority
nrtPS, ertPS, rtPS, UGS	UM Mode	GBR
BE	AM Mode	Non-GBR

Table 3-1: Mapping of Application QoS to RLC mode in NetSim

In the same function, the logical channel is also set to DTCH which is the dedicated traffic channel. Next, comes the MAC_OUT function. This function determines what the current device is connected to i.e., if it is a UE, it finds the associated gNB, else if the current device is a gNB it finds the associated UEs. The SDAP header is then added which contains the QFI. Note that the NetSim 5G NR library only supports unicast transmissions (broadcast/multicast is not supported).

After this is the SendToNetwork function. This function is called when a packet is at MAC-IN. The function creates the Network Event, sets all the Event-Details and sends the packet to IP layer. And finally, the HandleMacIN function decides whether the packet must be sent to another interface or sent to network layer. The header is stripped off.

3.4.1 5G QoS characteristics

5G Quality of Service (QoS) model is based on QoS Flows. Each QoS flow has a unique identifier called QoS Flow Identifier (QFI). There are two types of flows: Guaranteed Bit Rate (GBR) QoS Flows and Non-GBR QoS Flows. Every QoS flow has a QoS profile that includes QoS parameters and QoS characteristics. Applicable parameters depend on GBR or non-GBR flow type. QoS characteristics are standardized or dynamically configured.

The current (as of v13.1) NetSim COTS build does not implement 5G QoS. All traffic flowing is categorized as non-GBR. A framework has been provided for users to modify the underlying code to implement QoS flow categorization in terms of:

1 Resource Type (GBR, Delay critical GBR or Non-GBR);

2 Priority Level.

3 Packet Delay Budget.

4 Packet Error Rate.

3.5 RLC (Based on specification 38.322)

NetSim RLC entity is based on 3GPP Technical specification 38.322. The RLC layer sits between PDCP and MAC layer. The RLC has three different modes of operation: TM (Transparent Mode), UM (Unacknowledge Mode) and AM (Acknowledge mode) as shown in diagram below Figure 3-5.

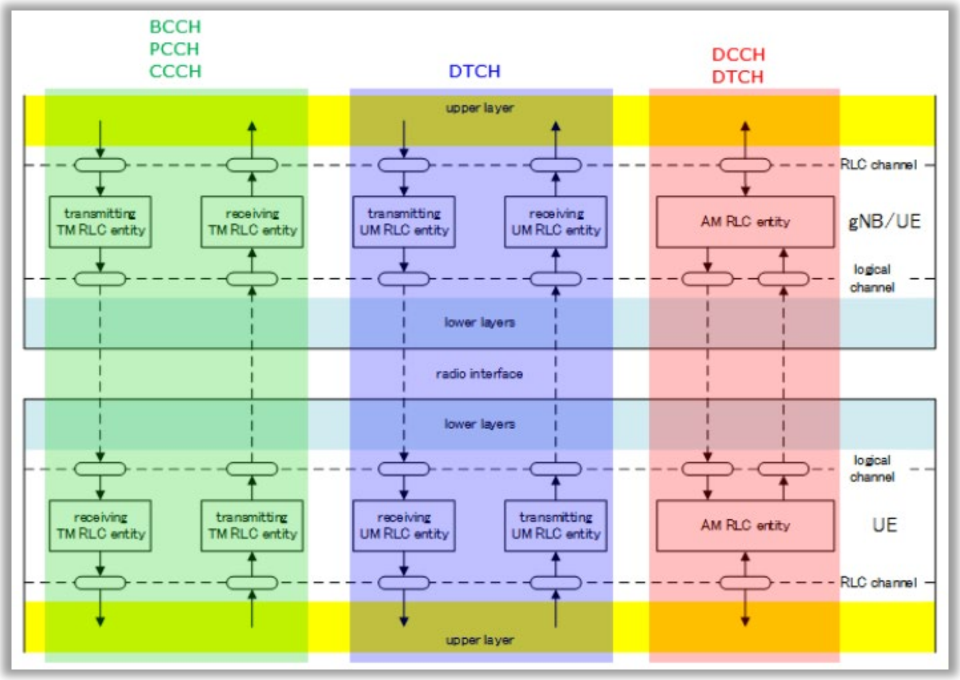


Figure 3-5: RLC Modes of operation and RLC Entities

A brief summary of key features of these modes is as follows:

- TM: No RLC Header, Buffering at Tx only, No Segmentation/Reassembly, No feedback (i.e, No ACK/NACK)
- UM: RLC Header, Buffering at both Tx and Rx, Segmentation/Reassembly, No feedback (i.e., No ACK/NACK)
- AM: RLC Header, Buffering at both Tx and Rx, Segmentation/Reassembly, Feedback (i.e., ACK/NACK)

Each of these modes can both transmit and receive data. In TM and UM, separate entity is used for transmission and reception, but in AM a single RLC entity perform both transmission and reception,

NetSim implements all the 7 entities for the RLC that are shown in *Figure 3-5: RLC Modes of operation and RLC Entities.* Note that each of logical channels use a specific RLC mode:

- BCCH, PCCH, CCCH use RLC TM only.
- DCCH use RLC AM only.
- DTCH use RLC UM or AM. (Which mode is used for each DTCH channel, is determined by RRC message).

The RLC entities provide the RLC service interface to the upper PDCP layer and the MAC service interface to the lower MAC layer. The RLC entities use the PDCP service interface from the upper PDCP layer and the MAC service interface from the lower MAC layer.

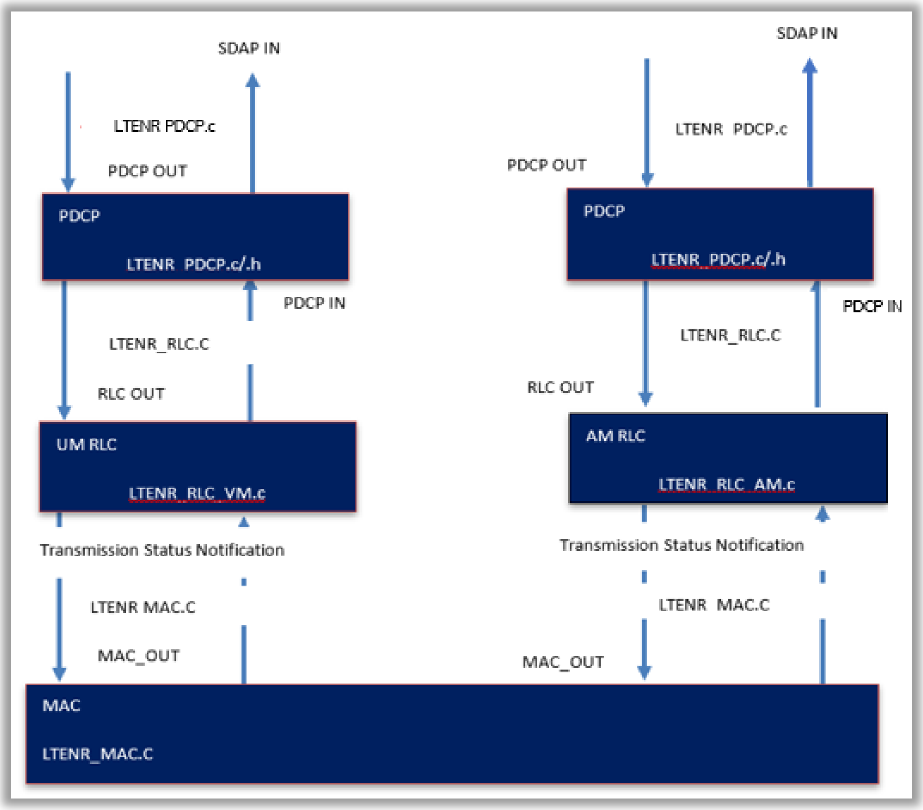


Figure 3-6: Implementation Model of PDCP, RLC and MAC entities

The main call at the transmit side RLC is done in the function *fn_NetSim_LTENR_RLC_HandlePDUFromUpperLayer()* in the file LTENR_RLC.c

Then the MAC Layer calls the following function in LTENR_RLC.c

UINT fn_NetSim_LTENR_RLC_BufferStatusNotificaton(NETSIM_ID d, NETSIM_ID in, NETSIM_ID r, NETSIM_ID rin, LTENR_LOGICALCHANNEL logicalChannel) to know the buffer status in order to do the scheduling

Once the MAC Layer allocates resources it calls the following function in LTENR_RLC.c

void fn_NetSim_LTENR_RLC_TransmissionStatusNotification(NETSIM_ID d, NETSIM_ID in, NETSIM_ID r, NETSIM_ID rin, UINT size, LTENR_LOGICALCHANNEL logicalChannel)

UM stands for 'Unacknowledged Mode'. 'Unacknowledged Mode' means 'it does not require any reception response from the other party'. 'Reception response' simply mean 'ACK' or 'NACK' from the other party. (UM mode is similar to TM mode in that it does not require any ACK/NACK from the other party, but it is different from TM in that it has its own header)

Per the figure below the RLC transmit side (All the RLC UM functionality is available in the file *LTENR_RLC_UM.c* in the project LTE_NR).

- Buffers the data and generates RLC Header. This is handled in NetSim by the function *void LTENR_RLC_UM_HandlePDUFromUpperLayer()*

- Segmentation of the RLC SDU and modification RLC Header (Some fields in RLC header may be changed based on the segmentation status)
- Adds RLC header.
  - The above two functionalities are handled in NetSim by the function UINT LTENR_RLC_UM_SEND_PDU (NETSIM_ID d, NETSIM_ID in,NETSIM_ID r, NETSIM_ID rin, UINT size, LTENR_LOGICALCHANNEL logicalChannel) which in turn calls the function static NetSim_PACKET* LTENR_RLC_UM_FRAGMENT_PACKET (NetSim_PACKET* p, UINT size, UINT sn) and the function static int LTENR_RLC_UM_ADD_HDR(NetSim_PACKET* p

NOTE: If you compare this in LTE process, it seems that UM RLC does not perform any 'Concatenation'. According to following statement from 38.322 v0.1.0, the 'concatenation' process is moved to MAC layer.

From RAN2 NR#1: Working assumption on no RLC concatenation taken at RAN2#96 is confirmed (i.e., concatenation of RLC PDUS is performed in MAC).

The main call at the receive side RLC is done in the function *void fn_NetSim_LTENR_RLC_HandleMACIN() in the file LTENR_RLC.c*

The RLC on the receive side:

- Buffers. Here the RLC waits for all the fragments to arrive.
  - This is handled in NetSim by the function void LTENR_RLC_UM_RECEIVE_PDU(). If there is no fragments then call LTENR_CallPDCPIN(); else call LTENR_RLC_UM_RECEIVE_PDU_WITH_SN();
- Reorders, if required
- Strips the RLC header
- Reassembles
  - The above three functionalities are handled in NetSim by the code in the region *#pragma region RLC_UM_RECEPTIONBUFFER*

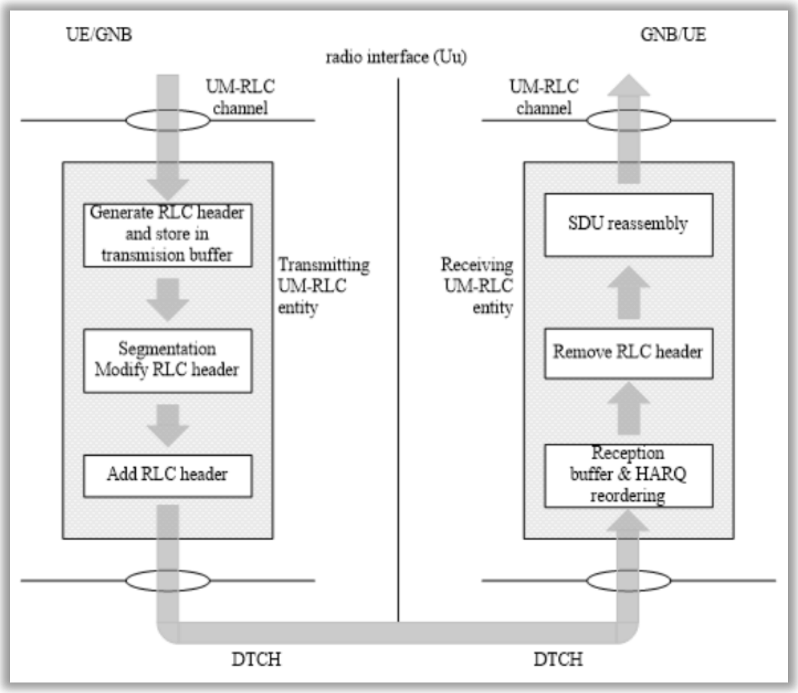


Figure 3-7: RLC UM working

NetSim GUI RLC Configurable parameters

The following timers are configured per TS 38.331 [5]:

a. **t-PollRetransmit**: This timer is used by the transmitting side of an AM RLC entity in order to retransmit a poll. Default value in NetSim is set to ms5(5 milli seconds). Range is provided in the GUI dropdown menu.
b. **t-Reassembly**: This timer is used by the receiving side of an AM RLC entity and receiving UM RLC entity in order to detect loss of RLC PDUs at lower layer. If *t-Reassembly* is running, *t-Reassembly* shall not be started additionally, i.e. only one *t-Reassembly* per RLC entity is running at a given time. Default value in NetSim is set to ms5(5 milli seconds). Range is provided in the GUI dropdown menu.
c. **t-StatusProhibit**: This timer is used by the receiving side of an AM RLC entity in order to prohibit transmission of a STATUS PDU. Default value in NetSim is set to ms5(5 milli seconds). Range is provided in the GUI dropdown menu. The following parameters are configured per TS 38.331 [5]:
d. **maxRetxThreshold**: This parameter is used by the transmitting side of each AM RLC entity to limit the number of retransmissions corresponding to an RLC SDU, including its segments. Default value in NetSim is set to t1. Range is provided in the GUI dropdown menu.
e. **pollPDU**: This parameter is used by the transmitting side of each AM RLC entity to trigger a poll for every *pollPDU* PDUs. Default value in NetSim is set to p4(PDUs). Range is provided in the GUI dropdown menu.
f. **pollByte**: This parameter is used by the transmitting side of each AM RLC entity to trigger a poll for every *pollByte* bytes. Default value in NetSim is set as kB25 (KBytes). Range is provided in the GUI dropdown menu.

3.6 RLC-AM (Based on specification 38.322)

AM' stands for 'Acknowledge Mode'. This mean an ACK/NACK is required from the receiver unlike RLC-UM where no ACK/NACK is required from the receiver. The code for RLC-AM mode is written in the file LTENR_RLC_AM.c

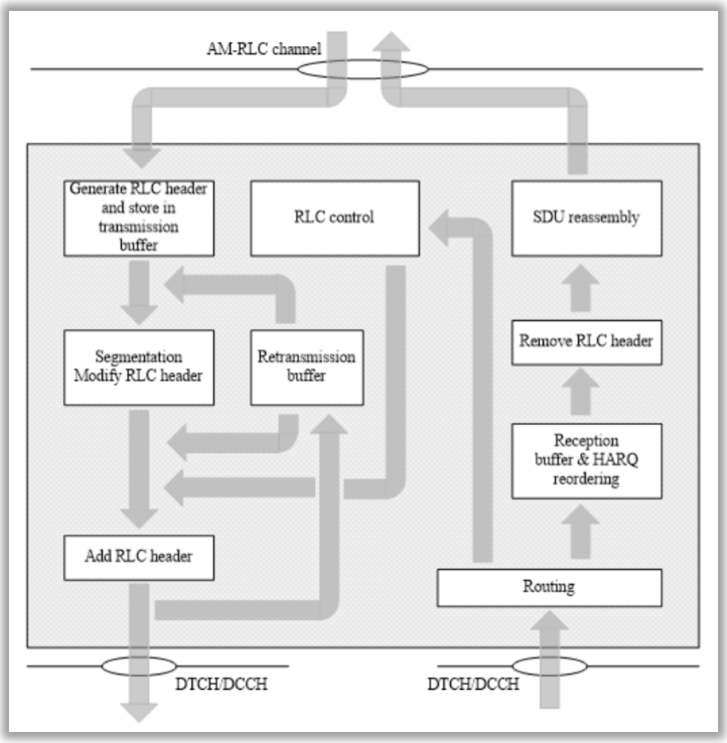


Figure 3-8: RLC AM Working

The functionality of RLC-AM is:

After RLC transmitters does the segmentation/concatenation process, it adds RLC header and then it creates two identical copies and transmit the one copy of the data out to lower layer (MAC) and sends another copy to Retransmission buffer.

If the RLC gets Nack or does not get any response from the receiver for a certain period of time, the RLC PDU in the retransmission buffer gets transmitted again. If the RLC get ACK, the copy of the packet in retransmission buffer is discarded.

There are four buffers maintained in RLC-AM. There is no size defined in the standard and hence NetSim implements an infinite buffer (see LTENR_RLC.h and LTENR_RLCBuffer.c for related code). There are 3 buffers for transmit operations and 1 for receive operation:

1. Transmission buffer: Queues SDUs received from higher layer (PDCP)
2. Transmitted buffer: Queues SDUs that has been transmitted but for which ACK/NACK has not yet received.
3. Re-transmission Buffer: Queues RLC SDUs which are considered for retransmission. (i.e. for which NACK has been received)

4. Reception Buffer: Queues fragments of SDUs (receiver side)

The MAC sub layer then seeks a Buffer Status Report from the RLC.

The entry functions for RLC-AM is defined in the section #pragma region RLCAM_OUT. The first function called is *void LTENR_RLCAM_HandlePDUFromUpperLayer()*

Here the packet is added to the Transmission Buffer. Then based on the MAC scheduler, the MAC layer sends a notification to RLC, which in turn sends a packet by first checking the Re Transmission Buffer followed by the Transmission-Buffer. These functions are also in the same region.

The T_POLLRetransmit determines if a packet needs to be re-transmitted. If RLCAM- Ack is not received packet is moved from transmitted buffer to retransmission buffer. The codes for T_POLLRetransmit are in the section #pragma region RLCAM_T_POLLRetransmit.

3.6.1 Transmit Operations

The transmitting side of an AM RLC entity shall prioritize transmission of RLC control PDUs over AMD PDUs. The transmitting side of an AM RLC entity shall prioritize transmission of AMD PDUs containing previously transmitted RLC SDUs or RLC SDU segments over transmission of AMD PDUs containing not previously transmitted RLC SDUs or RLC SDU segments. The transmitting side of an AM RLC entity shall maintain a transmitting window according to the state variable

TX_Next_Ack as follows:

- a SN falls within the transmitting window if TX_Next_Ack <= SN < TX_Next_Ack + AM_Window_Size;

- a SN falls outside of the transmitting window otherwise.

The transmitting side of an AM RLC entity shall not submit to lower layer any AMD PDU whose SN falls outside of the transmitting window.

For each RLC SDU received from the upper layer, the AM RLC entity shall:

- associate a SN with the RLC SDU equal to TX_Next and construct an AMD PDU by setting the SN of the AMD PDU to TX_Next;

- increment TX_Next by one.

When submitting an AMD PDU that contains a segment of an RLC SDU, to lower layer, the transmitting side of an AM.

RLC entity shall:

- set the SN of the AMD PDU to the SN of the corresponding RLC SDU.

The transmitting side of an AM RLC entity can receive a positive acknowledgement (confirmation of successful reception by its peer AM RLC entity) for an RLC SDU by the following:

- STATUS PDU from its peer AM RLC entity.

When receiving a positive acknowledgement for an RLC SDU with SN = x, the transmitting side of an AM RLC entity shall:

- send an indication to the upper layers of successful delivery of the RLC SDU;

- set TX_Next_Ack equal to the SN of the RLC SDU with the smallest SN, whose SN falls within the range

TX_Next_Ack <= SN <= TX_Next and for which a positive acknowledgment has not been received yet.

3.6.2 Receive Operations

The receiving side of an AM RLC entity shall maintain a receiving window according to the state variable RX_Next as follows:

- a SN falls within the receiving window if RX_Next <= SN < RX_Next + AM_Window_Size;

- a SN falls outside of the receiving window otherwise.

When receiving an AMD PDU from lower layer, the receiving side of an AM RLC entity shall:

- either discard the received AMD PDU or place it in the reception buffer.

- if the received AMD PDU was placed in the reception buffer:

- update state variables, reassemble and deliver RLC SDUs to upper layer and start/stop t-Reassembly as needed when t-Reassembly expires, the receiving side of an AM RLC entity shall:

- update state variables and start t-Reassembly as needed.

After submitting an AMD PDU including a poll to lower layer, the transmitting side of an AM RLC entity shall:

- set POLL_SN to the highest SN of the AMD PDU among the AMD PDUs submitted to lower layer;

- if t-PollRetransmit is not running:

- start t-PollRetransmit.

- else:

- restart t-PollRetransmit

3.6.3 Actions when a RLC PDU is received from a lower layer

At the Receive side the functionality is handled in the section #pragma region RLCAM_IN. The entry function in the receive side is void LTENR_RLC_AM_RECEIVE_PDU(). The receives the AMPDU and checks if

1. It is within the receive window.
2. The packet is not already received i.e. not duplicate

If both the conditions are true, the AMPDU is placed in the Reception Buffer and starts the ReassemblyTimer. If the PDU has a PollRequest then it starts constructing the StatusPDU. The code for this is in the section #pragma region RLCAM_STATUSPDU_SEND

3.6.4 Reception of a STATUS report

Upon reception of a STATUS report from the receiving RLC AM entity the transmitting side of an AM RLC entity shall:

- if the STATUS report comprises a positive or negative acknowledgement for the RLC SDU with sequence number equal to POLL_SN:

- if t-PollRetransmit is running:

- stop and reset t-PollRetransmit

3.7 PDCP (Based on specification 38.322)

The PDCP layer receives a packet (data/control) from the upper layer, executes the PDCP functions and then transmits it to a lower layer.

PDCP Entity: The PDCP entities are located in the PDCP sublayer. NetSim currently implements one PDCP entity per UE (users can add more by modifying the code). The same PDCP entity is associated with both the control and the user plane.

The source code files related to PDCP are:

- LTENR_PDCP.c
- LTENR_PDCP.h

and the primitives are void fn_NetSim_LTENR_PDCP_TransmitPDCPSDU(), to send the PDCP SDU to a lower layer, and fn_NetSim_LTENR_PDCP_ReceivePDCPSDU()

The PDCP functionality supported (see LTENR_PDCP.c) in NetSim is:

- Transmit PDCP SDU
    - Sets the PDCP Sequence Number
    - Adds RLC Header.
    - Calls RLC service primitive.
- PDCP Association
    - This call back function is invoked when the UE associates/dissociates from a gNB.
- Maintenance of PDCP sequence numbers (to know more check the PDCP entity structure)
- Discard Timer:

    - When the discardTimer expires for a PDCP SDU, or the successful delivery of a PDCP SDU is confirmed by PDCP status report, the transmitting PDCP entity shall discard the PDCP SDU along with the corresponding PDCP Data PDU.
    - Discarding a PDCP SDU already associated with a PDCP SN causes a SN gap in the transmitted PDCP Data PDUs, which increases PDCP reordering delay in the receiving PDCP entity.
    - NetSim Specific (can be seen in the event trace upon completion of simulation)
        - Event Type: TIMER_EVENT
        - Sub Event Type: PDCP_DISCARDTIMER
- Transmission Buffer (size is assumed to infinite): This is where PDCP SDU's are stored before being sent down to a lower layer.
- PDCP Entity: The PDCP Entity structure is defined in LTENR_PDCP.h
- PDCP State variables.
- TREORDERING Timer.
- Receive buffer.

3.8 MAC Layer

3.8.1 Overview

NetSim 5G NR MAC implements the following features:

- Multiplexing/de-multiplexing of MAC SDUs into/from transport blocks for DL-SCH and UL-SCH data transfer
- Buffer status reporting
- MAC Scheduler

3.8.2 MAC Scheduler

At each gNB the MAC scheduler decides the PRB allocation, in a slot, for DL and UL, for each carrier. Control packets such as the buffer status report (BSR) and UL assignment, are assumed to be sent out of band. The resources for transmission of these packets are part of Overhead as defined in 3.10. The MAC scheduler works as follows:

- Round Robin: It divides the available PRBs among the active flows, i.e., those logical channels which have a non-empty RLC queue. The MCS for each user is calculated according to the received CQIs.
- Proportional fair: It allocates PRBs in proportion to the CQI of the active flows. The allocation for each user is *not* in the ratio of reported rate to its fading-averaged value.
- Max throughput: It allocates PRBs to the active flow(s) to maximize the achievable rate. In other words, it selects the user that sees the highest CQI.

- Fair Scheduler: It ensures equal throughputs for all active flows.

Note that these are MAC scheduling algorithms, and do not use the QoS parameter that can be set in the Application properties in NetSim's GUI.

3.9 PHY Layer

3.9.1 Overview of the PHY implementation

NetSim is a packet level simulator for simulating the performance of end-to-end applications over various packet transport technologies. NetSim can scale to simulating networks with 100s of end-systems, routers, switches, etc. NetSim provides estimates of the statistics of application-level performance metrics such as throughput, delay, packet-loss, and statistics of network-level processes such as buffer occupancy, collision probabilities, etc.

In order to achieve a scalable simulation, that can execute in reasonable time on desktop level computers, in all networking technologies the details of the physical layer techniques have been abstracted up to the point that bit-error probabilities can be obtained from which packet error probabilities are obtained.

Of all the wireless access technologies implemented in NetSim, the most sophisticated is 5G NR, in which the physical layer utilizes a variety of techniques that go well beyond even 4G LTE. These include multiple subcarrier bandwidths in the same system, slot lengths that depend on the subcarrier bandwidth, flexible time-division duplexing, a wide range of constellation sizes and coding rates, multiuser MIMO-OFDM, etc. Particularly with regard to MIMO-OFDM, with the attendant channel estimation (the errors therein), and the complexities of signal processing, NetSim has taken the design decision to replace these by idealized, symbol level models, where the statistics of the effective stochastic channel gains, and the statistics of the effective stochastic noise and interference are modelled in an idealized setting. Such models then permit the calculation of the required bit error rates, and thereby code block error rates, etc.

Overview of the 5G NR PHY:

- 5G NR utilizes an implementation of OFDMA, with several different carrier bandwidths, and a wide range of modulation and coding schemes.
- Users would be sharing the same RF bandwidth but would be using different modulation schemes and thus obtaining different bit rates. As the devices involved in the communication move around, the radio channel between them also keeps changing.
- The received SNR is determined from pathloss calculated per the 3GPP's stochastic propagation models. The models provide signal attenuation as an output. Several parameters are used in the model, including the distance between the transmitter and the receiver.

- A CQI is computed for all the symbols in one TB, based on the SNR calculated on the data channels (DL and UL). The SNR calculation is done at the start of the simulation, then every UE measurement interval and also at every instant a UE moves. In calculating SNR, the noise power is obtained from $N = k \times T \times B$.
- Based on the SNR, the Adaptive Modulation and Coding (AMC) functionality determines the values of Q, the modulation order, and R, the code rate, in the TBS formula. The SNR is computed on a per UE level for UL and DL.
- The transport block size in NetSim is as per the MAC procedure for TBS determination standardized in TS 38.214 Section 5.1.3.2 (DL) and 6.1.4.2 (UL).
- An approximate estimate of the TBS per carrier is.

$$n_{info} = R \times \log_2 Q \times v \times n_{sc}^{rb} \times n_{symbol} \times N_{PRB} \times (1 - OH)$$

  Where R is the code rate, Q is the modulation order, v is the number of MIMO layers, n_{sc}^{rb} is the number of sub carriers per resource block, n_{symbol} is the number of symbols per slot, N_{PRB} is the number of PRBs and OH is the overheads specified in the standard.
- The available PHY resource is shared dynamically between the users, with the resource allocation being dynamically adjusted per user demands and channel conditions. The MAC Scheduler determines the data (how much to and from, which UE and gNB) that is to be transmitted, from the higher layer RLC buffer, in units of Physical Resource Blocks (PRBs). It is transmitted at a rate determined using R, code rate and Q, modulation order of the UE – gNB channel.

3.9.2 Beamforming in NetSim

- For a transmitter (gNB or eNB) with t antennas and a receiver with r antennas, the $r \times t$ channel gain matrix (between every transmit-receive antenna pair) has complex Gaussian elements. We assume in the standard model that the complex Gaussian elements are statistically independent across elements, and each element is a circularly symmetric Gaussian. We denote this matrix by H.
- For the channel matrix H being defined as above, the Wishart Matrix is defined as follows:

$$W = H H^{\dagger} \quad r < t,$$

$$W = H^{\dagger} H \quad r \geq t$$

  Therefore, letting $m = \min(r, t)$, W is an $m \times m$ nonnegative definite matrix, with eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \cdots \geq \lambda_L > 0 = \lambda_{L+1} = \cdots = \lambda_m$. It is these eigenvalues that are used in the parallel SISO models described below.

- NetSim permits the user to enable or disable a stochastic fading model. Fading is modelled by the elements of H being time varying, with some coherence time. Such time variation results in the eigenvalues of W also varying. NetSim models such time variation by letting the user define a *coherence time* during which the eigenvalues are kept fixed. For each (r, t) value, NetSim maintains a list of samples of eigenvalues for the corresponding Wishart matrix. To model fading, a new set of eigenvalues is used by NetSim in successive coherence times.

- Putting the above discussions together, if fast fading with eigen-beamforming is enabled in NetSim's GUI, then the MIMO link is modelled by several SISO channels (see below), with the symbol level channel gain being derived from the eigenvalues of the Wishart matrix.

  $$BeamFormingGain\ (dB) = 10\log_{10}(EigenValue)$$

  It must be noted that the eigenvectors are not required as they are only a part of the receive and transmit signal processing, and NetSim only needs to work with the equivalent symbol-by-symbol flat fading SISO channels.
- If fast fading is disabled, NetSim reduces the MIMO transmission to a set of parallel, independent channels with constant gain, since the Beam forming gain does not change with time.

3.9.3 MIMO Beamforming Assumptions in NetSim

NetSim makes the following assumptions to simplify MIMO operations for a packet-simulator:

- Operation in spatial multiplexing mode only and not in transmit diversity mode.
- The $LayerCount = Min\ (N_t, N_r)$ where N_t is the number of transmit antennas and N_r is equal to the number of receive antennas.
- The rank of the channel is assumed to be equal to the layer count. NetSim doesn't perform any Rank indicator (RI) computations.
- Each layer is reduced to a flat fading SISO channel, i.e., for layer $j, 1 \leq j \leq LayerCount$,

  $$y_j = \sqrt{\lambda_j}\, x_j + w_j$$

  where, x_j is the symbol transmitted, λ_j is the corresponding eigenvalue of the Wishart matrix obtained as in the previous section, w_j is circular symmetric complex Gaussian noise, and y_j is the complex valued baseband received symbol.
- Since the distance between the transmitter and receiver is much larger than the antenna spacings, a common pathloss is assumed for every layer. The pathloss is modelled, as usual, using distance dependent pathloss (power law), log normal shadowing, and a statistical model for fast fading (e.g., Rayleigh fading).
- Then, given the transmit power in the symbol x_j, the layer SNR can be obtained directly from the flat fading SISO equivalent model displayed above.
- It is assumed that the transmit power is equally split between all $Layers$ transmitted. At a high SNR, (iterative) water-filling will lead to nearly equal power allocation across all subcarriers and all layers [1].

- Downlink parallel transmission to multiple users is enabled by utilising multiple parallel resource blocks. Within each resource block, all MIMO layers are transmitted to the same UE.
- UEs receive no interference from other gNBs, and a gNB does not receive interference from UEs connected to any other gNB.
- Error free channel: This arises due to the practical fact that the adaptive MCS algorithm chooses the modulation order and coding scheme based on the SNR, in such a way that the data is decoded successfully at the receiver with a very high probability.
- The MAC scheduler will assign the subcarriers to the UEs. If required all available subcarriers can also be assigned to a single UE.
- The channel is flat across the bandwidth per user. Modeling frequency selective fading within each user has been avoided to reduce computation time; NetSim already chooses a different fading gain every coherence time. Hence a further averaging over frequency is not modelled. Note that scheduler does not allot RBs based on CQI feedback and hence modelling frequency selectivity is not necessary.

In summary, NetSim models the effect of eigen-beamforming in MIMO systems via the eigenvalues of the gram matrix formed using (random) channel instantiations. These eigenvalues are used to compute layer-wise SNRs and the corresponding CQI. The CQI values are used by a scheduler to fix the TBS parameters, and this in turn determines the throughput.

NetSim's power lies in its ability to incorporate the impact of link-level factors (such as beamforming) on the network-level performance with high precision and computational efficiency. This, in turn, allows the simulator to scale to 10s of gNBs and 100s of UEs, and yet return performance results in a short time.

3.9.4 PHY: Omitted Features

The currently omitted features include:

- BLER
  - NetSim currently assumes an error free channel. While received SNR is calculated NetSim currently does not further calculate the BLER based on the received SNR
- HARQ
- Physical control channels
  - While calculating the TBS capacity, a fixed overhead is reduced to account for the control channels. This overhead fraction varies for UL and DL, across FR1 and FR2, and is provided in the standard.
- Antenna modelling
- Random access procedure
- Reporting/receiving control information/
- Power control

- Inter gNB interference.

3.9.5 NR Frequency Bands

The definition of frequency ranges is per the table given below Table 3-2.

Frequency range designation	Corresponding frequency range
FR1	410 MHz – 7125 MHz
FR2	24250 MHz – 52600 MHz

Table 3-2: NR Frequency Bands Ranges

3.9.5.1 NR Band – FR 1

The FR1 bands (per 3GPP TS 38.101-1 V15.5.0 (2019-03)) implemented in NetSim are those that run.

TDD in Duplex mode, namely n34, n38, n39, n40, n41, n50, n51, n77, n78, n79, as shown below Table 3-3.

FDD in Duplex mode, namely n1, n3, n7, n8, n20, n25, n28, n66, n70, and n71 as shown below Table 3-3.

NR operating band	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
~~n2~~	~~1850 MHz – 1910 MHz~~	~~1930 MHz – 1990 MHz~~	~~FDD~~
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
~~n5~~	~~824 MHz – 849 MHz~~	~~869 MHz – 894 MHz~~	~~FDD~~
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
~~n12~~	~~699 MHz – 716 MHz~~	~~729 MHz – 746 MHz~~	~~FDD~~
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
~~n74~~	~~1427 MHz – 1470 MHz~~	~~1475 MHz – 1518 MHz~~	~~FDD~~
~~n75~~	~~N/A~~	~~1432 MHz – 1517 MHz~~	~~SDL~~
~~n76~~	~~N/A~~	~~1427 MHz – 1432 MHz~~	~~SDL~~
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
~~n80~~	~~1710 MHz – 1785 MHz~~	~~N/A~~	~~SUL~~
~~n81~~	~~880 MHz – 915 MHz~~	~~N/A~~	~~SUL~~

~~n82~~	~~832 MHz – 862 MHz~~	~~N/A~~	~~SUL~~
~~n83~~	~~703 MHz – 748 MHz~~	~~N/A~~	~~SUL~~
~~n84~~	~~1920 MHz – 1980 MHz~~	~~N/A~~	~~SUL~~
~~n86~~	~~1710 MHz – 1780 MHz~~	~~N/A~~	~~SUL~~

Table 3-3: NR operating bands in FR1 in NetSim

3.9.5.1.1 Maximum transmission bandwidth configuration

The maximum transmission bandwidth configuration N_{RB} for each UE channel bandwidth and subcarrier spacing is specified below Table 3-4.

SCS (kHz)	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	90 MHz	100 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
15	25	52	79	106	133	160	216	270	N/A	N/A	N/A	N/A
30	11	24	38	51	65	78	106	133	162	217	245	273
60	N/A	11	18	24	31	38	51	65	79	107	121	135

Table 3-4: Maximum transmission bandwidth configuration N_{RB}

3.9.5.1.2 Minimum guardband and transmission bandwidth configuration

The minimum guardband for each UE channel bandwidth and SCS is specified below Table 3-5.

SCS (kHz)	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	90 MHz	100 MHz
15	242.5	312.5	382.5	452.5	522.5	592.5	552.5	692.5	N/A	N/A	N/A	N/A
30	505	665	645	805	785	945	905	1045	825	925	885	845
60	N/A	1010	990	1330	1310	1290	1610	1570	1530	1450	1410	1370

Table 3-5: Minimum guardband for each UE channel bandwidth and SCS (kHz)

NOTE: The minimum guardbands have been calculated using the following equation: ($BW_{Channel}$ x 1000 (kHz) - N_{RB} x SCS x 12) / 2 - SCS/2, where N_{RB} are from Table 5.3.2-1.

3.9.5.2 NR Band – FR 2

The FR2 bands (per 3GPP TS 38.101-2 V15.5.0 (2019-03)) implemented in NetSim as shown below Table 3-6.

Operating Band	Uplink (UL) operating band BS receive UE transmit			Downlink (DL) operating band BS transmit UE receive			Duplex Mode
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}	
n257	26500 MHz	–	29500 MHz	26500 MHz	–	29500 MHz	TDD
n258	24250 MHz	–	27500 MHz	24250 MHz	–	27500 MHz	TDD
n260	37000 MHz	–	40000 MHz	37000 MHz	–	40000 MHz	TDD
n261	27500 MHz	–	28350 MHz	27500 MHz	–	28350 MHz	TDD

Table 3-6: NR operating bands in FR2 in NetSim

3.9.5.2.1 Maximum transmission bandwidth configuration

The maximum transmission bandwidth configuration N_{RB} for each UE channel bandwidth and subcarrier spacing is specified below.

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N/A

120	32	66	132	264

Standards Table 5.3.2-1: Maximum transmission bandwidth configuration N_{RB}

3.9.5.2.2 Minimum guardband and transmission bandwidth configuration

The minimum guardband for each UE channel bandwidth and SCS is specified below.

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz
60	1210	2450	4930	N/A
120	1900	2420	4900	9860

Standards Table 5.3.2-1: Minimum guardband for each UE channel bandwidth and SCS (kHz)

NOTE: The minimum guardbands have been calculated using the following equation: ($BW_{Channel}$ x 1000 (kHz) - N_{RB} x SCS x 12) / 2 - SCS/2, where N_{RB} are from Table 5.3.2-1.

The minimum guardband of receiving BS SCS 240 kHz SS/PBCH block for each UE channel bandwidth is specified below.

SCS (kHz)	100 MHz	200 MHz	400 MHz
240	3800	7720	15560

Standards Table 5.3.3-2: Minimum guardband (kHz) of SCS 240 kHz SS/PBCH block

NOTE: The minimum guardband in Table 5.3.3-2 is applicable only when the SCS 240 kHz SS/PBCH block is received adjacent to the edge of the UE channel bandwidth within which the SS/PBCH block is located.

3.9.6 UE channel bandwidth

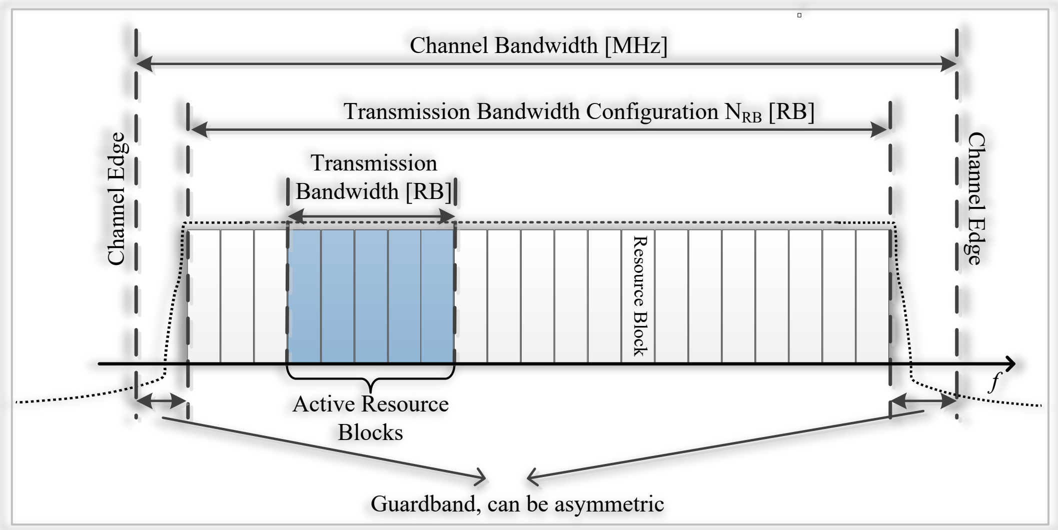
3.9.6.1 General

The UE channel bandwidth supports a single NR RF carrier in the uplink or downlink at the UE. From a BS perspective, different UE channel bandwidths may be supported within the same spectrum for transmitting to and receiving from UEs connected to the BS. Transmission of multiple carriers to the same UE (CA) or multiple carriers to different UEs within the BS channel bandwidth can be supported.

From a UE perspective, the UE is configured with one or more BWP / carriers, each with its own UE channel bandwidth. The UE does not need to be aware of the BS channel bandwidth or how the BS allocates bandwidth to different UEs.

The placement of the UE channel bandwidth for each UE carrier is flexible but can only be completely within the BS channel bandwidth.

The relationship between the channel bandwidth, the guardband and the maximum transmission bandwidth configuration is shown in **Figure 5.3.3-1.**



Standards Figure 5.3.3-1: Definition of the channel bandwidth and the maximum transmission bandwidth configuration for one NR channel

3.9.7 Frame structure and physical resources

3.9.7.1 General

Throughout this document, unless otherwise noted, the size of various fields in the time domain is expressed in time units $T_c = 1/(\Delta f_{max} \cdot N_f)$ where $\Delta f_{max} = 480 \cdot 10^3$ Hz and $N_f = 4096$ The constant $\kappa = T_s / T_c = 64$ where $T_s = 1/(\Delta f_{ref} \cdot N_{f,ref})$, $\Delta f_{ref} = 15 \cdot 10^3$ Hz and $N_{f,ref} = 2048$.

3.9.7.2 Numerologies

Multiple OFDM numerologies are supported as given by **Table 4.2-1** where μ and the cyclic prefix for a bandwidth part are obtained from the higher-layer parameter *subcarrierSpacing* and *cyclicPrefix*, respectively.

μ	$\Delta f = 2^{\mu} \cdot 15$ [kHz]	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

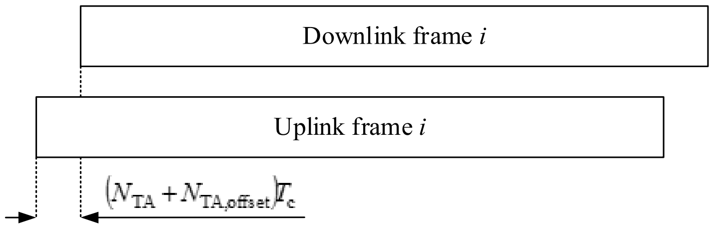
Standards Table 4.2-1: Supported transmission numerologies

3.9.7.3 Frames and subframes

Downlink and uplink transmissions are organized into frames with $T_f = (\Delta f_{max} N_f / 100) \cdot T_c = 10$ ms duration, each consisting of ten subframes of $T_{sf} = (\Delta f_{max} N_f / 1000) \cdot T_c = 1$ ms duration. The number of consecutive OFDM symbols per subframe is $N_{symb}^{subframe,\mu} = N_{symb}^{slot} N_{slot}^{subframe,\mu}$. Each frame is divided into two equally-sized half-frames of five subframes each with half-frame 0 consisting of subframes 0 – 4 and half-frame 1 consisting of subframes 5 – 9.

There is one set of frames in the uplink and one set of frames in the downlink on a carrier.

Uplink frame number i for transmission from the UE shall start $T_{\text{TA}} = (N_{\text{TA}} + N_{\text{TA,offset}})T_{\text{c}}$ before the start of the corresponding downlink frame at the UE where $N_{\text{TA,offset}}$ is given by [5, TS 38.213].



Standards Figure 4.3.1-1: Uplink-downlink timing relation

3.9.7.4 Slots

For subcarrier spacing configuration μ, slots are numbered $n_{\text{s}}^{\mu} \in \{0, \ldots, N_{\text{slot}}^{\text{subframe},\mu} - 1\}$ in increasing order within a subframe and $n_{\text{s,f}}^{\mu} \in \{0, \ldots, N_{\text{slot}}^{\text{frame},\mu} - 1\}$ in increasing order within a frame. There are $N_{\text{symb}}^{\text{slot}}$ consecutive OFDM symbols in a slot where $N_{\text{symb}}^{\text{slot}}$ depends on the cyclic prefix as given by **Tables 4.3.2-1** and **4.3.2-2**. The start of slot n_{s}^{μ} in a subframe is aligned in time with the start of OFDM symbol $n_{\text{s}}^{\mu} N_{\text{symb}}^{\text{slot}}$ in the same subframe.

OFDM symbols in a slot can be classified as 'downlink', 'flexible', or 'uplink'. Signaling of slot formats is described in subclause 11.1 of [5, TS 38.213].

In a slot in a downlink frame, the UE shall assume that downlink transmissions only occur in 'downlink' or 'flexible' symbols.

In a slot in an uplink frame, the UE shall only transmit in 'uplink' or 'flexible' symbols.

A UE not capable of full-duplex communication among a group of cells is not expected to transmit in the uplink in one cell within the group of cells earlier than $N_{\text{Rx-Tx}} T_{\text{c}}$ after the end of the last received downlink symbol in the same or different cell within the group of cells where $N_{\text{Rx-Tx}}$ is given by. **Table 4.3.2-3**

A UE not capable of full-duplex communication among a group of cells is not expected to receive in the downlink in one cell within the group of cells earlier than $N_{\text{Tx-Rx}} T_{\text{c}}$ after the end of the last transmitted uplink symbol in the same or different cell within the group of cells where $N_{\text{Tx-Rx}}$ is given by **Table 4.3.2-3**.

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

Standards Table 4.3.2-1: Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
2	12	40	4

Standards Table 4.3.2-2: Number of OFDM symbols per slot, slots per frame, and slots per subframe for extended cyclic prefix

Transition time	FR1	FR2
$N_{Tx\text{-}Rx}$	25600	13792
$N_{Rx\text{-}Tx}$	25600	13792

Standards Table 4.3.2-3: Transition time $N_{Rx\text{-}Tx}$ and $N_{Tx\text{-}Rx}$

3.9.8 Channel state information

Perfect CSIT and CSIR: The channel matrix H is assumed to be known perfectly and instantaneously at the transmitter and receiver, respectively. With perfect CSIT the transmitter can adapt its transmission rate (MCS) relative to the instantaneous channel state (SNR).

3.9.8.1 Channel quality indicator (CQI)

The CQI indices and their interpretations are given in **Table 5.2.2.1-2** or **Table 5.2.2.1-4** for reporting CQI based on QPSK, 16QAM and 64QAM. The CQI indices and their interpretations are given in **Table 5.2.2.1-3** for reporting CQI based on QPSK, 16QAM, 64QAM and 256QAM.

A CQI is computed for all the symbols in one TB, based on the SNR calculated on the data channels (DL and UL). The SNR calculation is done at the start of the simulation, then every UE measurement interval and at every instant a UE moves. In calculating SNR, the noise power is obtained from $N = k \times T \times B$. Based on the SNR, the Adaptive Modulation and Coding (AMC) functionality determines the values of Q, the modulation order, and R, the code rate, in the TBS formula. The SNR is computed on a per UE level for UL and DL.

The modulation order and code rate is based on the table chosen by the user. In the GUI users can select “table1” (corresponding to **Table 5.2.2.1-2)**, “table2” (corresponding to **Table 5.2.2.1-3**) or “table3” (corresponding to **Table 5.2.2.1-4**). Block error probability is currently not implemented in NetSim and hence is not used for deciding the table.

NetSim does not implement Sub-band Offset. The AMC determines a *wideband* CQI which indicates the highest rate Modulation and coding scheme (MCS), that it can reliably decode, if the entire system bandwidth were allocated to that user.

A combination of modulation scheme and transport block size corresponds to a CQI index if:

- the combination could be signaled for transmission on the PDSCH in the CSI reference resource according to the Transport Block Size determination described in Subclause 5.1.3.2, and
- the modulation scheme is indicated by the CQI index, and

- the combination of transport block size and modulation scheme when applied to the reference resource results in the effective channel code rate which is the closest possible to the code rate indicated by the CQI index. If more than one combination of transport block size and modulation scheme results in an effective channel code rate equally close to the code rate indicated by the CQI index, only the combination with the smallest of such transport block sizes is relevant.

CQI index	modulation	code rate x 1024	Efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Standards Table 5.2.2.1-2: 4-bit CQI Table 1

CQI	modulation	code rate x 1024	Efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	193	0.3770
3	QPSK	449	0.8770
4	16QAM	378	1.4766
5	16QAM	490	1.9141
6	16QAM	616	2.4063
7	64QAM	466	2.7305
8	64QAM	567	3.3223
9	64QAM	666	3.9023
10	64QAM	772	4.5234
11	64QAM	873	5.1152
12	256QAM	711	5.5547
13	256QAM	797	6.2266
14	256QAM	885	6.9141
15	256QAM	948	7.4063

Standards Table 5.2.2.1-3: 4-bit CQI Table 2

CQI index	modulation	code rate x 1024	Efficiency
0	out of range		
1	QPSK	30	0.0586
2	QPSK	50	0.0977
3	QPSK	78	0.1523
4	QPSK	120	0.2344
5	QPSK	193	0.3770
6	QPSK	308	0.6016
7	QPSK	449	0.8770
8	QPSK	602	1.1758
9	16QAM	378	1.4766
10	16QAM	490	1.9141
11	16QAM	616	2.4063
12	64QAM	466	2.7305
13	64QAM	567	3.3223
14	64QAM	666	3.9023
15	64QAM	772	4.5234

Standards Table 5.2.2.1-4: 4-bit CQI Table 3

3.9.9 Efficiency

In NetSim efficiency is calculated per the Shannon rate as

$$Efficiency = log_2(1 + \frac{E_b}{N_0})$$

Where $\frac{E_b}{N_0}$ is the ratio of the signal to noise in linear power scale, while SNR is the ratio in logarithmic decibel scale.

3.9.10 Modulation order, target code rate, and TBS determination

To determine the modulation order, target code rate, and transport block size(s) in the physical downlink shared channel, the UE shall first.

- determine the modulation order (Q_m) and target code rate (R) based on the procedure defined in Subclause 5.1.3.1, and

and second

- the UE shall use the number of layers (υ), the total number of allocated PRBs before rate matching (n_{PRB}) to determine to the transport block size based on the procedure defined in Subclause 5.1.3.2.

The UE is not expected to handle any transport blocks (TBs) in a 14 consecutive-symbol duration for normal CP (or 12 for extended CP) ending at the last symbol of the latest PDSCH transmission within an active BWP on a serving cell whenever

$$2^{\max(0,\mu-\mu')}.\sum_{i\in S}\left\lceil\frac{C_i'}{L_i}\right\rceil x_i.F_i > \left\lceil\frac{X}{4}\right\rceil.\frac{1}{R_{LBRM}}.TBS_{LBRM}$$

where, for the serving cell,

- S is the set of TBs belonging to PDSCH(s) that are partially or fully contained in the consecutive-symbol duration
- for the *i*th TB
- C_i' is the number of scheduled code blocks for as defined in [5, 38.212].
- L_i is the number of OFDM symbols assigned to the PDSCH
- x_i is the number of OFDM symbols of the PDSCH contained in the consecutive-symbol duration
- $F_i = \max_{j=0,\dots,J-1}(\min(k_{0,i}^j + E_i^j, N_{cb,i}))$ based on the values defined in Subclause 5.4.2.1 [5, TS 38.212]
- $k_{0,i}^j$ is the starting location of RV for the jth transmission
- $E_i^j = \min(E_r)$ of the scheduled code blocks for the jth transmission
- $N_{cb,i}$ is the circular buffer length

- $J-1$ is the current (re)transmission for the ith TB
- μ' corresponds to the subcarrier spacing of the BWP (across all configured BWPs of a carrier) that has the largest configured number of PRBs
- in case there is more than one BWP corresponding to the largest configured number of PRBs, μ' follows the BWP with the largest subcarrier spacing.
- μ corresponds to the subcarrier spacing of the active BWP
- R_{LBRM} = 2/3 as defined in Subclause 5.4.2.1 [5, TS 38.212]
- TBS_{LBRM} as defined in Subclause 5.4.2.1 [5, TS 38.212]
- X as defined for downlink in Subclause 5.4.2.1 [5, TS 38.212].

If the UE skips decoding, the physical layer indicates to higher layer that the transport block is not successfully decoded.

For a *j*-th serving cell, if higher layer parameter *processingType2Enabled* of *PDSCH-ServingCellConfig* is configured for the serving cell and set to *enable,* or if at least one $I_{MCS} > W$ for a PDSCH, where W = 28 for MCS **tables 5.1.3.1-1** and **5.1.3.1-3**, and W = 27 for MCS **table 5.1.3.1-2**, the UE is not required to handle PDSCH transmissions, if the following condition is not satisfied:

$$\frac{\sum_{m=0}^{M-1} V_{j,m}}{L \times T_s^{\mu}} \leq DataRateCC$$

where

- L is the number of symbols assigned to the PDSCH
- M is the number of TB(s) in the PDSCH
- $T_s^{\mu} = \frac{10^{-3}}{2^{\mu} \cdot N_{symb}^{slot}}$ where μ is the numerology of the PDSCH
- for the *m*-th TB, $V_{j,m} = C' \cdot \left\lfloor \frac{A}{C} \right\rfloor$
- *A* is the number of bits in the transport block as defined in Subclause 7.2.1 [5, TS 38.212]
- *C* is the total number of code blocks for the transport block defined in Subclause 5.2.2 [5, TS 38.212]
- C' is the number of scheduled code blocks for the transport block as defined in Subclause 5.4.2.1 [5, TS 38.212]
- $DataRateCC$ [Mbps] is computed by the approximate maximum data rate given by Subclause 4.1.2 in [13, TS 38.306] from the band/band combination signaling for the serving cell, including the scaling factor *f(i).*

3.9.10.1 Modulation order and target code rate determination

The user can select from the following MCS tables, for each gNB and associated UEs, from the GUI:

- QAM64 **Table 5.1.3.1-1**
- QAM256 **Table 5.1.3.1-2**
- QAM64LowSE **Table 5.1.3.1-3**

The UE and gNB then uses this table to determine the modulation order Q_m and Code Rate, R. Different tables can be chosen for DL (gNB to UE) and for UL (UE to gNB). The UL table index selection based on transform precoding selection in the GUI is given below.

Transform Precoding	MCS Table (PUSCH Config)	MCS Table Index
Enabled	QAM256	5.1.3.1 – 2
Enabled	QAM64LowSE	6.1.4.1 – 2
Enabled	QAM64	6.1.4.1 – 1
Disabled	QAM256	5.1.3.1 – 2
Disabled	QAM64LowSE	5.1.3.1 – 3
Disabled	QAM64	5.1.3.1 – 1

Figure 3-9: Uplink MCS Table index determination based on transform precoding and MCS table selection in GUI

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate *R* x [1024]	Spectral efficiency
0	2	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
6	2	449	0.8770
7	2	526	1.0273
8	2	602	1.1758
9	2	679	1.3262
10	4	340	1.3281
11	4	378	1.4766
12	4	434	1.6953
13	4	490	1.9141
14	4	553	2.1602
15	4	616	2.4063
16	4	658	2.5703
17	6	438	2.5664
18	6	466	2.7305
19	6	517	3.0293
20	6	567	3.3223
21	6	616	3.6094
22	6	666	3.9023
23	6	719	4.2129
24	6	772	4.5234
25	6	822	4.8164
26	6	873	5.1152
27	6	910	5.3320
28	6	948	5.5547
29	2	Reserved	
30	4	Reserved	
31	6	Reserved	

Standards Table 5.1.3.1-1: MCS index table 1 for PDSCH

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate *R* x [1024]	Spectral efficiency
0	2	120	0.2344
1	2	193	0.3770
2	2	308	0.6016
3	2	449	0.8770
4	2	602	1.1758
5	4	378	1.4766
6	4	434	1.6953
7	4	490	1.9141
8	4	553	2.1602
9	4	616	2.4063
10	4	658	2.5703
11	6	466	2.7305
12	6	517	3.0293
13	6	567	3.3223
14	6	616	3.6094
15	6	666	3.9023
16	6	719	4.2129
17	6	772	4.5234
18	6	822	4.8164
19	6	873	5.1152
20	8	682.5	5.3320
21	8	711	5.5547
22	8	754	5.8906
23	8	797	6.2266
24	8	841	6.5703
25	8	885	6.9141
26	8	916.5	7.1602
27	8	948	7.4063
28	2	Reserved	
29	4	Reserved	
30	6	Reserved	
31	8	Reserved	

Standards Table 5.1.3.1-2: MCS index table 2 for PDSCH

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate *R* x [1024]	Spectral efficiency
0	2	30	0.0586
1	2	40	0.0781
2	2	50	0.0977
3	2	64	0.1250
4	2	78	0.1523
5	2	99	0.1934
6	2	120	0.2344
7	2	157	0.3066
8	2	193	0.3770
9	2	251	0.4902
10	2	308	0.6016
11	2	379	0.7402
12	2	449	0.8770
13	2	526	1.0273
14	2	602	1.1758
15	4	340	1.3281
16	4	378	1.4766
17	4	434	1.6953
18	4	490	1.9141
19	4	553	2.1602
20	4	616	2.4063
21	6	438	2.5664
22	6	466	2.7305
23	6	517	3.0293
24	6	567	3.3223
25	6	616	3.6094

26	6	666	3.9023
27	6	719	4.2129
28	6	772	4.5234
29	2	Reserved	
30	4	Reserved	
31	6	Reserved	

Standards Table 5.1.3.1-3: MCS index table 3 for PDSCH

3.9.11 Transport block size (TBS) determination

The procedure for TBS determination is standardized in TS 38.214 Section 5.1.3.2 (DL) and 6.1.4.2 (UL). The standard specifies the TBS determination through Step 1, Step 2, Step 3, and Step 4, all which are implemented in NetSim.

NetSim first determines the TBS as specified below:

1) The UE shall first determine the number of REs (N_{RE}) $\mathrm{N_{RE}}$)within the slot.

- A UE first determines the number of REs allocated for PDSCH within a PRB (N'_{RE}) by $N'_{RE} = N_{sc}^{RB} \cdot N_{symb}^{sh} - N_{DMRS}^{PRB} - N_{oh}^{PRB}$, where $N_{sc}^{RB} = 12$ is the number of subcarriers in a physical resource block, N_{symb}^{sh} $\mathrm{N_{symb}^{slot}}$ is the number of symbols of the PDSCH allocation within the slot, N_{DMRS}^{PRB} $\mathrm{N_{DMRS}^{PRB}}$ is the number of REs for DM-RS per PRB in the scheduled duration and N_{oh}^{PRB} $\mathrm{N_{oh}^{PRB}}$is the overhead configured by higher layer parameter *and* N_{oh}^{PRB} is set to 0.

- A UE determines the total number of REs allocated for PDSCH (N_{RE})$\mathrm{N_{RE}}$) by $N_{RE} = \min(156, N'_{RE}) \cdot n_{PRB}$ $\mathrm{N_{RE}} = \mathrm{\bar{N}'_{RE}} * \mathrm{n_{PRB}}$, where n_{PRB} is the total number of allocated PRBs for the UE.

2) Intermediate number of information bits (N_{info}) $\mathrm{TBS_{temp}}$)is obtained by $N_{info} = N_{RE} \cdot R \cdot Q_m \cdot \upsilon$ $\mathrm{TBS_{temp}} = \mathrm{N_{RE}} * \mathrm{R} * \mathrm{Q_m} * \upsilon$.

3) When $N_{info} \leq 3824$, TBS is determined as follows

- quantized intermediate number of information bits $N'_{info} = \max\left(24, 2^n \cdot \left\lfloor \frac{N_{info}}{2^n} \right\rfloor\right)$, where $n = \max(3, \lfloor \log_2(N_{info}) \rfloor - 6)$.

- use **Table 5.1.3.2-1** find the closest TBS that is not less than N'_{info}.

Index	TBS	Index	TBS	Index	TBS	Index	TBS
1	24	31	336	61	1288	91	3624
2	32	32	352	62	1320	92	3752
3	40	33	368	63	1352	93	3824
4	48	34	384	64	1416		
5	56	35	408	65	1480		

6	64	36	432	66	1544		
7	72	37	456	67	1608		
8	80	38	480	68	1672		
9	88	39	504	69	1736		
10	96	40	528	70	1800		
11	104	41	552	71	1864		
12	112	42	576	72	1928		
13	120	43	608	73	2024		
14	128	44	640	74	2088		
15	136	45	672	75	2152		
16	144	46	704	76	2216		
17	152	47	736	77	2280		
18	160	48	768	78	2408		
19	168	49	808	79	2472		
20	176	50	848	80	2536		
21	184	51	888	81	2600		
22	192	52	928	82	2664		
23	208	53	984	83	2728		
24	224	54	1032	84	2792		
25	240	55	1064	85	2856		
26	256	56	1128	86	2976		
27	272	57	1160	87	3104		
28	288	58	1192	88	3240		
29	304	59	1224	89	3368		
30	320	60	1256	90	3496		

Standards Table: TBS for $N_{info} \le 3824$

4) When $N_{info} > 3824$, TBS is determined as follows.

- quantized intermediate number of information bits $N'_{info} = \max\left(3840, 2^n \times round\left(\frac{N_{info} - 24}{2^n}\right)\right)$, where $n = \lfloor \log_2(N_{info} - 24) \rfloor - 5$ and ties in the round function are broken towards the next largest integer.

- if $R \le 1/4$

$$TBS = 8 \cdot C \cdot \left\lceil \frac{N'_{info} + 24}{8 \cdot C} \right\rceil - 24 \text{, where } C = \left\lceil \frac{N'_{info} + 24}{3816} \right\rceil$$

else

if $N'_{info} > 8424$

$$TBS = 8 \cdot C \cdot \left\lceil \frac{N'_{info} + 24}{8 \cdot C} \right\rceil - 24 \text{, where } C = \left\lceil \frac{N'_{info} + 24}{8424} \right\rceil$$

Else

$$TBS = 8 \cdot \left\lceil \frac{N'_{info} + 24}{8} \right\rceil - 24$$

end if

end if

else if **Table 5.1.3.1-2** is used and $28 \le I_{MCS} \le 31$,

3.9.12 Out of coverage

As explained in the assumptions, NetSim does not model physical control channels or reference signals. All measurements are made on the physical data channels. The downlink received SNR is determined from large scale pathloss and shadowing calculated per the stochastic propagation models in the 3GPPTR38.900 standard, and fast fading calculated from the H matrix. This SNR calculation is done at the start of the simulation, and then at every instant a UE moves. It is a single wideband measurement at the center frequency. Interference from other gNBs is not considered in the SNR calculations.

Out of coverage in NetSim is based on the calculated spectral efficiency of the physical data channel. Spectral Efficiency is equal to $log_2\left(1 + \frac{E_b}{N_0}\right)$. A UE is out-of-coverage when this spectral efficiency falls below a threshold. This threshold is the value of the spectral efficiency of index 1 per 3GPP 38.214 Table 5.2.2.1.-2 for CQI Table 1, or 5.2.2.1.-3 for CQI Table 2, or 5.2.2.1.-4 for CQI Table 3.

The NetSim log would report CQI/MCS as 0 whenever this condition occurs. Note that the RRC connection is not released and NetSim does not currently model Radio Link Failures (RLF). If the UE's spectral efficiency, with the same serving gNB again crosses the threshold, data transmissions can occur. Due to mobility, if the UE's spectral efficiency from a different gNB, crosses threshold then handover procedure is initiated.

3.9.13 CA Configuration Table (based on TR 38 716 01-01 Rel 16 NR)

The Intraband CA configuration is based on TR 38716 01-01 Rel 16 NR. The interband CA configuration is based on 38 716 02-00 for 2 bands DL / x bands UL, and TR 38.716 03 01 for 3 bands DL and 1 band UL.

Carrier aggregation can be configured in the gNB's Physical layer properties. Following are the various configuration options that are available:

TDD Bands					
CA Configuration Table					
CA Configuration	**CA Count**	**CA Type**	**Frequency Range**	**Uplink Low (MHz)**	**Uplink High (MHz)**
INTER_BAND_CA					
CA_2DL_1UL_n39_n41	2	CA1, CA2	FR1	1880, 2496	1920, 2690

CA_2DL_2UL_n39_n41	2	CA1, CA2	FR1	1880, 2496	1920, 2690
CA_2DL_1UL_n41_n79	2	CA1, CA2	FR1	2496, 4400	2690, 5000
CA_2DL_2UL_n41_n79	2	CA1, CA2	FR1	2496, 4400	2690, 5000
CA_2DL_1UL_n40_n41	2	CA1, CA2	FR1	2300, 2496	2400, 2690
CA_2DL_2UL_n40_n41	2	CA1, CA2	FR1	2300, 2496	2400, 2690
CA_2DL_1UL_n50_n78	2	CA1, CA2	FR1	1432, 3300	1517, 3800
CA_2DL_2UL_n50_n78	2	CA1, CA2	FR1	1432, 3300	1517, 3800
CA_2DL_1UL_n41_n50	2	CA1, CA2	FR1	2496, 1432	2690, 1517
CA_2DL_2UL_n41_n50	2	CA1, CA2	FR1	2496, 1432	2690, 1517
CA_2DL_1UL_n39_n79	2	CA1, CA2	FR1	1880, 4400	1920, 5000
CA_2DL_2UL_n39_n79	2	CA1, CA2	FR1	1880, 4400	1920, 5000
CA_2DL_1UL_n40_n78	2	CA1, CA2	FR1	2300, 3300	2400, 3800
CA_2DL_2UL_n40_n78	2	CA1, CA2	FR1	2300, 3300	2400, 3800
CA_2DL_1UL_n40_n79	2	CA1, CA2	FR1	2300, 4400	2400, 5000
CA_2DL_2UL_n40_n79	2	CA1, CA2	FR1	2300, 4400	2400, 5000
CA_2DL_1UL_n77_n258	2	CA1, CA2	FR1, FR2	3300, 24250	4200, 27500
CA_2DL_2UL_n77_n258	2	CA1, CA2	FR1, FR2	3300, 24250	4200, 27500
CA_2DL_1UL_n78_n258	2	CA1, CA2	FR1, FR2	3300, 24250	3800, 27500
CA_2DL_2UL_n78_n258	2	CA1, CA2	FR1, FR2	3300, 24250	3800, 27500
CA_2DL_1UL_n79_n258	2	CA1, CA2	FR1, FR2	4400, 24250	5000, 27500
CA_2DL_2UL_n79_n258	2	CA1, CA2	FR1, FR2	4400, 24250	5000, 27500
CA_2DL_1UL_n78_n257	2	CA1, CA2	FR1, FR2	3300, 26500	3800, 29500
CA_2DL_2UL_n78_n257	2	CA1, CA2	FR1, FR2	3300, 26500	3800, 29500
CA_2DL_1UL_n41_n260	2	CA1, CA2	FR1, FR2	2496, 37000	2690, 40000
CA_2DL_2UL_n41_n260	2	CA1, CA2	FR1, FR2	2496, 37000	2690, 40000
INTRA_BAND_CONTIGOUOUS_CA					
CA_2DL_n41C_1UL_n41A	2	CA1, CA2	FR1	2496, 2496	2690, 2690
CA_2DL_n257G_2UL_n257G	2	CA1, CA2	FR2	26500, 26500	29500, 29500
CA_3DL_n257H_3UL_n257G	3	CA1, CA2, CA3	FR2	26500, 26500, 26500	29500, 29500, 29500
CA_3DL_n257H_3UL_n257H	3	CA1, CA2, CA3	FR2	26500, 26500, 26500	29500, 29500, 29500
CA_4DL_n257I_4UL_n257G	4	CA1, CA2, CA3, CA4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CA_4DL_n257I_4UL_n257H	4	CA1, CA2, CA3, CA4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CA_4DL_n257I_4UL_n257I	4	CA1, CA2, CA3, CA4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CA_5DL_n257J_5UL_n257G	5	CA1, CA2, CA3, CA4, CA5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CA_5DL_n257J_5UL_n257H	5	CA1, CA2, CA3, CA4, CA5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CA_5DL_n257J_5UL_n257I	5	CA1, CA2, CA3, CA4, CA5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500

CA_5DL_n257J_5UL_n257J	5	CA1, CA2, CA3, CA4, CA5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CA_6DL_n257K_6UL_n257G	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CA_6DL_n257K_6UL_n257H	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CA_6DL_n257K_6UL_n257I	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CA_6DL_n257K_6UL_n257J	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CA_6DL_n257K_6UL_n257K	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257G	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257H	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257I	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257J	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257K	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_7DL_n257L_7UL_n257L	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257G	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257H	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257I	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257J	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257K	8	CA1, CA2, CA3, CA4,	FR2	26500, 26500, 26500, 26500,	29500, 29500, 29500, 29500,

		CA5, CA6, CA7, CA8		26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257L	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_8DL_n257M_8UL_n257M	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CA_n258B	2	CA1, CA2	FR2	24250, 24250	27500, 27500
CA_n258C	3	CA1, CA2, CA3	FR2	24250, 24250, 24250	27500, 27500, 27500
CA_n258D	2	CA1, CA2	FR2	24250, 24250	27500, 27500
CA_n258E	3	CA1, CA2, CA3	FR2	24250, 24250, 24250	27500, 27500, 27500
CA_n258F	4	CA1, CA2, CA3, CA4	FR2	24250, 24250, 24250, 24250	27500, 27500, 27500, 27500
CA_n258G	2	CA1, CA2	FR2	24250, 24250	27500, 27500
CA_n258H	3	CA1, CA2, CA3	FR2	24250, 24250, 24250	27500, 27500, 27500
CA_n258I	4	CA1, CA2, CA3, CA4	FR2	24250, 24250, 24250, 24250	27500, 27500, 27500, 27500
CA_n258J	5	CA1, CA2, CA3, CA4, CA5	FR2	24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500
CA_n258K	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500, 27500
CA_n258L	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	24250, 24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500, 27500, 27500
CA_n258M	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	24250, 24250, 24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500
INTRA_BAND_NONCONTIGUOUS_CA					
CA_2DL_n41(2A)_1UL_n41A	2	CA1, CA2	FR1	2496, 2496	2690, 2690
CA_n260(5A)	5	CA1, CA2, CA3, CA4, CA5	FR2	37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000
CA_n260(6A)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CA_n260(7A)	7	CA1, CA2, CA3, CA4, CA5, CA6, CA7	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n260(8A)	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n260(2D)	4	CA1, CA2, CA3, CA4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000
CA_n260(2G)	4	CA1, CA2, CA3, CA4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000

CA_n260(3G)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CA_n260(4G)	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n260(2H)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CA_n260(2O)	4	CA1, CA2, CA3, CA4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000
CA_n260(3O)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CA_n260(4O)	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n260(2P)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CA_n260(4P)	12	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, CA10, CA11, CA12	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n260(2Q)	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CA_n261(2H)	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CA_n261(2I)	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CA_n261(2D)_n261A	4	CA1, CA2, CA3, CA4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CA_n261(2G)_n261A	4	CA1, CA2, CA3, CA4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CA_n261(3G)_n261A	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CA_n261(4G)_n261A	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CA_n261(2O)_n261A	4	CA1, CA2, CA3, CA4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CA_n261(4O)_n261A	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CA_n261(7O)_n261A	14	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8,	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500,	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350,

		CA9, CA10, CA11, CA12, CA13, CA14		27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CA_n261(2P)_n261A	6	CA1, CA2, CA3, CA4, CA5, CA6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CA_n261(2Q)_n261A	8	CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
SINGLE_BAND					
n34	1	CA1	FR1	2010	2025
n38	1	CA1	FR1	2570	2620
n39	1	CA1	FR1	1880	1920
n40	1	CA1	FR1	2300	2400
n41	1	CA1	FR1	2496	2690
n50	1	CA1	FR1	1432	1517
n51	1	CA1	FR1	1427	1432
n77	1	CA1	FR1	3300	4200
n78	1	CA1	FR1	3300	3800
n79	1	CA1	FR1	4400	5000
n257	1	CA1	FR2	26500	29500
n258	1	CA1	FR2	24250	27500
n260	1	CA1	FR2	37000	40000
n261	1	CA1	FR2	27500	28350
FDD Bands					
CA Configuration	**CA Count**	**CA Type**	**Frequency Range**	**F_Low (MHz)**	**F_High (MHz)**
INTER_BAND_CA					
CA_n1A_n8A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1920 880 2110 925	1980 915 2170 960
CA_n1A_n28A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1920 703 2110 758	1980 748 2170 803
CA_n3A_n8A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 880 1805 925	1785 915 1880 960
CA_n3A_n28A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 703 1805 758	1785 748 1880 803
CA_n7A_n28A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	2500 703 2620 758	2570 748 2690 803
CA_n7A_n66A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	2500 1710 2620 2110	2570 1780 2690 2200
CA_n20A_n28A	2	CA1_UL CA2_UL CA1_DL	FR1	832 703 791	862 748 821

		CA2_DL		758	803
CA_n25A_n71A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1850 663 1930 617	1915 698 1995 652
CA_n66A_n70A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 1695 2110 1995	1780 1710 2200 2020
CA_n66B_n70A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 1695 2110 1995	1780 1710 2200 2020
CA_n66(2A)_n71A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 663 2110 617	1780 698 2200 652
CA_n70A_n71A	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1695 663 1995 617	1710 698 2020 652
CA_n66A_n70A_n71A	3	CA1_UL CA2_UL CA3_UL CA1_DL CA2_DL CA3_DL	FR1	1710 1695 663 2110 1995 617	1780 1710 698 2200 2020 652
CA_n66B_n70A_n71A	3	CA1_UL CA2_UL CA3_UL CA1_DL CA2_DL CA3_DL	FR1	1710 1695 663 2110 1995 617	1780 1710 698 2200 2020 652
CA_n66(2A)_n70A_n71A	3	CA1_UL CA2_UL CA3_UL CA1_DL CA2_DL CA3_DL	FR1	1710 1695 663 2110 1995 617	1780 1710 698 2200 2020 652
INTRA_BAND_CONTIGUOUS_CA					
CA_n1B	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1920 1920 2110 2110	1980 1980 2170 2170
CA_n7B	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	2500 2500 2620 2620	2570 2570 2690 2690
CA_n66B	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 1710 2110 2110	1780 1780 2200 2200
CA_n71B	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	663 663 617 671	698 698 652 652
INTRA_BAND_NONCONTIGUOUS_CA					
CA_n3(2A)	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 1710 1805 1805	1782 1785 1880 1880

CA_n7(2A)	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	2500 2500 2620 2620	2570 2570 2690 2690
CA_n25(2A)	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1850 1850 1930 1930	1915 1915 1995 1995
CA_n66(2A)	2	CA1_UL CA2_UL CA1_DL CA2_DL	FR1	1710 1710 2110 2110	1780 1780 2200 2200

Table 3-7: CA Configuration Table

3.10 Supported max data rate

For NR, the approximate data rate for a given number of aggregated carriers in a band or band combination is computed as follows.

$$\text{data rate (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^{J} \left(v_{Layers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} \left(1 - OH^{(j)}\right) \right)$$

wherein

J is the number of aggregated component carriers in a band or band combination

R_{max} = 948/1024

For the j-th Component Carrier,

$v_{Layers}^{(j)}$ is the maximum number of supported layers given by higher layer parameter *maxNumberMIMO-LayersPDSCH* for downlink and maximum of higher layer parameters *maxNumberMIMO-LayersCB-PUSCH* and *maxNumberMIMO-LayersNonCB-PUSCH* for uplink.

$Q_m^{(j)}$ is the maximum supported modulation order given by higher layer parameter *supportedModulationOrderDL* for downlink and higher layer parameter *supportedModulationOrderUL* for uplink.

$f^{(j)}$ is the scaling factor given by higher layer parameter *scalingFactor* and can take the values 1, 0.8, 0.75, and 0.4

μ is the numerology (as defined in TS 38.211 [6])

T_s^{μ} is the average OFDM symbol duration in a subframe for numerology μ, i.e., $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$ Note that normal cyclic prefix is assumed, which has 14 ODFM symbols per slot or $14 \times 2^{\mu}$ symbols per millisecond.

$N_{PRB}^{BW(j),\mu}$ is the maximum Resource Block allocation in bandwidth $BW^{(j)}$ with numerology μ as defined in 5.3 TS 38.101-1 [2] and 5.3 TS 38.101-2 [3], where $BW^{(j)}$ is the UE supported maximum bandwidth in the given band or band combination. The number of subcarriers per physical resource block (PRB) is fixed to 12

$OH^{(j)}$ is the overhead and takes the following values.

0.14, for frequency range FR1 for DL

0.18, for frequency range FR2 for DL

0.08, for frequency range FR1 for UL

0.10, for frequency range FR2 for UL

NOTE: Only one of the UL or SUL carriers (the one with the higher data rate) is counted for a cell operating SUL.

The approximate maximum data rate can be computed as the maximum of the approximate data rates computed using the above formula for each of the supported band or band combinations.

For EUTRA in case of MR-DC, the approximate data rate for a given number of aggregated carriers in a band or band combination is computed as follows.

$$\text{Data rate (in Mbps)} = 10^{-3} * \sum_{j=1}^{J} \mathrm{TBS}_j$$

wherein

J is the number of aggregated EUTRA component carriers in MR-DC band combination.

TBS_j is the total maximum number of DL-SCH transport block bits received within a 1ms TTI for j-th CC, as derived from TS36.213 [22] based on the UE supported maximum MIMO layers for the j-th carrier and based on the modulation order and number of PRBs based on the bandwidth of the j-th carrier.

The approximate maximum data rate can be computed as the maximum of the approximate data rates computed using the above formula for each of the supported band or band combinations.

For MR-DC, the approximate maximum data rate is computed as the sum of the approximate maximum data rates from NR and EUTRA.

3.11 mmWave Propagation Models (Per 3GPPTR38.900 Channel Model)

3.11.1 Pathloss

In NetSim the pathloss calculations are done:

- Every UE measurement report between each gNB and its associated UEs
- Every time a UE moves, between that UE and all gNBs in the network.

The pathloss models are summarized in **Table 7.4.1-1** and the distance definitions are indicated in **Figure 7.4.1-1** and **Figure 7.4.1-2**. Note that the distribution of the shadow fading is log-normal, and its standard deviation for each scenario is given in **Table 7.4.1-1**.

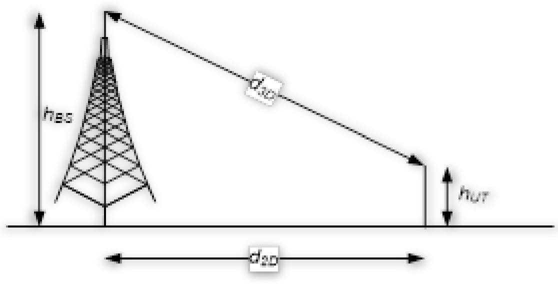


Figure7.4.1-1: Definition of d_{2D} and d_{3D} for outdoor UTs

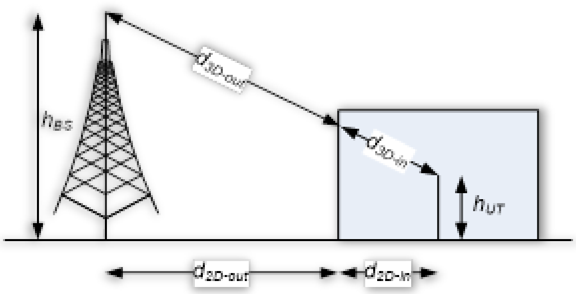


Figure 7.4.1-2: Definition of d_{2D-out}, d_{2D-in} and d_{3D-out}, d_{3D-in} for indoor UTs

Note that

$$d_{3D-out} + d_{3D-in} = \sqrt{(d_{2D-out} + d_{2D-in})^2 + (h_{BS} - h_{UT})^2} \qquad (7.4\text{-}1)$$

Table 7.4.1-1: Pathloss model				
Scenario	**LOS/NLOS**	**Pathloss [dB], f_c is in GHz and d is in meters, see note 6**	**Shadow fading std [dB]**	**Applicability range, antenna height default values**
RMa	LOS	$PL_{\text{RMa-LOS}} = \begin{cases} PL_1 & 10m \le d_{2D} \le d_{BP} \\ PL_2 & d_{BP} \le d_{2D} \le 10\text{km} \end{cases}$, see note 5 $PL_1 = 20\,log_{10}(40\pi d_{3D} f_c/3) + min(0.03h^{1.72}, 10)\,log_{10}(d_{3D}) - min(0.044h^{1.72}, 14.77) + 0.002\,log_{10}(h) d_{3D}$ $PL_2 = PL_1(d_{BP}) + 40\,log_{10}(d_{3D}/d_{BP})$	$\sigma_{SF} = 4$ $\sigma_{SF} = 6$	$h_{BS} = 35\text{m}$ $h_{UT} = 1.5m$ $W = 20m$ $h = 5m$ h = avg. building height W = avg. street width The applicability ranges: $5m \le h \le 50m$ $5m \le W \le 50m$ $10\text{m} \le h_{BS} \le 150m$ $1m \le h_{UT} \le 10m$
	NLOS	$PL_{\text{RMa-NLOS}} = max(PL_{\text{RMa-LOS}}, PL'_{\text{RMa-NLOS}})$ for $10m \le d_{2D} \le 5\text{km}$ $PL'_{\text{RMa-NLOS}} = 161.04 - 7.1\,log_{10}(W) + 7.5\,log_{10}(h) - (24.37 - 3.7(h/h_{BS})^2)\,log_{10}(h_{BS}) + (43.42 - 3.1\,log_{10}(h_{BS}))(log_{10}(d_{3D}) - 3) + 20\,log_{10}(f_c) - (3.2(log_{10}(11.75 h_{UT}))^2 - 4.97)$	$\sigma_{SF} = 8$	
UMa	LOS	$PL_{\text{UMa-LOS}} = \begin{cases} PL_1 & 10m \le d_{2D} \le d'_{BP} \\ PL_2 & d'_{BP} \le d_{2D} \le 5\text{km} \end{cases}$, see note 1 $PL_1 = 28.0 + 22\,log_{10}(d_{3D}) + 20\,log_{10}(f_c)$ $PL_2 = 28.0 + 40\,log_{10}(d_{3D}) + 20\,log_{10}(f_c) - 9\,log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2)$	$\sigma_{SF} = 4$	$1.5m \le h_{UT} \le 22.5m$ $h_{BS} = 25\text{m}$
	NLOS	$PL_{\text{UMa-NLOS}} = max(PL_{\text{UMa-LOS}}, PL'_{\text{UMa-NLOS}})$ for $10m \le d_{2D} \le 5\text{km}$ $PL'_{\text{UMa-NLOS}} = 13.54 + 39.08\log_{10}(d_{3D}) + 20\log_{10}(f_c) - 0.6(h_{UT} - 1.5)$	$\sigma_{SF} = 6$	$1.5m \le h_{UT} \le 22.5m$ $h_{BS} = 25m$ Explanations: see note 3
		Optional $\text{PL} = 32.4 + 20\,log_{10}(f_c) + 30\,log_{10}(d_{3D})$	$\sigma_{SF} = 7.8$	
UMi - Street Canyon	LOS	$PL_{\text{UMi-LOS}} = \begin{cases} PL_1 & 10m \le d_{2D} \le d'_{BP} \\ PL_2 & d'_{BP} \le d_{2D} \le 5\text{km} \end{cases}$, see note 1 $PL_1 = 32.4 + 21\,log_{10}(d_{3D}) + 20\,log_{10}(f_c)$ $PL_2 = 32.4 + 40\,log_{10}(d_{3D}) + 20\,log_{10}(f_c) - 9.5\,log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2)$	$\sigma_{SF} = 4$	$1.5m \le h_{UT} \le 22.5m$ $h_{BS} = 10m$
	NLOS	$PL_{\text{UMi-NLOS}} = max(PL_{\text{UMi-LOS}}, PL'_{\text{UMi-NLOS}})$ for $10m \le d_{2D} \le 5\text{km}$ $PL'_{\text{UMi-NLOS}} = 35.3\log_{10}(d_{3D}) + 22.4 + 21.3\log_{10}(f_c) - 0.3(h_{UT} - 1.5)$	$\sigma_{SF} = 7.82$	$1.5m \le h_{UT} \le 22.5m$ $h_{BS} = 10m$ Explanations: see note 4

		Optional $PL = 32.4 + 20\,log_{10}(f_c) + 31.9\,log_{10}(d_{3D})$	$\sigma_{SF} = 8.2$	
InH - Office	LOS	$PL_{InH-LOS} = 32.4 + 17.3\,log_{10}(d_{3D}) + 20\,log_{10}(f_c)$	$\sigma_{SF} = 3$	$1m \le d_{3D} \le 150m$
	NLOS	$PL_{InH-NLOS} = max(PL_{InH-LOS}, PL'_{InH-NLOS})$ $PL'_{InH-NLOS} = 38.3\,log_{10}(d_{3D}) + 17.30 + 24.9\,log_{10}(f_c)$	$\sigma_{SF} = 8.03$	$1m \le d_{3D} \le 150m$
		Optional $PL'_{InH-NLOS} = 32.4 + 20\,log_{10}(f_c) + 31.9\,log_{10}(d_{3D})$	$\sigma_{SF} = 8.29$	$1m \le d_{3D} \le 150m$

Note 1: Breakpoint distance $d'_{BP} = 4\, h'_{BS}\, h'_{UT}\, f_c/c$, where f_c is the centre frequency in Hz, $c = 3.0\times10^8$ m/s is the propagation velocity in free space, and h'_{BS} and h'_{UT} are the effective antenna heights at the BS and the UT, respectively. The effective antenna heights h'_{BS} and h'_{UT} are computed as follows: $h'_{BS} = h_{BS} - h_E$, $h'_{UT} = h_{UT} - h_E$, where h_{BS} and h_{UT} are the actual antenna heights, and h_E is the effective environment height. For UMi h_E = 1.0m. For UMa h_E=1m with a probability equal to $1/(1+C(d_{2D}, h_{UT}))$ and chosen from a discrete uniform distribution uniform(12,15,…,(h_{UT}-1.5)) otherwise. With $C(d_{2D}, h_{UT})$ given by

$$\boldsymbol{C(d_{2D}, h_{UT})} = \begin{cases} \boldsymbol{0} & \boldsymbol{, h_{UT} < 13m} \\ \boldsymbol{\left(\frac{h_{UT}-13}{10}\right)^{1.5} g(d_{2D})} & \boldsymbol{, 13m \le h_{UT} \le 23m} \end{cases},$$

where

$$\boldsymbol{g(d_{2D})} = \begin{cases} \boldsymbol{0} & \boldsymbol{, d_{2D} \le 18m} \\ \boldsymbol{\frac{5}{4}\left(\frac{d_{2D}}{100}\right)^{3} exp\left(\frac{-d_{2D}}{150}\right)} & \boldsymbol{, 18m < d_{2D}} \end{cases}.$$

Note that h_E depends on d_{2D} and h_{UT} and thus needs to be independently determined for every link between BS sites and UTs. A BS site may be a single BS or multiple co-located BSs.

Note 2: The applicable frequency range of the PL formula in this table is $0.5 < f_c < f_H$ GHz, where f_H = 30 GHz for RMa and f_H = 100 GHz for all the other scenarios. It is noted that RMa pathloss model for >7 GHz is validated based on a single measurement campaign conducted at 24 GHz.

Note 3: UMa NLOS pathloss is from TR36.873 with simplified format and $PL_{UMa-LOS}$ = Pathloss of UMa LOS outdoor scenario.

Note 4: $PL_{UMi-LOS}$ = Pathloss of UMi-Street Canyon LOS outdoor scenario.

Note 5: Break point distance $d_{BP} = 2\pi\, h_{BS}\, h_{UT}\, f_c/c$, where f_c is the centre frequency in Hz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h_{BS} and h_{UT} are the antenna heights at the BS and the UT, respectively.

Note 6: f_c denotes the center frequency normalized by 1GHz, all distance related values are normalized by 1m, unless it is stated otherwise.

3.11.2 LOS probability

The Line-Of-Sight (LOS) probabilities are given in **Table 7.4.2-1**.

Scenario	LOS probability (distance is in meters)
RMa	$Pr_{\text{LOS}} = \begin{cases} 1 & , d_{\text{2D-out}} \leq 10m \\ exp\left(-\frac{d_{\text{2D-out}} - 10}{1000}\right) & , 10m < d_{\text{2D-out}} \end{cases}$
UMi - Street canyon	$Pr_{\text{LOS}} = \begin{cases} 1 & , d_{\text{2D-out}} \leq 18m \\ \frac{18}{d_{\text{2D-out}}} + exp\left(-\frac{d_{\text{2D-out}}}{36}\right)\left(1 - \frac{18}{d_{\text{2D-out}}}\right) & , 18m < d_{\text{2D-out}} \end{cases}$
Uma	$Pr_{\text{LOS}} = \begin{cases} 1 \\ \left[\frac{18}{d_{\text{2D-out}}} + exp\left(-\frac{d_{\text{2D-out}}}{63}\right)\left(1 - \frac{18}{d_{\text{2D-out}}}\right)\right]\left(1 + C'(h_{\text{UT}})\frac{5}{4}\left(\frac{d_{\text{2D-out}}}{100}\right)^3 exp\left(-\frac{d_{\text{2D-out}}}{150}\right)\right) \end{cases}$ where $C'(h_{\text{UT}}) = \begin{cases} 0 & , h_{\text{UT}} \leq 13m \\ \left(\frac{h_{\text{UT}} - 13}{10}\right)^{1.5} & , 13m < h_{\text{UT}} \leq 23m \end{cases}$
Indoor - Mixed office	$Pr_{\text{LOS}} = \begin{cases} 1 & , d_{\text{2D-in}} \leq 1.2m \\ exp\left(-\frac{d_{\text{2D-in}} - 1.2}{4.7}\right) & , 1.2m < d_{\text{2D-in}} < 6.5m \\ exp\left(-\frac{d_{\text{2D-in}} - 6.5}{32.6}\right) \cdot 0.32 & , 6.5m \leq d_{\text{2D-in}} \end{cases}$
Indoor - Open office	$Pr_{\text{LOS}} = \begin{cases} 1 & , d_{\text{2D-in}} \leq 5m \\ exp\left(-\frac{d_{\text{2D-in}} - 5}{70.8}\right) & , 5m < d_{\text{2D-in}} \leq 49m \\ exp\left(-\frac{d_{\text{2D-in}} - 49}{211.7}\right) \cdot 0.54 & , 49m < d_{\text{2D-in}} \end{cases}$
Note:	The LOS probability is derived with assuming antenna heights of 3m for indoor, 10m for UMi, and 25m for Uma

Standards Table 7.4.2-1: LOS probability

3.11.3 O2I penetration loss

3.11.3.1 O2I building penetration loss

The pathloss incorporating O2I building penetration loss is modelled as in the following:

$$\text{PL} = \text{PL}_b + \text{PL}_{\text{tw}} + \text{PL}_{\text{in}} + N(0, \sigma_P^2) \qquad (7.4\text{-}2)$$

where PL_b is the basic outdoor path loss given in Subclause 7.4.1, where $d_{3\text{D}}$ is replaced by $d_{3\text{D-out}} + d_{3\text{D-in}}$. PL_{tw} is the building penetration loss through the external wall, PL_{in} is the inside loss dependent on the depth into the building, and σ_P is the standard deviation for the penetration loss.

PL_{tw} is characterized as:

$$\mathrm{PL}_{tw} = \mathrm{PL}_{npi} - 10\,log_{10} \sum_{i=1}^{N} \left(p_i \times 10^{\frac{L_{material\_i}}{-10}} \right) \qquad (7.4\text{-}3)$$

PL_{npi} is an additional loss is added to the external wall loss to account for non-perpendicular incidence; $L_{material\_i} = a_{material\_i} + b_{material\_i} \cdot f$, is the penetration loss of material *i*, example values of which can be found in **Table 7.4.3-1**; p_i is proportion of *i*-th materials, where $\sum_{i=1}^{N} p_i = 1$; and *N* is the number of materials.

Material	Penetration loss [dB]
Standard multi-pane glass	$L_{\mathrm{glass}} = 2 + 0.2f$
IRR glass	$L_{\mathrm{IIRglass}} = 23 + 0.3f$
Concrete	$L_{\mathrm{concrete}} = 5 + 4f$
Wood	$L_{\mathrm{wood}} = 4.85 + 0.12f$
Note: f is in GHz	

Standards Table 7.4.3-1: Material penetration losses

Table 7.4.3-2 gives $\mathrm{PL}_{\mathrm{tw}}$, $\mathrm{PL}_{\mathrm{in}}$ and σ_P for two O2I penetration loss models. The O2I penetration is UT-specifically generated and is added to the SF realization in the log domain.

	Path loss through external wall: $\mathrm{PL}_{\mathrm{tw}}$ in [dB]	Indoor loss: $\mathrm{PL}_{\mathrm{in}}$ in [dB]	Standard deviation: σ_P in [dB]
Low-loss model	$5 - 10\,log_{10}\left(0.3 \cdot 10^{\frac{-L_{\mathrm{glass}}}{10}} + 0.7 \cdot 10^{\frac{-L_{\mathrm{concrete}}}{10}}\right)$	0.5 $d_{\mathrm{2D-in}}$	4.4
High-loss model	$5 - 10\,log_{10}\left(0.7 \cdot 10^{\frac{-L_{\mathrm{IIRglass}}}{10}} + 0.3 \cdot 10^{\frac{-L_{\mathrm{concrete}}}{10}}\right)$	0.5 $d_{\mathrm{2D-in}}$	6.5

Standards Table 7.4.3-2: O2I building penetration loss model

$d_{\mathrm{2D-in}}$ is minimum of two independently generated uniformly distributed variables between 0 and 25 m for UMa and UMi-Street Canyon, and between 0 and 10 m for RMa. $d_{\mathrm{2D-in}}$ shall be UT-specifically generated.

Both low-loss and high-loss models are applicable to UMa and UMi-Street Canyon.

Only the low-loss model is applicable to RMa.

3.11.3.2 O2I model usage

The O2I Models such as Low Loss and High Loss are associated with the type of material used in the buildings and is used to calculate the penetration loss in case of an indoor scenario. In case of scenario where UE's are not inside a building these parameters will not have any impact on the results. In an indoor scenario, users will be able to notice difference in the SNR.

3.12 Additional Loss Model

Apart from the channel losses per the 3GPPTR38.900 specifications, NetSim allows modelling additional losses using MATLAB. This includes attenuation due to rain, fog, and gas.

Note that this implementation interfaces with MATLAB R2020(a/b). Lower versions of MATLAB are not directly supported.

The following is required to run these models:

- An installed version of MATLAB R2020(a/b) in the same system where NetSim is installed or in a different system in the same network.
- Registration of MATLAB as a COM server. Reference: https://in.mathworks.com/help/releases/R2020a/matlab/ref/comserver.html?s_tid=doc_ta

3.12.1 Configuration

Additional Loss Model can be configured in the gNB's 5G_RAN interface properties under channel models section of Physical Layer as shown below:

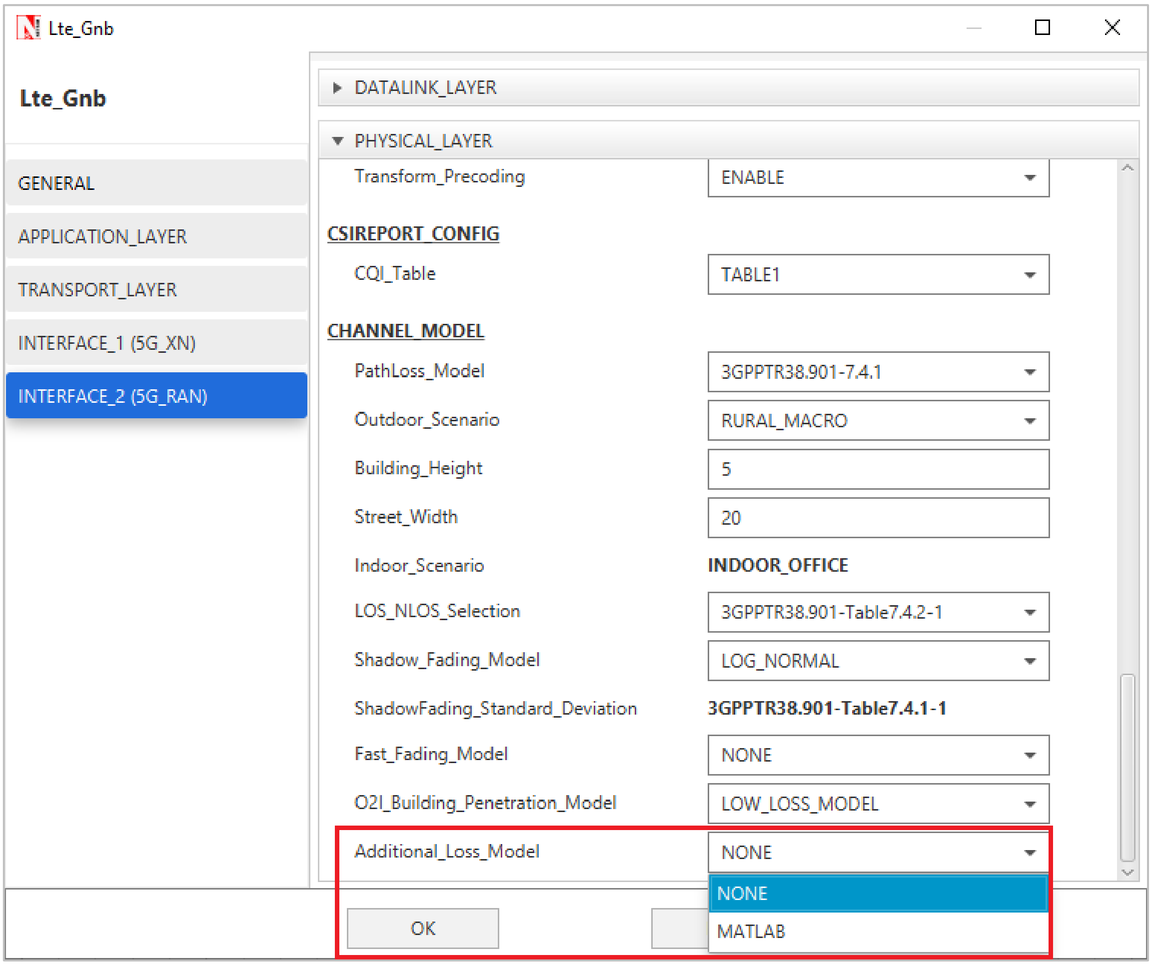


Figure 3-10: gNB >Interface (5G_RAN) >Physical layer properties

Similarly, this can be configured in the eNB's LTE interface properties under channel models section of Physical Layer as shown below:

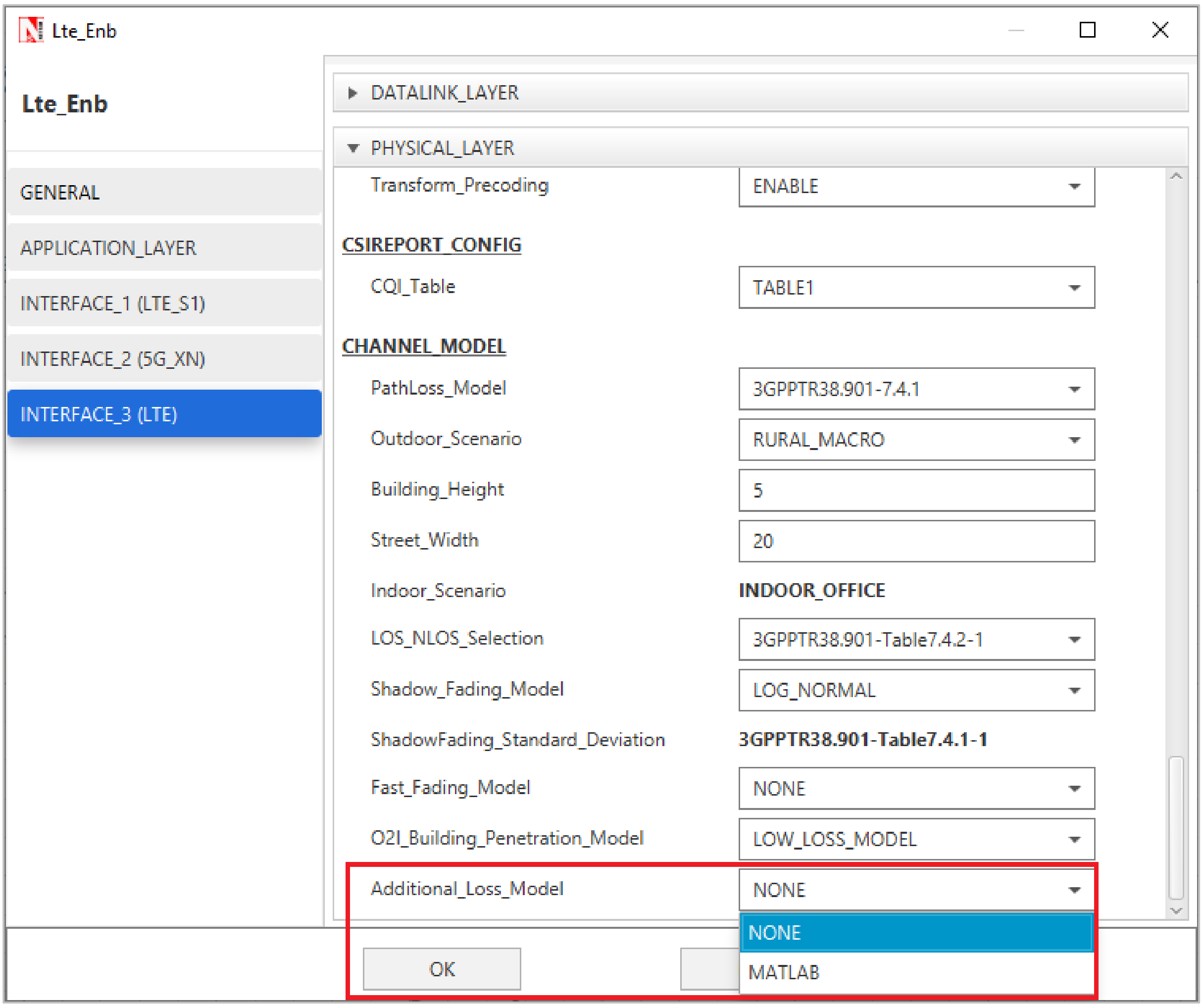


Figure 3-11: eNB >Interface (LTE) >Physical layer properties

Additional Loss Model is set to NONE by default. When MATLAB is selected, MATLAB MODEL drop down with options GAS, FOG, and RAIN will appear along with associated parameters as shown below:

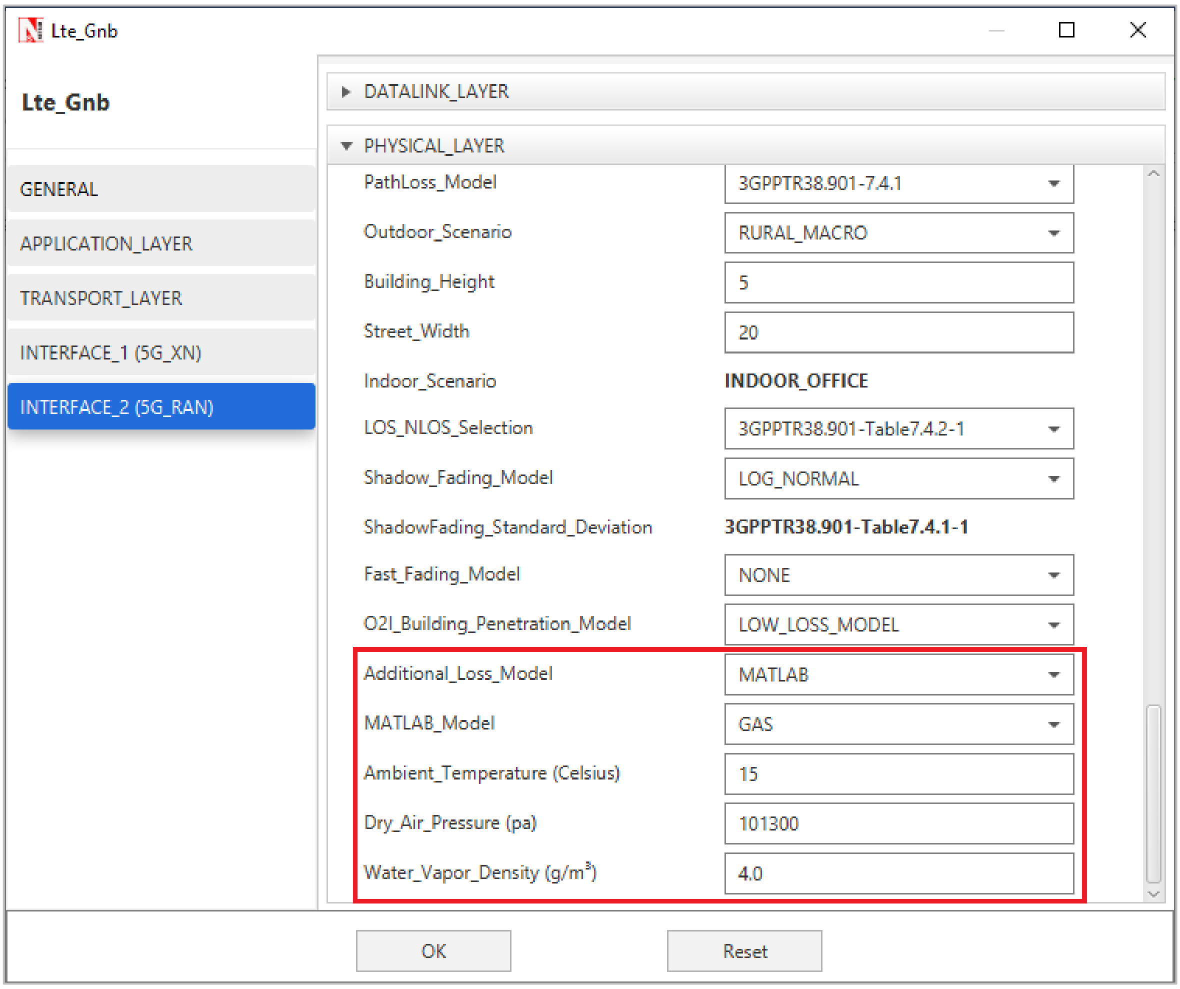


Figure 3-12: Additional Loss Model set to MATLAB in gNB >Interface (5G_RAN) >Physical layer properties

Each model has associated parameters that can be configured, which is listed in the table below:

Additional Loss Model	Associated Parameters	Value
RAIN	Rain Rate (mm/hr)	16(default), Range 0 to 100
	Tilt Angle	0(default), Range -90 to 90
	Elevation Angle	0(default), Range -90 to 90
	Exceedance Rain (%)	0.01(default), Range 0.001 to 1
GAS	Ambient Temperature (Celsius)	15(default), Range -50 to 50
	Dry Air Pressure (pa)	101300(default), Range 50000 to 300000
	Water Vapor Density (g/m^3)	4(default), Range 1 to 10
FOG	Ambient Temperature (Celsius)	15(default), Range -50 to 50
	Liquid Water Density ((g/m^3)	0.5(default), Range 0 to 5

Table 3-8: Parameters in the various MATLAB additional loss models

Note: Rain and Gas models support frequencies from 1 to 1000 GHz and Fog model supports frequencies from 10 to 1000 GHz only.

3.12.2 Running Simulation

When Additional Loss Model option is set to MATLAB NetSim Simulation console waits for MATLAB Interface process to connect.

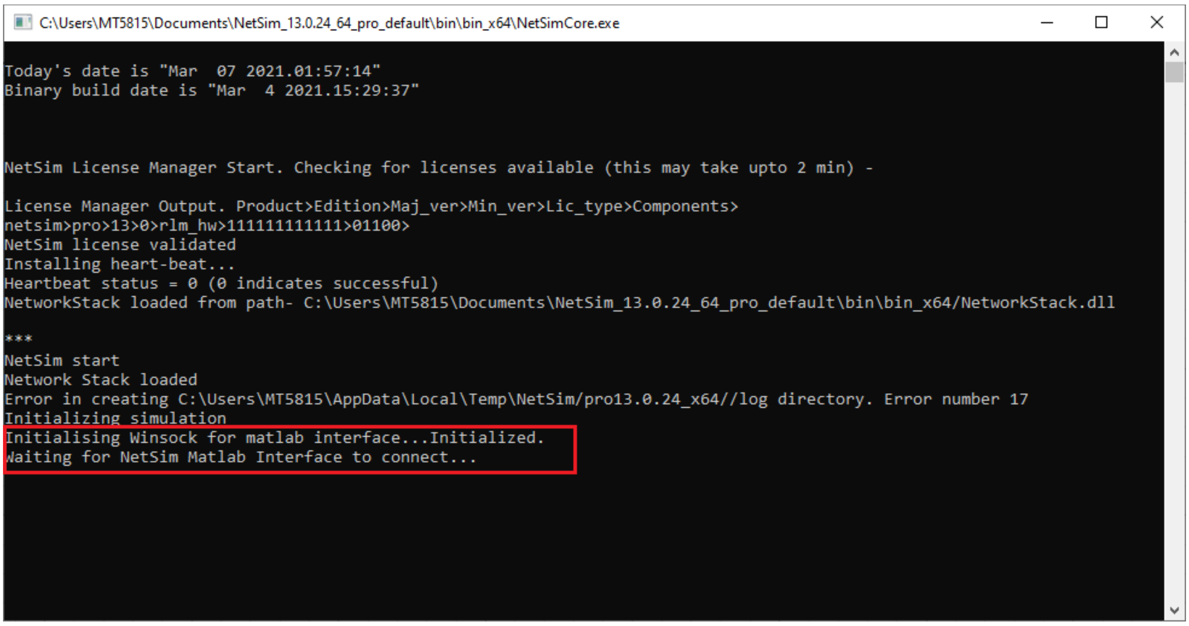
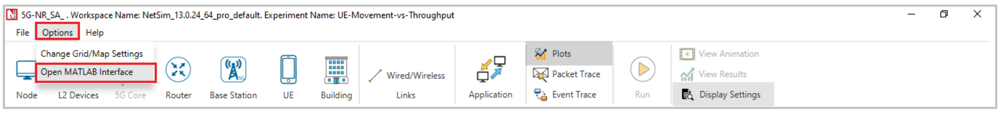


Figure 3-13: NetSim Simulation console waits for MATLAB Interface process to connect

MATLAB Interface process can be started and connected to the running instance of NetSim simulation using one of the following methods depending on where MATLAB is installed:

- If MATLAB is installed in the same system where NetSim is installed. MATLAB Interface process can be launched directly from the design window of NetSim.
  - Go to Options Menu and select the Open MATLAB Interface option as shown below:



  - Click on the OK button when the following message is displayed.

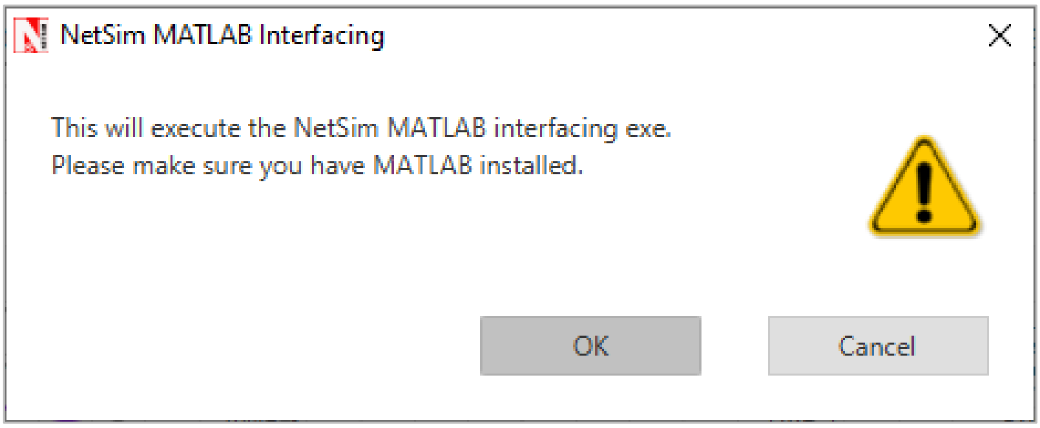


Figure 3-14: MATLAB Interface warning message

- If MATLAB is installed in a different system in the same network, then MATLABInterface.exe (present in <NetSim_Install_Directory>/bin folder), can be started in that system, manually from command prompt and the IP address of the system where NetSim simulation has started can be passed as an argument as shown below:

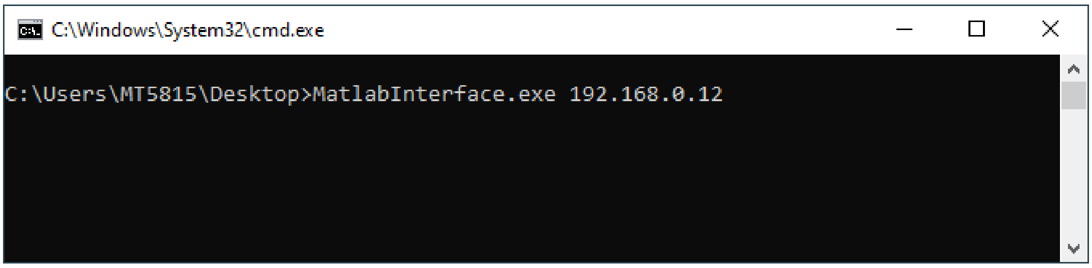


Figure 3-15: MATLAB interface over an IP address

In both above cases, the MATLAB Interface process starts MATLAB process (MATLAB command window will open in minimized state) after which simulation in NetSim will start. During the simulation communication between NetSim and MATLAB is established to send inputs from NetSim to MATLAB pathloss models and to receive pathloss from MATLAB to NetSim happens via the MATLAB Interface process as shown below:

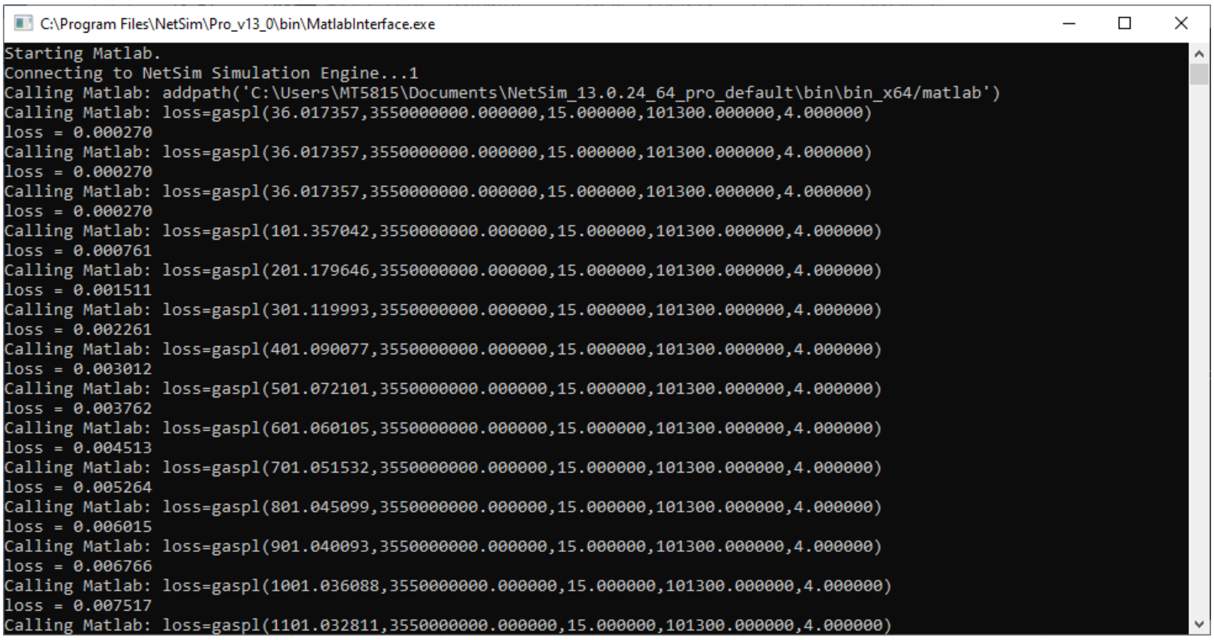


Figure 3-16: Runtime MATLAB interfacing window

The pathloss value obtained from MATLAB is added to the total loss calculated as per the 3GPPTR38.900 specifications. At simulation end the MATLAB Interface process closes the MATLAB process that it started.

3.13 5G Core

NetSim 5G core functionality was introduced in NetSim v13.

This 5G core includes entities, which reside within the core devices (and partially within the gNB) such as Session Management Function (SMF), Access and Mobility Management Function (AMF) and User Plane Function (UPF) and the protocols these entities use for operation.

The NetSim 5G core model provides users the means to simulate the end-to-end IP connectivity. It supports interconnection of multiple UEs to the Internet/Cloud via the Radio Access Network or RAN. The RAN consists of multiple gNBs. These gNBs connect to the 5G core in the backhaul. In NetSim, the 5G core comprises of a single AMF, SMF and UPF.

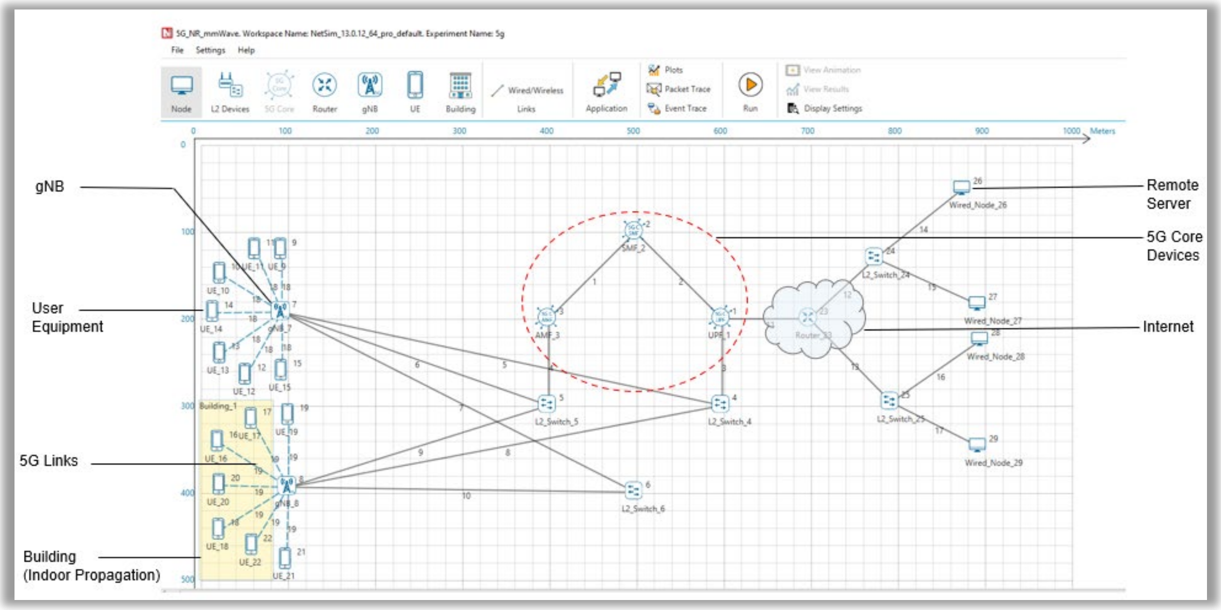


Figure 3-17: 5G Network scenario consisting of multiple UEs and gNBs connected to 5G Core - AMF, SMF and UP. The UPF is connects out to the Data Network/ Internet.

NetSim 5G Core model has been designed as follows:

1. The Packet type supported in NetSim 5G Core is IPv4.
2. A single set of SMF/UPF/AMF entities are only available. Scenarios with inter SMF mobility / inter AMF mobility are not supported in NetSim.
3. It is possible for a single UE to use different applications with different QoS models. Hence, multiple EPS Bearers are supported for each UE. This includes necessary classification of TCP/UDP traffic over IP done at the UE in the Uplink and at the UPF in the downlink.
4. The NetSim 5G model allows users to perform an XN based handover between two gNBs.

In the 5G standalone architecture, the roles played by each of the entities are different.

1. A UE has the following interactions:
   a. The random-access procedure to initiate communication with the gNB.
   b. Setup the RRC connection with the gNB.
   c. Perform NAS level authentication.

   d. Handle the RRC Reconfiguration from the gNB and this message sets up the default PDU session.
   e. The UE concludes the registration procedure.
   f. Data flow takes place in both the downlink and uplink directions.
2. The gNB acts as a bridge between the UE and the 5G Core. The gNB:
   a. Handles the random-access request from the UE and assign resources for initiating the RRC connection.
   b. Sets up the RRC connection with the UE. SRB1 is set up at this point. Starting at this point the gNB starts assigning downlink and uplink resources to the UE.
   c. Transports the Registration Request from the UE to the AMF.
   d. Carries the NAS signalling between the UE and the gNB.
   e. The 5G Core initiates the default PDU session setup. A Registration Accept is also received from the UE.
   f. Activates the default PDU session via the RRC Reconfiguration message. It also transports the Registration Complete message to the AMF.
   g. The downlink and uplink data flow takes place between the UE and the Internet.
3. The AMF or Access Mobility Function coordinates the 5G Standalone registration procedure.
   a. Handles the Initial UE Message from the gNB. This message carries the Registration Request from the UE.
   b. On receiving the Registration Request, the AMF obtains the UE context.
   c. AMF updates the SMF context and sends an Initial Context Setup Request to activate the default PDU session. The message also carries the Registration Accept message from the AMF.
   d. When the gNB signals that the Initial Context setup has been completed, the AMF updates the SMF context.
   e. The AMF also notifies the SMF when the session is ready for uplink and downlink data transfer.
   f. All messages related to session management are forwarded over the N11 reference interface to the Session Management Function (SMF).
4. The SMF or Session Management Function serves as a control plane entity and it is responsible for the session management.
   a. The SMF assigns an IP address to be used for sending uplink data.
   b. The SMF selects the UPF to be used for the session.
   c. The SMF updates the UPF using PFCP messages via the N4 control-data plane interface.
5. The UPF or User Plane function is a data plane component that handles user data.

a. The UPF is completely controlled from the SMF using the N4 interface. The SMF uses the Packet Forwarding Control Protocol (PFCP) to update the data plane.
b. The UPF is responsible for packet routing and forwarding, packet inspection, QoS handling, and external PDU session for interconnecting Data Network (DN), in the 5G architecture.
c. The UPF represents the data plane evolution of a Control and User Plane Separation (CUPS) strategy and is introduced as an extension to existing Evolved Packet Cores (EPCs).
d. The UPF identifies user plane traffic flow based on information received from the SMF over the N4 reference point. The N4 interface employs the Packet Forwarding Control Protocol (PFCP).

3.13.1 5G Interfaces

5G Interfaces present in NetSim are as follows:

1. 5G_N1_N2: N1-N2 is the reference point between the gNB (gNodeB) and the AMF.
2. 5G_N3: Interface between the RAN (gNB) and the (UPF).
3. 5G_N4: Interface between the Session Management Function (SMF) and the UPF
4. 5G_N6: Interface between the Data Network (DN) and the UPF.
5. 5G_N11: Interface between the SMF and AMF.
6. 5G_XN: Interface between two RAN (gNB) nodes.

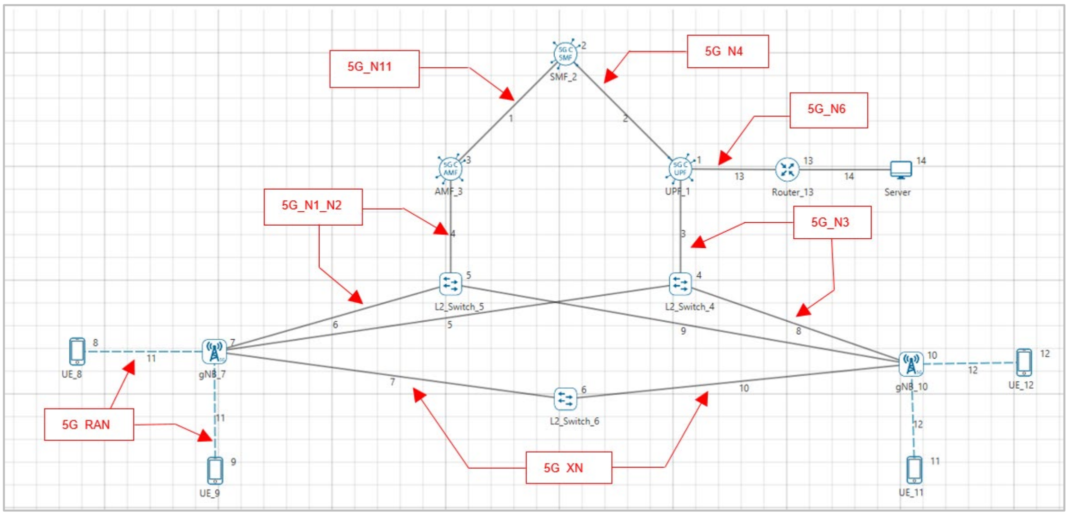


Figure 3-18: 5G Network scenario depicting the 5G Interfaces in NetSim

The NG-AP interface (N2) provides control plane interaction between the gNB and the AMF. In NetSim, this interface is modelled in an abstract manner, with direct interaction between the gNB and the AMF. The encoding of NGAP messages and information elements specified in [TS36413] is not implemented.

The NG-AP primitives that are modelled are:

1. INITIAL UE MESSAGE AND REGISTRATION REQUEST
2. INITIAL CONTEXT SETUP REQUEST
3. INITIAL CONTEXT SETUP RESPONSE AND REGISTRATION COMPLETE
4. PATH SWITCH REQUEST
5. PATH SWITCH REQUEST ACKNOWLEDGE

The N11 interface provides control plane interaction between the SMF and the AMF using the GTPv2-C protocol specified in [TS29274]. In NetSim, this interface is modelled with direct interaction between the SMF and the AMF objects, without implementing the encoding of the messages.

The N11 primitives that are modelled are:

1. CREATE SESSION REQUEST
2. CREATE SESSION RESPONSE
3. MODIFY BEARER REQUEST
4. MODIFY BEARER RESPONSE

Of these primitives, the first two are used during the initial UE attachment for the establishment of the N2-U bearers; the other two are used during handover to switch the N2-U bearers from the source gNB to the target gNB as a consequence of the reception by the AMF of a PATH SWITCH REQUEST NG-AP message.

3.13.2 Cell Selection and UE attach procedure

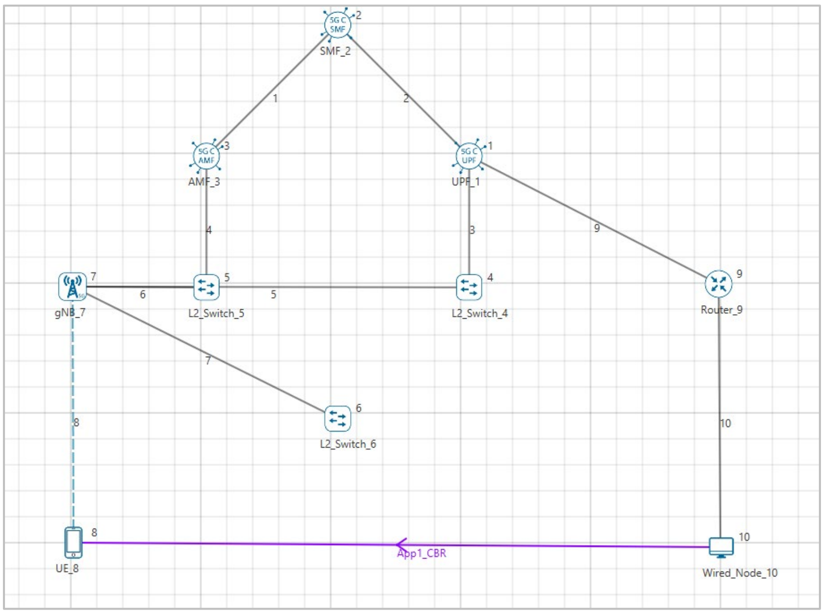


Figure 3-19: A 5G network scenario with a Single UE connected to a gNB which is connected to the 5G Core and the UE downloads data from the Server (Wired Node)

As an example, consider a 5G network scenario with 5G Core devices (which consists of AMF, SMF, UPF and three L2 Switches), a UE which is connected to a gNB, and in the server side, a Wired Node which is connected to a Router which is connected to the 5G core via UPF.

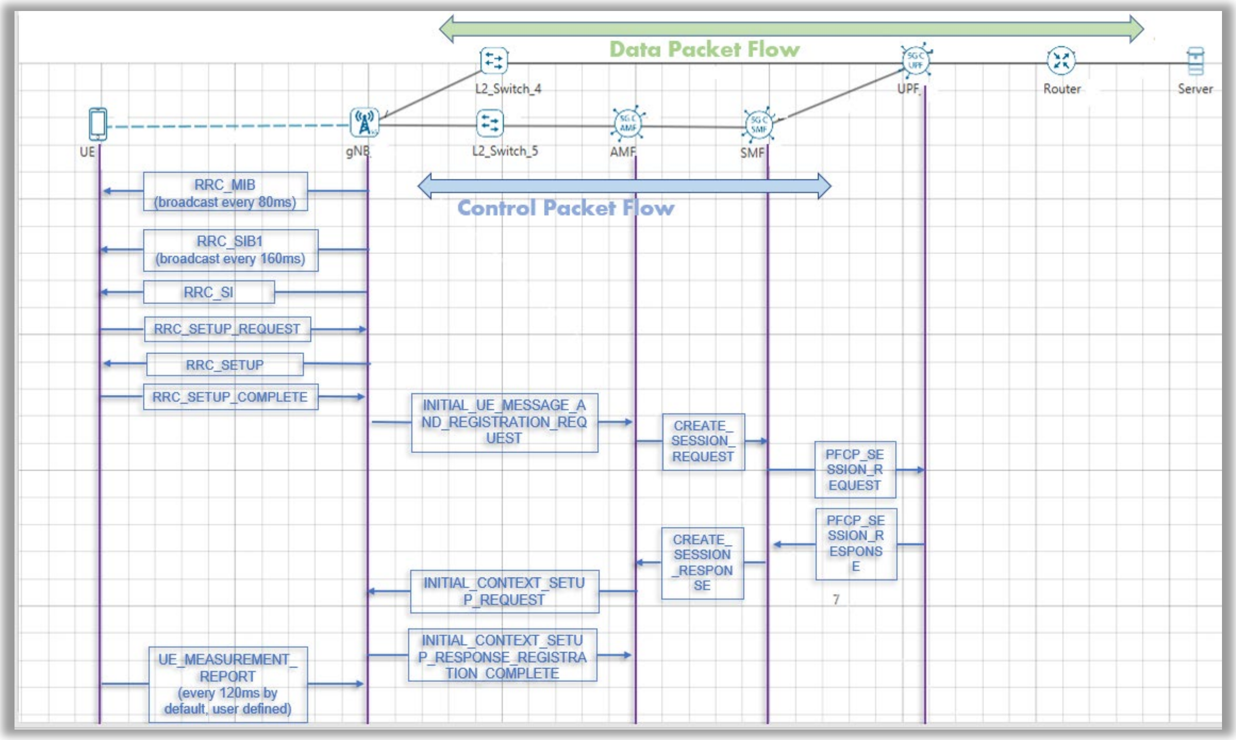


Figure 3-20: UE Attach Procedure

The attachment process is as follows:

1. Radio Resource Control – MIB(Master Information Block) packets are broadcast by each gNB to all the UEs. These packets are transmitted periodically every 80 ms.
   - If the number of gNBs is 'm' and the number of UEs is 'n', then the number of MIB packets transmitted each time will be 'm x n'
   - The transmission of MIB packet starts from the MAC Layer. The transmission time can be calculated from the MAC Layer Arrival Time in the packet trace.
   - The size of each MIB packet is 8 Bytes and can be observed in the Phy Layer Payload field in the packet trace.
2. RRC System Information Block 1 packets are broadcast by the gNBs to all the UEs. These packets are transmitted periodically every 160ms.
   - The transmission of SIB1 packet starts from the MAC Layer. The transmission time can be calculated from the MAC Layer Arrival Time in the packet trace.
   - If the number of gNBs is 'm' and the number of UEs is 'n', then the number of MIB packets transmitted each time will be 'm x n'

- The size of each SIB1 packet is 8 Bytes. This can be observed in the Phy Layer Payload field in the packet trace.

3. After the first set of packets, the cell selection occurs as explained below.
   - The UE attaches itself initially to the gNB from which it receives the highest SNR.
   - If SNR from multiple gNBs is equal, the UE will attach to the gNB with the lowest ID.
   - The gNB to which the UE is connected by the user in NetSim GUI at the network design stage, is only for visual purposes. It plays no role in determining which gNB the UE will attach to
4. RRC System Information are broadcast by the selected gNBs to all UEs when the cell selection is complete.
   - The SI packet is sent only once during the simulation. It is not sent after every Handover.
   - It occurs at 160.9ms.
   - The transmission of SI packet starts from the MAC Layer. The transmission time can be calculated from the MAC Layer Arrival Time in the packet trace.
   - The size of each SI packet is 8 Bytes. The size of the packet can be calculated from the Phy Layer Payload field in the packet trace.
5. The RRC Setup Request will be sent by the UE to the connected gNB within 2.5ms of receipt of RRC SI packet
   - The RRC Setup Request is sent with the random UE-Identity and an establishment cause. This can be observed in the Headers column of the packet trace.
6. The RRC Setup message is used to establish SRB1.
   - Selected gNB sends the setup to UE which contains RRCTransactionIdentifier, RRCResponsetype, PDCP Properties: UEID and GNBID, DiscardDelayTimer, T_Reordering, Hdr Type, SN=0, dcBit.
   - RRC Setup Packet Size is 24 Bytes. The size of the packet can be calculated from the Phy Layer Payload field in the packet trace.
   - UE stops the timer (T300) when it receives the RRC Setup message.
   - UE makes a transition to RRC connected mode.
7. The RRC Setup Complete message is used to confirm the successful completion of an RRC connection establishment.
   - UE sends this message on receipt of the RRC Setup message.

- Contains RRCTransactionIdentifier, SelectedPLMNIdentity, AMFIdentifier, Gaumi Type, Hdr Type, SN, dcBit

8. UE sends UE_MEASUREMENT_REPORT to the connected gNB. The measurement report is sent by each UE to its serving gNB and it contains SINR from all gNBs

If the SNR from another gNB is offset greater than SNR from serving gNB, it leads to handover. After the handover procedure is completed RRC Reconfiguration would happen between target gNB and UE. The UE will then send the UE MEASUREMENT REPORT to this gNB.

These can be observed in the NetSim Packet Trace.

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	80000	
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	160000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	160000	
0	N/A	Control_Packet	RRC_SI	GNB-7	UE-8	GNB-7	UE-8	N/A	160999	
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-8	GNB-7	UE-8	GNB-7	N/A	161999	
0	N/A	Control_Packet	RRC_SETUP	GNB-7	UE-8	GNB-7	UE-8	N/A	162999	
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-8	GNB-7	UE-8	GNB-7	N/A	163999	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-7	AMF-3	GNB-7	SWITCH-5	164999	164999	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-7	AMF-3	SWITCH-5	AMF-3	164999	164999	

Figure 3-21: RRC connection establishment in Packet Trace

3.13.3 5G Core connection management process

This functionality is based on (3gpp 38.413)

1. The gNB will introduce the UE to the 5G Core after the initial gNB- UE attachment process.
2. The gNB will send Initial UE message and Registration request to the selected AMF (In NetSim, there is only one AMF). The message will be transmitted when gNB receives the first NAS message to be transmitted from the radio link after the RRC Setup Complete
3. Upon receiving the UE message and registration request, the AMF will send Create Session Request to the SMF in-order to create a session for the UE.
4. The SMF will send the PFCP Session Request to UPF to denote that the UE is present in the network and the data packet flow may occur to UPF and to create/ establish/ modify PFCP session for UE.
5. Further, AMF will send the Initial Context Setup Request to the gNB to confirm the setup of a UE context.
6. The gNB will send Initial Context Setup and Registration Complete message to the AMF and then the UE will be associated with the core.

These can be observed in NetSim Packet Trace file

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(U
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	RRC_SI	GNB-7	UE-8	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	GNB-7	UE-8	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_REQUEST	GNB-7	AMF-3	GNB-7	SWITCH-5	164999	1
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_REQUEST	GNB-7	AMF-3	SWITCH-5	AMF-3	164999	1
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	165035.24	1650
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	165053.36	1650
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	165071.48	1650
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	165089.6	165
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-7	AMF-3	SWITCH-5	165107.72	1651
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-7	SWITCH-5	GNB-7	165107.72	1651
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE	GNB-7	AMF-3	GNB-7	SWITCH-5	165148.12	1651
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE	GNB-7	AMF-3	SWITCH-5	AMF-3	165148.12	1651
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A

Figure 3-22: 5G Core connection management process

When the UE attachment is completed, the data packets will be transmitted from the source to the destination via the UPF.

3.14 5G Non Stand Alone (NSA)

3.14.1 Overview

NSA leverages the existing LTE radio access and core network (EPC) to anchor 5G NR using the Dual Connectivity feature. This solution provides a seamless option to deploy 5G services with very less disruption in the network. The eNB is connected to the EPC through the LTE_S1 interface and to the gNB through the XN interface. The gNB can be connected to the EPC through the LTE_S1 interface and other gNBs through the XN interface. Similarly, the eNBs and gNBs will be connected to 5G Core through the N1_N2, and N3 interfaces and gNB-eNB and gNB-gNB connections through the XN interface. The control packets like RRC MIB, RRC SIB1, RRC SI in NSA modes will be transmitted from the master nodes to the UE. Similarly, the UE will send the UE_MEASUREMENT_REPORT and RRC_SETUP messages to the master nodes. The master node will be selected according to the deployment option selected.

The NSA modes in NetSim 5G module includes:

1. Option 3 where only LTE core/ EPC is present and no 5G Core devices are present. Here, eNB is the Master Cell and gNB is the Secondary Cell. Option 3 is categorized into:
    a. **Option 3**: Only eNB connects to EPC and eNB and gNB connects to the XN interface.
    b. **Option 3a**: Both eNB and gNB connects to the EPC. gNB connects to the XN interface and eNB does not XN interface.
    c. **Option 3x:** Both eNB and gNB connects to the EPC. eNB and gNB connects to the XN interface.
2. Option 4 where only 5G Core devices are present, and EPC is not available. Here, gNB is the Master Cell and eNB is the Secondary Cell. Option 4 is categorized into:

a. **Option 4:** Only gNB connects to all the 5G Core interfaces. eNB connects to the XN interface.

b. **Option 4a:** gNB connects to all 5G Core interfaces and eNB connects to AMF and UPF through respective interfaces.

3. Option 7 where only 5G Core devices are present, and EPC is not available. Here, eNB is the Master Cell and gNB is the Secondary Cell. Option 7 is categorized into:

a. **Option 7:** eNB connects to all 5G Core interfaces. gNB connects only to the XN interface.

b. **Option 7a:** gNB connects to all the 5G Core interfaces. eNB connects to AMF and UPF through the respective interfaces.

c. **Option 7x:** gNB and eNB connects to all the 5G Core interfaces.

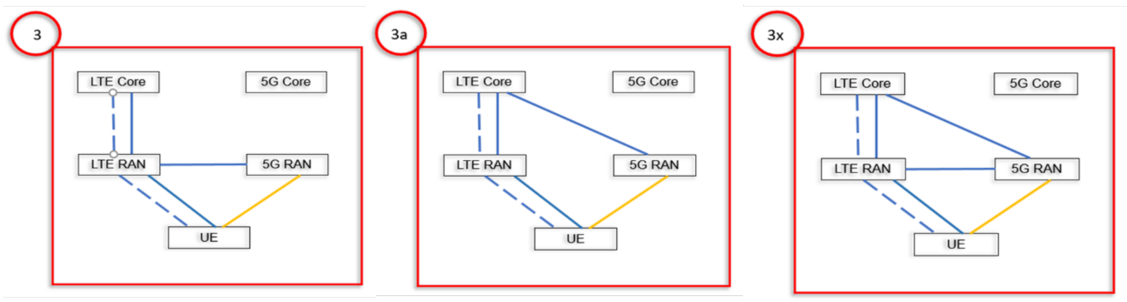


Figure 3-23: NSA deployment - Option 3, Option 3a and Option 3x Networking modes

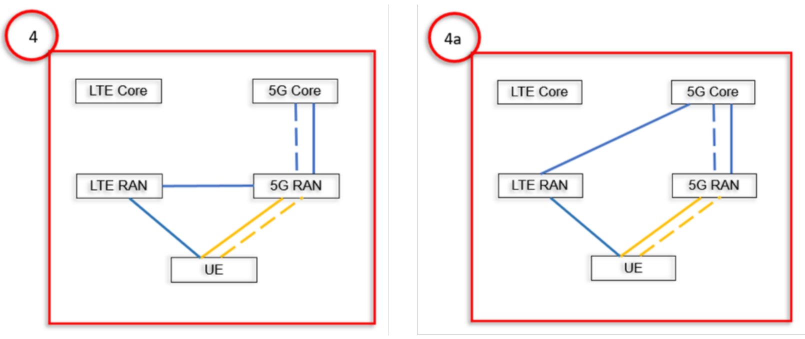


Figure 3-24: NSA deployment - Option 4, Option 4a Networking modes

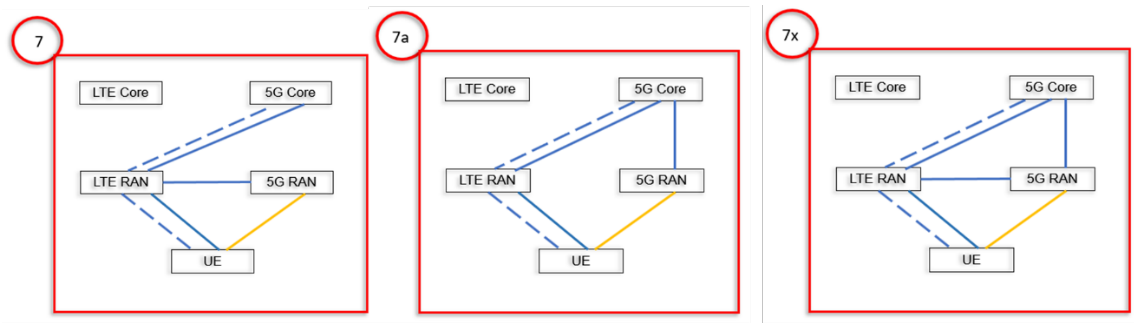


Figure 3-25: NSA deployment - Option 7, Option 7a and Option 7x Networking modes

In Options 3, 4 and 7, the secondary node is not directly connected with the LTE-EPC/ 5G-Core. On reception of a packet, the secondary node, transmits all packet to the master node via the XN interface for uplink cases and for downlink cases, the core / EPC transmits the packets to the master node and the master node splits the traffic between itself and the secondary node, since there is no connection between the core and secondary node. The master node also transmits the packets to the UE.

In options 3a, 4a and 7a, the split happens at the EPC/UPF.

In options 3x and 7x, when the EPC/ core receives the traffic, it is split between master node and secondary node. On reception of the traffic, the master node again splits traffic between itself and secondary node. Hence, the secondary node receives traffic from both the sides.

The splitting happens according to the Alternative Splitting Algorithm (Users can modify the code and develop their own splitting algorithms)

3.14.2 Option 3/3a/3x

The standardized NSA EPC networking architecture includes Option 3, Option 3a, and Option 3x.

Non-standalone option 3 is where radio access network is composed of eNBs as the master node and gNBs as the secondary. The radio access network is connected to EPC (Evolved Packet Core).

3.14.2.1 Option 3

Option 3 represents a network having both LTE and NR radio access but using only the EPC core of LTE to route the Control signals. In this option, LTE is used as the control plane anchor for NR, and both LTE and NR are used for user data traffic (user plane).

Option 3 involves routing of 5G data through the eNB.

All uplink/downlink data flows to and from the LTE part of the LTE/NR base station, i.e., to and from the eNB. The eNB then decides which part of the data it wants to forward to the 5G gNB over the XN interface. The gNB never communicates with the 4G core network directly.

In the Option 3 networking mode, the XN interface traffic between eNB and gNB.

Traffic is split across 4G and 5G at eNodeB. Hence, eNB is the Master Cell.

In NetSim Option 3 of NSA mode connects the eNB to the EPC using LTE_S1 interface. The gNBs and eNBs are inter-connected in option 3 using the XN interface via a Layer 2 Switch and the UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

The data flows from the eNB and the eNB decides which part of data is to be forwarded to the gNB over the XN interface.

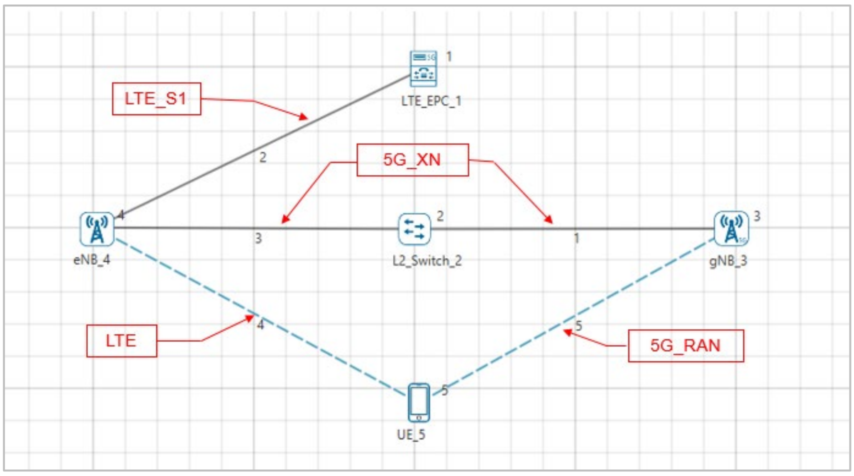


Figure 3-26: NSA deployment - Option 3 networking mode in NetSim

3.14.2.2 Option 3a

In the option 3a, both the eNB and the gNB can directly talk to the LTE core network but they cannot directly talk with each other over the XN interface. This means that a single data bearer cannot share the load over LTE and NR.

There is only control plane traffic in the XN interface. The dynamic switching between 5G and 4G is not supported in Option 3a. The traffic is split across 5G and 4G at the EPC.

In NetSim Option 3a of NSA mode connects the eNB and gNB to the EPC using LTE_S1 interface. Hence, the eNB and gNB can directly communicate with the EPC. Since XN interface is not present for eNB and it is present for gNB in this deployment option, gNB and eNB cannot communicate with each other. the UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

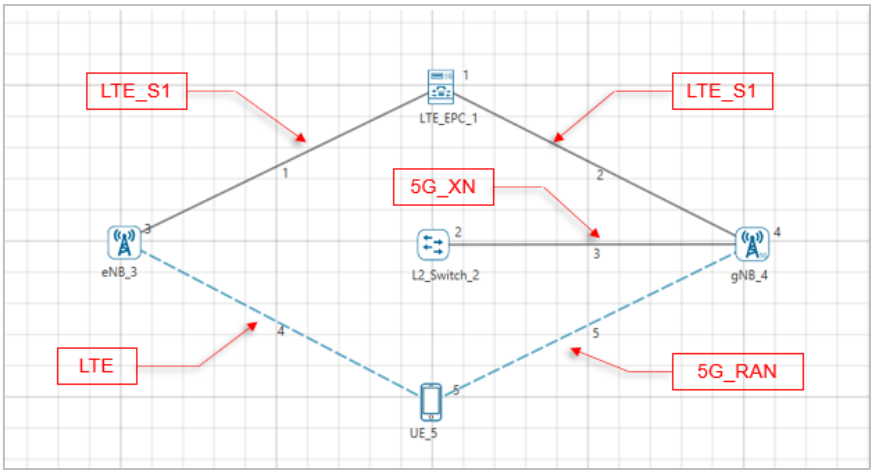


Figure 3-27: NSA deployment - Option 3a networking mode in NetSim

3.14.2.3 Option 3x

In this deployment option, user data traffic will flow directly to the 5G gNB part of the base station. From there, it is delivered over the air to the mobile device. A part of the data can also be forwarded over the XN interface to the eNB and from there to the UE.

There is a little LTE user plane traffic in the XN interface. The traffic is split across 4G and 5G at the gNB.

In NetSim, deployment option 3x connects both eNB and gNB to the EPC using LTE_S1 interface. The gNBs and eNBs are inter-connected using the XN interface via a Layer 2 Switch which allows the communication between eNB and gNB and the UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

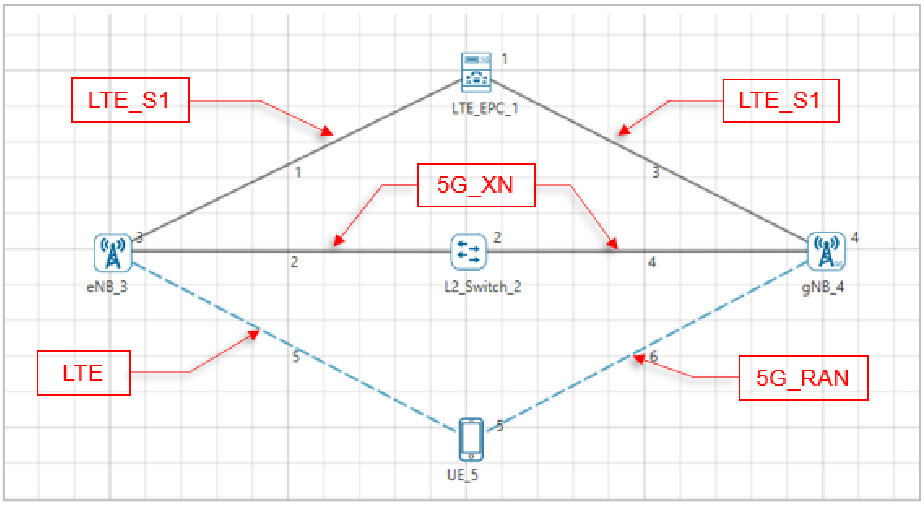


Figure 3-28: NSA deployment - Option 3x networking mode in NetSim

3.14.3 Option 4/4a

The EPC or the LTE Core in Option 3/3a/3x is replaced by the 5G Core in Option 4. The master node is the LTE NR cell or gNB and the secondary node is LTE cell or eNB.

3.14.3.1 Option 4

In Option 4 of Non-Stand-alone mode, both LTE and 5G NR radio access technologies are deployed and controlled through only the 5G Core, i.e., AMF, SMF and UPF.

The gNB has both the NG-U and NG-C interfaces. Both eNB and gNB connects over the XN interface. The interface between gNB and AMF is called N2 interface and the interface between gNB and UPF is called N3 interface, So the control plane is over N2 interface and user plane is over N3 interface.

The eNB is not connected to 5G Core, hence data traffic is split over the XN interface. The gNB is connected to 5G Core with NG-U and NG-C.

In NetSim, the gNB is connected to the UPF via Switch_4 using the 5G_N3 interface and to the AMF via Switch_5 using the 5G_N1_N2 interface, hence, gNB communicates directly with the 5G Core and eNB does not communicate directly with the 5G Core. The gNBs and eNBs are inter-connected using the XN interface via a Layer 2 Switch and the UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

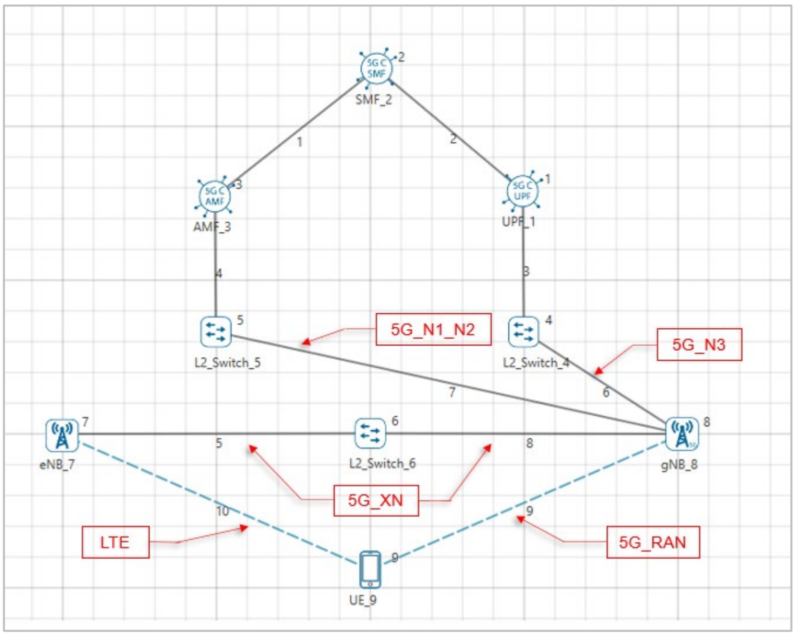


Figure 3-29: NSA deployment- Option 4 networking mode in NetSim

3.14.3.2 Option-4a

In Option 4a, the eNB is not connected to gNB over XN interface, but it is connected to 5G Core over the NG-U interface.

The gNB has both NG-U and NG-C interface. Data traffic is split between 4G and 5G at the 5G Core, specifically the UPF.

In NetSim, the gNB and eNB are connected to the UPF via Switch_4 using the 5G_N3 interface and to the AMF via Switch_5 using the 5G_N1_N2 interface. The gNBs we can inter-connected using the XN interface and does not have XN interface for eNBs. hence direct communication between eNB and gNB is not possible. The UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

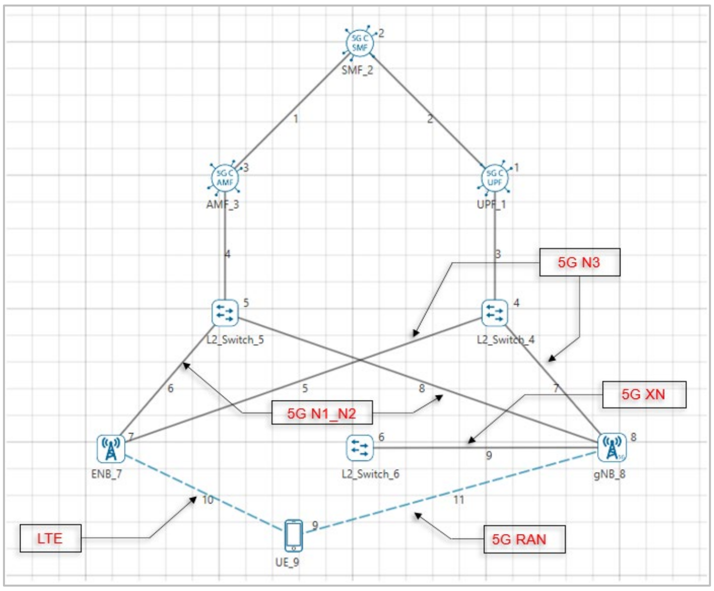


Figure 3-30: NSA deployment- Option 4a networking mode in NetSim

3.14.4 Option 7/7a/7x

The eNB has NG-U and NG-C interfaces to 5G Core and eNB connects with gNB over XN interface. The master node is the LTE cell or eNB and the secondary node is the LTE-NR cell or gNB in these deployment options.

3.14.4.1 Option-7

In Option 7, the gNB does not communicate to 5G Core. Data traffic flows through eNB communicating to and from the 5G Core. Some part of the data can be transferred through gNB over the XN interface.

In NetSim, the eNBs are connected to the UPF via Switch_4 using the 5G_N3 interface and to the AMF via Switch_5 using the 5G_N1_N2 interface. The gNBs and eNBs are inter-connected using the XN interface and hence direct communication between eNB and gNB is possible. The UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface. The data is delivered to the UE when it comes to the 5G NR through the LTE-RAN.

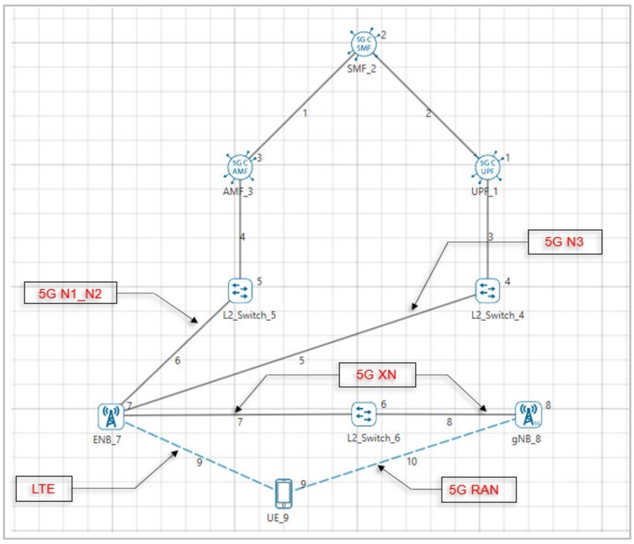


Figure 3-31: NSA deployment- Option 7 networking mode in NetSim

3.14.4.2 Option-7a

In Option 7a, eNB and gNB are not connected via the XN interface and instead gNB is connected to 5G Core over NG-U. The eNB is connected to 5G Core over NG-C and NG-U. Data traffic is split at the 5GC (UPF).

In NetSim, the gNB and eNB are connected to the UPF via Switch_4 using the 5G_N3 interface and to the AMF via Switch_5 using the 5G_N1_N2 interface. The gNBs does not have an XN Interface and eNBs inter-connected using the XN interface and hence direct communication between eNB and gNB is not possible. The UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

The user data goes directly from the 5G Core to the gNB and then to the UE.

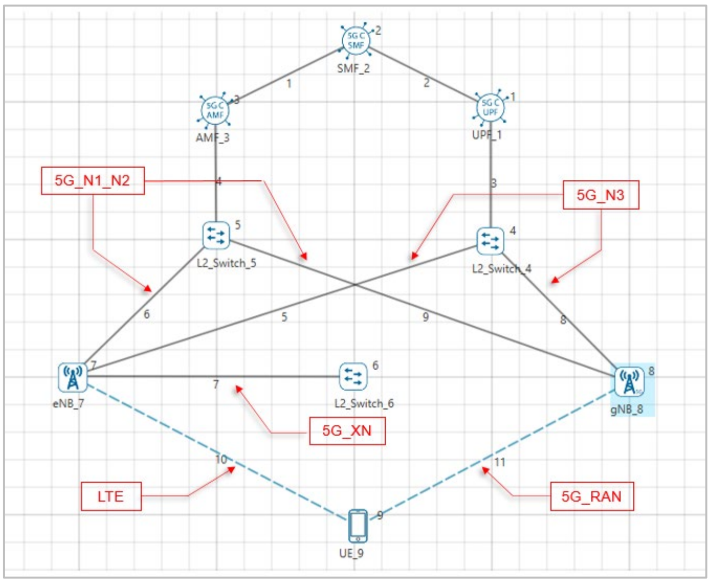


Figure 3-32: NSA deployment- Option 7a networking mode in NetSim

3.14.4.3 Option-7x

Data traffic is split across eNB and gNB by gNB. Data flows to and from the network through gNB and 5GC over NG-U and control plane is carried over NG-C from NG eNB to 5GC, a part of the data is split between gNB and NG eNB over the Xn interface.

In NetSim, the gNB and eNB are connected to the UPF via Switch_4 using the 5G_N3 interface and to the AMF via Switch_5 using the 5G_N1_N2 interface. The gNBs and eNBs are inter-connected using the XN interface and hence direct communication between eNB and gNB takes place. The UEs present in the network consists of two interfaces, an LTE interface and a 5G_RAN interface.

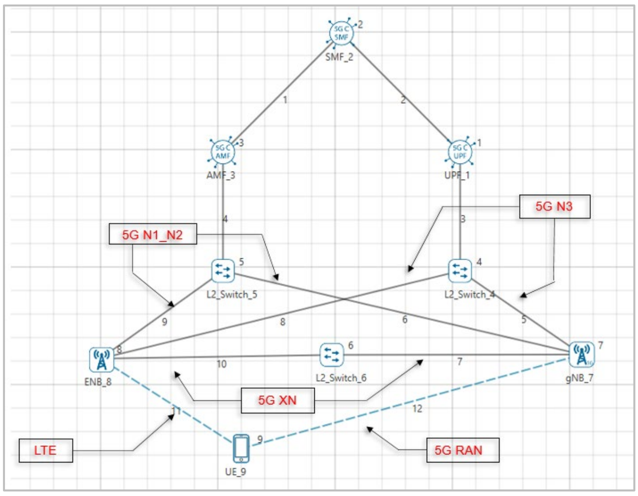


Figure 3-33: NSA deployment- Option 7x networking mode in NetSim

3.15 NSA Packet Flow

3.15.1 Option 3

Consider the following network scenario:

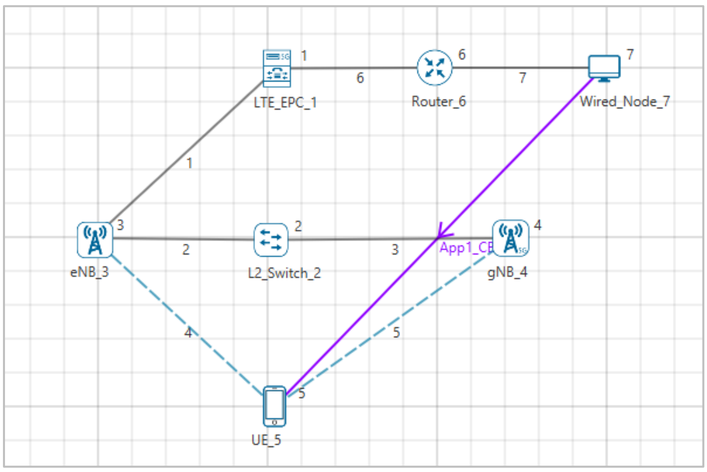


Figure 3-34: NSA deployment - Option 3 networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

eNB is the Master Node and gNB is the Secondary Node in Options 3, 3a and 3x.

The packet flow in the network takes place as explained below:

1. The MN, eNB will broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. After the RRC connection, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the L2Switch.
7. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
8. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
9. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
10. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the EPC and from the EPC it goes to the MN, eNB, and from the eNB it will be transmitted to the UE.
11. The second data packet will flow to eNB from EPC and then to the gNB through the L2Switch (via XN interface) and then to the UE.
12. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:

A	B	C	D	E	F	G	H	L	M	
PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	40000	41000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	80000	81000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	80000	81000	
0	N/A	Control_Packet	RRC_SI	ENB-3	UE-5	ENB-3	UE-5	81499	83000	
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-5	ENB-3	UE-5	ENB-3	83499	84000	
0	N/A	Control_Packet	RRC_SETUP	ENB-3	UE-5	ENB-3	UE-5	84499	85000	
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-5	ENB-3	UE-5	ENB-3	85499	86000	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	ENB-3	SWITCH-2	86499	86499	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	SWITCH-2	GNB-4	86499	86508.96	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	GNB-4	SWITCH-2	86518.92	86518.92	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	SWITCH-2	ENB-3	86518.92	86528.88	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	120000	120000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	120000	121000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	160000	161000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	160000	161000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	200000	201000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	240000	240000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	240000	241000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	240000	241000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	280000	281000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	320000	321000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	320000	321000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	360000	360000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	360000	361000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	400000	401000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	400000	401000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	440000	441000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	480000	480000	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

A	B	C	D	E	F	G	H	L	M	
PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ST
1	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000000	1000000	
2	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000116	1000122.08	
1	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000126.12	1000126.12	
3	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000232	1000244.16	
2	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000248.2	1000248.2	
1	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1000250.16	1000250.16	
4	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000348	1000366.24	
3	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000370.28	1000370.28	
2	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1000372.24	1000372.24	
4	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000492.36	1000492.36	
3	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1000494.32	1000494.32	
2	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	SWITCH-2	1000496.28	1000496.28	
4	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1000616.4	1000616.4	
2	0	CBR	App1_CBR	NODE-7	UE-5	SWITCH-2	GNB-4	1000496.28	1000624	
4	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	SWITCH-2	1000740.44	1000740.44	
4	0	CBR	App1_CBR	NODE-7	UE-5	SWITCH-2	GNB-4	1000740.44	1000868.16	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000374.2	1001000	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000374.2	1001000	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000618.36	1001000	
2	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1000496.28	1001000	
4	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1000740.44	1001000	
4	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1000740.44	1001000	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000618.36	1003000	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

61010 records found

Figure 3-35: Packet flow can be analyzed using the Packet Trace

3.15.2 Option 3a

Consider the following network scenario:

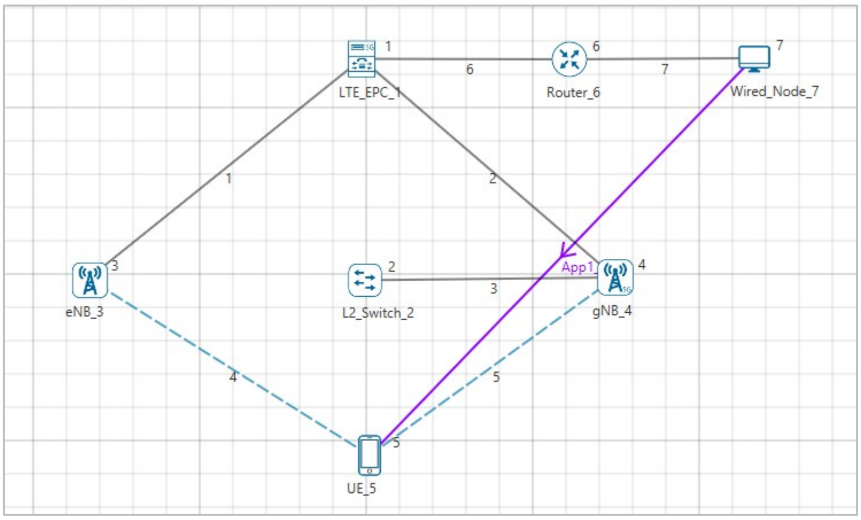


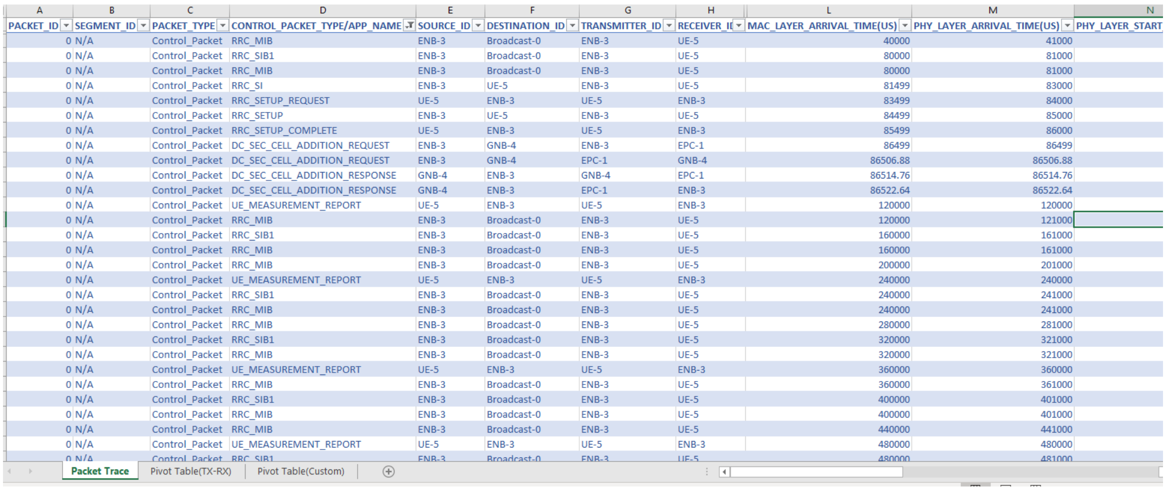
Figure 3-36: NSA deployment - Option 3a networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

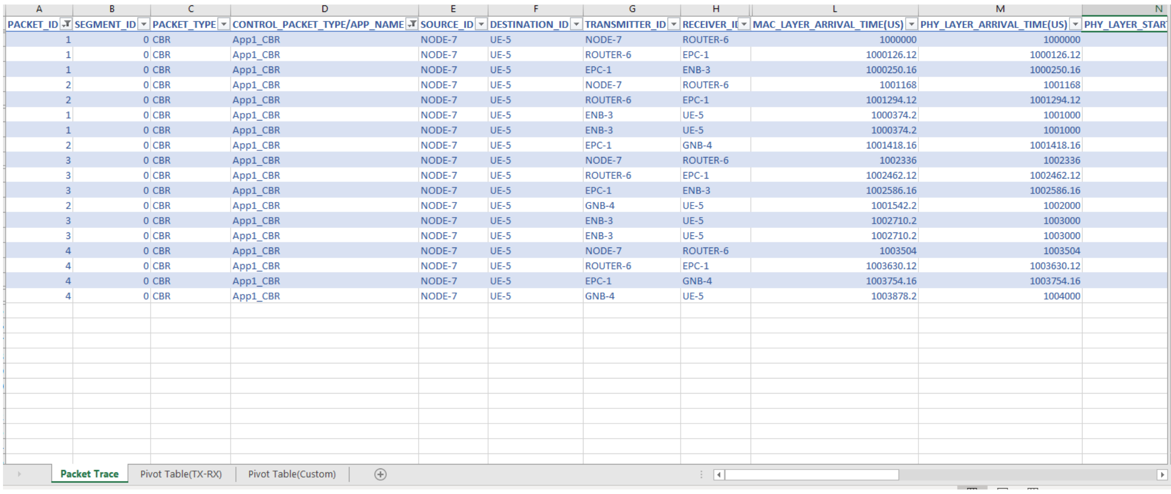
The packet flow in the network takes place as explained below:

1. The MN, eNB will broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. After the RRC connection, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the EPC.
7. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
8. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
9. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
10. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the EPC and from the EPC it goes to the MN, eNB, and from the eNB it will be transmitted to the UE.
11. The second data packet will flow from EPC to the gNB and then to the UE.
12. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_START
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	40000	41000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	80000	81000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	80000	81000	
0	N/A	Control_Packet	RRC_SI	ENB-3	UE-5	ENB-3	UE-5	81499	83000	
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-5	ENB-3	UE-5	ENB-3	83499	84000	
0	N/A	Control_Packet	RRC_SETUP	ENB-3	UE-5	ENB-3	UE-5	84499	85000	
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-5	ENB-3	UE-5	ENB-3	85499	86000	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	ENB-3	EPC-1	86499	86499	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	EPC-1	GNB-4	86506.88	86506.88	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	GNB-4	EPC-1	86514.76	86514.76	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	EPC-1	ENB-3	86522.64	86522.64	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	120000	120000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	120000	121000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	160000	161000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	160000	161000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	200000	201000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	240000	240000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	240000	241000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	240000	241000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	280000	281000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	320000	321000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	320000	321000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	360000	360000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	360000	361000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	400000	401000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	400000	401000	
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	440000	441000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	480000	480000	
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	480000	481000	



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_START
1	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000126.12	1000126.12	
1	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1000250.16	1000250.16	
2	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1001168	1001168	
2	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1001294.12	1001294.12	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000374.2	1001000	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000374.2	1001000	
2	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1001418.16	1001418.16	
3	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1002462.12	1002462.12	
3	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	ENB-3	1002586.16	1002586.16	
2	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1001542.2	1002000	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1002710.2	1003000	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1002710.2	1003000	
4	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1003504	1003504	
4	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1003630.12	1003630.12	
4	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1003754.16	1003754.16	
4	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1003878.2	1004000	

Figure 3-37: Packet flow can be analyzed using the Packet Trace

3.15.3 Option 3x

Consider the following network scenario:

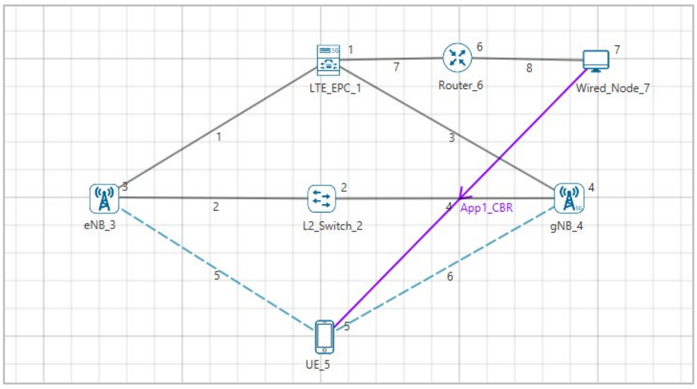


Figure 3-38: NSA deployment - Option 3x networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

The packet flow in the network takes place as explained below:

1. The MN, eNB will broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. After the RRC connection, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the L2Switch.
7. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
8. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
9. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
10. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the EPC and from the EPC it goes to the gNB and then to the MN, eNB via L2Switch, and from the eNB it will be transmitted to the UE.
11. The second data packet will flow from EPC to the gNB and then to the UE.
12. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SI	ENB-3	UE-5	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	ENB-3	UE-5	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	ENB-3	SWITCH-2	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-3	GNB-4	SWITCH-2	GNB-4	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	GNB-4	SWITCH-2	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-4	ENB-3	SWITCH-2	ENB-3	N/A	N/A	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-5	ENB-3	UE-5	ENB-3	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-3	Broadcast-0	ENB-3	UE-5	N/A	N/A	N/A

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIV
1	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	SWITCH-2	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	SWITCH-2	ENB-3	1000000	1000000	
2	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1001168	1001168	
2	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1001168	1001168	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000000	1000000	
1	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1000000	1000000	
2	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1001168	1001168	
3	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	SWITCH-2	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	SWITCH-2	ENB-3	1002336	1002336	
2	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1001168	1001168	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1002336	1002336	
3	0	CBR	App1_CBR	NODE-7	UE-5	ENB-3	UE-5	1002336	1002336	
4	0	CBR	App1_CBR	NODE-7	UE-5	NODE-7	ROUTER-6	1003504	1003504	
4	0	CBR	App1_CBR	NODE-7	UE-5	ROUTER-6	EPC-1	1003504	1003504	
4	0	CBR	App1_CBR	NODE-7	UE-5	EPC-1	GNB-4	1003504	1003504	
4	0	CBR	App1_CBR	NODE-7	UE-5	GNB-4	UE-5	1003504	1003504	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

Figure 3-39: Packet flow can be analyzed using the Packet Trace

3.15.4 Option 4

Consider the following network scenario:

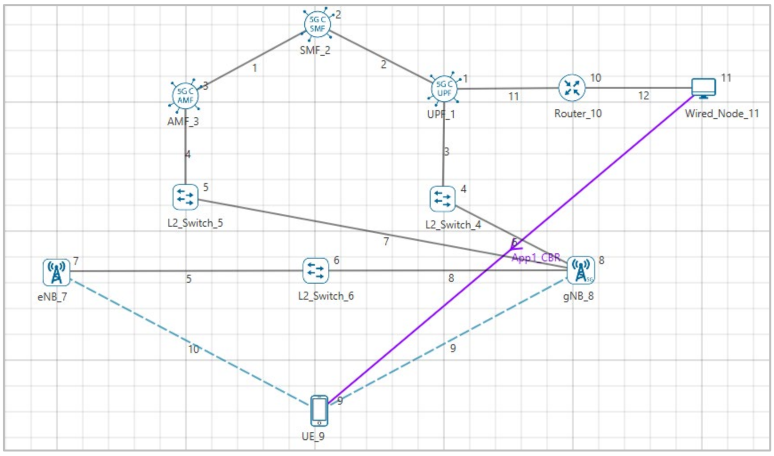


Figure 3-40: NSA deployment - Option 4 networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

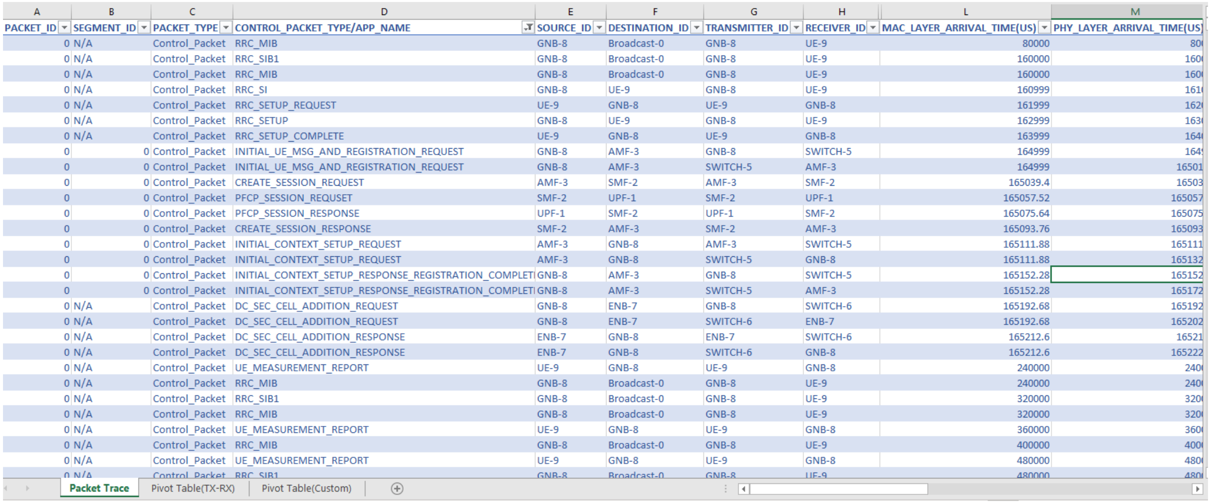
gNB is the Master Node and eNB is the Secondary Node in Options 4 and 4a.

The packet flow in the network takes place as explained below:

1. The MN, gNB will broadcast the RRC_MIB packets to the UE every 80 ms and RRC_SIB1 every 160 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the gNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the gNB.
4. On receiving the RRC_Setup_Request packet, the gNB will acknowledge the request by transmitting RRC_Setup packet to the UE.

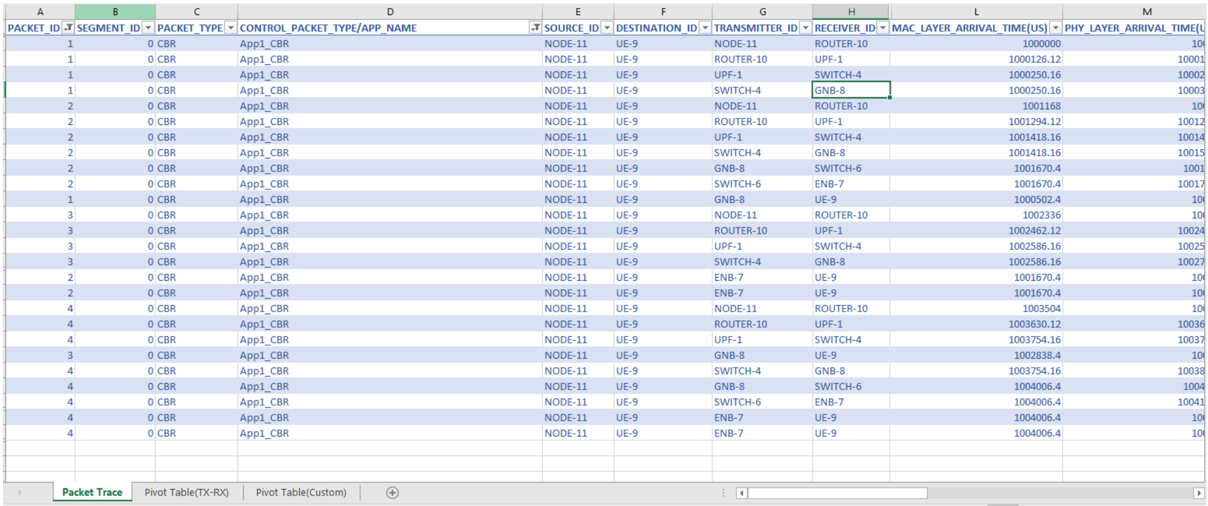
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. The gNB will send INITIAL_UE_MSG_AND_REGISTRATION_REQUEST to the AMF via L2Switch_5 through the N1_N2 interface.
7. AMF will send CREATE_SESSION_REQUEST to SMF through N11 interface.
8. SMF will send PFCP_SESSION_REQUEST to UPF through N4 interface.
9. UPF will send back the response packet to SMF, i.e, PFCP_SESSION_RESPONSE
10. SMF will send back the response packet to AMF, i.e., CREATE_SESSION_RESPONSE
11. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the gNB via Switch_5.
12. On the receipt of Context setup request, gNB will send INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE packet to the AMF via switch_5 through the N1_N2 interface.
13. This marks the completion of UE registration process.
14. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the L2Switch_6.
15. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
16. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
17. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
18. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, gNB via Switch_4 through the N3 interface, and from the gNB it will be transmitted to the UE through the RAN interface.
19. The second data packet will flow from UPF to the gNB via Switch_4 and from the gNB, the packet gets transmitted to the eNB via Switch_6 through the XN interface and then to the UE.
20. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(US)
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	80000	80
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	160000	160
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	160000	160
0	N/A	Control_Packet	RRC_SI	GNB-8	UE-9	GNB-8	UE-9	160999	161
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-9	GNB-8	UE-9	GNB-8	161999	162
0	N/A	Control_Packet	RRC_SETUP	GNB-8	UE-9	GNB-8	UE-9	162999	163
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-9	GNB-8	UE-9	GNB-8	163999	164
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_REQUEST	GNB-8	AMF-3	GNB-8	SWITCH-5	164999	164
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_REQUEST	GNB-8	AMF-3	SWITCH-5	AMF-3	164999	16501
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	165039.4	16503
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	165057.52	165057
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	165075.64	165075
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	165093.76	165093
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-8	AMF-3	SWITCH-5	165111.88	165111
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-8	SWITCH-5	GNB-8	165111.88	165132
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETI	GNB-8	AMF-3	GNB-8	SWITCH-5	165152.28	165152
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETI	GNB-8	AMF-3	SWITCH-5	AMF-3	165152.28	165172
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	GNB-8	ENB-7	GNB-8	SWITCH-6	165192.68	165192
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	GNB-8	ENB-7	SWITCH-6	ENB-7	165192.68	165202
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	ENB-7	GNB-8	ENB-7	SWITCH-6	165212.6	16521
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	ENB-7	GNB-8	SWITCH-6	GNB-8	165212.6	165222
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	240000	240
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	240000	240
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	320000	320
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	320000	320
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	360000	360
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	400000	400
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	480000	480
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	480000	480

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARRIVAL_TIME(U
1	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1000000	10
1	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1000126.12	10001
1	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1000250.16	10002
1	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1000250.16	10003
2	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1001168	10
2	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1001294.12	10012
2	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1001418.16	10014
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1001418.16	10015
2	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	SWITCH-6	1001670.4	1001
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	ENB-7	1001670.4	10017
1	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1000502.4	10
3	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1002336	10
3	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1002462.12	10024
3	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1002586.16	10025
3	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1002586.16	10027
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1001670.4	10
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1001670.4	10
4	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1003504	10
4	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1003630.12	10036
4	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1003754.16	10037
3	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1002838.4	10
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1003754.16	10038
4	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	SWITCH-6	1004006.4	1004
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	ENB-7	1004006.4	10041
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1004006.4	10
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1004006.4	10

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

Figure 3-41: Packet flow can be analyzed using the Packet Trace

3.15.5 Option 4a

Consider the following network scenario:

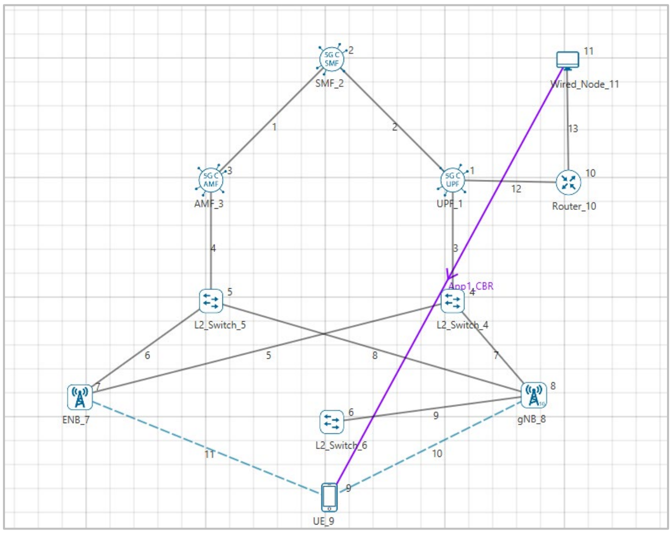


Figure 3-42: NSA deployment - Option 4a networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

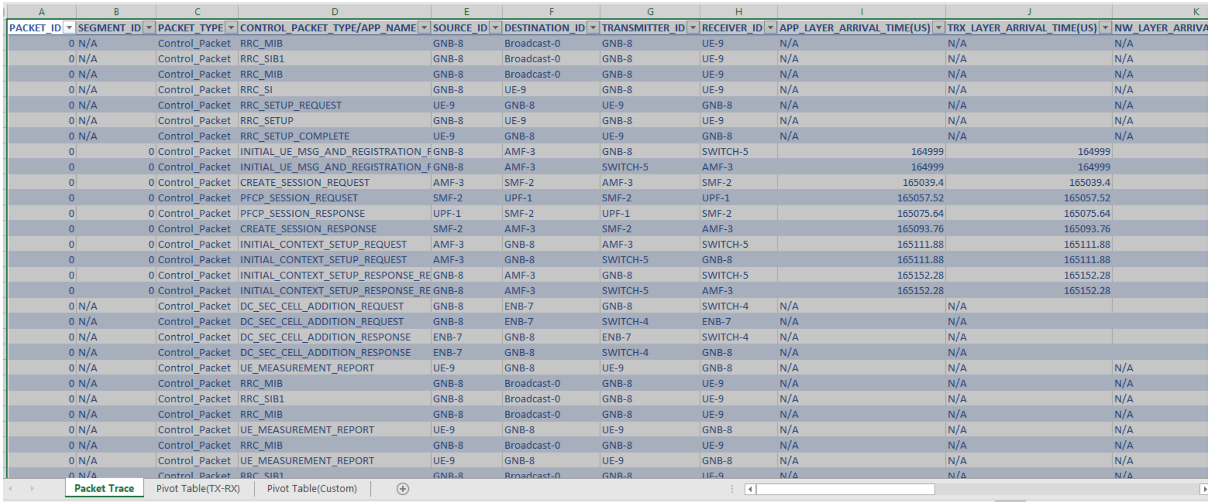
The packet flow in the network takes place as explained below:

1. The MN, gNB will broadcast the RRC_MIB packets to the UE every 80 ms and RRC_SIB1 every 160 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the gNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the gNB.
4. On receiving the RRC_Setup_Request packet, the gNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. The gNB will send INITIAL_UE_MSG_AND_REGISTRATION_REQUEST to the AMF via L2Switch_5 through the N1_N2 interface.
7. AMF will send CREATE_SESSION_REQUEST to SMF through N11 interface.
8. SMF will send PFCP_SESSION_REQUEST to UPF through N4 interface.
9. UPF will send back the response packet to SMF, i.e, PFCP_SESSION_RESPONSE
10. SMF will send back the response packet to AMF, i.e., CREATE_SESSION_RESPONSE.
11. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the gNB via Switch_5.
12. On the receipt of Context setup request, gNB will send INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE packet to the AMF via switch_5 through the N1_N2 interface.
13. This marks the completion of UE registration process.
14. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_4.
15. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
16. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
17. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
18. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, gNB via Switch_4

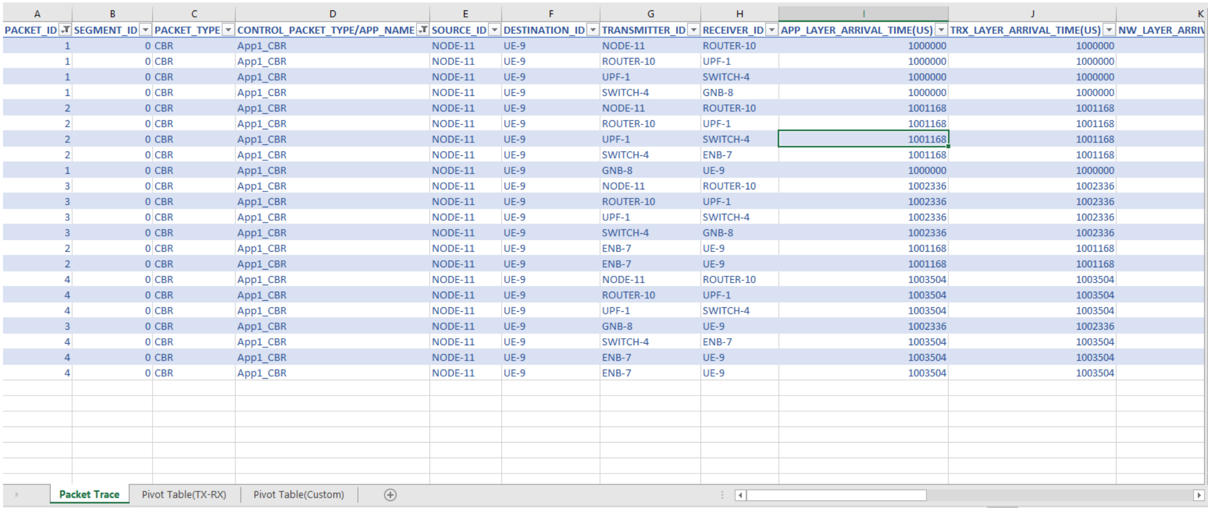
through the N3 interface, and from the gNB it will be transmitted to the UE through the RAN interface.

19. The second data packet will flow from UPF to the eNB via Switch_4 and then to the UE.
20. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SI	GNB-8	UE-9	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-9	GNB-8	UE-9	GNB-8	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	GNB-8	UE-9	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-9	GNB-8	UE-9	GNB-8	N/A	N/A	N/A
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-8	AMF-3	GNB-8	SWITCH-5	164999	164999	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-8	AMF-3	SWITCH-5	AMF-3	164999	164999	
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	165039.4	165039.4	
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	165057.52	165057.52	
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	165075.64	165075.64	
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	165093.76	165093.76	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-8	AMF-3	SWITCH-5	165111.88	165111.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-8	SWITCH-5	GNB-8	165111.88	165111.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	GNB-8	AMF-3	GNB-8	SWITCH-5	165152.28	165152.28	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	GNB-8	AMF-3	SWITCH-5	AMF-3	165152.28	165152.28	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	GNB-8	ENB-7	GNB-8	SWITCH-4	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	GNB-8	ENB-7	SWITCH-4	ENB-7	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	ENB-7	GNB-8	ENB-7	SWITCH-4	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	ENB-7	GNB-8	SWITCH-4	GNB-8	N/A	N/A	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A	N/A



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIV
1	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1001168	1001168	
1	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1000000	1000000	
3	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1002336	1002336	
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1001168	1001168	
4	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1003504	1003504	
3	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1002336	1002336	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1003504	1003504	

Figure 3-43: Packet flow can be analyzed using the Packet Trace

3.15.6 Option 7

Consider the following network scenario:

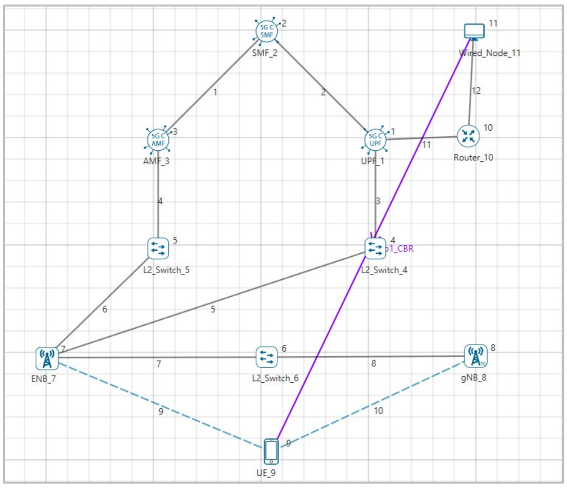


Figure 3-44: NSA deployment - Option 7 networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

eNB is the MN and gNB is the SN in deployment options 7, 7a and 7x.

The packet flow in the network takes place as explained below:

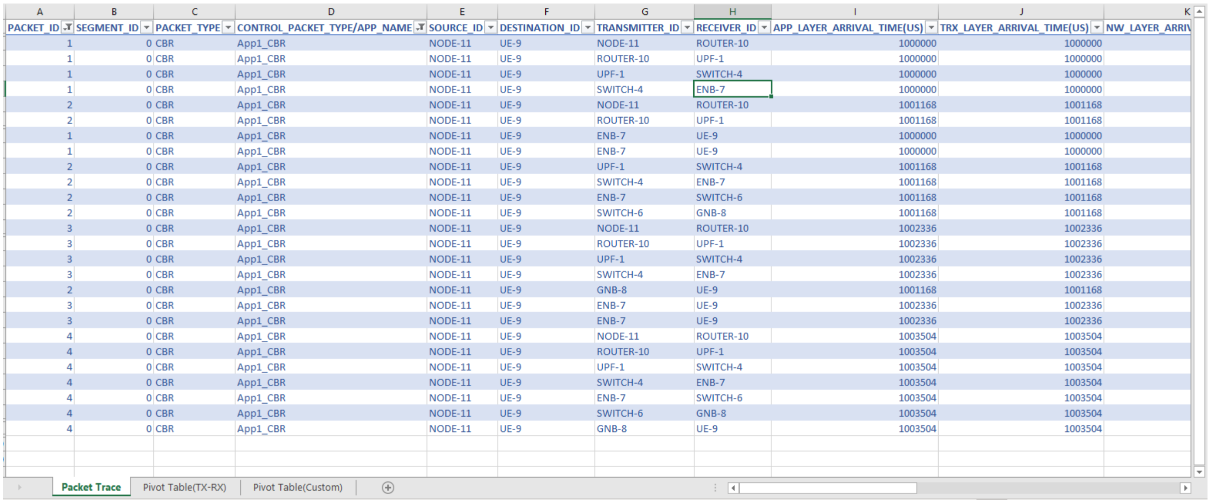
1. The MN, eNB will send broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. The eNB will send INITIAL_UE_MSG_AND_REGISTRATION_REQUEST to the AMF via L2Switch_5 through the N1_N2 interface.
7. AMF will send CREATE_SESSION_REQUEST to SMF through N11 interface.
8. SMF will send PFCP_SESSION_REQUEST to UPF through N4 interface.
9. UPF will send back the response packet to SMF, i.e, PFCP_SESSION_RESPONSE
10. SMF will send back the response packet to AMF, i.e., CREATE_SESSION_RESPONSE.
11. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the eNB via Switch_5.
12. On the receipt of Context setup request, eNB will send INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE packet to the AMF via switch_5 through the N1_N2 interface.
13. This marks the completion of UE registration process.

14. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_6.
15. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e., DC_SEC_CELL_ADDITION_RESPONSE.
16. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
17. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
18. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, eNB via Switch_4 through the N3 interface, and from the eNB it will be transmitted to the UE through the LTE interface.
19. The second data packet will flow from UPF to the eNB via Switch_4 and then from eNB to the gNB via Switch_6 through XN interface and then to the UE.
20. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim's Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SI	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	ENB-7	SWITCH-5	86499	86499	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	SWITCH-5	AMF-3	86499	86499	
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	86539.4	86539.4	
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	86557.52	86557.52	
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	86575.64	86575.64	
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	86593.76	86593.76	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	AMF-3	SWITCH-5	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	SWITCH-5	ENB-7	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	ENB-7	SWITCH-5	86652.28	86652.28	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	SWITCH-5	AMF-3	86652.28	86652.28	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	ENB-7	SWITCH-6	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	SWITCH-6	GNB-8	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	GNB-8	SWITCH-6	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	SWITCH-6	ENB-7	N/A	N/A	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)



PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIV
1	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1001168	1001168	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	SWITCH-6	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	GNB-8	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1002336	1002336	
2	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
4	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	SWITCH-6	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	GNB-8	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1003504	1003504	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

Figure 3-45: Packet flow can be analyzed using the Packet Trace

3.15.7 Option 7a

Consider the following network scenario:

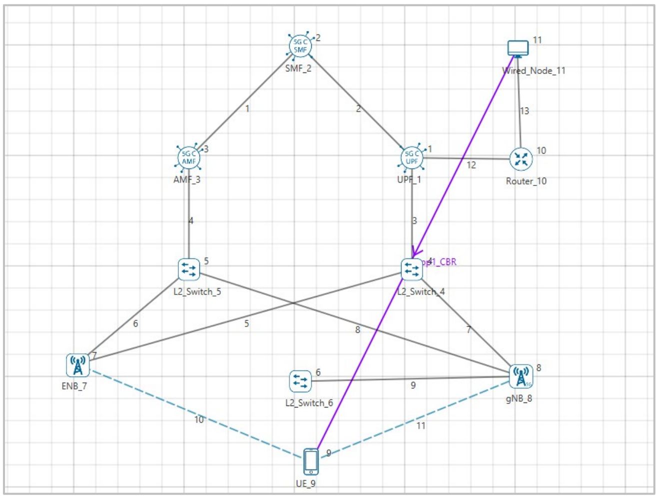


Figure 3-46: NSA deployment - Option 7a networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

The packet flow in the network takes place as explained below:

1. The MN, eNB will send broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.

6. The eNB will send INITIAL_UE_MSG_AND_REGISTRATION_REQUEST to the AMF via L2Switch_5 through the N1_N2 interface.
7. AMF will send CREATE_SESSION_REQUEST to SMF through N11 interface.
8. SMF will send PFCP_SESSION_REQUEST to UPF through N4 interface.
9. UPF will send back the response packet to SMF, i.e, PFCP_SESSION_RESPONSE
10. SMF will send back the response packet to AMF, i.e., CREATE_SESSION_RESPONSE.
11. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the eNB via Switch_5.
12. On the receipt of Context setup request, eNB will send INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE packet to the AMF via switch_5 through the N1_N2 interface.
13. This marks the completion of UE registration process.
14. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_4.
15. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
16. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
17. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
18. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, eNB via Switch_4 through the N3 interface, and from the eNB it will be transmitted to the UE through the LTE interface.
19. The second data packet will flow from UPF to the gNB via Switch_4 and then from gNB to the UE.
20. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

Packet flow can be analyzed using NetSim’s Packet Animation. Packet flow can be analyzed using the Packet Trace log file as shown below:

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SI	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	ENB-7	SWITCH-5	86499	86499	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	SWITCH-5	AMF-3	86499	86499	
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	86539.4	86539.4	
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	86557.52	86557.52	
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	86575.64	86575.64	
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	86593.76	86593.76	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	AMF-3	SWITCH-5	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	SWITCH-5	ENB-7	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	ENB-7	SWITCH-5	86652.28	86652.28	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	SWITCH-5	AMF-3	86652.28	86652.28	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	ENB-7	SWITCH-4	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	SWITCH-4	GNB-8	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	GNB-8	SWITCH-4	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	SWITCH-4	ENB-7	N/A	N/A	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
1	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1001168	1001168	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1002336	1002336	
2	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
4	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	GNB-8	1003504	1003504	
5	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1004672	1004672	
6	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1005840	1005840	
4	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1003504	1003504	
6	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1005840	1005840	
6	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1005840	1005840	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

Figure 3-47: Packet flow can be analyzed using the Packet Trace

3.15.8 Option 7x

Consider the following network scenario:

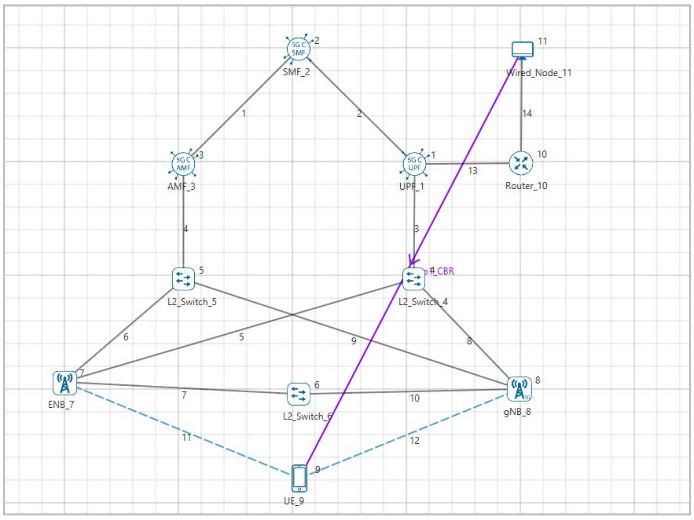


Figure 3-48: NSA deployment - Option 7x networking mode in NetSim

All the devices have the default properties, application start time was set to 1s and scenario is simulated for 10s.

The packet flow in the network takes place as explained below:

1. The MN, eNB will send broadcast the RRC_MIB packets to the UE every 40 ms and RRC_SIB1 every 80 ms.
2. After the transmission of the RRC_MIB and RRC_SIB1 packets, the eNB will send RRC_SI packet to the UE.
3. After reception of RRC_SI packet, UE will send RRC_Setup_Request to the eNB.
4. On receiving the RRC_Setup_Request packet, the eNB will acknowledge the request by transmitting RRC_Setup packet to the UE.
5. The UE will send back the RRC_Setup_Complete packet on the receipt of RRC_Setup message.
6. The eNB will send INITIAL_UE_MSG_AND_REGISTRATION_REQUEST to the AMF via L2Switch_5 through the N1_N2 interface.
7. AMF will send CREATE_SESSION_REQUEST to SMF through N11 interface.
8. SMF will send PFCP_SESSION_REQUEST to UPF through N4 interface.
9. UPF will send back the response packet to SMF, i.e, PFCP_SESSION_RESPONSE
10. SMF will send back the response packet to AMF, i.e., CREATE_SESSION_RESPONSE.
11. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the eNB via Switch_5.
12. On the receipt of Context setup request, eNB will send INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE packet to the AMF via switch_5 through the N1_N2 interface.
13. This marks the completion of UE registration process.
14. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_6.
15. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e., DC_SEC_CELL_ADDITION_RESPONSE.
16. The UE will now send the UE_MEASUREMENT_REPORT every 120 ms to the MN which contains the SNR information. The time interval at which the measurement report is to be transmitted can be set by the user in the eNB/ gNB properties-> Interface_ LTE/ 5G_RAN -> Datalink Layer.
17. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
18. As per the current splitting algorithm in NetSim, the first data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, eNB via Switch_4

through the N3 interface, and from the eNB it will be transmitted to the UE through the LTE interface.

19. The second data packet will flow from UPF to the eNB via Switch_4 and then from eNB to the gNB via Switch_6 through XN interface and then to the UE.
20. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

The packet flow can be analyzed using the Packet Trace file as shown below:

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVA
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SI	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_REQUEST	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP	ENB-7	UE-9	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SETUP_COMPLETE	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	ENB-7	SWITCH-5	86499	86499	
0	0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	ENB-7	AMF-3	SWITCH-5	AMF-3	86499	86499	
0	0	Control_Packet	CREATE_SESSION_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	86539.4	86539.4	
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	86557.52	86557.52	
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	86575.64	86575.64	
0	0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	86593.76	86593.76	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	AMF-3	SWITCH-5	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	ENB-7	SWITCH-5	ENB-7	86611.88	86611.88	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	ENB-7	SWITCH-5	86652.28	86652.28	
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_RE	ENB-7	AMF-3	SWITCH-5	AMF-3	86652.28	86652.28	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	ENB-7	SWITCH-6	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_REQUEST	ENB-7	GNB-8	SWITCH-6	GNB-8	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	GNB-8	SWITCH-6	N/A	N/A	
0	N/A	Control_Packet	DC_SEC_CELL_ADDITION_RESPONSE	GNB-8	ENB-7	SWITCH-6	ENB-7	N/A	N/A	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	ENB-7	UE-9	ENB-7	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_SIB1	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A
0	N/A	Control_Packet	RRC_MIB	ENB-7	Broadcast-0	ENB-7	UE-9	N/A	N/A	N/A

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIV
1	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1001168	1001168	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
1	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1000000	1000000	
2	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	SWITCH-6	1001168	1001168	
2	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	GNB-8	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1002336	1002336	
2	0	CBR	App1_CBR	NODE-11	UE-9	GNB-8	UE-9	1001168	1001168	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
3	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	UE-9	1002336	1002336	
4	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	ENB-7	SWITCH-6	1003504	1003504	
4	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-6	GNB-8	1003504	1003504	
5	0	CBR	App1_CBR	NODE-11	UE-9	NODE-11	ROUTER-10	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	ROUTER-10	UPF-1	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	UPF-1	SWITCH-4	1004672	1004672	
5	0	CBR	App1_CBR	NODE-11	UE-9	SWITCH-4	ENB-7	1004672	1004672	

Packet Trace | Pivot Table(TX-RX) | Pivot Table(Custom)

Figure 3-49: Packet flow can be analyzed using the Packet Trace

3.16 Handover

3.16.1 Use of SNR instead of RSRP

NetSim is a packet-level simulator for simulating the performance of end-to-end applications over various packet transport technologies. NetSim can scale to simulating networks with 100s of UEs, gNBs, routers, switches, etc. In order to achieve a scalable simulation, that can execute in reasonable time on desktop-level computers, many details of the physical layer techniques have been abstracted.

In 5G, NetSim does not model control channels; there are no pilots/reference/synchronization signals. The channel matrix H is assumed to be known perfectly and instantaneously at the transmitter and receiver, respectively. Hence there is no RSRP, and all signal power related calculations are done using the data channel itself. Therefore, the hand-over is based on the SNR measured at the s-gNB and the t-gNB.

3.16.2 Handover algorithm

The handover logic of NetSim 5G library is based on the *Strongest Adjacent Cell Handover Algorithm* (Ref: Handover within 3GPP LTE: Design Principles and Performance. Konstantinos Dimou. Ericcson Research). The algorithm enables each UE to connect to that gNB which provides the highest SNR. Therefore, a *handover occurs the moment a better gNB - adjacent cell has offset stronger RSRP (measured as SNR in NetSim) - is detected*. If there is more than one gNB with offset higher signal strength, then the gNB with the highest signal strength becomes the target gNB.

This algorithm is similar to *38.331, 5.5.4.4 Event A3* wherein Neighbor cell's RSRP becomes Offset better than serving cell's RSRP. Note that in NetSim report-type is *periodical* and not *eventTrigerred* since NetSim is a discrete event simulator and not a continuous time simulator. Therefore, the signal strength comparisons between source-gNB and all other gNBs is done every time a UE Measurement report is received at the source gNB. The signal strength compared is the average of all layers across all carriers.

This algorithm is susceptible to ping-pong handovers; continuous handovers between the serving and adjacent cells on account of changes in SNR due mobility and shadow-fading. At one instant the adjacent cell's SNR could be higher and the very next it could be the original serving cell's RSRP, and so on. To solve this problem the algorithm uses:

- Hysteresis (Hand-over-margin, HOM) which adds a SNR threshold (Adjacent_cell_SNR - Serving_cell_SNR > Hand-over-margin or hysteresis), and
- Time-to-trigger (TTT) or hysterisis which adds a time threshold.

This HOM is part of NetSim implementation while TTT can be implemented as a custom project in NetSim.

3.16.3 Packet flow during handover

NetSim implements on those aspects of the 5G handover procedure that directly affects network performance. Other aspects of the handover, for example security, are either not implemented or abstracted since they do not affect network performance. Handovers can occur in RRC_CONNECTED (during active Tx or Rx) or in RRC_IDLE states (no Tx or Rx).

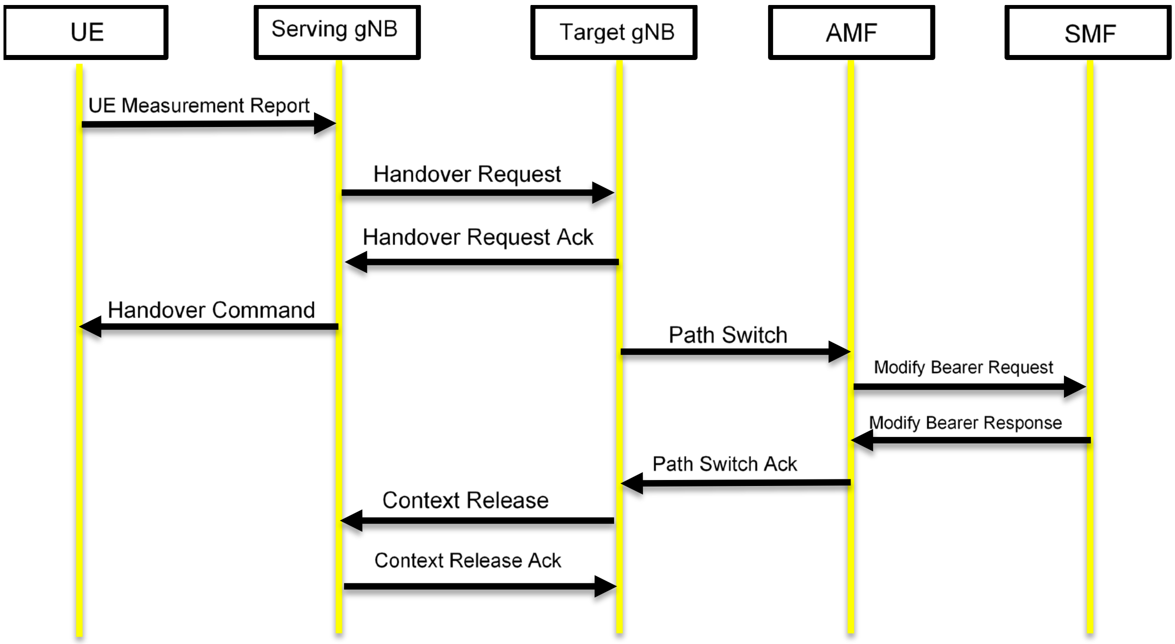


Figure 3-50: Control packet flow in the 5G handover process

The packet flow (which can be observed from the packet trace) is as follows:

1. Once the UE connection and association procedures are completed, the UE sends a UE_MEASUREMENT_REPORT every UE_Measurement_Report_Interval to the connected gNB. UE_Measurement_Report_Interval is by default set as 120ms in NetSim and is a user configurable parameter.
2. At some time, neighbor cell RSRP (measured as SNR in NetSim) becomes offset higher than serving cell RSRP.
3. Immediately after receiving the next UE_MEASUREMENT_REPORT, source gNB (also sometimes called serving gNB) sends a HANDOVER REQUEST to the target (neighbor) gNB. This packet is sent through the Xn interface via a 5G-Core Switch. All the links in the 5G Core are by default 10 Gbps.
4. The Target gNB sends back HANDOVER REQUEST ACK to serving gNB, again via the Xn interface. If the HANDOVER REQUEST or the HANDOVER REQUEST ACK are errored then if the target gNB signal strength continues to be offset higher than source gNB signal strength, step 1 is repeated at the next UE_MEASUREMENT_REPORT.
5. After receiving HANDOVER REQUEST ACK the serving gNB sends the HANDOVER COMMAND to UE.
6. Then HANDOVER COMMAND packet is send by source gNB to the UE.
7. The target gNB then sends RRC Reconfiguration msg to UE. If UE is in RRC Connected mode than the target gNB is assigned as new source gNB for the UE.

8. The target gNB will send the PATH SWITCH packet to the AMF through the N1-N2 interface (via a core switch).
9. When the AMF receives the PATH SWITCH packet, it sends MODIFY BEARER REQUEST to the SMF. This is over the N11 interface.
10. The SMF on receiving the MODIFY BEARER REQUEST sends back the MODIFY BEARER RESPONSE to the AMF.
11. On receiving the MODIFY BEARER RESPONSE from the SMF, AMF acknowledges the Path switch request sent by the target gNB by sending the PATH SWITCH ACK packet back to the target gNB. This is over the N1-N2 interface, via a 5GC switch.
12. The target gNB the sends a UE CONTEXT RELEASE to source gNB, and the source gNB sends back UE CONTEXT RELEASE ACK to target gNB. The context release request and ack packets are sent between the source and target gNB via the Xn interface.
13. Then RRC Reconfiguration takes place between target gNB and UE.
14. UE starts sending the UE MEASUREMENT REPORT to the new source gNB

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_AR
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-10	N/A	18560000	
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	18560000	
0	N/A	Control_Packet	RRC_SIB1	GNB-8	Broadcast-0	GNB-8	UE-10	N/A	18560000	
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	18560000	
0	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-10	N/A	18560000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-7	UE-9	GNB-7	N/A	18600000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-10	GNB-8	UE-10	GNB-8	N/A	18600000	
0	N/A	Control_Packet	HANDOVER_REQUEST	GNB-7	GNB-8	GNB-7	SWITCH-6	18600999	18600999	
0	N/A	Control_Packet	HANDOVER_REQUEST	GNB-7	GNB-8	SWITCH-6	GNB-8	18600999	18600999	
0	N/A	Control_Packet	HANDOVER_REQUEST_ACK	GNB-8	GNB-7	GNB-8	SWITCH-6	18601027.88	18601027.88	
0	N/A	Control_Packet	HANDOVER_REQUEST_ACK	GNB-8	GNB-7	SWITCH-6	GNB-7	18601027.88	18601027.88	
0	N/A	Control_Packet	HANDOVER_COMMAND	GNB-7	UE-9	GNB-7	UE-9	N/A	18601056.76	
0	0	Control_Packet	PATH_SWITCH	GNB-8	AMF-3	GNB-8	SWITCH-5	18602999	18602999	
0	0	Control_Packet	PATH_SWITCH	GNB-8	AMF-3	SWITCH-5	AMF-3	18602999	18602999	
0	0	Control_Packet	MODIFY_BEARER_REQUEST	AMF-3	SMF-2	AMF-3	SMF-2	18603035.24	18603035.24	
0	0	Control_Packet	MODIFY_BEARER_RESPONSE	SMF-2	AMF-3	SMF-2	AMF-3	18603053.36	18603053.36	
0	0	Control_Packet	PATH_SWICTH_ACK	AMF-3	GNB-8	AMF-3	SWITCH-5	18603071.48	18603071.48	
0	0	Control_Packet	PATH_SWICTH_ACK	AMF-3	GNB-8	SWITCH-5	GNB-8	18603071.48	18603071.48	
0	N/A	Control_Packet	UE_CONTEXT_RELEASE	GNB-8	GNB-7	GNB-8	SWITCH-6	18603111.88	18603111.88	
0	N/A	Control_Packet	UE_CONTEXT_RELEASE	GNB-8	GNB-7	SWITCH-6	GNB-7	18603111.88	18603111.88	
0	N/A	Control_Packet	UE_CONTEXT_RELEASE_ACK	GNB-7	GNB-8	GNB-7	SWITCH-6	18603140.76	18603140.76	
0	N/A	Control_Packet	UE_CONTEXT_RELEASE_ACK	GNB-7	GNB-8	SWITCH-6	GNB-8	18603140.76	18603140.76	
0	N/A	Control_Packet	RRC_RECONFIGURATION	GNB-8	UE-9	GNB-8	UE-9	N/A	18602999	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-10	GNB-8	UE-10	GNB-8	N/A	18720000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-9	GNB-8	UE-9	GNB-8	N/A	18720000	

Figure 3-51: Screen shot of NetSim packet trace file showing the control packets involved in handover. Some columns have been hidden before the last column.

3.17 LTENR Results, Packet Trace and Plots

Parameter	Description
AppID	Application ID
QFI	QOS Flow ID
SDAP Entity	SDAP Entity
SrcID	Source ID
DestID	Destination ID
SrcIP:Port	Tuple of Source IP and Port Number
DestIP:Port	Tuple of Source IP and Port Number
Packet Tx	Total packets transmitted for a QFI
Packet Rx	Total packets received for a QFI
Delay	Average delay of all received packets within an average window
PER (Packet Error Rate)	Packet Error Rate Plot
PDB (Packet Delay Budget)	Packet Delay Budget Plot

Table 3-9: LTENR results Packet trace parameter descriptions

3.17.1 LTE NR Packet trace

The LTE NR packet trace file has in its last column the field LTENR_PACKET_INFO. This field has information relating to PDCP header and RLC header. The packet trace file can be opened from results dashboard.

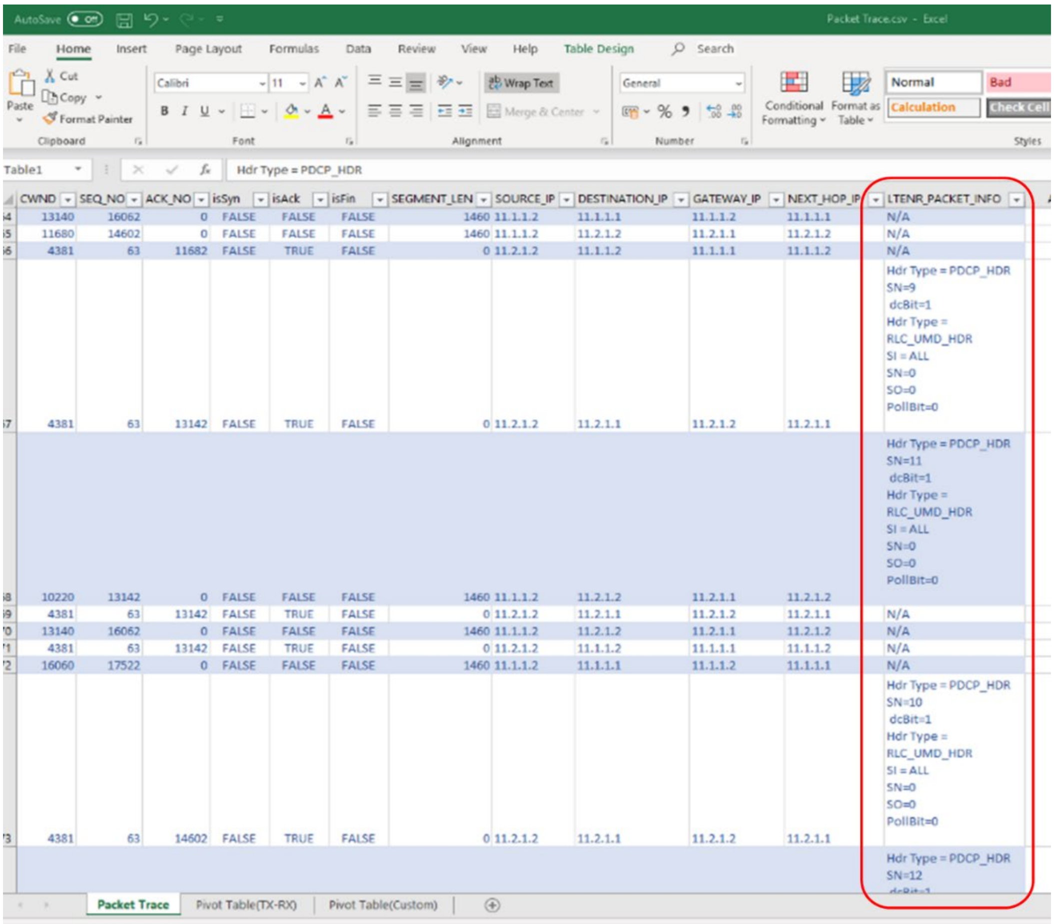


Figure 3-52: LTE NR Packet Trace. Depending on Excel settings in some cases the entire header may not be displayed. User can do Ctrl + A (Select All) -> Right Click -> Format Cells -> Alignment -> Wrap Text to view the complete header.

3.17.2 PDCP and RLC Headers logged in Packet Trace

The PDCP and RLC header fields are logged in the LTENR_PACKET_INFO field of NetSim's packet trace.

The PDCP header fields are.

- D/C field termed as dCBit in NetSim. This is 0 for control PDU and 1 for Data PDU
- SN field termed SN in NetSim. This provides the sequence number of the PDCP PDU

The RLC header fields are.

- Header Type: If the packet is TMD, UMD or AMD PDU
- Segment Information (SI) field: The meaning of each possible SI field value is defined in the table below Table 3-10.

Value	Description
SI=ALL	Data field contains all bytes of RLC SDU
SI=FIRST	Data field contains first segment of an RLC SDU
SI=LAST	Data field contains last segment of an RLC SDU
SI=MIDDLE	Data field contains neither the first nor the last segment of RLC SDU

Table 3-10: RLC header fields

- SN: The SN field indicates the sequence number of the corresponding RLC SDU. For RLC AM, the sequence number is incremented by one for every RLC SDU. For RLC UM, the sequence number is incremented by one for every segmented RLC SDU. RLC service data units (SDUs) coming from the upper layer are segmented or concatenated to RLC protocol data units (PDUs) which has a predefined size. Each PDU is assigned its own sequence number (SN). RLC AM on receiver side will reassemble these PDUs into SDUs using the sequence number.
- SO: The SO field indicates the position of the RLC SDU segment in bytes within the original RLC SDU. Specifically, the SO field indicates the position within the original RLC SDU to which the first byte of the RLC SDU segment in the Data field corresponds.
- Pollbit: The P field indicates whether or not the transmitting side of an AM RLC entity requests a STATUS report from its peer AM RLC entity. 0 indicated that the Status report not requested, while 1 indicates that the Status report is requested.

3.17.3 LTENR Event Trace

3.17.3.1 Sub event types

1. LTENR_StartFrame

- Downlink and uplink transmissions are organized into frames.
- There is one set of frames in the uplink and one set of frames in the downlink on a carrier.
- This event is triggered when a frame is formed.
- As frame length is 10ms, the event gets triggered every 10ms.

(LTENR->LTENR_Phy.c-> LTENR_addStartFrameEvent())

2. LTENR_Start_Subframe

- Each frame consists of 10 subframes.
- Event gets triggered every 1 ms

  (LTENR->LTENR_Phy.c-> LTENR_addStartSubFrameEvent ())

3. LTENR_StartSlot

- Sub frames are divided into slots.
- Slot size depends on Numerology (μ)
- Event gets triggered every $\frac{1}{2^{\mu}}$ ms

  (LTENR->LTENR_Phy.c-> LTENR_addStartSlotEvent ())

4. LTENR_Generate_RRC_MIB

- The timer event triggered every 80ms to generate and broadcast MIB packets from gNBs to all UEs.

  (LTE-NR->LTENR_GNBRRC.c->fn_NetSim_LTENR_GNBRRC_GenerateMIB())

5. **LTENR_Generate_RRC_SIB1**
   - The timer event triggered every 160ms to generate and broadcast SIB1 packets from gNB to all UEs.

     (LTE-NR-> LTENR_GNBRRC.c-> fn_NetSim_LTENR_GNBRRC_GenerateSIB1())
6. **LTENR_Generate_RRC_SI**
   - Timer event triggered when the selected gNB broadcasts RRC_SI packets to all the UEs.
   - This event is triggered only once, at 160.9ms, during the initial attachment process.

     (LTE-NR->LTENR_GNBRRC.c->fn_NETSIM_LTENR_SUBEVENT_GENERATE_SI())
7. **LTENR_Generate_RRC_Setup_Request**
   - Triggered when RRC setup request gets transmitted by UE to connected gNB
8. **LTENR_RRC_T300**
   - The timer event triggered when RRC_Setup_Request is sent by UE to gNB.
   - The timer T300 stops when the RRC_setup message is received by the UE

     (LTENR->LTEGNBRRC.c->LTENR_RRC_START_T300()

     and LTENR_RRC_STOP_T300() (line #1290))
9. **LTENR_Generate_RRC_Setup**
   - Event triggered when RRC_Setup message is sent by the selected gNB to the UE.
   - The RRC_Setup message is generated to establish the RRC connection between the UE and the gNB.

     (LTENR->LTEGNBRRC.c->fn_NetSIM_LTENR_RRC_GENERATE_RRCSETUP())
10. **LTENR_Generate_RRC_Setup_Complete**
    - Timer event triggered during the successful establishment of RRC connection.
11. **LTENR_Generate_RRC_UE_Measurement_Report_Request**
    - Timer event triggered every 120ms, when the gNB sends measurement report request to UE.
12. **LTENR_Generate_RRC_UE_Mesurement_Report**
    - Timer event triggered when UE sends measurement report to the serving gNB which contains SINR information from all the gNBs.
    - Triggered at 240ms after RRC connection establishment and then triggered every 120ms.
13. **PDCP_DiscardTimer**
    - When the discardTimer expires for a PDCP SDU, or the successful delivery of a PDCP SDU is confirmed by PDCP status report, the transmitting PDCP entity shall discard the PDCP SDU along with the corresponding PDCP Data PDU

- Discarding a PDCP SDU already associated with a PDCP SN causes a SN gap in the transmitted PDCP Data PDUs, which increases PDCP reordering delay in the receiving PDCP entity.
  (LTENR->LTENR_PDCP.c-LTENR_PDCP_START_DISCARD_TIMER ())

14. LTENR_Generate_NAS_Handover_Request

- Timer event triggered when the initial Handover_Request is sent by the serving gNB. The handover request is triggered when the SNR from target gNB exceeds the serving gNB by a margin of 3db.

15. Handover_Request_Ack

- Timer event triggered when the target gNB receives handover request from the serving gNB and sends back an acknowledgement for the handover request.

16. Handover_Request_Command

- Triggered when gNB sends Handover_Command to UE after receipt of Handover Request Ack

17. Handover_Request_Command_Handle

- Event triggered when UE dissociates from interface of serving gNB and associates with interface of target gNB during a handover.
- Functions like FindInterface(), pathswitch() and RRC_Reconfiguration() are called in this function
  (LTENR->LTENR_NAS.c->fn_NetSim_LTENR_NAS_GENERATE_HANDOVER_COMMAND_HANDLE())

18. Path_Switch

- Triggered when the target gNB sends the pathswitch packet to the EPC in order to transfer the data path from serving gNB to target gNB.

19. Path_Switch_Ack

- Triggered when EPC sends acknowledgement to the target gNB on the receipt of the path-switch request.

20. UE_Context_Release

- Event triggered after successful handover procedure.
- Triggered when target gNB sends context release packet to the serving gNB

21. UE_Context_Release_Ack

- Triggered when acknowledgement is provided by serving gNB to the target gNB on receipt of context release packet.

3.18 Enable detailed logs in 5G NR

A detailed 5G NR log can be enabled by a user, by going to the file LTE_NR.c, and then onto the function bool get_ltenr_log_status(), and changing the return status to true.

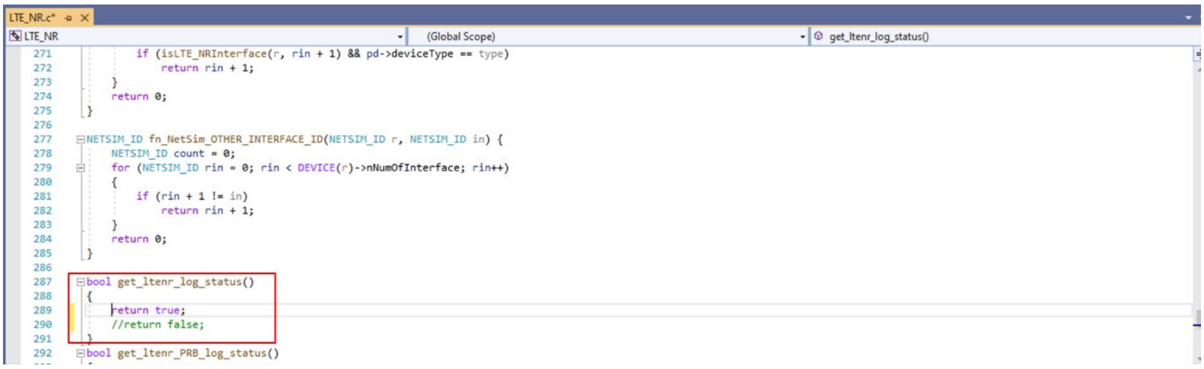


Figure 3-53: Enable LTE_NR log file in visual studio

Then rebuild the code and run the simulation.

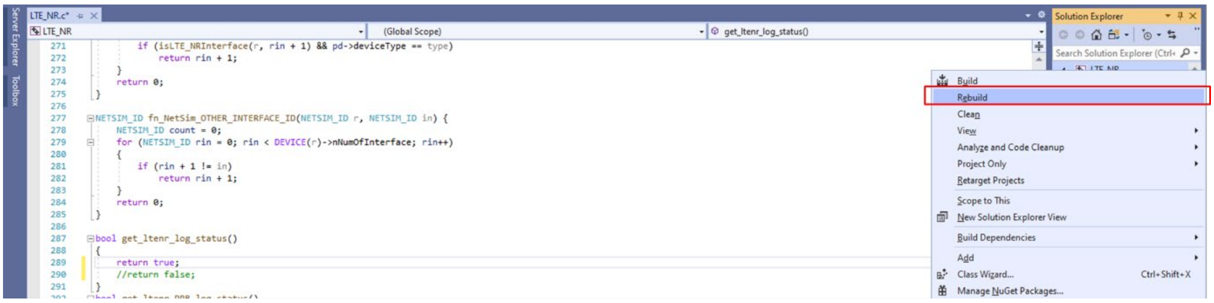


Figure 3-54: Rebuild 5G Project

The log file will be available under Log Files menu in the left panel of the Results Window.

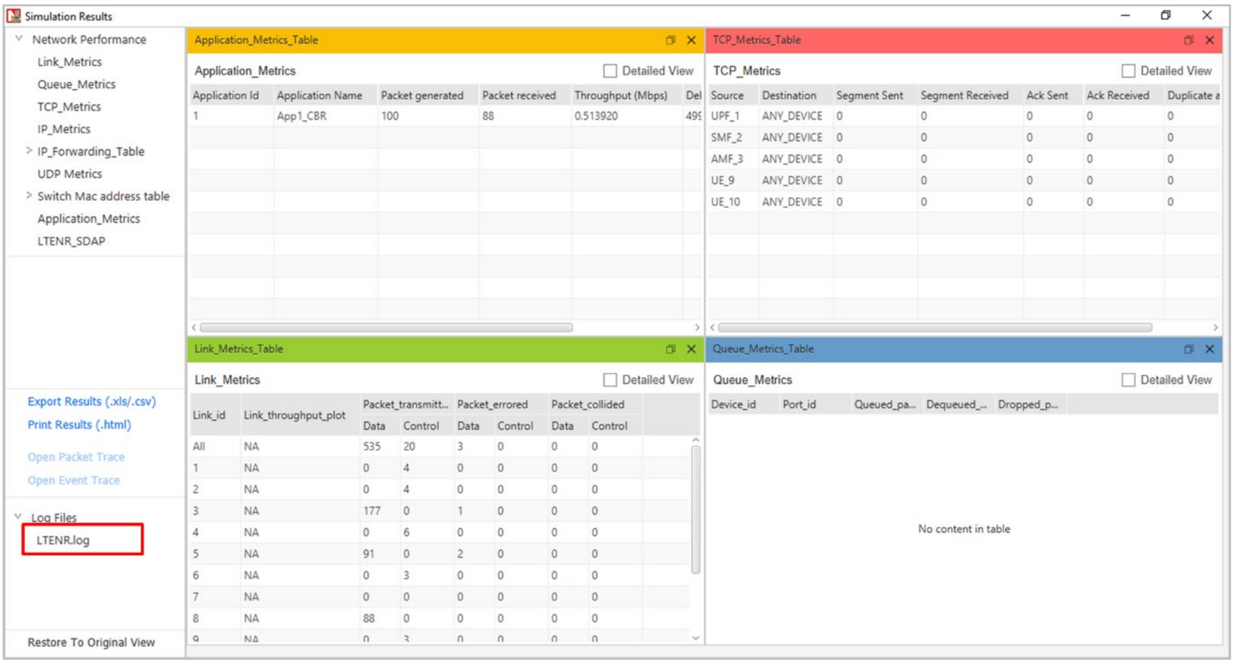


Figure 3-55: Results Window

Among various values noted in the log file is the CQI and MCS information. For example, a user would see in the log file:

CQI Table

15 256QAM 948 7.406300

MCS Table

27 256QAM 8 948.000000 7.406300

The CQI information is according to the 38-214 **Table 5.2.2.1-2, 5.2.2.1-3, 5.2.2.1-4**. And in the above example:

- CQI Index: 15
- Modulation: 256QAM
- Code Rate x [1024]: 948
- Efficiency: 7.406300

The MCS information is according to the 38-214 **Table 5.1.3.1-1, 5.1.3.1-2, 5.1.3.1-3**. And in the above example:

- MCS Index:27
- Modulation: 256QAM
- Modulation Order: 8
- Target code Rate x [1024]: 948.000000
- Spectral efficiency: 7.406300

4 Featured Examples

4.1 Understand 5G simulation flow through LTENR log file

Open NetSim, Select **Examples ->5G NR ->5G Log File and Packet Trace** then click on the tile in the middle panel to load the example as shown in below screenshot

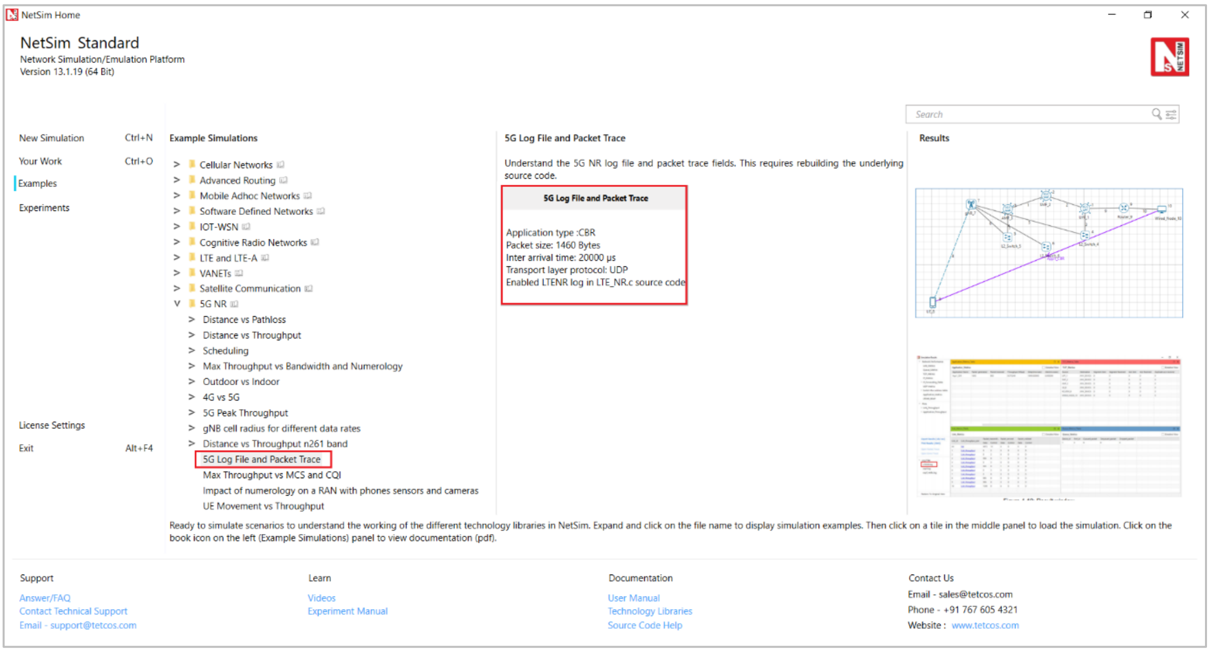


Figure 4-1: List of scenarios for the example of 5G Log File and Packet Trace

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

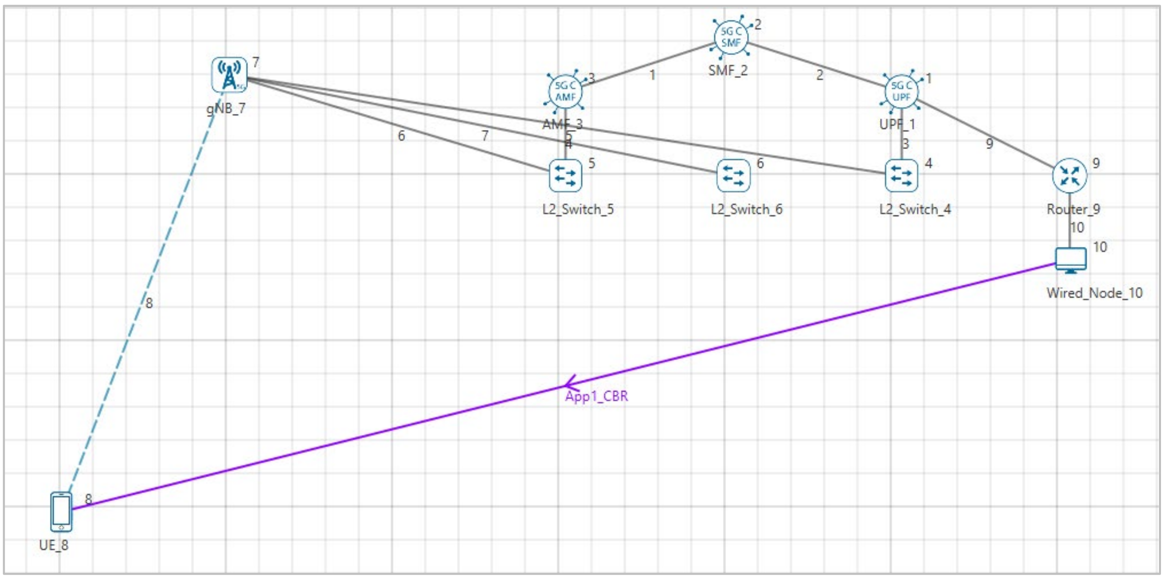


Figure 4-2: Network set up for studying the 5G Log File and Packet Trace

Settings done in example config file:

1. CBR application source id as 10 and destination id as 8 with Packet_Size as 1460 and InterArrival_Time as 20000 (Generation rate of 0.584 Mbps). Transport Protocol is set to **UDP**.
2. Set other properties to default.
3. The log file can enable per the information provided in Section 3.18.
4. Enable Plots and Run Simulation for 10s.

To view and study the 5GNR design/flow of the simulation, use the LTENR.log file which can be opened post simulation from Results Window > Log Files.

For logging additional information relating to Buffer-status-notification and Transmission-status-notification, open the source code and inside the LTE NR project, uncomment the lines given below in stdafx.h

stdafx.h

```
#define LTENR_SDAP_LOG

#define LTENR_PDCP_LOG

#define LTENR_RLC_BUFFERSTATUSREPORTING_LOG
```

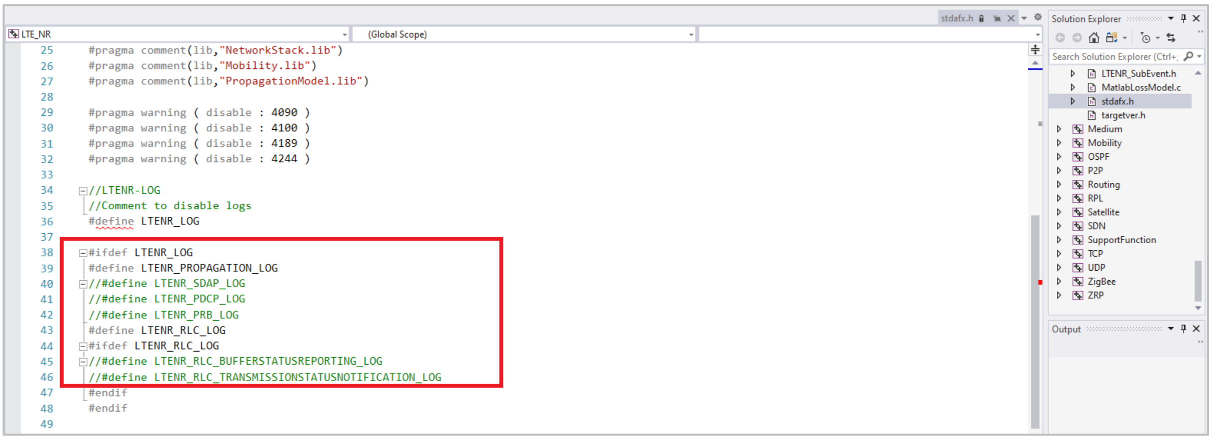


Figure 4-3: LTENR code to log Buffer-status-notification and Transmission-status-notification

Rebuild the code to enable logs per Section 3.18 in the 5G-NR manual. Note that log files would generally be quite large (>10 MB of size). In the GUI enable packet trace and event trace before running the simulation. Run the simulation. Open the packet trace and ltenr.log file from the results window.

1. The Physical Resource Block (PRB) list is formed at the beginning of the log file. This corresponds to 1 slot $\left(\frac{1}{2^{\mu}}\ ms\right)$ in time-domain and $15 * 12 * 2^{\mu}$ kHz in frequency domain.

LTENR.log

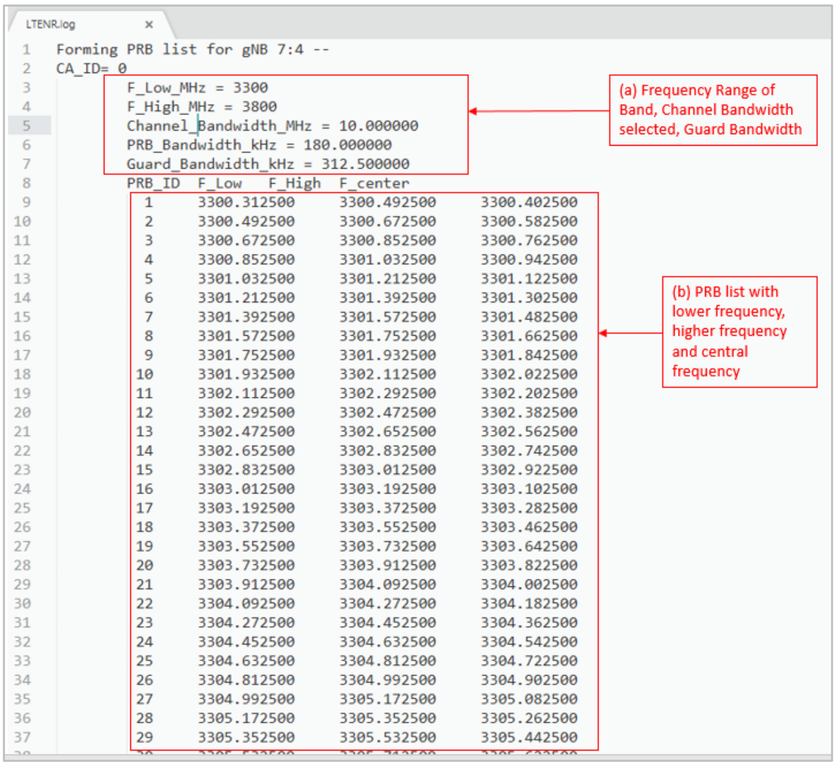
```
Forming PRB list for gNB 7:4 --
CA_ID= 0
        F_Low_MHz = 3300
        F_High_MHz = 3800
        Channel Bandwidth_MHz = 10.000000
        PRB_Bandwidth_kHz = 180.000000
        Guard_Bandwidth_kHz = 312.500000
        PRB_ID  F_Low    F_High  F_center
          1     3300.312500     3300.492500     3300.402500
          2     3300.492500     3300.672500     3300.582500
          3     3300.672500     3300.852500     3300.762500
          4     3300.852500     3301.032500     3300.942500
          5     3301.032500     3301.212500     3301.122500
          6     3301.212500     3301.392500     3301.302500
          7     3301.392500     3301.572500     3301.482500
          8     3301.572500     3301.752500     3301.662500
          9     3301.752500     3301.932500     3301.842500
         10     3301.932500     3302.112500     3302.022500
         11     3302.112500     3302.292500     3302.202500
         12     3302.292500     3302.472500     3302.382500
         13     3302.472500     3302.652500     3302.562500
         14     3302.652500     3302.832500     3302.742500
         15     3302.832500     3303.012500     3302.922500
         16     3303.012500     3303.192500     3303.102500
         17     3303.192500     3303.372500     3303.282500
         18     3303.372500     3303.552500     3303.462500
         19     3303.552500     3303.732500     3303.642500
         20     3303.732500     3303.912500     3303.822500
         21     3303.912500     3304.092500     3304.002500
         22     3304.092500     3304.272500     3304.182500
         23     3304.272500     3304.452500     3304.362500
         24     3304.452500     3304.632500     3304.542500
         25     3304.632500     3304.812500     3304.722500
         26     3304.812500     3304.992500     3304.902500
         27     3304.992500     3305.172500     3305.082500
         28     3305.172500     3305.352500     3305.262500
         29     3305.352500     3305.532500     3305.442500
         30     3305.532500     3305.712500     3305.622500
         31     3305.712500     3305.892500     3305.802500
```

$15 * 2 * 2^{\mu}$ KHz

Figure 4-4: LTE NR Log File- PRB List

2. The naming convention used in the ltenr log file is gNB <gnb ID>:<Interface>. For example, gNB 7:4 means gNB 7 interface 4.

    - For each numerology and carrier, a resource grid of (max. number of resource blocks for that numerology) * (number of sub-carriers per resource block) and (number of symbols per sub-frame of that numerology) is defined.
    - In this example the GUI settings (gNB 5G-RAN interface Physical Layer) are:
        - μ (numerology) is set 0.
        - No. of resource blocks (PRB count) = 52
        - No. of sub-carriers per PRB = 12
        - No. of symbols per sub-frame of numerology (0) = 1.
    - The log file explains the PRB list for gNB (7) on interface (4):
        - The lowest (F_Low_MHz) and highest frequency (F_High_MHz) for the Uplink/Downlink operating bands are logged first along with the channel bandwidth (MHz), PRB bandwidth(kHz) and guard bandwidth(kHz).
        - The list defines the lower frequency, upper frequency, and central frequency in MHz for each physical resource block of the PRB count.



```
LTENR.log
Forming PRB list for gNB 7:4 --
CA_ID= 0
        F_Low_MHz = 3300
        F_High_MHz = 3800
        Channel_Bandwidth_MHz = 10.000000
        PRB_Bandwidth_kHz = 180.000000
        Guard_Bandwidth_kHz = 312.500000
        PRB_ID  F_Low    F_High   F_center
         1      3300.312500     3300.492500     3300.402500
         2      3300.492500     3300.672500     3300.582500
         3      3300.672500     3300.852500     3300.762500
         4      3300.852500     3301.032500     3300.942500
         5      3301.032500     3301.212500     3301.122500
         6      3301.212500     3301.392500     3301.302500
         7      3301.392500     3301.572500     3301.482500
         8      3301.572500     3301.752500     3301.662500
         9      3301.752500     3301.932500     3301.842500
        10      3301.932500     3302.112500     3302.022500
        11      3302.112500     3302.292500     3302.202500
        12      3302.292500     3302.472500     3302.382500
        13      3302.472500     3302.652500     3302.562500
        14      3302.652500     3302.832500     3302.742500
        15      3302.832500     3303.012500     3302.922500
        16      3303.012500     3303.192500     3303.102500
        17      3303.192500     3303.372500     3303.282500
        18      3303.372500     3303.552500     3303.462500
        19      3303.552500     3303.732500     3303.642500
        20      3303.732500     3303.912500     3303.822500
        21      3303.912500     3304.092500     3304.002500
        22      3304.092500     3304.272500     3304.182500
        23      3304.272500     3304.452500     3304.362500
        24      3304.452500     3304.632500     3304.542500
        25      3304.632500     3304.812500     3304.722500
        26      3304.812500     3304.992500     3304.902500
        27      3304.992500     3305.172500     3305.082500
        28      3305.172500     3305.352500     3305.262500
        29      3305.352500     3305.532500     3305.442500
```


Figure 4-5: LTE NR Log File- Lower, Higher and Central Frequencies for PRB List

3. The UE association/dissociation is done which is logged. UE (8) on interface (1) associates with gNB (7) on interface (4). During UE association:
    - The Adaptive Modulation and Coding (AMC) information is initialized for Uplink and Downlink:
        - AMC information: Links Spectral efficiency is calculated and based on this Channel quality indicator (CQI) (Includes the CQI index, modulation, code rate and efficiency) and Modulation coding scheme (MCS) (Includes the MCS index, modulation, modulation order, code rate and spectral efficiency) is read from the standard table and setup for both Downlink and Uplink.

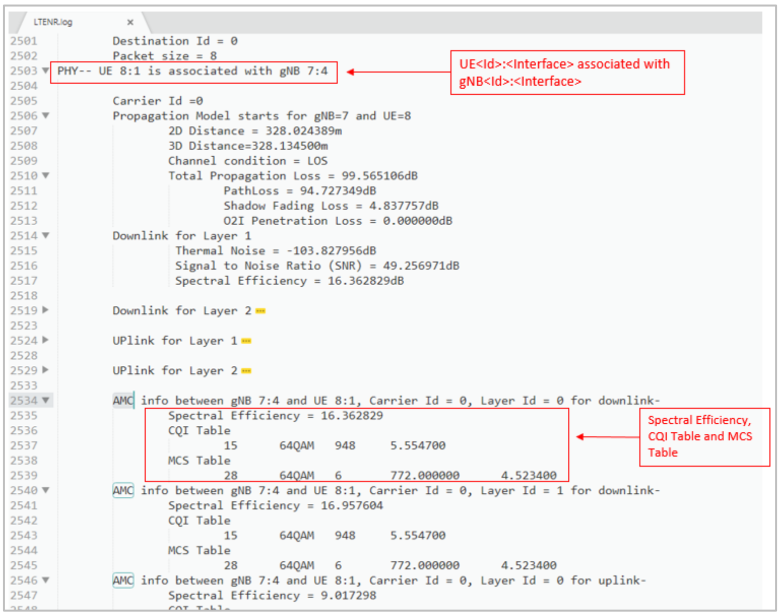


Figure 4-6: LTE NR Log File- UE Association

4. The numerology is equal to 0, hence the slots/sub-frame = 1 and there will be 10 sub-frames per frame. Accordingly, the frames, sub-frames and slots are created as shown below:

   - A new frame gets started for the gNB, where the frame id=1, start time and the end time of the frame are logged.
   - After the frame-1 starts, the sub-frame for the same gnb is started within the frame. The frame id=1, sub-frame id=1, start time and end time are logged
   - Within frame-1, sub-frame-1 a slot is started. This slot's ID (1), slot type (Uplink), start time and end time are logged.

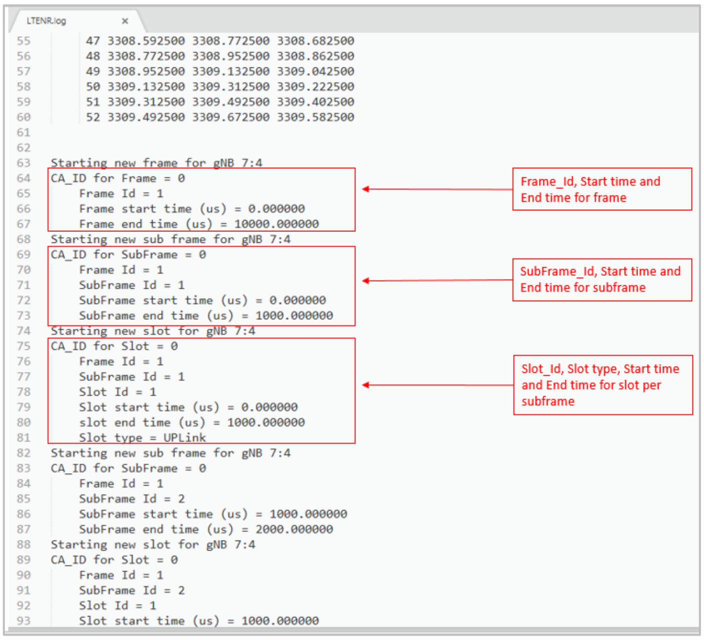


Figure 4-7: LTE NR Log File- Frame and Sub Frame list with start time and end time

5. The RLC-sublayer will check the UE buffer for packets. Based on the logical channel (DTCH) and the transmission mode (UM, AM), the entity is identified, and the buffer size of each mode is read. The combined buffer size of all the modes gives the total buffer size (number of bytes to be processed).
6. The RLC sub-layer then processes the transmission status notification for downlink:
   - Initially the RLC transmission for the control takes place, where the transmission status for each of the control logical channels i.e., BCCH, CCCH, DCCH and PCCH is calculated based on the mode (TM & AM) they support.
   - While calculating the transmission status for control, the RLC sends the Physical Data Unit (PDU) based on the mode (TM or AM).
   - Later the RLC transmission for the data packet happens, where the transmission status for traffic logical channel i.e., DTCH is calculated based on the AM and UM mode it supports.
   - DTCH channel supports Un-Ack mode (UM). It checks for the buffer and if the buffer isn't NULL:
     - It will find the buffer that matches the logical channel, and it only proceeds further if the size of the PDU is within the minimum RLC PDU size.
     - If the message packet is NULL (or) message type is user data & the payload of PDU is greater than size of PDU, it fragments the UM data buffer packet (or else) the buffer is marked for removal.
     - Then the RLC sends the PDU to the MAC layer. And then the RLC buffer gets updated.
7. At time 1000502.4 μs packet arrives at the Service Data Adaptation Protocol (SDAP) sub layer in the gNB:
   - As the packet arrives at the SDAP sub-layer, the SDAP header is appended to the Packet with header size.
   - SDAP sets the RLC mode (here, acknowledge mode) based on QoS, and the logical channel (DTCH) is chosen.
8. The packet is passed to the Packet Data Convergence Protocol (PDCP) sub-layer at gNB:
   - Packet is enqueued to the transmission (Tx) buffer and discard time is started.
   - PDCP header is added, and packet is passed to the RLC sub-layer.
9. The packet is then passed to the Radio Link Control (RLC) sub-layer at gNB and is added to the transmission buffer.

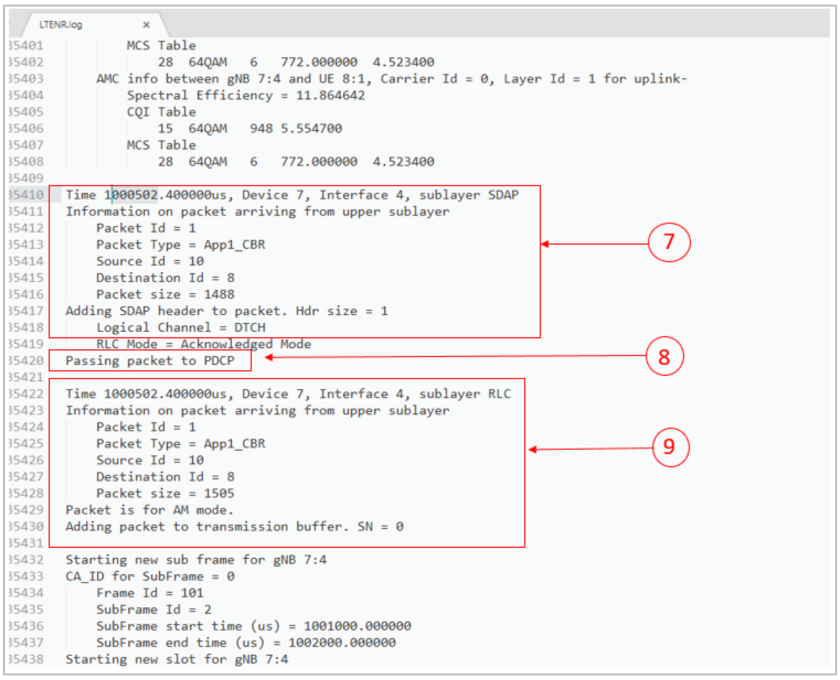


Figure 4-8: LTE NR Log File- SDAP, PDCP and RLC sublayers

10. Now a new sub frame id - 2 with slot id - 1 gets created for the frame id - 1. Here the slot type (Downlink)

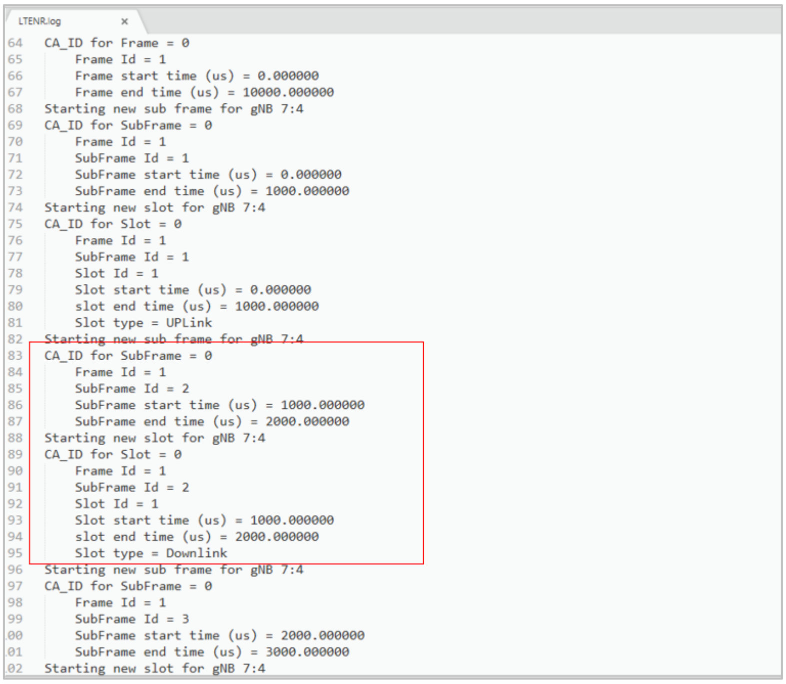


Figure 4-9: LTE NR Log File- Frame Id and slot Id

11. The RRC related packets like RRC_MIB, RRC_SIB1 arrives are RLC Sub-layer and the packets are added to the transmission buffer.

```
LTENR.log
    slot end time (us) = 160000.000000
    Slot type = Downlink

Time 160000.000000us, Device 7, Interface 4, sublayer RLC
Information on packet arriving from upper sublayer
    Packet Id = 0
    Packet Type = RRC_SIB1
    Source Id = 7
    Destination Id = 0
    Packet size = 8
Packet is TM mode.
Adding packet to transmission buffer.


Time 160000.000000us, Device 7, Interface 4, sublayer RLC
Information on packet arriving from upper sublayer
    Packet Id = 0
    Packet Type = RRC_MIB
    Source Id = 7
    Destination Id = 0
    Packet size = 8
Packet is TM mode.
Adding packet to transmission buffer.

Starting new frame for gNB 7:4
CA_ID for Frame = 0
    Frame Id = 17
    Frame start time (us) = 160000.000000
    Frame end time (us) = 170000.000000
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 17
    SubFrame Id = 1
    SubFrame start time (us) = 160000.000000
    SubFrame end time (us) = 161000.000000
Starting new slot for gNB 7:4
CA_ID for Slot = 0
    Frame Id = 17
    SubFrame Id = 1
```

Figure 4-10: LTE NR Log File- RRC Packet details

12. The data packet is sent from the transmission buffer in DTCH logical channel (for downlink) from gNB to UE. This packet is sent to the MAC sub-layer and the packet is then added to the transmitted buffer.

13. The packet enters the Radio Link Control (RLC) protocol sub-layer in the MAC layer at the UE:

    - The PDU (Physical Data Unit) is received at the UE, specific to RLC mode:
    - The AMPDU header of the packet is received and logged. If the sequence number of the PDU is outside the receiving window, the PDU is discarded.
    - It checks if the PDU is already present in the reception buffer. If present it drops the PDU and if the PDU is not present in the reception buffer, then it is added to the reception buffer: The sequence index (SI), sequence number (SN), and sequence order (SO) for the corresponding mode also get updated.
    - Checks if all the Service Data Unit (SDU) byte segments of the PDU packet have been received. If not, it waits for the remaining SDU's before transmitting packet. The reassembly is done for all the SDU if all the SDU byte segments of PDU packet are received.
    - Checks if the reassembly timer is started or not and stops if started and vice-versa.
    - And the status report of RLC-AM is set as delayed.

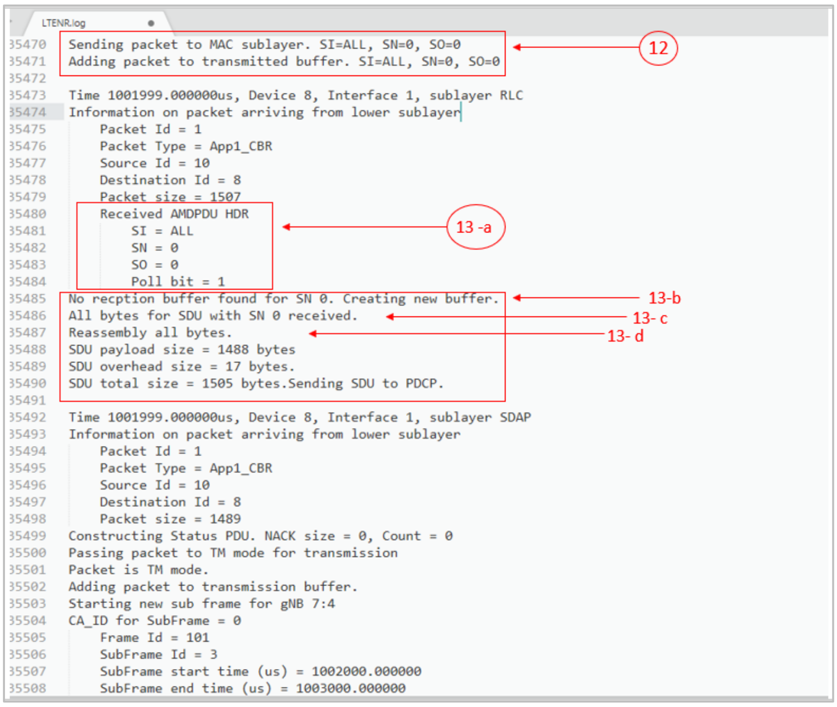


Figure 4-11: LTE NR Log File- MAC sublayer, AMDPDU Header

14. If the header exists, the STATUSPDU is constructed, else the status will be marked as delayed and the packet will pass to TM mode for transmission. PDU is handed over to RLC TM mode and packet gets added to transmission buffer.

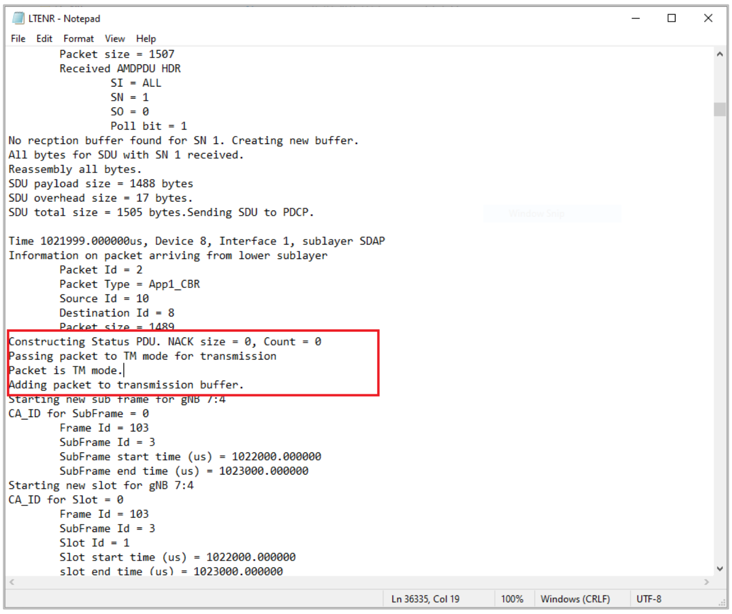


Figure 4-12: LTE NR Log File- STATUSPDU Construction

15. The packet is received by the PDCP sub-layer. The PDCP state variables like the receive sequence number(sn), receive hyper frame number(hfn) and the receive count are calculated.

16. Next the STATUSPDU gets transmitted from the UE to the gNB (See Packet Trace)

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(US)	TRX_LAYER_ARRIVAL_TIME(US)	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	480000	
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	480000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	480000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	560000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	600000	
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	640000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	640000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	720000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	720000	
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	800000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	800000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	840000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	880000	
0	N/A	Control_Packet	UE_MEASUREMENT_REPORT	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	960000	
0	N/A	Control_Packet	RRC_SIB1	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	960000	
0	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-8	N/A	N/A	N/A	960000	
1	0	CBR	App1_CBR	NODE-10	UE-8	NODE-10	ROUTER-9	1000000	1000000	1000000	1000000	
1	0	CBR	App1_CBR	NODE-10	UE-8	ROUTER-9	UPF-1	1000000	1000000	1000126.12	1000126.12	
1	0	CBR	App1_CBR	NODE-10	UE-8	UPF-1	SWITCH-4	1000000	1000000	1000250.16	1000250.16	
1	0	CBR	App1_CBR	NODE-10	UE-8	SWITCH-4	GNB-7	1000000	1000000	1000250.16	1000250.16	
1	0	CBR	App1_CBR	NODE-10	UE-8	GNB-7	UE-8	1000000	1000000	1000250.16	1000502.4	
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	1001999	
2	0	CBR	App1_CBR	NODE-10	UE-8	NODE-10	ROUTER-9	1020000	1020000	1020000	1020000	
2	0	CBR	App1_CBR	NODE-10	UE-8	ROUTER-9	UPF-1	1020000	1020000	1020126.12	1020126.12	
2	0	CBR	App1_CBR	NODE-10	UE-8	UPF-1	SWITCH-4	1020000	1020000	1020250.16	1020250.16	
2	0	CBR	App1_CBR	NODE-10	UE-8	SWITCH-4	GNB-7	1020000	1020000	1020250.16	1020250.16	
2	0	CBR	App1_CBR	NODE-10	UE-8	GNB-7	UE-8	1020000	1020000	1020250.16	1020502.4	
0	N/A	Control_Packet	STATUSPDU	UE-8	GNB-7	UE-8	GNB-7	N/A	N/A	N/A	1021999	
3	0	CBR	App1_CBR	NODE-10	UE-8	NODE-10	ROUTER-9	1040000	1040000	1040000	1040000	
3	0	CBR	App1_CBR	NODE-10	UE-8	ROUTER-9	UPF-1	1040000	1040000	1040126.12	1040126.12	
3	0	CBR	App1_CBR	NODE-10	UE-8	UPF-1	SWITCH-4	1040000	1040000	1040250.16	1040250.16	
3	0	CBR	App1_CBR	NODE-10	UE-8	SWITCH-4	GNB-7	1040000	1040000	1040250.16	1040250.16	

Figure 4-13: 5G NR Packet Trace

17. The packet enters the Radio Link Control (RLC) protocol sub-layer in the MAC layer at the UE. Specific to the RLC mode (TM), it receives the Physical Data Unit (PDU) at the UE:

    - Based on the control data type of the packet, the case is chosen.
    - Since it is STATUSPDU type, the STATUSPDU packet is received accordingly at the gNB. And the RLCAM transmitted buffer is cleared, and poll retransmit timer is stopped.

4.2 Effect of distance on pathloss for different channel models

Open NetSim, Select **Examples ->5G NR ->Distance vs Pathloss** then click on the tile in the middle panel to load the example as shown in below screenshot

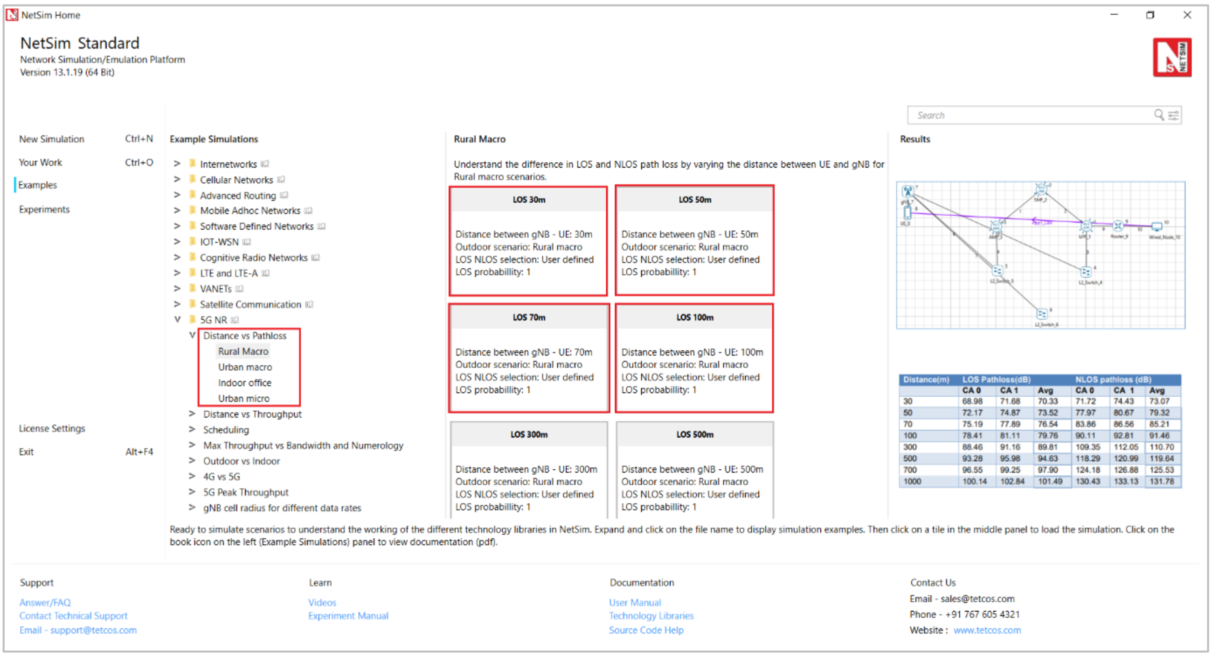


Figure 4-14: List of scenarios for the example of Distance vs Pathloss

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

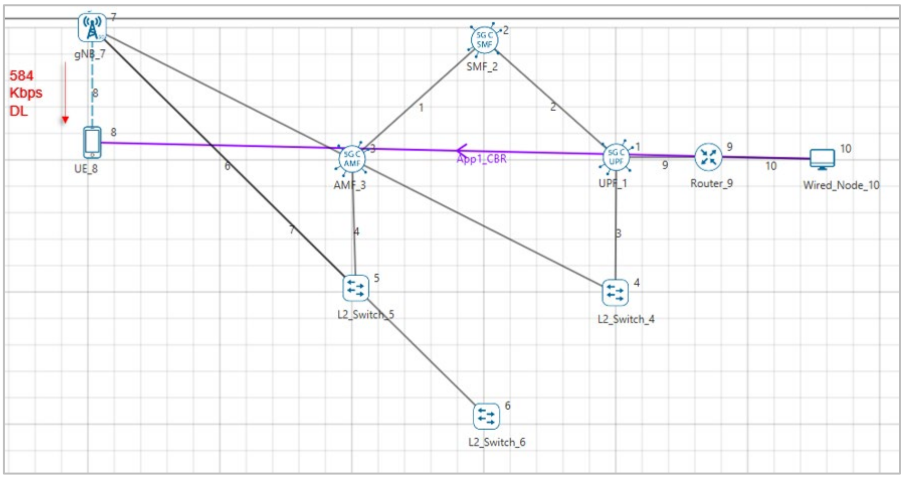


Figure 4-15: Network set up for studying the Distance vs Pathloss

4.2.1 Rural-Macro:

4.2.1.1 Line-of-Sight (LOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER.

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	RURAL_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-1: gNB >Interface (5G_RAN) >Physical layer properties

3. CBR application source id as 10 and destination id as 8 with packet size as 1460Bytes and Inter_Arrival_time as 20000µs (Generation Rate=0.584). Transport Protocol is set to **UDP.** Additionally, the **"Start Time(s)"** parameter is set to 1s, while configuring the application.
4. Set UE height as 10m.
5. Set other properties to default.
6. Plots are enabled in NetSim GUI.
7. The log file can enable per the information provided in Section 3.18.

8. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR.log file. Note down the Pathloss.

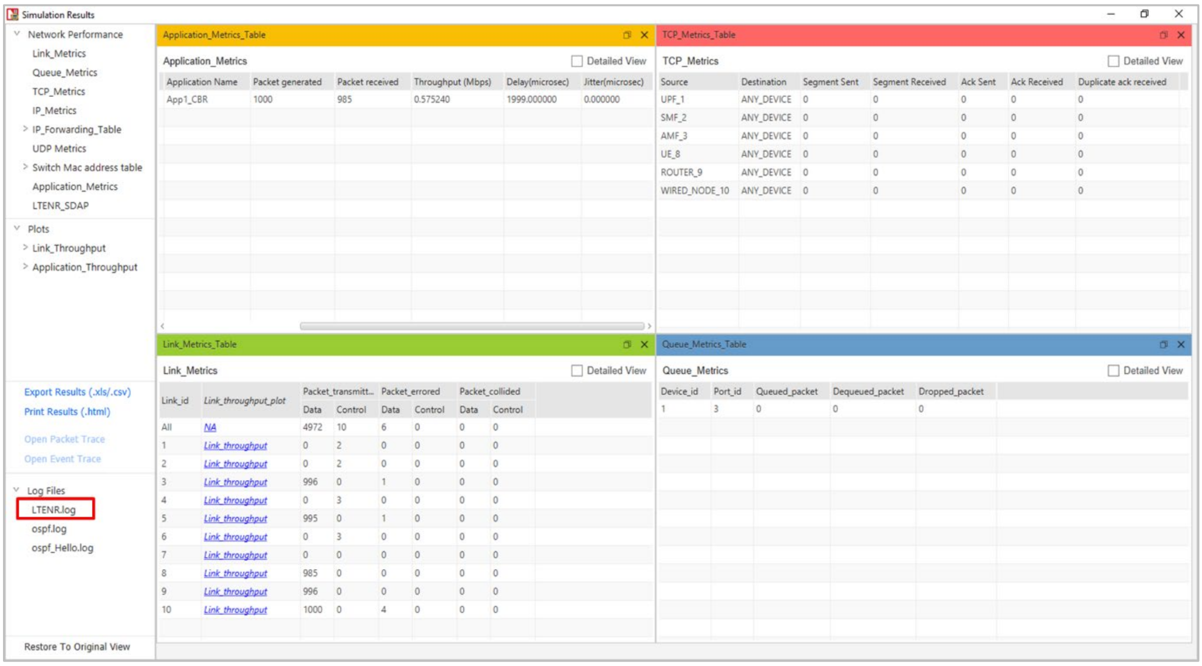
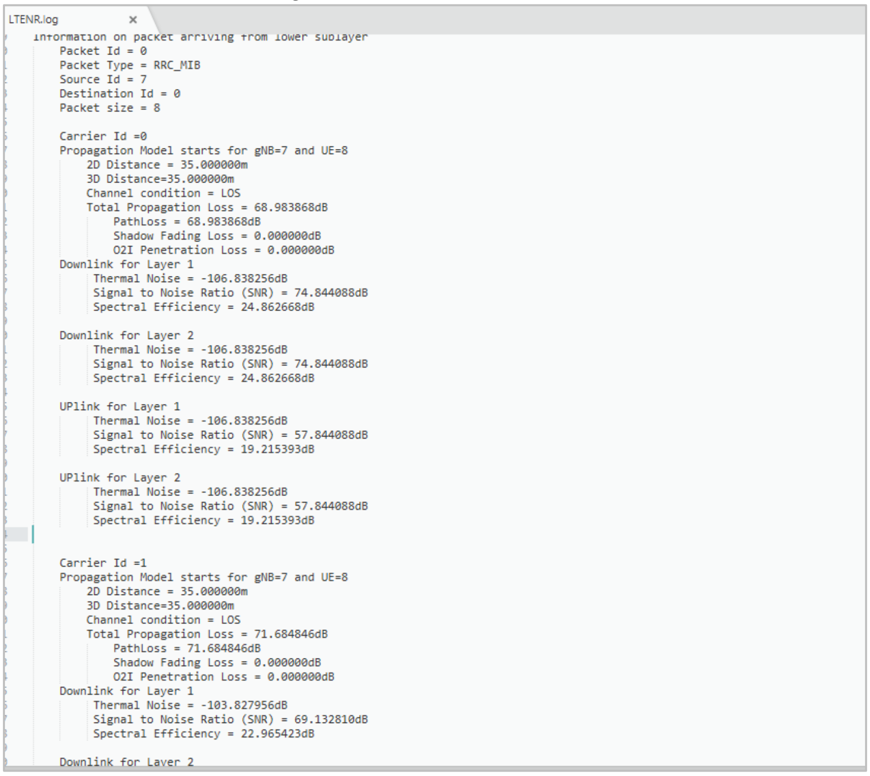


Figure 4-16: Results window


LTENR.log

```
information on packet arriving from lower sublayer
    Packet Id = 0
    Packet Type = RRC_MIB
    Source Id = 7
    Destination Id = 0
    Packet size = 8

    Carrier Id =0
    Propagation Model starts for gNB=7 and UE=8
        2D Distance = 35.000000m
        3D Distance=35.000000m
        Channel condition = LOS
        Total Propagation Loss = 68.983868dB
            PathLoss = 68.983868dB
            Shadow Fading Loss = 0.000000dB
            O2I Penetration Loss = 0.000000dB
    Downlink for Layer 1
         Thermal Noise = -106.838256dB
         Signal to Noise Ratio (SNR) = 74.844088dB
         Spectral Efficiency = 24.862668dB

    Downlink for Layer 2
         Thermal Noise = -106.838256dB
         Signal to Noise Ratio (SNR) = 74.844088dB
         Spectral Efficiency = 24.862668dB

    UPlink for Layer 1
         Thermal Noise = -106.838256dB
         Signal to Noise Ratio (SNR) = 57.844088dB
         Spectral Efficiency = 19.215393dB

    UPlink for Layer 2
         Thermal Noise = -106.838256dB
         Signal to Noise Ratio (SNR) = 57.844088dB
         Spectral Efficiency = 19.215393dB


    Carrier Id =1
    Propagation Model starts for gNB=7 and UE=8
        2D Distance = 35.000000m
        3D Distance=35.000000m
        Channel condition = LOS
        Total Propagation Loss = 71.684846dB
            PathLoss = 71.684846dB
            Shadow Fading Loss = 0.000000dB
            O2I Penetration Loss = 0.000000dB
    Downlink for Layer 1
         Thermal Noise = -103.827956dB
         Signal to Noise Ratio (SNR) = 69.132810dB
         Spectral Efficiency = 22.965423dB

    Downlink for Layer 2
```

Figure 4-17: LTENR Log file

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

4.2.1.2 Non-Line-of-Sight (NLOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER.

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	RURAL_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-2: gNB >Interface (5G_RAN) >Physical layer properties

3. Set all other properties same as LOS example.
4. Plots are enabled in NetSim GUI.
5. The log file can enable per the information provided in Section 3.18.
6. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open ltenr.log file. Note down the Pathloss.

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

4.2.1.3 Result:

Distance(m)	LOS Pathloss(dB)			NLOS pathloss (dB)		
	CA 0	**CA 1**	**Avg**	**CA 0**	**CA 1**	**Avg**
30	68.98	71.68	70.33	71.72	74.43	73.07
50	72.17	74.87	73.52	77.97	80.67	79.32
70	75.19	77.89	76.54	83.86	86.56	85.21
100	78.41	81.11	79.76	90.11	92.81	91.46
300	88.46	91.16	89.81	109.35	112.05	110.70
500	93.28	95.98	94.63	118.29	120.99	119.64
700	96.55	99.25	97.90	124.18	126.88	125.53
1000	100.14	102.84	101.49	130.43	133.13	131.78

Table 4-3: Results Comparison for LOS and NLOS pathloss vs. Distance

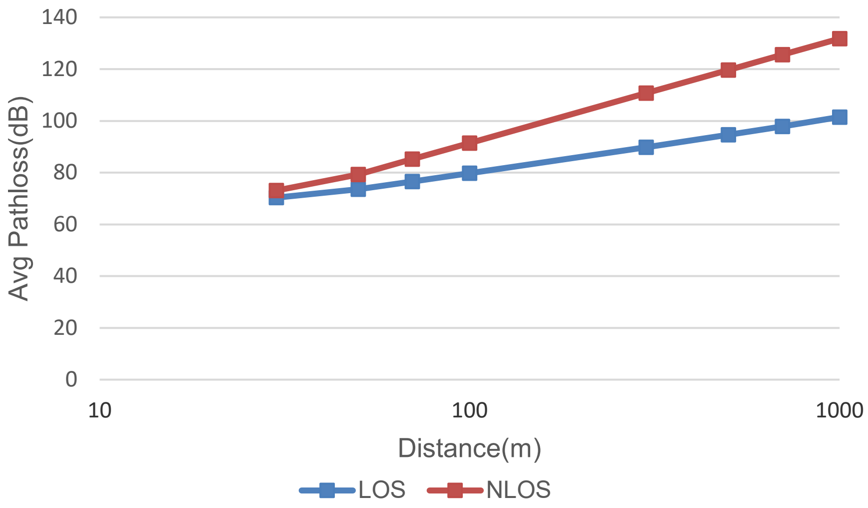


Figure 4-18: Plot of Distance vs. Avg Pathloss

4.2.2 Urban-Macro:

4.2.2.1 Line-of-Sight (LOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	URBAN_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-4: gNB >Interface (5G_RAN) >Physical layer properties

3. CBR application source id as 10 and destination id as 8 with packet size as 1460Bytes and Inter_Arrival_time as 20000µs (Generation Rate=0.584). Transport Protocol is set to **UDP.** Additionally, the **"Start Time(s)"** parameter is set to 1s, while configuring the application.
4. Set UE height as 10m.
5. Set other properties to default.
6. Plots are enabled in NetSim GUI.
7. The log file can enable per the information provided in Section 3.18.

8. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR.log file. Note down the Pathloss.

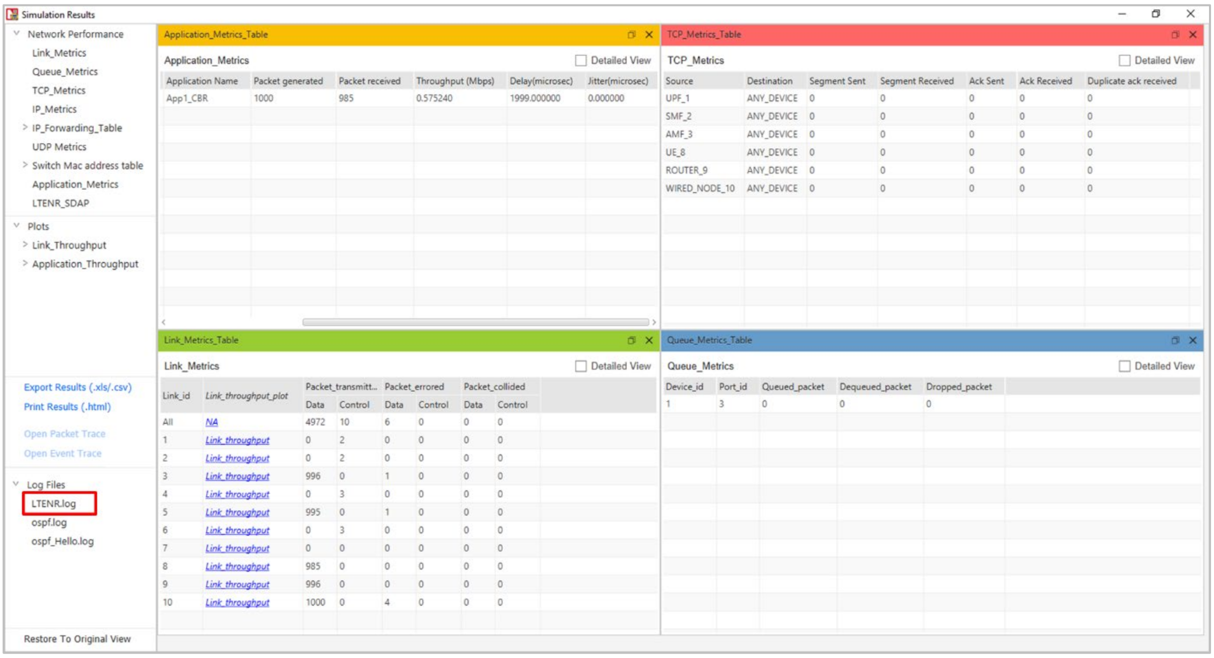


Figure 4-19: Result window

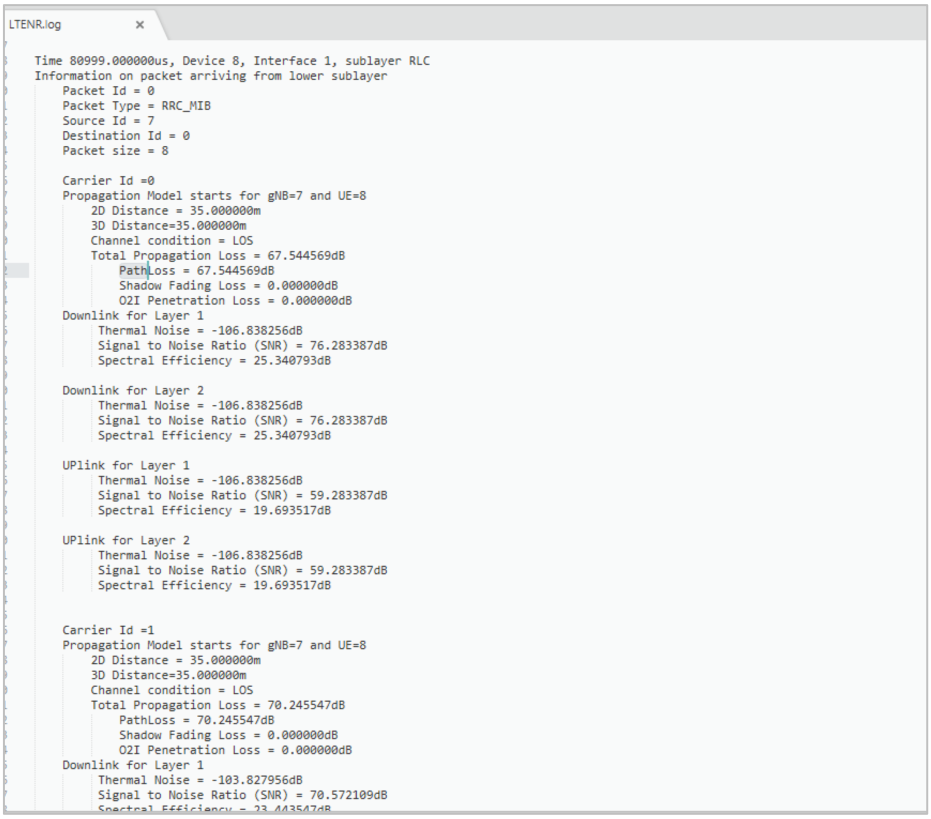


Figure 4-20: LTENR Log file

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

Note: *The minimum distance for rural macro and urban macro is 35m. Below 35m, the 2D and 3D distance will be 35m in ltenr log file.*

4.2.2.2 Non-Line-of-Sight (NLOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	RURAL_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-5: gNB >Interface (5G_RAN) >Physical layer properties

3. Set all other properties same as LOS example.
4. Plots are enabled in NetSim GUI.
5. The log file can enable per the information provided in Section 3.18
6. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open ltenr.log file. Note down the Pathloss.

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

4.2.2.3 Result:

Distance(m)	LOS Pathloss(dB)			NLOS pathloss (dB)		
	CA 0	CA 1	Avg	CA 0	CA 1	Avg
30	67.54	70.24	68.89	74.35	77.05	75.70
50	70.95	73.65	72.30	80.41	83.11	81.76
70	74.16	76.86	75.51	86.12	88.82	87.47
100	77.57	80.27	78.92	92.17	94.87	93.52
300	88.07	90.77	89.42	110.82	113.52	112.17
500	92.95	95.65	94.30	119.49	122.19	120.84
700	96.16	98.86	97.51	125.20	127.90	126.55
1000	99.57	102.27	100.92	131.25	133.95	132.60

Table 4-6: Results Comparison for LOS and NLOS pathloss vs. Distance

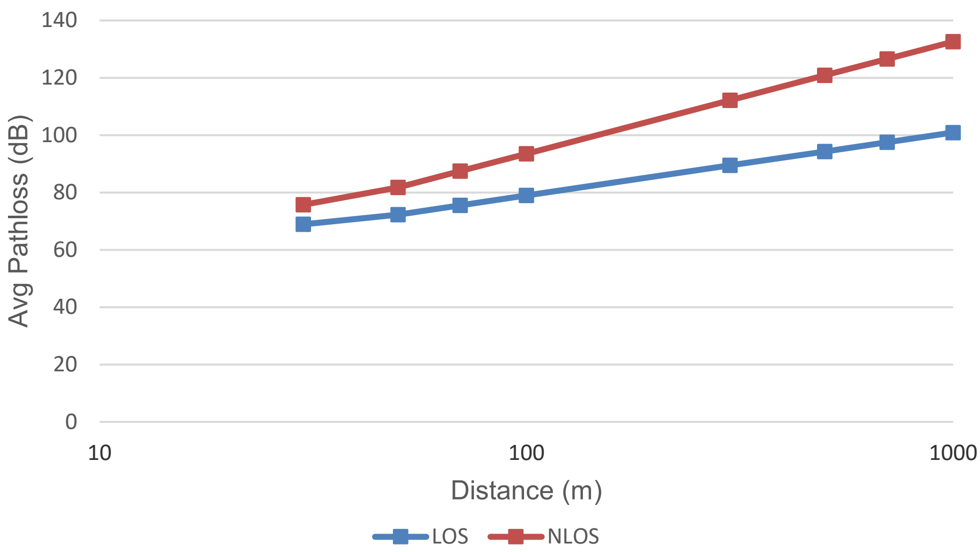


Figure 4-21: Plot of Distance vs. Avg Pathloss

4.2.3 Urban-Micro:

4.2.3.1 Line-of-Sight (LOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	URBAN_MICRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-7: gNB >Interface (5G_RAN) >Physical layer properties

3. CBR application source id as 10 and destination id as 8 with packet size as 1460Bytes and Inter_Arrival_time as 20000µs (Generation Rate=0.584). Transport Protocol is set to **UDP.** Additionally, the **"Start Time(s)"** parameter is set to 1s, while configuring the application.
4. Set UE height as 10m.
5. Set other properties to default.
6. Plots are enabled in NetSim GUI.

7. The log file can enable per the information provided in Section 3.18.
8. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open ltenr.log file. Note down the Pathloss.

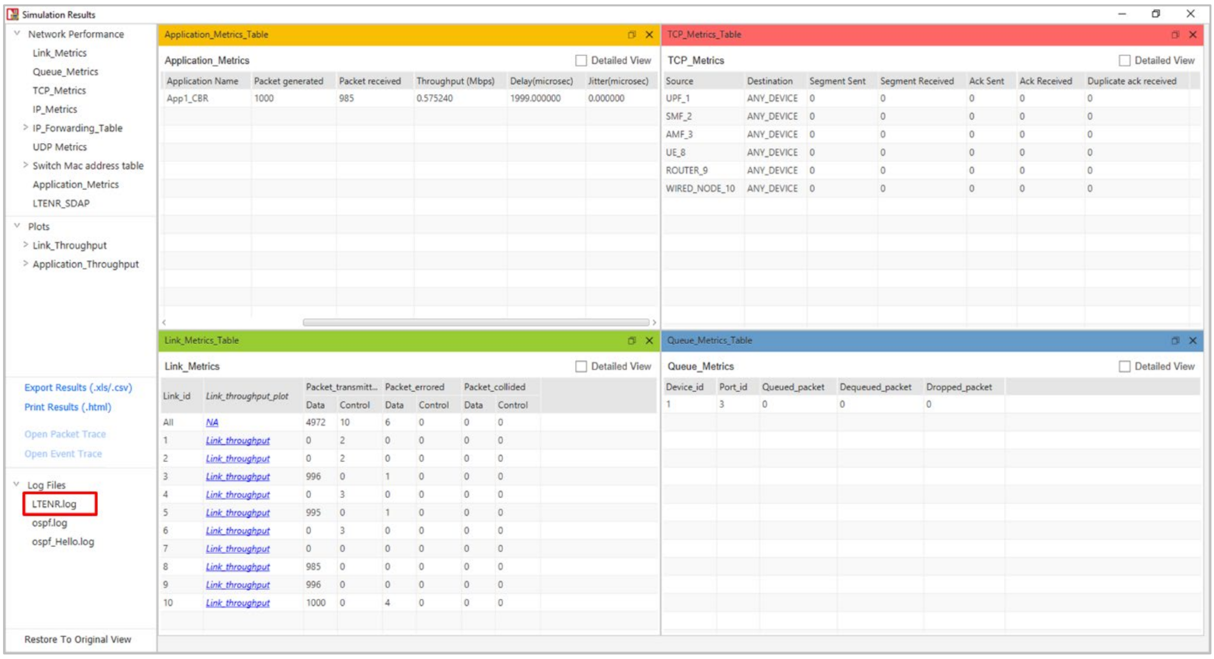


Figure 4-22: Result window

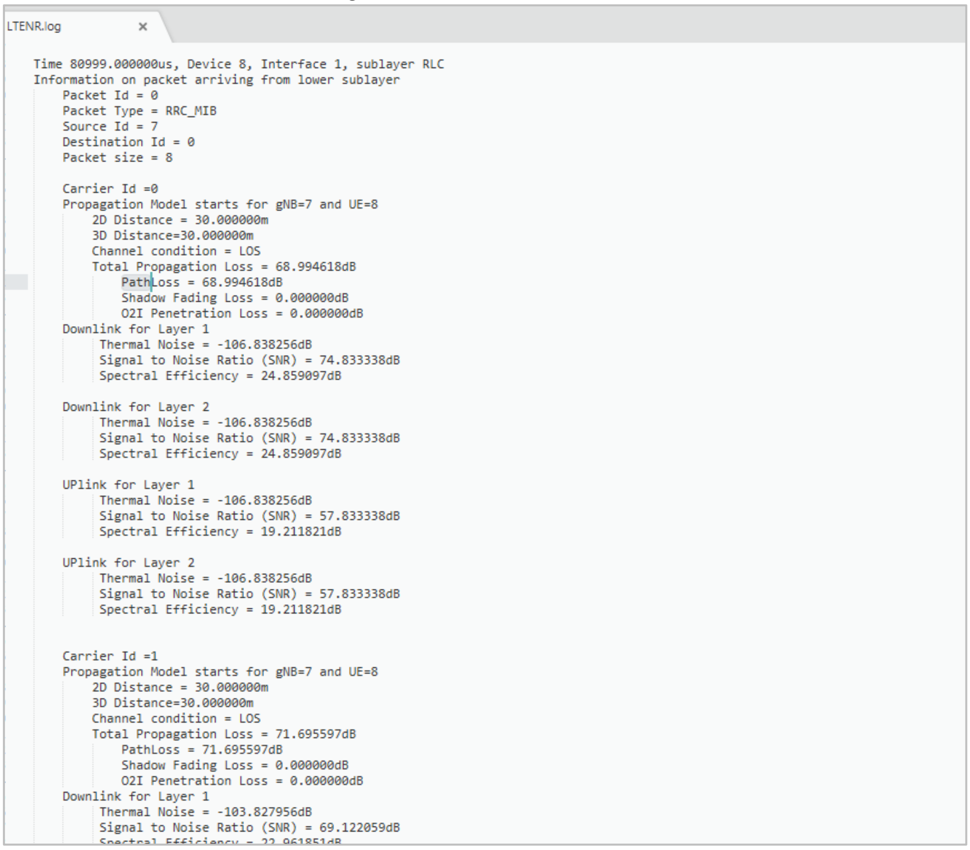


Figure 4-23: LTENR Log file

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

4.2.3.2 Non-Line-of-Sight (NLOS)

Settings done in example config file

1. Set distance between gNB_7 and UE_8 as 30m.
2. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER.

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	URBAN_MICRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-8: gNB >Interface (5G_RAN) >Physical layer properties

3. Set all other properties same as LOS example.
4. Plots are enabled in NetSim GUI.
5. The log file can enable per the information provided in Section 3.18.
6. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open ltenr.log file. Note down the Pathloss.

Go back to the scenario and change the distance between gNB and UE as 30, 50, 70, 100, 300, 500, 700, and 1000 and note down Pathloss value from the log file.

4.2.3.3 Result:

Distance(m)	LOS Pathloss (dB)			NLOS pathloss (dB)		
	CA 0	CA 1	Avg	CA 0	CA 1	Avg
30	68.99	71.69	70.34	77.92	80.80	79.36
50	73.65	76.35	75.00	85.76	88.63	87.195
70	76.72	79.42	78.07	90.91	93.79	92.35
100	79.97	82.67	81.32	96.38	99.26	97.82
300	89.99	92.69	91.34	113.22	116.10	114.66
500	94.65	97.35	96.00	121.06	123.93	122.495
700	97.72	100.42	99.07	126.21	129.09	127.65
1000	100.97	103.67	102.32	131.68	134.56	133.12

Table 4-9: Results Comparison for LOS and NLOS pathloss vs. Distance

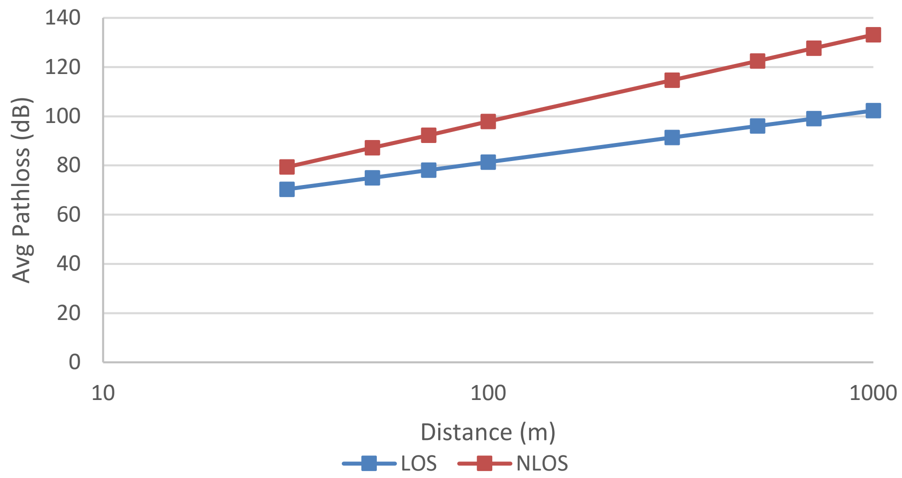


Figure 4-24: Plot of Distance vs. Avg Pathloss

4.2.4 Indoor-Office:

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

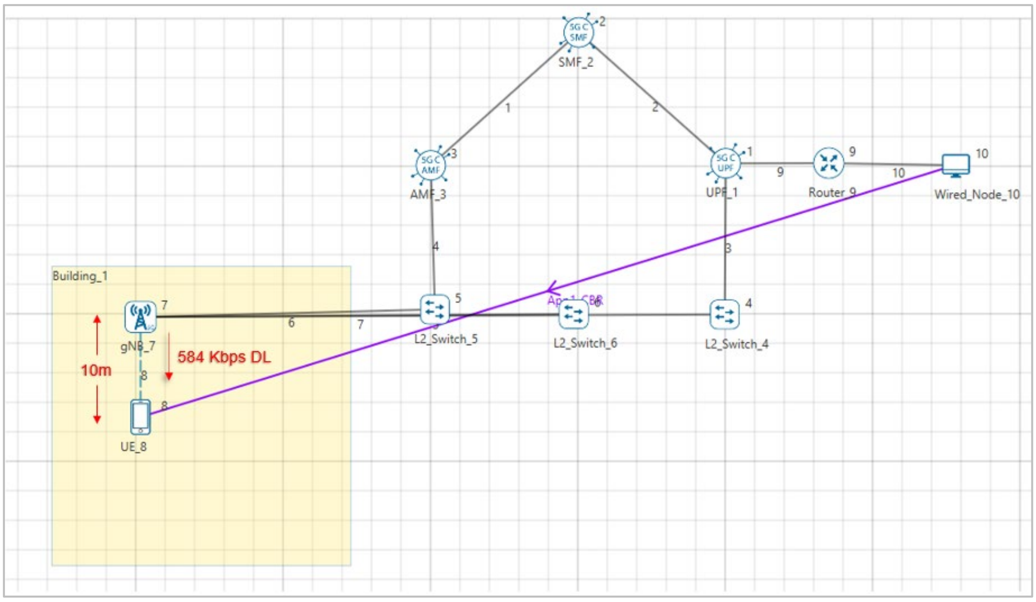


Figure 4-25: Network Topology for this experiment

4.2.4.1 Line-of-Sight (LOS)

Settings done in example config file

1. Drop the building and drop gNB and UE inside the building.
2. Set distance between gNB_7 and UE_8 as 10m.
3. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER.

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	RURAL_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	1
Indoor Scenario	INDOOR_OFFICE
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-10: gNB >Interface (5G_RAN) >Physical layer properties

4. CBR application source id as 10 and destination id as 8 with packet size as 1460Bytes and Inter_Arrival_time as 20000µs (Generation Rate=0.584). Transport Protocol is set to **UDP.** Additionally, the **“Start Time(s)”** parameter is set to 1s, while configuring the application.
5. Set UE height as 10m.
6. Set other properties to default.
7. Plots are enabled in NetSim GUI.
8. The log file can enable per the information provided in Section 3.18.
9. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR.log file. Note down the Pathloss.

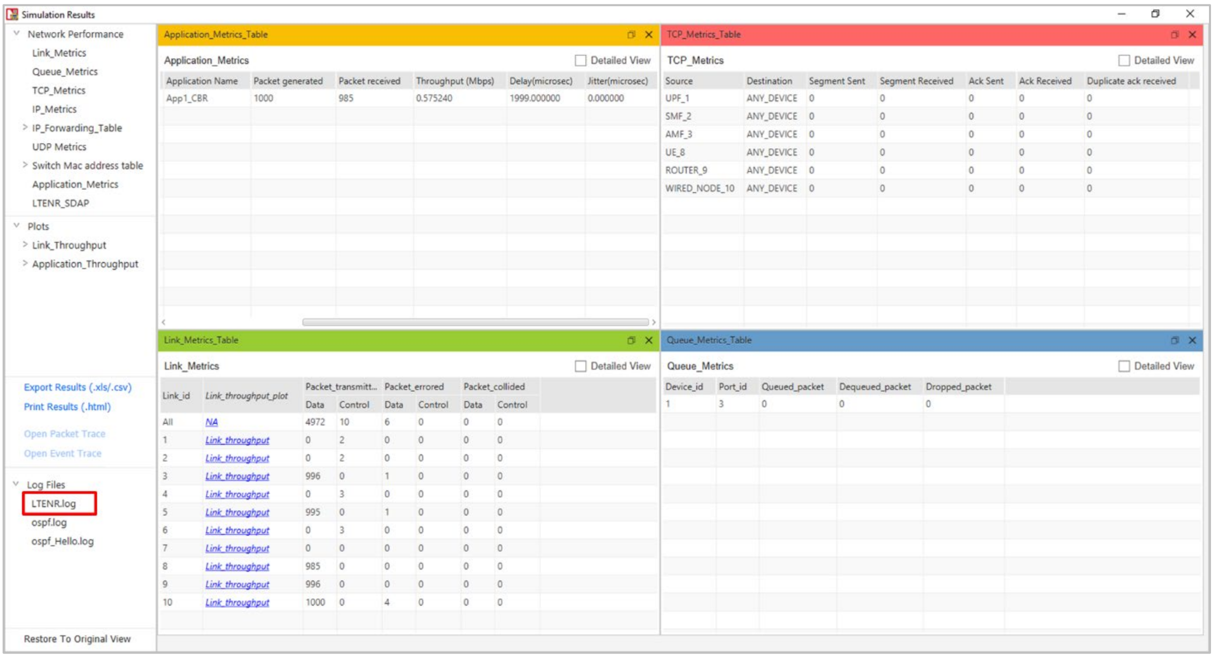
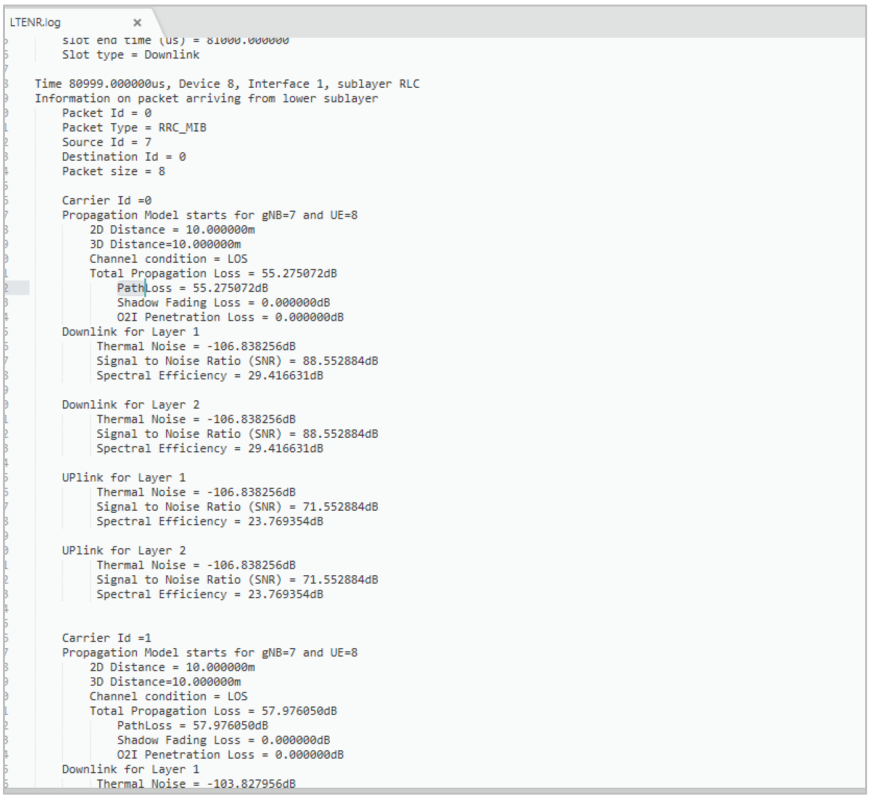


Figure 4-26: Results Window



```
LTENR.log ×
        slot end time (us) = 81000.000000
        Slot type = Downlink

    Time 80999.000000us, Device 8, Interface 1, sublayer RLC
    Information on packet arriving from lower sublayer
        Packet Id = 0
        Packet Type = RRC_MIB
        Source Id = 7
        Destination Id = 0
        Packet size = 8

        Carrier Id =0
        Propagation Model starts for gNB=7 and UE=8
            2D Distance = 10.000000m
            3D Distance=10.000000m
            Channel condition = LOS
            Total Propagation Loss = 55.275072dB
                PathLoss = 55.275072dB
                Shadow Fading Loss = 0.000000dB
                O2I Penetration Loss = 0.000000dB
        Downlink for Layer 1
             Thermal Noise = -106.838256dB
             Signal to Noise Ratio (SNR) = 88.552884dB
             Spectral Efficiency = 29.416631dB

        Downlink for Layer 2
             Thermal Noise = -106.838256dB
             Signal to Noise Ratio (SNR) = 88.552884dB
             Spectral Efficiency = 29.416631dB

        UPlink for Layer 1
             Thermal Noise = -106.838256dB
             Signal to Noise Ratio (SNR) = 71.552884dB
             Spectral Efficiency = 23.769354dB

        UPlink for Layer 2
             Thermal Noise = -106.838256dB
             Signal to Noise Ratio (SNR) = 71.552884dB
             Spectral Efficiency = 23.769354dB


        Carrier Id =1
        Propagation Model starts for gNB=7 and UE=8
            2D Distance = 10.000000m
            3D Distance=10.000000m
            Channel condition = LOS
            Total Propagation Loss = 57.976050dB
                PathLoss = 57.976050dB
                Shadow Fading Loss = 0.000000dB
                O2I Penetration Loss = 0.000000dB
        Downlink for Layer 1
             Thermal Noise = -103.827956dB
```

Figure 4-27: LTENR Log file

Go back to the scenario and change the distance between gNB and UE as 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 and note down Pathloss value from the log file.

4.2.4.2 Non-Line-of-Sight (NLOS)

Settings done in example config file

1. Drop the building and drop gNB and UE inside the building.
2. Set distance between gNB_7 and UE_8 as 10m.
3. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER.

Properties	
CA Type	INTER_BAND_CA
CA Configuration	CA_2DL_1UL_n39_n41
Pathloss Model	3GPPTR38.901-7.4.1
Outdoor_Scenario	RURAL_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
Indoor Scenario	INDOOR_OFFICE
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-11: gNB >Interface (5G_RAN) >Physical layer properties

4. Set all other properties same as LOS example.
5. Plots are enabled in NetSim GUI.
6. The log file can enable per the information provided in Section 3.18.
7. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open ltenr.log file. Note down the Pathloss.

Go back to the scenario and change the distance between gNB and UE as 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 and note down pathloss values from the log file.

4.2.4.3 Result:

Distance(m)	LOS Pathloss (dB)			NLOS pathloss (dB)		
	CA 0	CA 1	Avg	CA 0	CA 1	Avg
10	55.27	57.97	56.62	62.54	65.90	64.22
20	60.48	63.18	61.83	74.07	77.43	75.75
30	63.52	66.23	64.875	80.81	84.17	82.49
40	65.69	68.39	67.04	85.59	88.96	87.27
50	67.36	70.06	68.71	89.31	92.67	90.99
60	68.73	71.43	70.08	92.34	95.70	94.02
70	69.89	72.59	71.24	94.90	98.27	96.58
80	70.89	73.59	72.24	97.12	100.49	98.80
90	71.78	74.48	73.13	99.08	102.45	100.76
100	72.57	75.27	73.92	100.84	104.20	102.52

Table 4-12: Results Comparison for LOS and NLOS pathloss vs. Distance

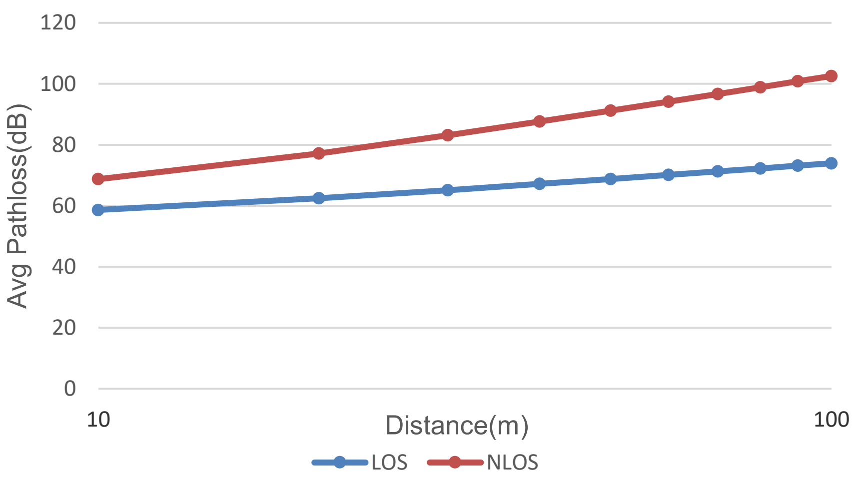


Figure 4-28: Plot of Distance vs. Avg Pathloss

4.3 Effect of UE distance on throughput in FR1 and FR2

In this example we understand how the downlink UDP throughput of a UE varies as its distance from a gNB is increased. Rebuild the code to enable logs per Section 3.18 in this manual. Open NetSim, Select **Examples ->5G NR ->Distance vs Throughput** then click on the tile in the middle panel to load the example as shown in below screenshot

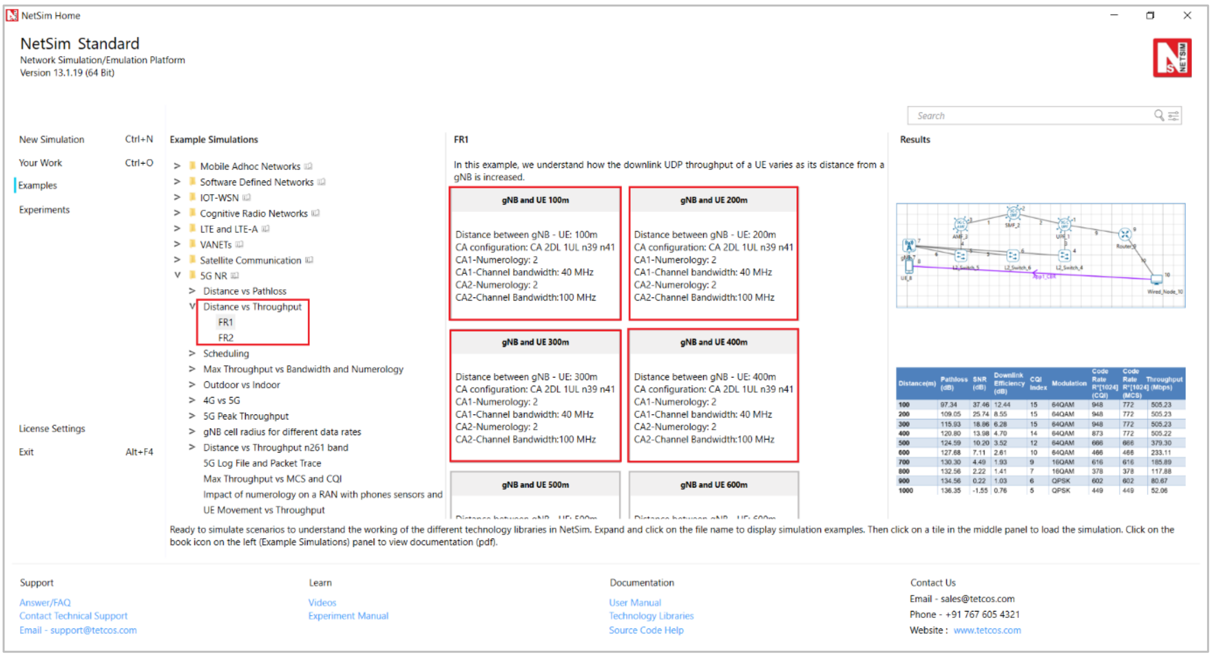


Figure 4-29: List of scenarios for the example of Distance vs Throughput

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

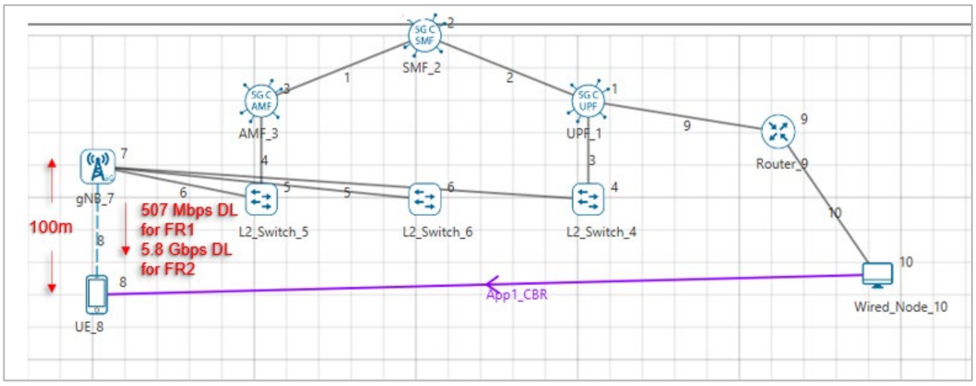


Figure 4-30: Network set up for studying the Distance vs Throughput

4.3.1 Frequency Range - FR1:

Settings done in example config file

1. Set grid length as 2500m from Environment setting.
2. Set distance between gNB_7 and UE_8 as 100m.
3. Go to Wired link properties and set the following properties as shown below.

Wired Link Properties	
Uplink_Speed	1000Mbps
Downlink_Speed	1000Mbps

Table 4-13: Wired Link Properties

4. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER, set the following properties as shown below Table 4-14.

Properties	
CA_Configuration	CA_2DL_1UL_n39_n41
CA1	
Numerology	2
Channel Bandwidth	40 MHz
CA2	
Numerology	2
Channel Bandwidth	100 MHz
Pathloss Model	3GPPTR38.901-7.4.1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	Low Loss Model
Outdoor_Scenario	URBAN_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0

Table 4-14: gNB >Interface (5G_RAN) >Physical layer properties

5. Set Tx_Antenna_Count and Rx_Antenna Count in gNB as 2 and 2.
6. Set Tx_Antenna_Count and Rx_Antenna_Count in UE as 2 and 2.
7. Go to Application properties and set the following properties as shown below Table 4-15.

Application Properties	
Source_Id	10
Destination_Id	8
QoS	UGS
Transport Protocol	UDP
Packet_Size	1460Bytes
Inter_Arrival_time	23µs
Start_Time	1s

Table 4-15: Application properties

8. The log file can enable per the information provided in Section 3.18.
9. Plots are enabled in NetSim GUI.
10. Run Simulation for 2s, after simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the scenario and change the distance between gNB and UE as 200, 300, 400, 500, 600, 700, 800, 900, and 1000m and note down throughput from the results window. The other parameters in table shown below can be noted down from the LTE NR log file.

4.3.2 Frequency Range - FR2:

Settings done in example config file

1. Set grid length as 2500m from Environment setting.
2. Set distance between gNB_7 and UE_8 as 50m.
3. Go to Wired link properties and set the following properties as shown below **Table 4-16.**

Wired Link Properties	
Uplink_Speed	10000Mbps
Downlink_Speed	10000Mbps

Table 4-16: Wired Link Properties

4. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER, set the following properties as shown below Table 4-17.

Properties		
Physical Layer Properties		
Frequency Range		FR2
CA Type		INTRA_BAND_NONCONTIGUOUS_CA
CA_Configuration		CA_n261(7O) _n261A
	Numerology	**Channel Bandwidth (MHz) per carrier**
CA1, CA2, CA3, CA4, CA5, CA6, CA7, CA8, CA9, CA10, CA11, CA12, CA13, CA14	3	100
Pathloss Model		3GPPTR38.901-7.4.1
Shadow Fading Model		None
Fading _and_Beamforming		NO_FADING
O2I Building Penetration Model		Low Loss Model
Outdoor_Scenario		URBAN_MACRO
LOS_NLOS_Selection		USER_DEFINED
LOS Probability		0

Table 4-17: gNB >Interface (5G_RAN) >Physical layer properties

5. Set Tx_Antenna_Count and Rx_Antenna Count in gNB as 2 and 2.
6. Set Tx_Antenna_Count and Rx_Antenna_Count in UE as 2 and 2.
7. Go to Application properties and set the following properties as shown below Table 4-18.

Application Properties	
Source_Id	10
Destination_Id	8

QoS	UGS
Transport Protocol	UDP
Packet_Size	1460Bytes
Inter_Arrival_time	2µs
Start_Time	1s

Table 4-18: Application properties

8. The log file can enable per the information provided in Section 3.18.
9. Plots are enabled in NetSim GUI.
10. Run Simulation for 1.05s, after simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the scenario and change the distance between gNB and UE as 50, 100, 150, and 200 and note down throughput from the results window. The other parameters in the table shown below can be noted down from the LTENR log file.

Results:

Note: The values of Carrier_Id=0 present in the log file have been considered in the tables given below. (SNR and spectral efficiency are shown for downlink Layer1).

Distance(m)	Pathloss (dB)	SNR (dB)	Downlink Efficiency (dB)	CQI Index	Modulation	Code Rate R*[1024] (CQI)	Code Rate R*[1024] (MCS)	Throughput (Mbps)
100	97.34	37.46	12.44	15	64QAM	948	772	505.23
200	109.05	25.74	8.55	15	64QAM	948	772	505.23
300	115.93	18.86	6.28	15	64QAM	948	772	505.23
400	120.80	13.98	4.70	13	64QAM	772	772	453.74
500	124.59	10.20	3.52	11	64QAM	567	567	293.00
600	130.38	0.43	1.07	9	16QAM	616	616	185.89
700	130.30	4.49	1.93	8	16QAM	490	490	131.40
800	135.27	-4.45	0.44	6	QPSK	602	602	80.67
900	134.6	0.22	1.03	5	QPSK	449	449	52.06
1000	139.05	-8.24	0.20	4	QPSK	308	308	36.68

Table 4-19: FR1 - Variation of pathloss, SNR, Efficiency, CQI, Modulation, code rates and throughput as the distance of the UE from the gNB is increased.

Distance(m)	Pathloss (dB)	SNR (dB)	Downlink Efficiency (dB)	CQI Index	Modulation	Code Rate R*[1024] (CQI)	Code Rate R*[1024] (MCS)	Throughput (Mbps)
50	109.10	21.72	7.22	15	64QAM	948	772	4167.19
100	120.68	10.13	3.50	11	64QAM	567	567	3127.90
150	127.53	3.28	1.64	7	16QAM	378	378	1329.18
200	132.40	-1.58	0.76	4	QPSK	308	308	522.09

Table 4-20: FR 2 - Variation of pathloss, SNR, Efficiency, CQI, Modulation, code rates and throughput as the distance of the UE from the gNB is increased.

Increase in distance leads to an increase in pathloss, which in turn hence leads to lower received power (and lower SNR). The lower SNR leads to a lower MCS, in turn a lower CQI and thereby results in lower throughputs. The drop for FR2 happens at a much faster rate in comparison to FR1. Note that the number of information bits is got from then Transport Block Size Determination calculations given in *Transport block size (*TBS) determination*.* The throughput would depend on the TBS.

4.4 Impact of MAC Scheduling algorithms on throughput, in a Multi UE scenario

In this example we understand how the scheduling algorithm affects the UDP download throughput of a multi-user (UE) system where the UE's are at different distances from the gNB. Open NetSim, Select **Examples ->5G NR ->Scheduling** then click on the tile in the middle panel to load the example as shown in below screenshot

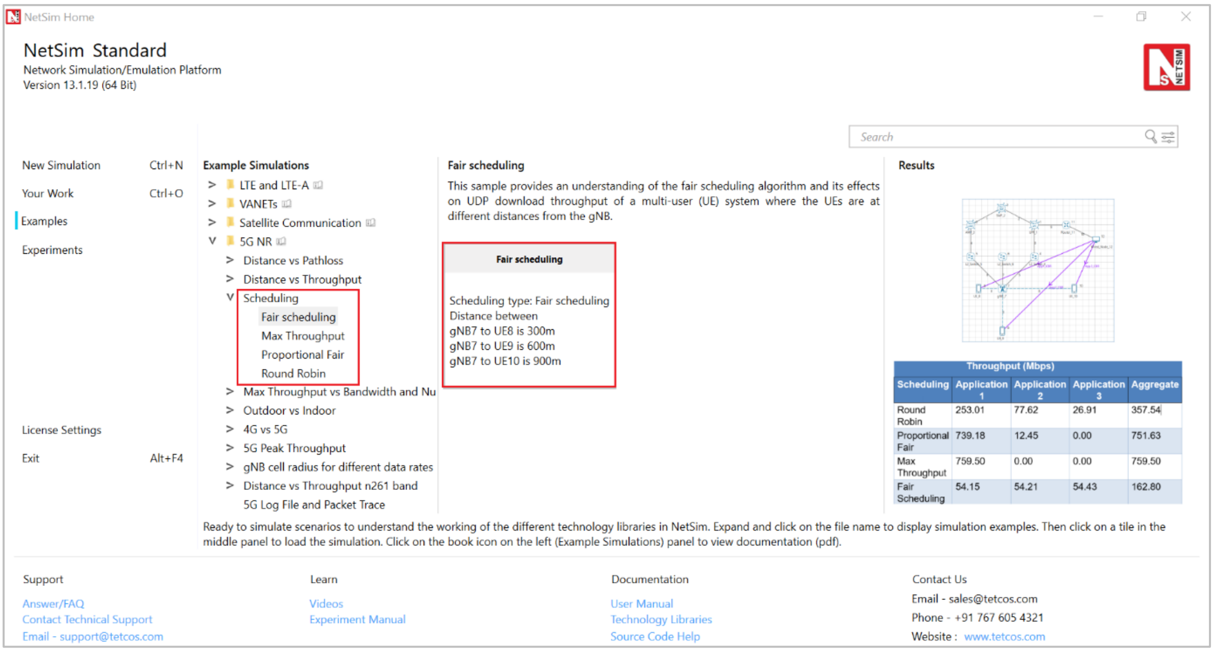


Figure 4-31: List of scenarios for the example of Scheduling

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

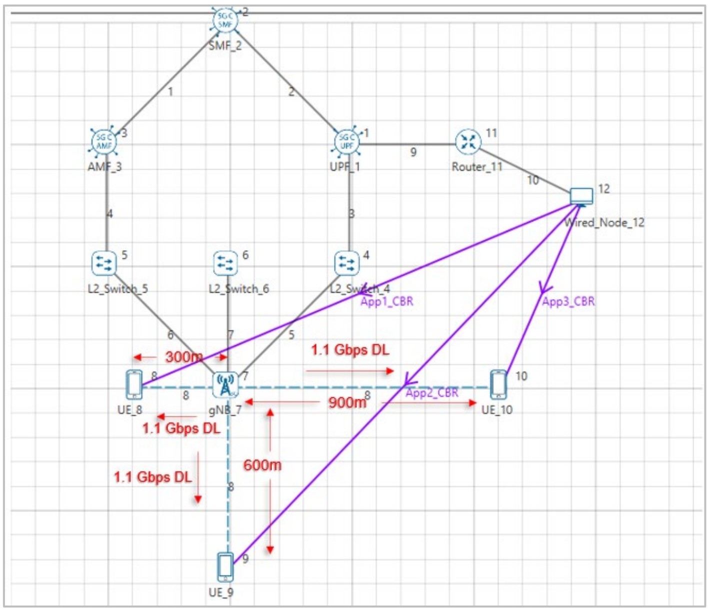


Figure 4-32: Network set up for studying the Scheduling

4.4.1 Round Robin

Settings done in example config file

1. Set grid length as 4000m from Environment setting.
2. Set distance as follows.
    a. gNB_7 to UE_8 = 300m
    b. gNB_7 to UE_9 = 600m, and
    c. gNB_7 to UE_10 = 900m
3. Go to Wired link properties and set the following properties as shown below Table 4-21.

Wired Link Properties	
Uplink_Speed	5000Mbps
Downlink_Speed	5000Mbps

Table 4-21: Wired Link Properties

4. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below **Table 4-22.**

Properties	
DataLink Layer Properties	
Scheduling Type	ROUND_ROBIN
Physical Layer Properties	
CA_Configuration	CA_2DL_1UL_n39_n41
CA1	
Numerology	2
Channel Bandwidth	40 MHz

CA2	
Numerology	2
Channel Bandwidth	100 MHz
Outdoor_Scenario	URBAN_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
Pathloss Model	3GPPTR38.901-7.4.1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	Low Loss Model

Table 4-22: gNB >Interface (5G_RAN) >Physical layer properties

5. Set Tx_Antenna_Count as 2 and Rx_Antenna_Count as 1 in gNB properties.
6. Set Tx_Antenna_Count as 1 and Rx_Antenna_Count as 2 in all the UEs.
7. Go to Application properties and set the following properties as shown below Table 4-23.

Application Properties			
	Application 1	**Application 2**	**Application 3**
Application Type	CBR	CBR	CBR
Source_Id	12	12	12
Destination_Id	8	9	10
QoS	UGS	UGS	UGS
Transport Protocol	UDP	UDP	UDP
Packet_Size	1460Bytes	1460Bytes	1460Bytes
Inter_Arrival_time	10µs	10µs	10µs
Start_Time	1s	1s	1s

Table 4-23: Application properties

8. Plots are enabled in NetSim GUI.
9. Run Simulation for 1.5s, after simulation completes go to metrics window and note down throughput value from application metrics.

4.4.2 Proportional Fair

Settings done in example config file:

1. Set all the properties as configured in Round Robin example and go to gNB properties → Interface (5G_RAN) → Data Link Layer properties, set Scheduling type as PROPORTIONAL_FAIR.
2. Run Simulation for 1.5s, after simulation completes go to metrics window and note down throughput value from application metrics.

4.4.3 Max Throughput

Settings done in example config file:

1. Set all the properties as configured in Round Robin example and go to gNB properties → Interface (5G_RAN) → Data Link Layer properties, set Scheduling type as MAX_THROUGHPUT.
2. Run Simulation for 1.5s, after simulation completes go to metrics window and note down throughput value from application metrics.

4.4.4 Fair Scheduling

Settings done in example config file:

1. Set all the properties as configured in Round Robin example and go to gNB properties → Interface (5G_RAN) → Data Link Layer properties, set Scheduling type as FAIR_SCHEDULING.
2. Run Simulation for 1.5s, after simulation completes go to metrics window and note down throughput value from application metrics.

Result: We first run the scenario with each of the UEs downloading a single application in standalone basis. This gives the maximum achievable rate per node. The results are below.

Distance from gNB (m)	Application Id	Throughput (Mbps)
300	1	759.50
600	2	233.06
900	3	80 .66

Table 4-24: UE throughputs if they were run standalone (without the other UEs downloading data)

We then run the same simulation with all the three UEs simultaneously downloading data.

Throughput (Mbps)				
Scheduling	**Application 1**	**Application 2**	**Application 3**	**Aggregate**
Round Robin	223.90	61.90	17.37	303.17
Proportional Fair	665.24	3.59	0	668.83
Max Throughput	672.13	0.00	0.00	672.13
Fair Scheduling	37.025	37.189	37.329	111.54

Table 4-25: UDP download throughputs for different scheduling algorithms when all three 3 UEs simultaneously downloading data

The PHY rate is decided based on the SNR. A UE closer to the gNB will get a higher date rate than a UE further away. In this example the distances from the gNB are such that UE10_Distance > UE9_Distance > UE8_Distance.

In Round Robin PRBs are allocated equally among all three nodes. However, throughputs are in the order UE8 > UE9 > UE10 because of their distances from the gNB. The individual throughputs seen by each of the UEs is exactly $\frac{1}{3}$ of the throughput as shown in Table 4-24.

In proportional fair scheduling the resource allocation is such that nearer UEs get proportionally higher allocation (based on CQI) when compared to further away UEs. In Max throughput scheduling the PRBs are allocated such that the system gets the maximum download throughput.

Fair scheduling provides strict fairness, and this results in all applications seeing equal throughput.

4.5 Max Throughput for various bandwidth and numerology configurations

Open NetSim, Select **Examples ->5G NR ->Max Throughput vs Bandwidth and Numerology** then click on the tile in the middle panel to load the example as shown in below screenshot

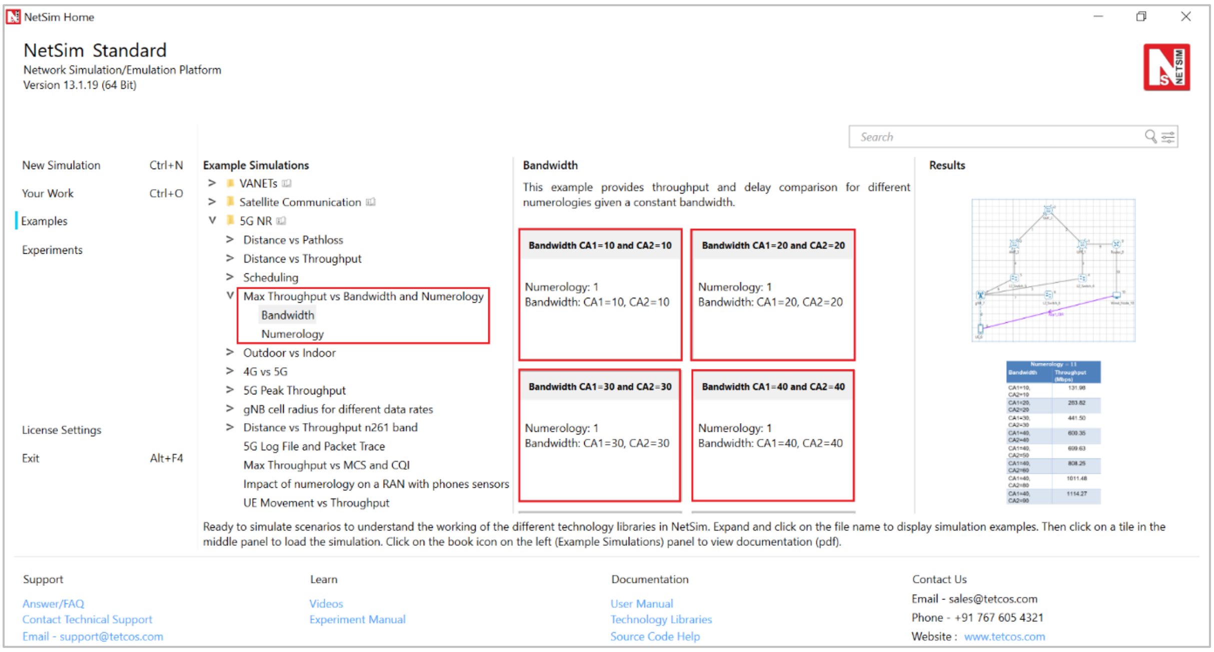


Figure 4-33: List of scenarios for the example of Max Throughput vs Bandwidth and Numerology

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

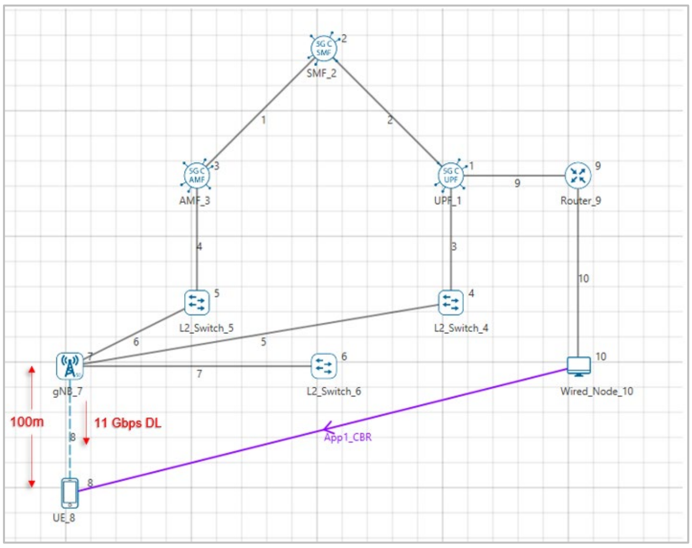


Figure 4-34: Network set up for studying the Max Throughput vs Bandwidth and Numerology

Settings done in example config file

Bandwidth CA1=10 and CA2=10 Sample

1. Set grid length as 1000m from Environment settings.
2. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below **Table 4-26.**

Properties	
Physical Layer Properties	
CA_Configuration	CA_2DL_1UL_n39_n41
Frequency Range	FR1
MCS Table	QAM256
CQI Table	TABLE2
Pathloss Model	None

Table 4-26: gNB >Interface (5G_RAN) >Physical layer properties

3. Set Tx_Antenna_Count as 2 and Rx_Antenna_Count as 1 in gNB propertis > Interface 5G_RAN > Physical Layer.
4. Set Tx_Antenna_Count as 1 and Rx_Antenna_Count as 2 in UE propertis > Interface 5G_RAN > Physical Layer.
5. Go to Wired link properties and set the following properties as shown below Table 4-27.

Wired Link Properties	
Uplink_Speed (Mbps)	100,000
Downlink_Speed (Mbps)	100,000

Table 4-27: Wired Link Properties

6. Go to Application properties and set the following properties as shown below Table 4-28.

Application Properties	
Source_Id	10
Destination_Id	8
Transport Protocol	UDP
Start_Time	1s
Packet_Size	1460 Bytes
Inter_Arrival_time	1µs
Generation Rate	10,000 Mbps

Table 4-28: Application properties

7. Plots are enabled in NetSim GUI.
8. Run Simulation for 1.01s, after simulation completes go to metrics window and note down throughput and delay value from application metrics.

For the first time set Numerology value as 1 in gNB properties and change CA1 bandwidth value as 10, 20, 30, and 40, CA2 bandwidth value as 10, 20, 30, 40, 50, 60, 80, 90, and 100 note down throughput.

For the second time set CA1 bandwidth value as 40, CA2 bandwidth value as 50 in gNB properties and change the Numerology value as 0, 1, and 2 and note down throughput.

Result:

Numerology = 1	
Bandwidth	**Throughput (Mbps)**
CA1=10, CA2=10	131.98
CA1=20, CA2=20	283.82
CA1=30, CA2=30	441.50
CA1=40, CA2=40	600.35
CA1=40, CA2=50	699.63
CA1=40, CA2=60	808.25
CA1=40, CA2=80	1011.48
CA1=40, CA2=90	1114.27
CA1=40, CA2=100	1218.22

Table 4-29: Results Comparison with constant Numerology vs. Bandwidth and throughput

Bandwidth	Numerology	Throughput (Mbps)	Delay (µs)
CA1=40, CA2=50	0	685.61	5708.27
CA1=40, CA2=50	1	699.63	5198.77
CA1=40, CA2=50	2	683.28	4955.03

Table 4-30: Results Comparison with different Numerology vs. Bandwidth, throughput and Delay

As Numerology increases the throughput remains almost the same while delay reduces.

4.6 Max Throughput for different MCS and CQI

Open NetSim, Select **Examples ->5G NR ->Max Throughput vs MCS and CQI** then click on the tile in the middle panel to load the example as shown in below screenshot

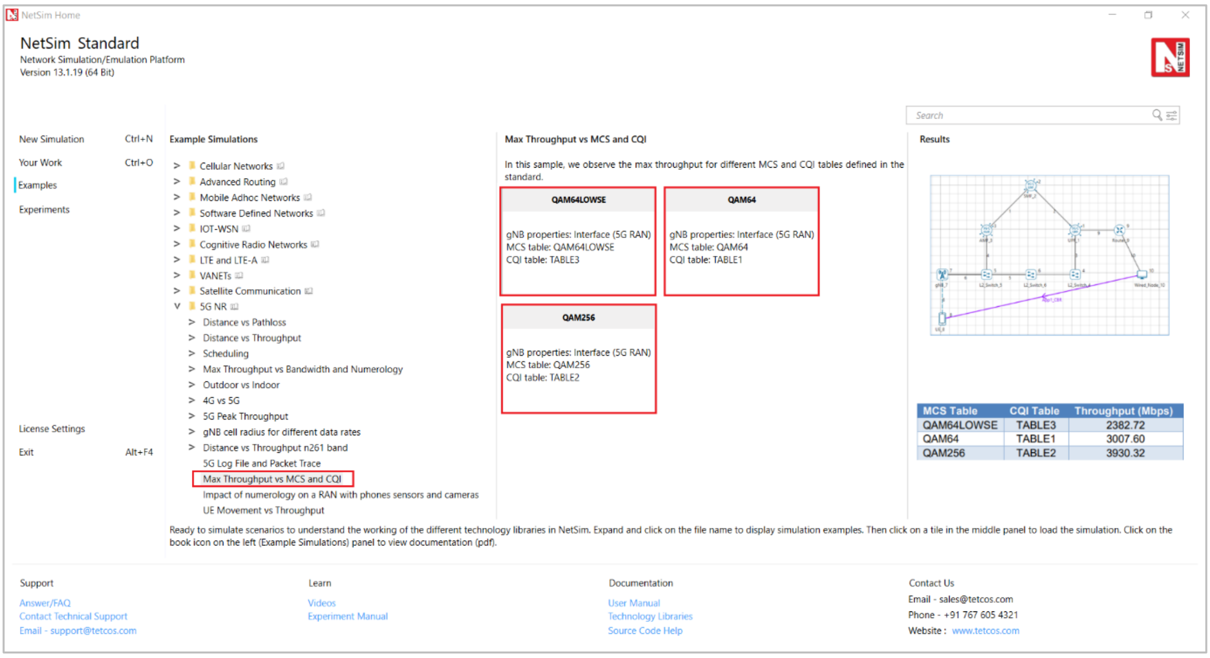


Figure 4-35: List of scenarios for the example of Max Throughput vs MCS and CQI

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

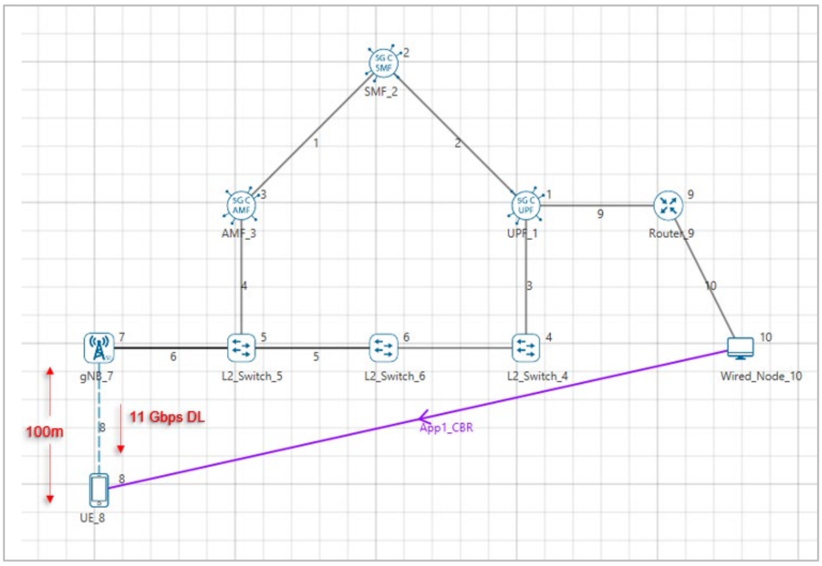


Figure 4-36: Network set up for studying the Max Throughput vs MCS and CQI

Settings done in example config file:

1. Set grid length as 1000m from Environment setting.
2. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below **Table 4-31.**

Properties		
Physical Layer Properties		
Frequency Range		FR2
CA_Configuration		CA_n261(2Q) _n261A
	Numerology	**Channel Bandwidth (MHz)**
CA1	2	100
CA2	2	100
CA3	2	100
CA4	2	100
CA5	2	100
CA6	2	100
CA7	2	100
CA8	2	100
Pathloss Model		None

Table 4-31: gNB >Interface (5G_RAN) >Physical layer properties

3. Go to Wired link properties and set the following properties as shown below Table 4-32.

Wired Link Properties	
Uplink_Speed (Mbps)	100000
Downlink_Speed (Mbps)	100000

Table 4-32: Wired Link Properties

4. Go to Application properties and set the following properties as shown below Table 4-33.

Application Properties	
Source_Id	10
Destination_Id	8
Transport Protocol	UDP
Start_Time	1s
Packet_Size	1460Bytes
Inter_Arrival_time	1µs
Generation Rate	10000Mbps

Table 4-33: Application properties

5. Plots are enabled in NetSim GUI.
6. Run Simulation for 1.002s, after simulation completes go to metrics window and note down throughput and delay value from application metrics.

For this Scenario set MCS Table as **QAM64LOWSE** and CQI Table as **TABLE3** and note down throughput.

Go Back to the Scenario and set MCS Table as **QAM64** and CQI Table as **TABLE1** and note down throughput.

Go Back to the Scenario and set MCS Table as **QAM256** and CQI Table as **TABLE2** and note down throughput.

Result:

MCS Table	CQI Table	Throughput (Mbps)
QAM64LOWSE	TABLE3	2382.72
QAM64	TABLE1	3007.60
QAM256	TABLE2	3930.32

Table 4-34: Results Comparison

4.7 Outdoor vs. Indoor Propagation

Open NetSim, Select **Examples ->5G NR -> Outdoor vs Indoor** then click on the tile in the middle panel to load the example as shown in below screenshot

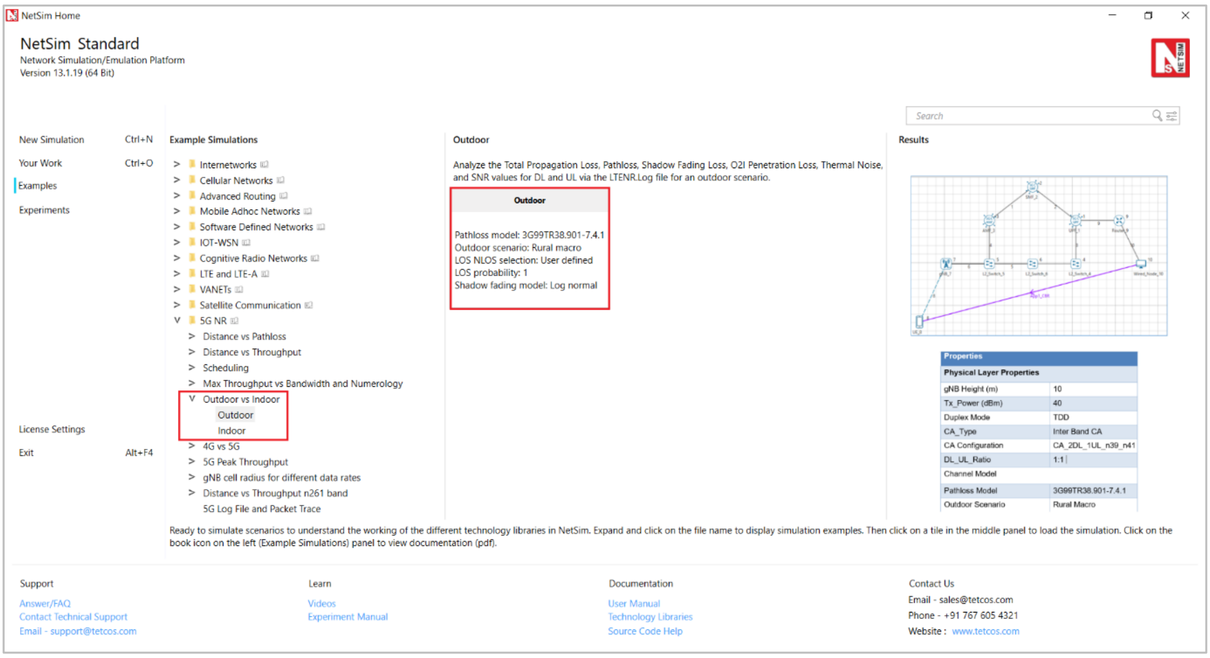


Figure 4-37: List of scenarios for the example of Outdoor vs Indoor

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

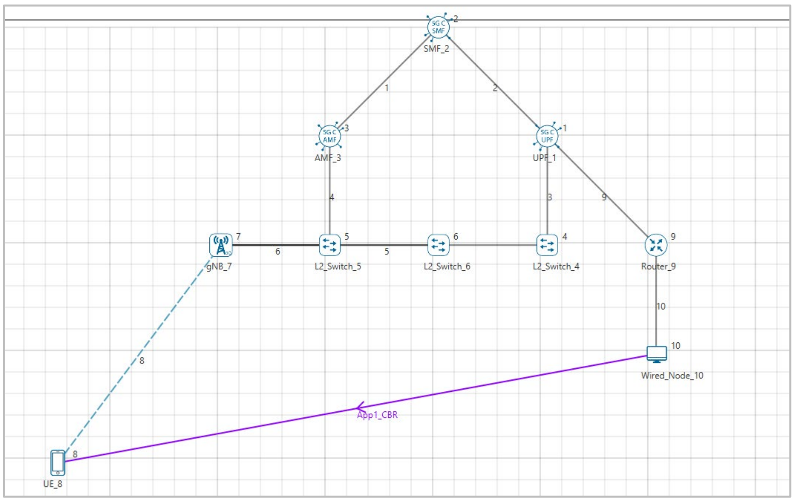


Figure 4-38: Network set up for studying the Outdoor

4.7.1 Outdoor

Settings done in example config file:

1. Set grid length as 1000m from Environment setting.
2. Set the following property as shown in below Table 4-35.

General Properties		
	X Coordinates	**Y Coordinates**
gNB Properties	300	200
UE Properties	150	400

Table 4-35: Device Positions

3. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below **Table 4-36.**

Properties	
Physical Layer Properties	
gNB Height (m)	10
Tx_Power (dBm)	40
Duplex Mode	TDD
CA_Type	Inter Band CA
CA Configuration	CA_2DL_1UL_n39_n41
DL_UL_Ratio	1:1
CA-1 Numerology Bandwidth (MHz)	0 5
CA-2 Numerology Bandwidth (MHz)	0 10
Channel Model	
Pathloss Model	3G99TR38.901-7.4.1
Outdoor Scenario	Rural Macro

LOS_NLOS_Selection	User Defined
LOS Probability	1
Shadow Fading Model	LOG_NORMAL
ShadowFading_Standard_Deviation	3G99TR38.901-7.4.1-1
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	LOW_LOSS_MODEL

Table 4-36: gNB >Interface (5G_RAN) >Physical layer properties

4. Set TX_Antenna_Count as 2 and RX_Antenna_Count as 1 in gNB properties.
5. Set TX_Antenna_Count as 1 and RX_Antenna_Count as 2 in gNB properties.
6. Set the CBR application between source id 10 and destination id 8 with Packet Size 1460 B and IAT 20000 µs and Transport Protocol is set to **UDP.**
7. Set application start time as 1 sec.
8. The log file can enable per the information provided in Section 3.18.
9. Plots are enabled in NetSim GUI.
10. Run simulation for 11 sec.

Go to metrics window expand Log Files option and open LTENR.log file.

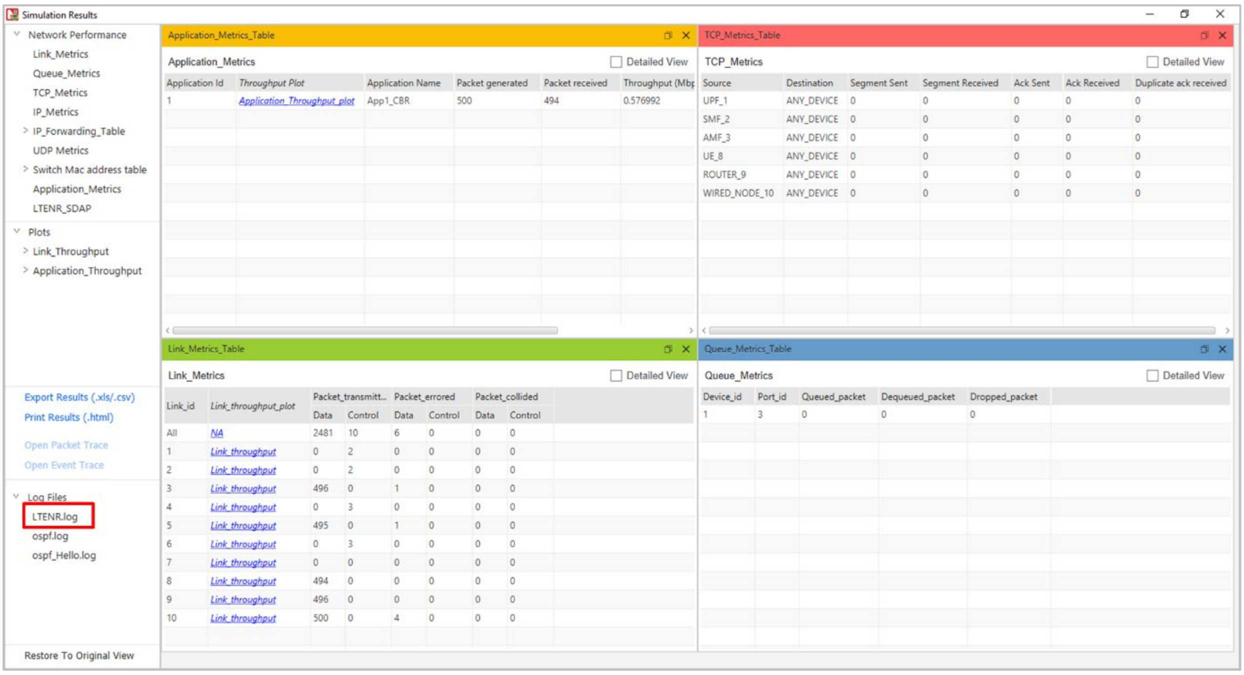


Figure 4-39: Results Window

Note down the Total Propagation Loss, Pathloss, Shadow Fading Loss, O2I Penetration Loss, Thermal Noise, and SNR values for downlink Layer1 ad Uplink Layer1.

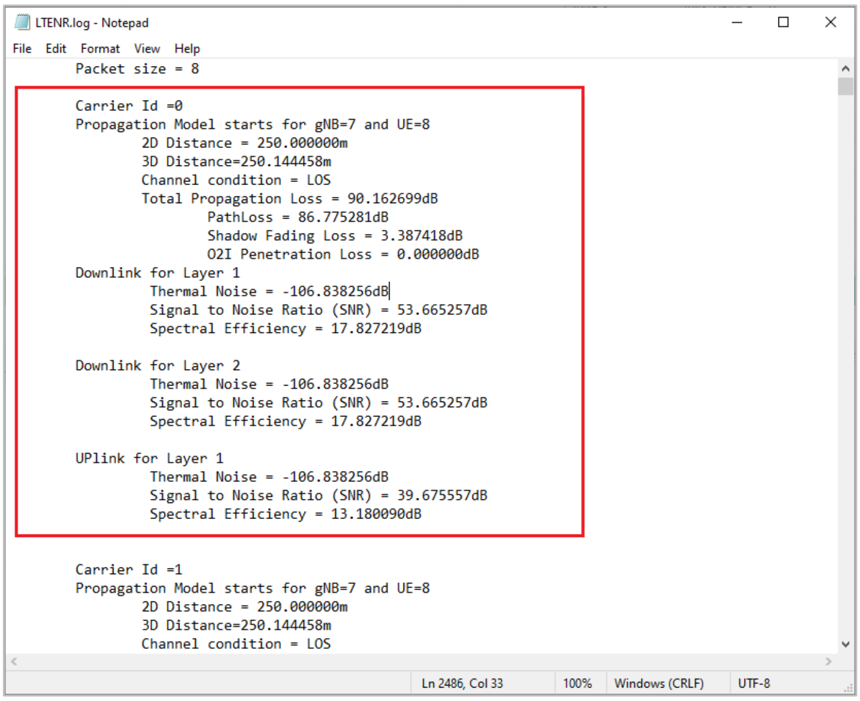


Figure 4-40: LTENR Log file

4.7.2 Indoor

The following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

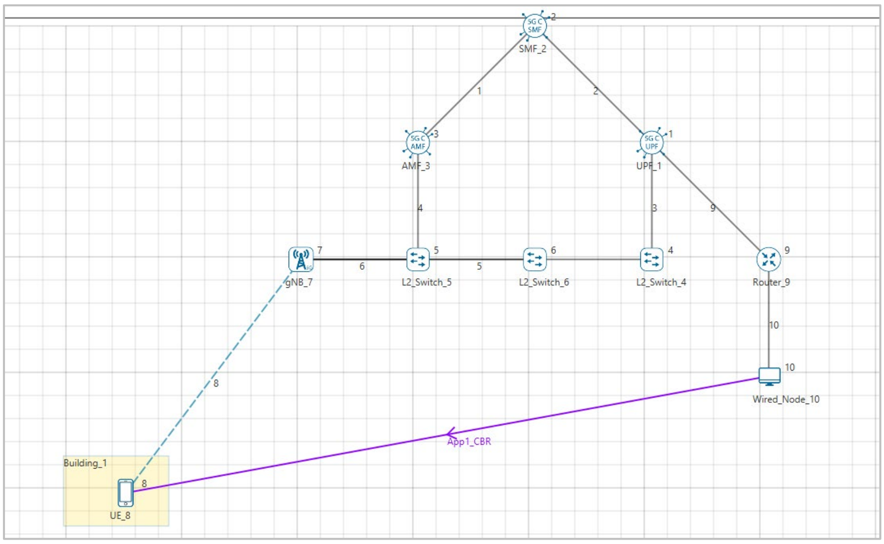


Figure 4-41: Network set up for studying the Indoor

Settings done in example config file:

1. Set grid length as 1000m from Environment setting.
2. Set the following property as shown in below **Table 4-37.**

General Properties		
	X Coordinate	**Y Coordinate**
Building Properties	50	100
gNB Properties	300	200

UE Properties	150	400

Table 4-37: Devices Positions

3. Go to the building properties, set Length_X as 60m and Breadth_Y as 90m.
4. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below **Table 4-38.**

Properties	
Physical Layer Properties	
gNB Height (m)	10
Tx_Power (dBm)	40
Duplex Mode	TDD
CA_Type	Inter Band CA
CA Configuration	CA_2DL_1UL_n39_n41
DL_UL_Ratio	1:1
CA-1 Numerology Bandwidth (MHz)	0 5
CA-2 Numerology Bandwidth (MHz)	0 10
Channel Model	
Pathloss Model	3G99TR38.901-7.4.1
Outdoor Scenario	Rural Macro
LOS_NLOS_Selection	User Defined
LOS Probability	1
Shadow Fading Model	LOG_NORMAL
ShadowFading_Standard_Deviation	3G99TR38.901-7.4.1-1
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	LOW_LOSS_MODEL

Table 4-38: gNB >Interface (5G_RAN) >Physical layer properties

5. Set TX_Antenna_Count as 1 and RX_Antenna_Count as 1 in gNB properties.
6. Set TX_Antenna_Count as 1 and RX_Antenna_Count as 1 in UE properties.
7. Set the CBR application between source id 10 and destination id 8 with Packet Size 1460 B and IAT 20000 µs and Transport Protocol is set to UDP.
8. Set application Start_Time as 1 sec.
9. The log file can enable per the information provided in Section 3.18.
10. Plots are enabled in NetSim GUI.
11. Run simulation for 11 sec.

Note down the Total Propagation Loss, Pathloss, Shadow Fading Loss, O2I Penetration Loss, Thermal Noise, and Signal to Noise Ratio (SNR)

Result:

Note: The values of Carrier_Id=0 present in the log file have been considered in the tables given below. (SNR values shown for downlink Layer1 ad Uplink Layer1).

	Outdoor	Indoor
Total Propagation Loss (dB)	90.16	108.38
PathLoss (dB)	86.77	86.77
Shadow Fading Loss (dB)	3.38	3.38
O2I Penetration Loss (dB)	0	18.22
Thermal Noise (dB)	-106.84	-106.84
Uplink Signal to Noise Ratio (SNR) (dB)	39.67	21.45
Downlink Signal to Noise Ratio (SNR) of Layer 1	53.66	38.45

Table 4-39: Outdoor and Indoor result comparisons

4.8 4G vs. 5G: Capacity analysis for video downloads

Open NetSim, Select **Examples ->5G NR -> 4G vs 5G** then click on the tile in the middle panel to load the example as shown in below screenshot

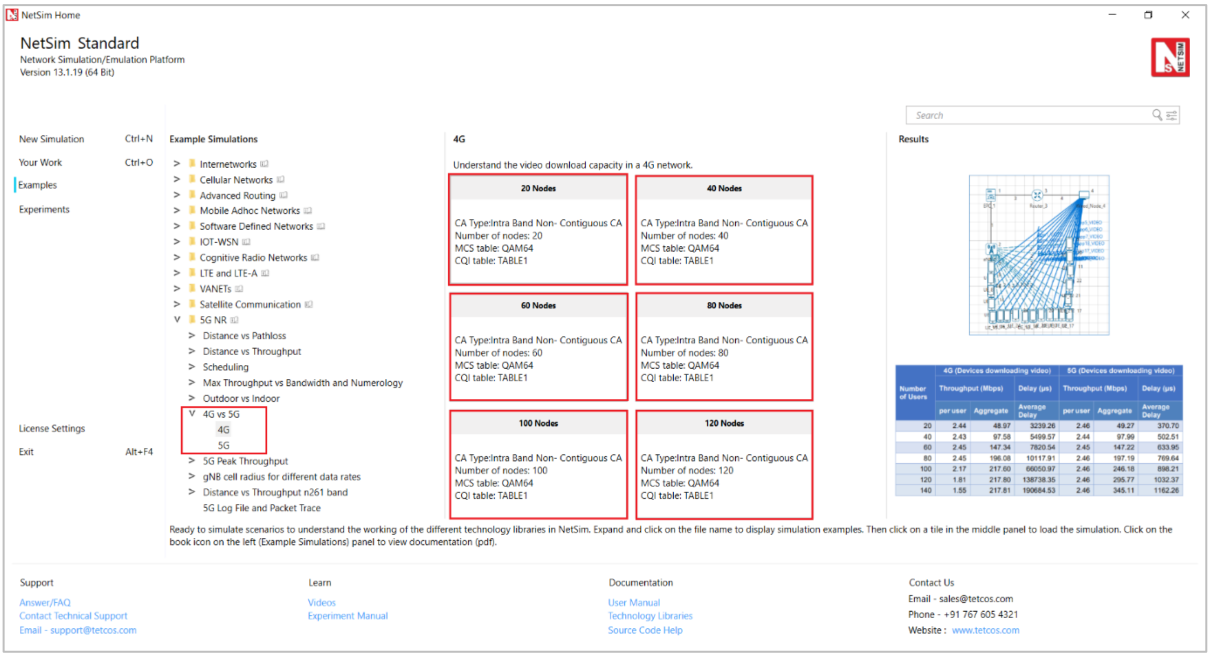


Figure 4-42: List of scenarios for the example of 4G vs 5G

4.8.1 4G

Under 4G click on 20 Nodes Sample, the following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

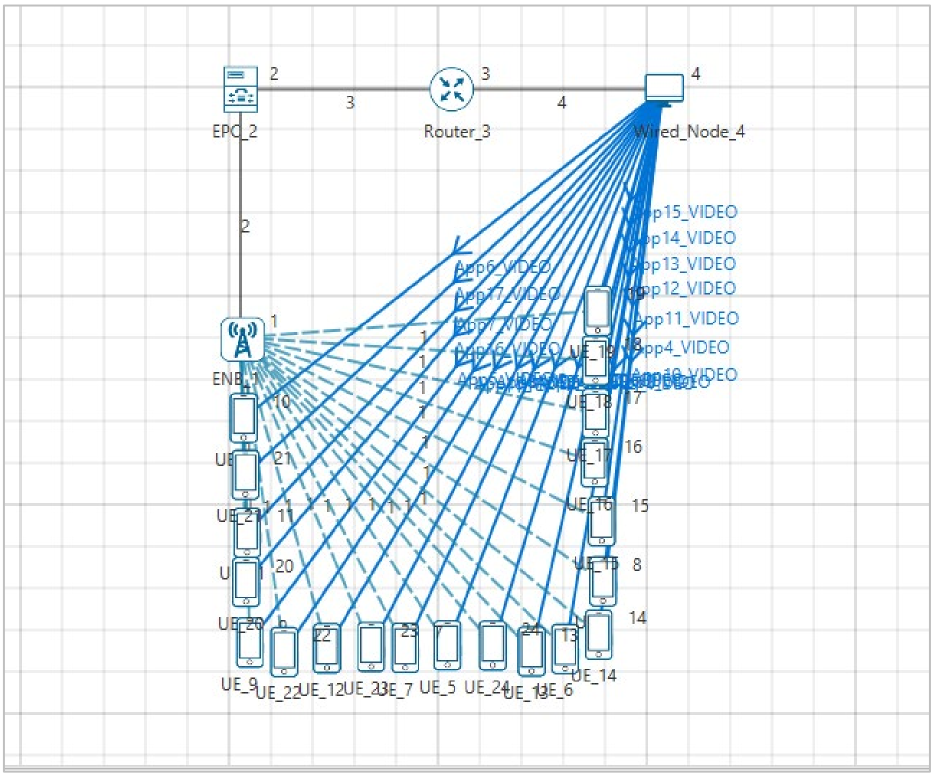


Figure 4-43: Network set up for studying the 4G

Settings done in example config file:

1. Set grid length as 1000m from Environment setting.
2. Set the following property as shown in below given Table 4-40.

eNB Properties -> Interface (LTE)	
CA Type	Intra Band Non- Contiguous CA
Frequency Range	FR1
CA_Configuration	CA_4DL_42C_2UL_42C_BCS1
DL_UL Ratio	1:1
CA1, CA2, CA3, CA4	
Numerology	0
Channel Bandwidth	20 MHz
MCS Table	QAM64
CQI Table	TABLE1
Pathloss Model	None

Table 4-40: eNB >Interface (LTE) >Physical layer properties

3. Frequency range FR1, Numerology = 0, Bandwidth = 20 MHz with QAM 64 MCS table represents a 4G configuration
4. Set Uplink speed and Downlink speed as 10000 Mbps and BER as 0 in all wired links.
5. Set Tx_Antenna_Count as 2 and Rx_Antenna_Count as 1 in eNB > Interface LTE > Physical Layer.

6. Set Tx_Antenna_Count as 1 and Rx_Antenna_Count as 2 in UE > Interface LTE > Physical Layer.
7. Set S20 applications Source id as 4 and Destination id as 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, and 24 and set the properties as shown below. This would generate 2.5 Mbps of traffic per user. Transport Protocol is set to **UDP** in all the application.

Application Properties	
Frame Per Sec	50
Pixel Per Frame	50000
Mu	1
Start_Time	1s

Table 4-41: Application properties

8. Plots are enabled in NetSim GUI.
9. Run simulation for 2 sec. After simulation completes go to metrics window and note down throughput and delay value from application metrics.

Increase number of UE's and number of applications as 40, 60, 80, and 100 and note down throughput and delay value from application metrics.

4.8.2 5G

Under 5G click on 20 Nodes Sample, the following network diagram illustrates, what the NetSim UI displays when you open the example configuration file.

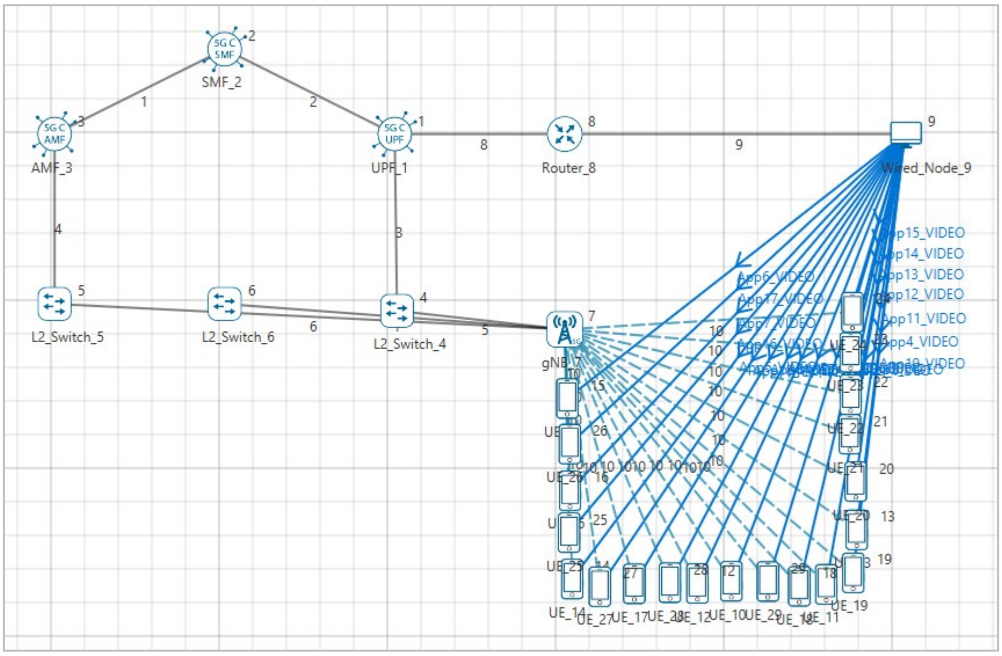


Figure 4-44: Network set up for studying the 5G

Settings done in example config file:

1. For the above 5G scenario set the following given properties Table 4-42.

gNB Properties -> Interface (5G_RAN)		
Pathloss Model	None	
DL_UL_Ratio	1:1	
Frequency Range	FR2	
CA_Configuration	CA_n261(2Q) _n261A	
	Numerology	**Channel Bandwidth (MHz)**
CA1, CA2, CA3, CA4, CA5, CA6, CA7 and CA8	3	100
MCS Table	QAM256	
CQI Table	TABLE2	

Table 4-42: gNB >Interface (5G_RAN) >Physical layer properties

2. The Tx_Antenna_Count was set to 2 and Rx_Antenna_Count was set to 1 in gNB > Interface 5G_RAN > Physical Layer.
3. The Tx_Antenna_Count was set to 1 and Rx_Antenna_Count was set to 2 in UE > Interface 5G_RAN > Physical Layer.
4. Frequency range FR2, Numerology = 3, Bandwidth = 100 MHz with QAM 256 MCS table represent a 5G configuration
5. The Uplink and Downlink speed was set to 10000 Mbps and BER were set to 0 in wired links.
6. Plots are enabled in NetSim GUI.
7. Run simulation for 2 sec. After simulation completes go to metrics window and note down throughput and delay value from application metrics.

Increase number of UE's and number of applications as 40, 60, 80, and 100 and note down throughput and delay value from application metrics.

$$Throughput\ Per\ User\ (Mbps) = \frac{Sum\ of\ throughputs\ (Mbps)}{Number\ of\ User}$$

$$Delay\ Per\ User\ (\mu s) = \frac{Sum\ of\ Delays\ (\mu s)}{Number\ of\ User}$$

Result:

Number of Users	4G (Devices downloading video)			5G (Devices downloading video)		
	Throughput (Mbps)		Delay (µs)	Throughput (Mbps)		Delay (µs)
	per user	Aggregate	Average Delay	per user	Aggregate	Average Delay
20	2.45	48.97	3232.59	2.46	49.27	370.70
40	2.44	97.58	5488.52	2.45	97.99	502.55
60	2.46	147.35	7823.46	2.45	147.22	633.95
80	2.45	196.09	10108.63	2.46	197.20	769.64

100	2.18	217.62	66100.55	2.46	246.18	898.21
120	1.82	217.81	138738.28	2.46	295.77	1032.37
140	1.56	217.82	190684.52	2.47	345.11	1162.26

Table 4-43: Aggregated and Average throughput and delay per user with different number of users for LTE 4G and 5G NR

For the given settings, the 4G network has a max download capacity available of about 217 Mbps. When this capacity is ready, as the number of users increases the throughput per user starts dropping in 4G. And the latency shoots up once this threshold is crossed. However, 5G can provide necessary bandwidth (has a capacity of 5+ Gbps) for each user to download at the full rate of 2.5 Mbps.

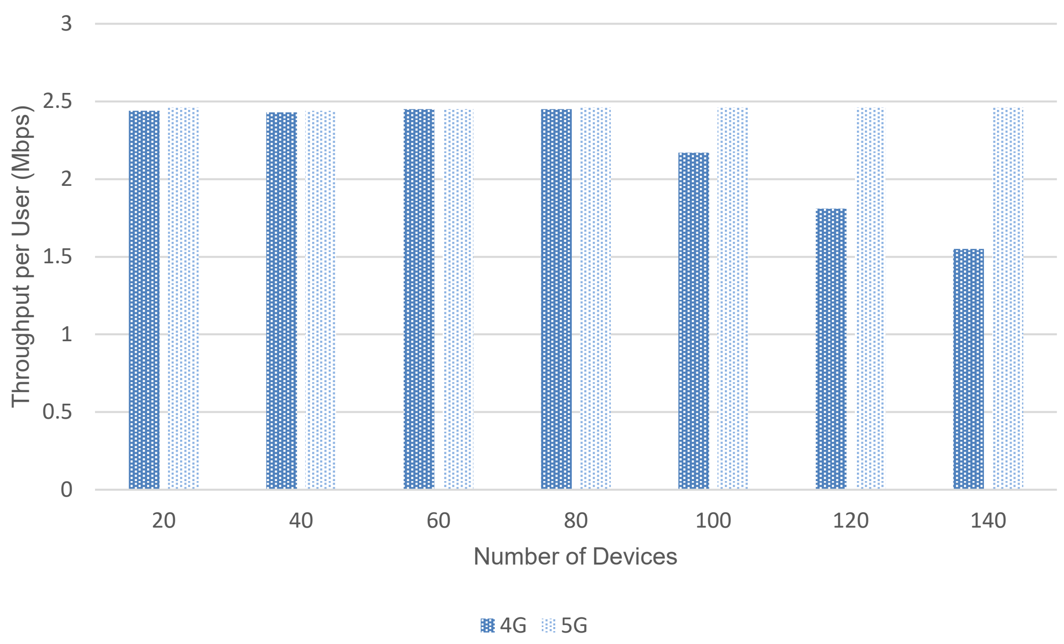


Figure 4-45: Throughput vs Number of Devices for 4G and 5G. The 4G per user throughput starts falling after 80 devices.

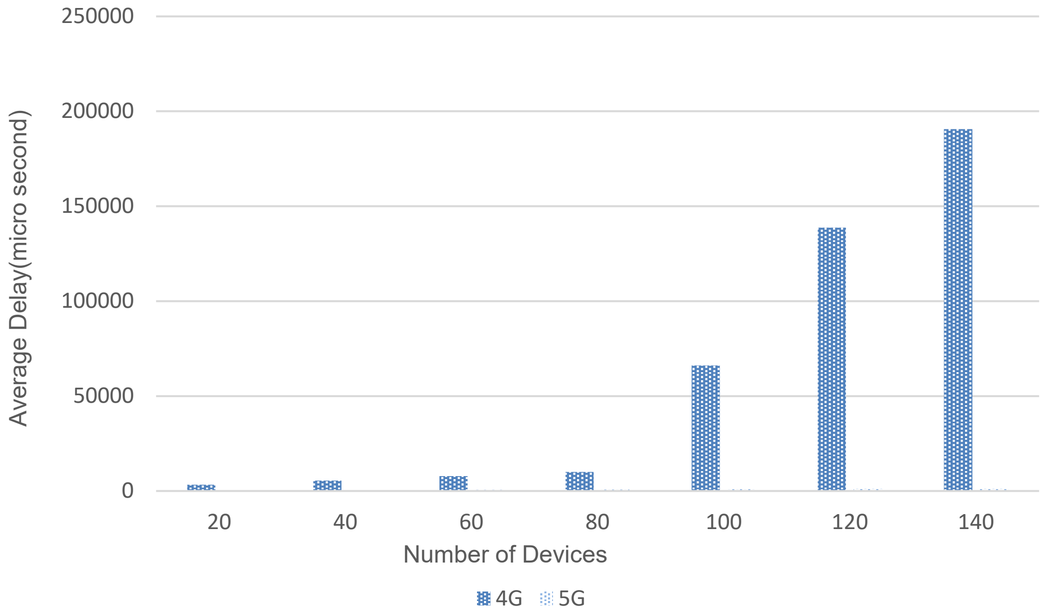


Figure 4-46: Plot of Latency vs Number of Devices. The 5G Network average delay is insignificant i.e., many orders of magnitude lower, and hence not visible in the plot.

4.9 5G-Peak-Throughput

Open NetSim, Select **Examples ->5G NR -> 5G Peak Throughput** then click on the tile in the middle panel to load the example as shown in below screenshot

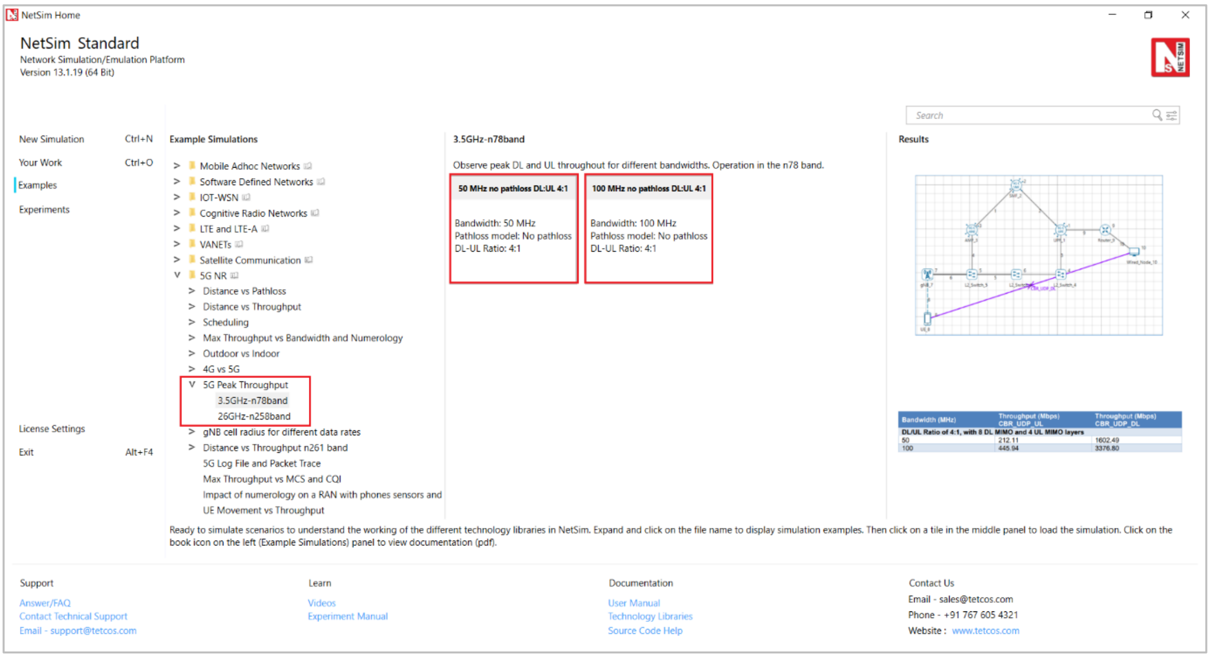


Figure 4-47: List of scenarios for the example of 5G Peak Throughput

4.9.1 3.5 GHz n78 band

The following network diagram illustrates, what the NetSim UI displays on clicking.

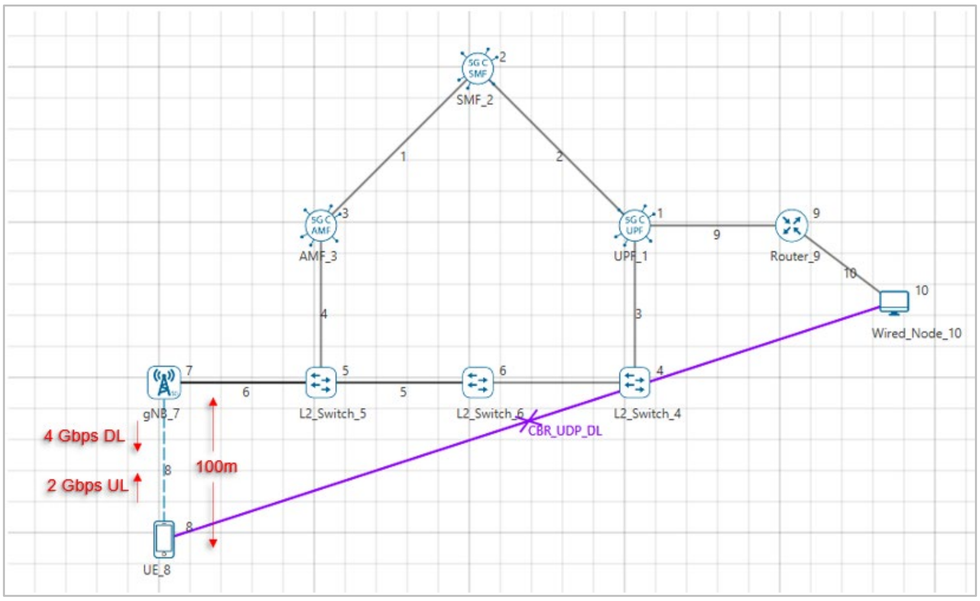


Figure 4-48: Network set up for studying the 5G Peak Throughput

Settings done in example config file:

1. Set the following property as shown in below given Table 4-44.

gNB Properties -> Interface (5G_RAN)	
Pathloss Model	None
Frequency Range	FR1
CA_Type	SINGLE_BAND
CA_Configuration	n78
DL/UL Ratio	4:1
CA1	
Numerology	2
Channel Bandwidth	50 MHz
MCS Table	QAM256
CQI Table	TABLE2

Table 4-44: gNB >Interface (5G_RAN) >Physical layer properties

2. The Tx_Antenna_Count was set to 8 and Rx_Antenna_Count was set to 4 in gNB > Interface 5G_RAN > Physical Layer.
3. The Tx_Antenna_Count was set to 4 and Rx_Antenna_Count was set to 8 in UE > Interface 5G_RAN > Physical Layer.
4. Wired link properties set Uplink speed and Downlink speed as 100000 Mbps.
5. Set 2 applications **Downlink** source node as 10, and destination node as 8, **Uplink** source node as 8, and destination node as 10. Transport Protocol is set to **UDP** in all the application.

Application Properties	
App_CBR_UDP_DL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (µs)	2.92
App_CBR_UDP_UL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (µs)	5.84

Table 4-45: Application properties

6. Plots are enabled in NetSim GUI.
7. Run simulation for 1.1 sec. After simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the Scenario and change channel bandwidth to 100 MHz, run simulation for 1.1 sec and note down throughput value from application metrics.

Result:

Bandwidth (MHz)	Throughput (Mbps) CBR_UDP_UL	Throughput (Mbps) CBR_UDP_DL
DL/UL Ratio of 4:1, with 8 DL MIMO and 4 UL MIMO layers		
50	212.11	1602.49
100	445.94	3376.80

Table 4-46: Results Comparison

4.9.2 26 GHz n258 band

Settings done in example config file:

1. Set the following property as shown in below **Table 4-47.**

gNB Properties -> Interface (5G_RAN)	
Pathloss Model	None
Frequency Range	FR2
CA_Type	SINGLE_BAND
CA_Configuration	n258
DL/UL Ratio	4:1
CA1	
Numerology	3
Channel Bandwidth	200 MHz
MCS Table	QAM256
CQI Table	TABLE2

Table 4-47: gNB >Interface (5G_RAN) >Physical layer properties

2. The Tx_Antenna_Count was set to 8 and Rx_Antenna_Count was set to 4 in gNB > Interface 5G_RAN > Physical Layer.
3. The Tx_Antenna_Count was set to 4 and Rx_Antenna_Count was set to 8 in UE > Interface 5G_RAN > Physical Layer.
4. Wired link properties set Uplink speed and Downlink speed as 100000 Mbps.
5. Set 2 applications **Downlink** source node as 10 destination node as 8**, Uplink** source node as 8 destination node as 10. Transport Protocol is set to **UDP** in all the application.

Application Properties	
App_CBR_UDP_DL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (µs)	1
App_CBR_UDP_UL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (µs)	4

Table 4-48: Application properties

6. Plots are enabled in NetSim GUI.
7. Run simulation for 1.1 sec. After simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the Scenario and change channel bandwidth to 400 MHz, run simulation for 1.1 sec and note down throughput value from application metrics.

Result:

Bandwidth (MHz)	Throughput (Mbps) CBR_UDP_UL	Throughput (Mbps) CBR_UDP_DL
DL/UL Ratio of 4:1, with 8 DL MIMO and 4 UL MIMO layers		
200	854.16	6293.53
400	1715.56	10787.99

Table 4-49: Results Comparison

4.10 Impact of distance on throughput for n261 band in LOS and NLOS states

Objective: We observe throughput of a UE (operating in the n261 band with a channel bandwidth of 100 MHz), moving away from the gNB from 1m to 3.5 Km. The variation of throughput is plotted in both LOS and NLOS states. Since 5G simulations take a long time to complete, and given our goal of studying throughput vs. distance, we have set an unrealistic speed of 20m every 10ms to complete the UE movement in a short time duration.

Open NetSim, Select **Examples ->5G NR -> Distance vs Throughput n261 band** then click on the tile in the middle panel to load the example as shown in below Figure 4-49.

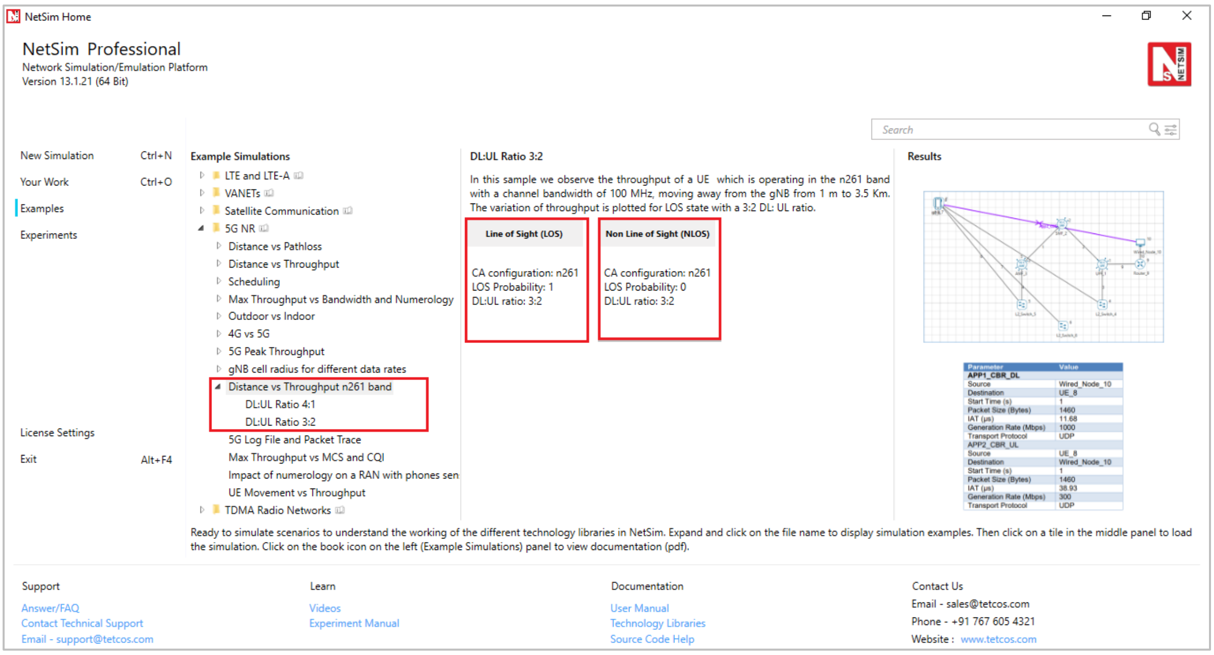


Figure 4-49: List of scenarios for the example of Distance vs Throughput n261 band

NetSim UI displays the configuration file corresponding to this experiment as shown below in Figure 4-50.

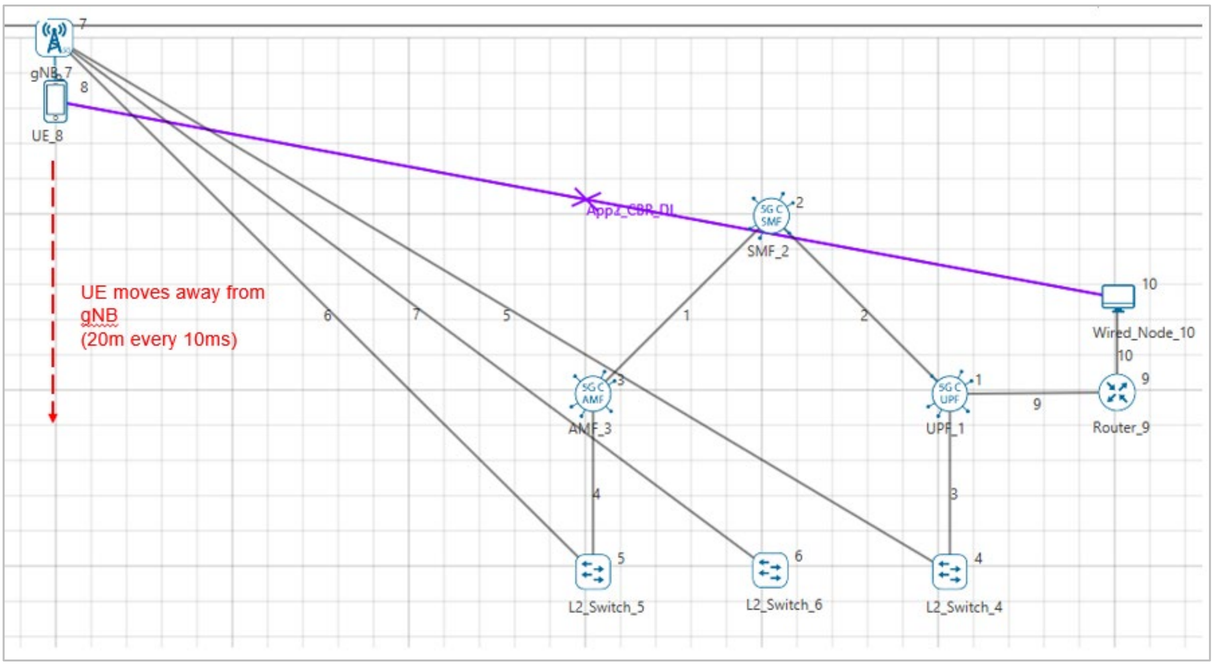


Figure 4-50: Network set up for studying the Distance vs Throughput n261 band

4.10.1 DL: UL Ratio 4:1

4.10.1.1 LOS and NLOS

The following settings were done to generate this sample:

Step 1: A network scenario is designed in NetSim GUI comprising of 1 gNB, 5G-Core, and 1 UE and 1 Router and 1 Wired Node in the **“5G NR”** Network Library.

Step 2: Grid Length was set to 5100 m x 5100 m.

Step 3: The device positions are set as per the table given below.

Device	UE_8	gNB_7
x- axis	500	500
y- axis	0	0

Table 4-50: Device general properties

Step 4: The following properties

Parameter	Value
Tx_Power	40
gNB Height	10m
CA Type	Single Band
CA Configuration	n261
DL-UL Ratio	4:1
Numerology	3
Channel Bandwidth	100 MHz
MCS Table	QAM64LOWSE
CQI Table	TABLE3
Outdoor Scenario	Urban Macro
Pathloss Model	3GPPTR38.901-7.4.1
LOS_NLOS_Selection	User Defined
LOS Probability	1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	Low Loss Model

Table 4-51: gNB >Interface (5G_RAN) >Physical layer properties

Step 5: Set Tx_Antenna_Count and Rx_Antenna_Count as 2 and 2 in gNB properties > Interface(5G_RAN) > Physical Layer.

Step 6: Set Tx_Antenna_Count and Rx_Antenna_Count as 2 and 2 in UE properties > Interface(5G_RAN) > Physical Layer.

Step 7: In the General Properties of UE 8, set Mobility Model as File Based Mobility

Step 8: Two CBR Application were generated from between the Wired_Node_10 and UE_8 with the following values.

Parameter	Value
APP1_CBR_DL	
Source	Wired_Node_10
Destination	UE_8
Start Time (s)	1
Packet Size (Bytes)	1460
IAT (µs)	11.68
Generation Rate (Mbps)	1000
Transport Protocol	UDP
APP2_CBR_UL	
Source	UE_8
Destination	Wired_Node_10
Start Time (s)	1

Packet Size (Bytes)	1460
IAT (μs)	97.33
Generation Rate (Mbps)	120
Transport Protocol	UDP

Table 4-52: Application Properties

File Based Mobility: In File Based Mobility, users can write their own custom mobility models and define the movement of the mobile users. Create a mobility.txt file for UE's involved in mobility with each step equal to 4 sec with distance 100 m. The NetSim Mobility File (mobility.txt) format is as follows:

$time 1.0 "$node_(7) 500.0 500.0"

$time 1.01 "$node_(7) 500.0 700.0"

$time 1.02 "$node_(7) 500.0 900.0"

…..

$time 2.72 "$node_(7) 500.0 34900.0"

$time 2.73 "$node_(7) 500.0 35100.0"

Step 9: Plots is enabled in NetSim GUI.

Step 10: Run simulation for 2.75s.

Step 11: Similarly, in **LOS**, set the LOS Probability to 0 in gNB properties and simulate the scenario for 1.3s.

Results:

Downlink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

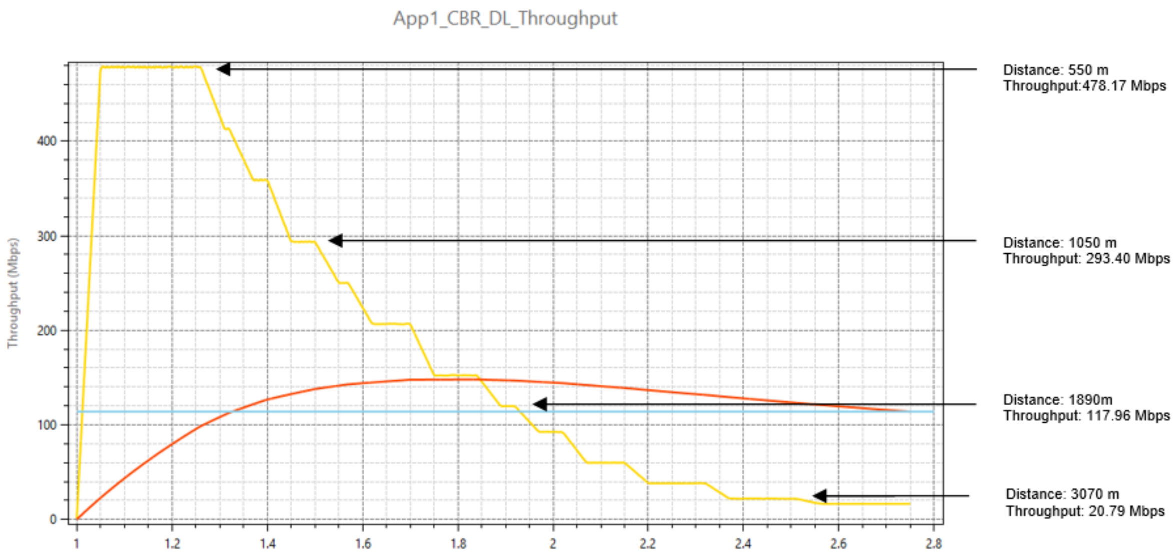


Figure 4-51: Downlink Application Throughput Plot in LOS mode

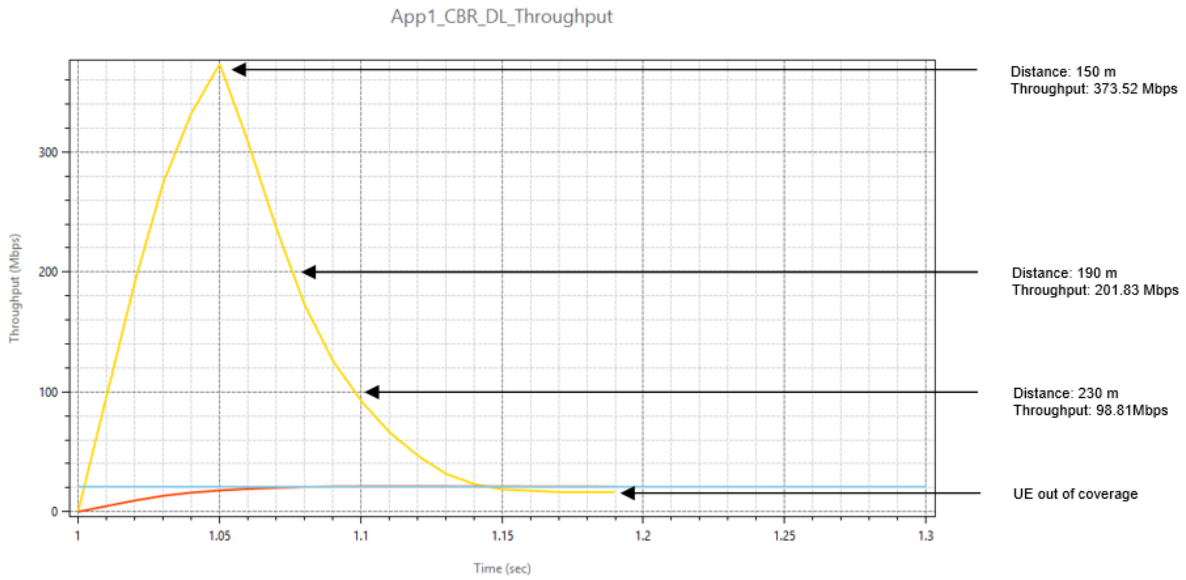


Figure 4-52: Downlink Application Throughput Plot in NLOS mode

Uplink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

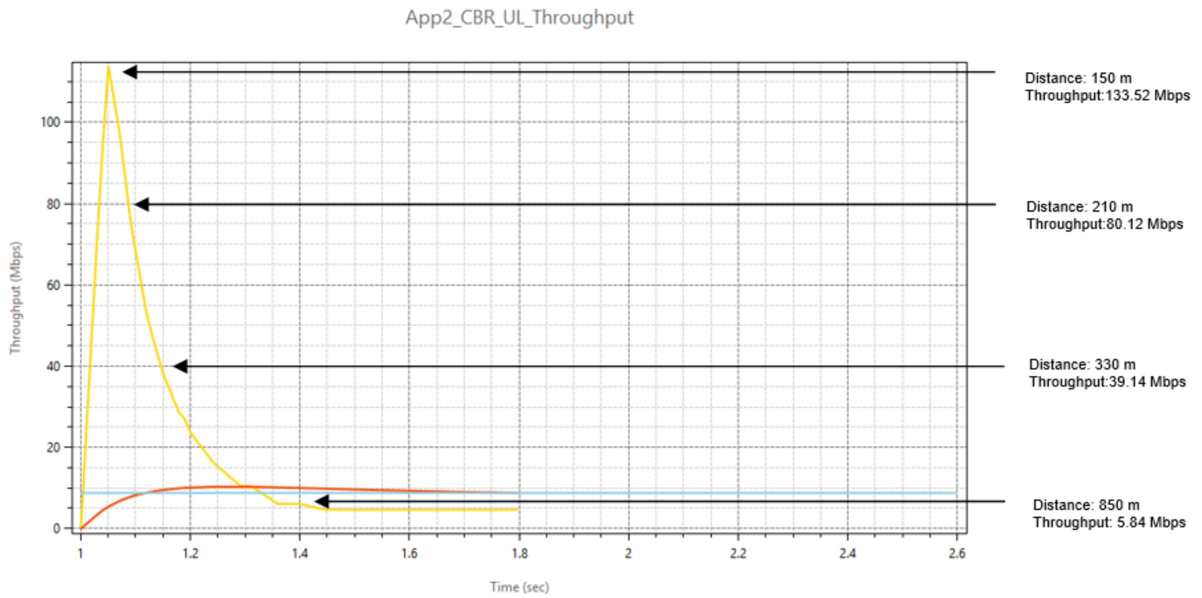


Figure 4-53: Uplink Application Throughput Plot in LOS mode

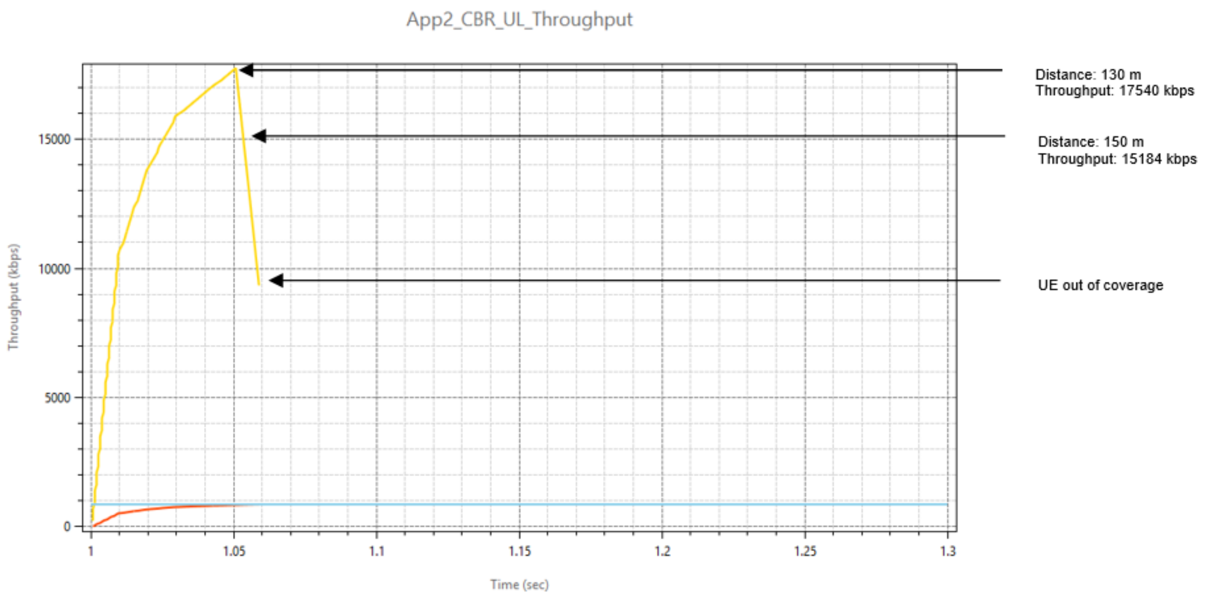


Figure 4-54: Uplink Application Throughput Plot in NLOS mode

Discussion: The downlink throughput of 479.17 Mbps is maintained till ~550m in LOS whereas, it is maintained till 150m in NLOS. Similarly, the uplink throughput of 133.52 Mbps is maintained till 150m in LOS whereas, it is maintained till 130m in NLOS. The Uplink throughput falls to the lowest level at ~750m in LOS and at ~150m in NLOS.

4.10.2 DL: UL Ratio 3:2

4.10.2.1 LOS and NLOS

Step 1: All the properties were set as in DL: UL-Ratio 4:1.

Step 2: In the gNB properties-> Interface 5G_RAN, the DL:UL ratio was set to 3:2.

Step 3: The following settings were done in application properties:

Parameter	Value
APP1_CBR_DL	
Source	Wired_Node_10
Destination	UE_8
Start Time (s)	1
Packet Size (Bytes)	1460
IAT (µs)	11.68
Generation Rate (Mbps)	1000
Transport Protocol	UDP
APP2_CBR_UL	
Source	UE_8
Destination	Wired_Node_10
Start Time (s)	1
Packet Size (Bytes)	1460
IAT (µs)	38.93
Generation Rate (Mbps)	300
Transport Protocol	UDP

Table 4-53: Application Properties

Step 3: Run simulation for 2.75s.

Step 4: Similarly, in LOS, set the LOS Probability to 0 in gNB properties and run simulation for 1.3s.

Results:

Downlink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

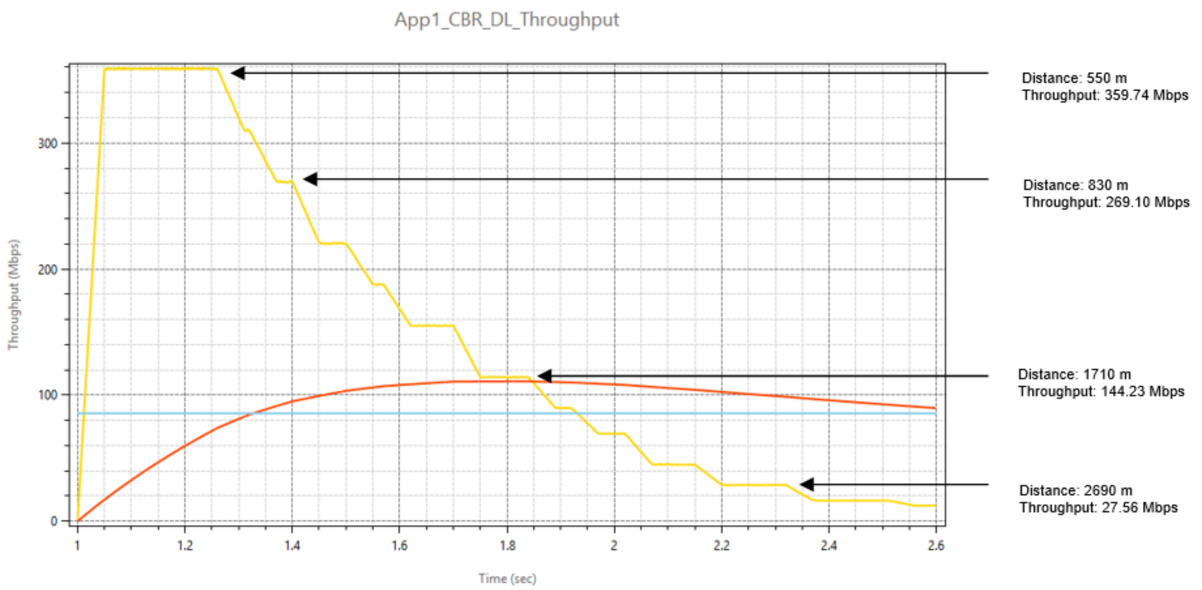


Figure 4-55: Downlink Application Throughput Plot in LOS mode

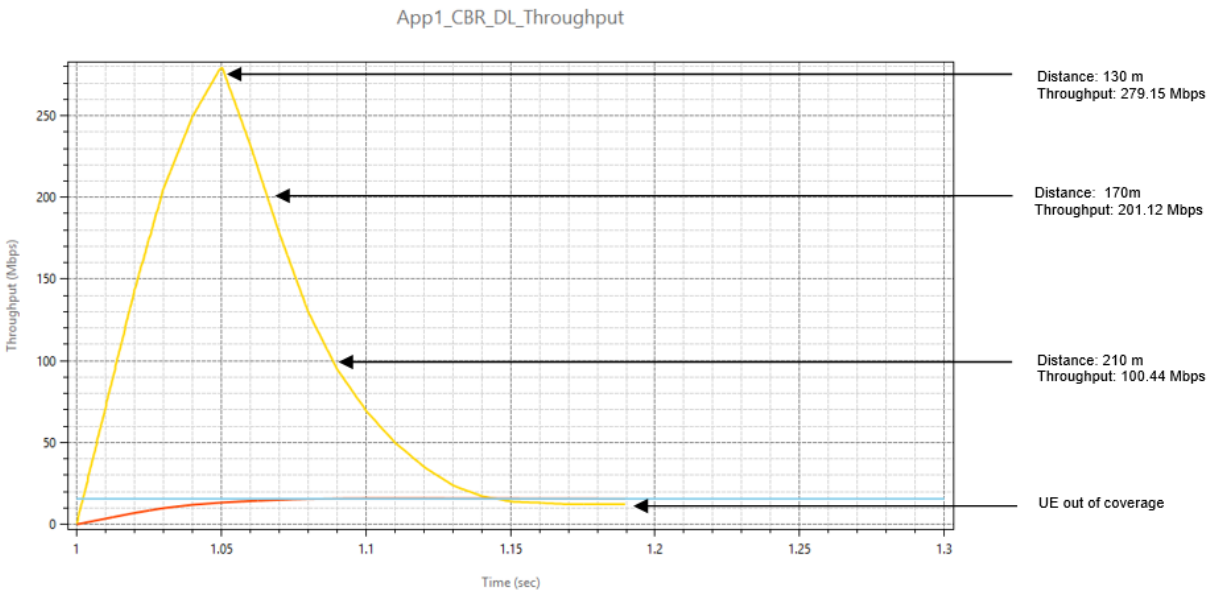


Figure 4-56: Downlink Application Throughput Plot in NLOS mode

Uplink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

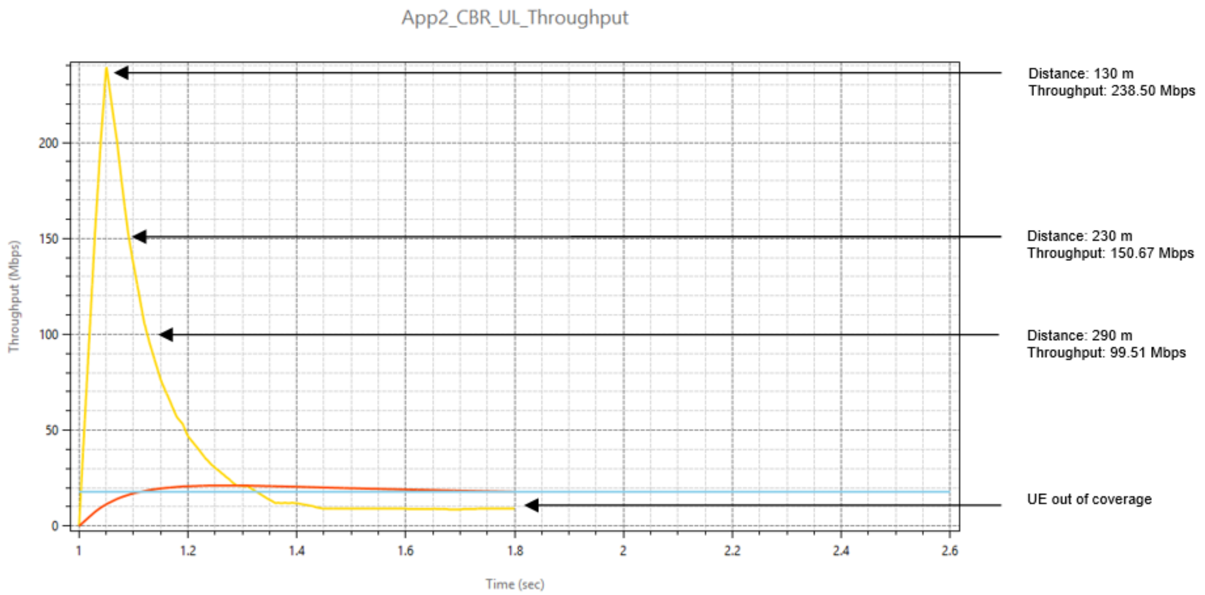


Figure 4-57: Uplink Application Throughput Plot in LOS mode

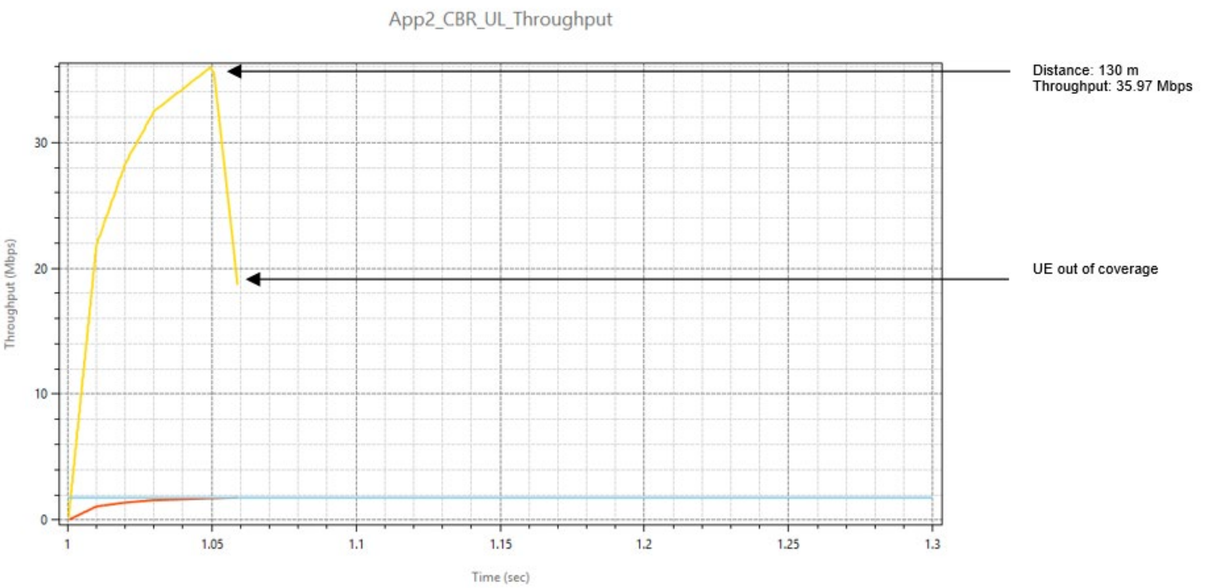


Figure 4-58: Uplink Application Throughput Plot in NLOS mode

Inference: The downlink throughput of 359.74 Mbps is maintained till ~550m in LOS whereas, it is maintained till 130m in NLOS. Similarly, the uplink throughput of 238.50 Mbps is maintained till 130m in LOS whereas, it is 35.97 Mbps maintained till 130m in NLOS. The Uplink throughput falls to the lowest level at ~750m in LOS and at ~150m in NLOS.

4.11 Urban gNB cell radius for different data rates

Open NetSim, Select **Examples->5G NR ->gNB cell radius for different data rates** then click on the tile in the middle panel to load the example as shown in below screenshot

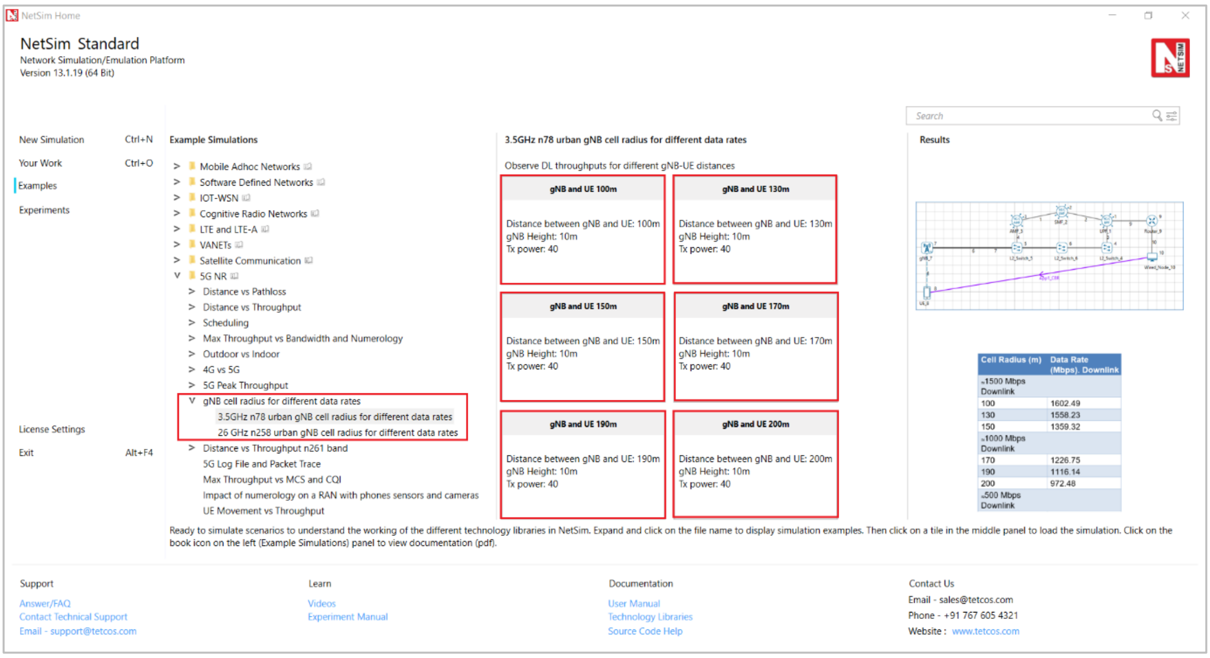


Figure 4-59: List of scenarios for the example of gNB cell radius for different data rates

4.11.1 3.5 GHz n78 urban gNB cell radius for different data rates

The following network diagram illustrates, what the NetSim UI displays on clicking.

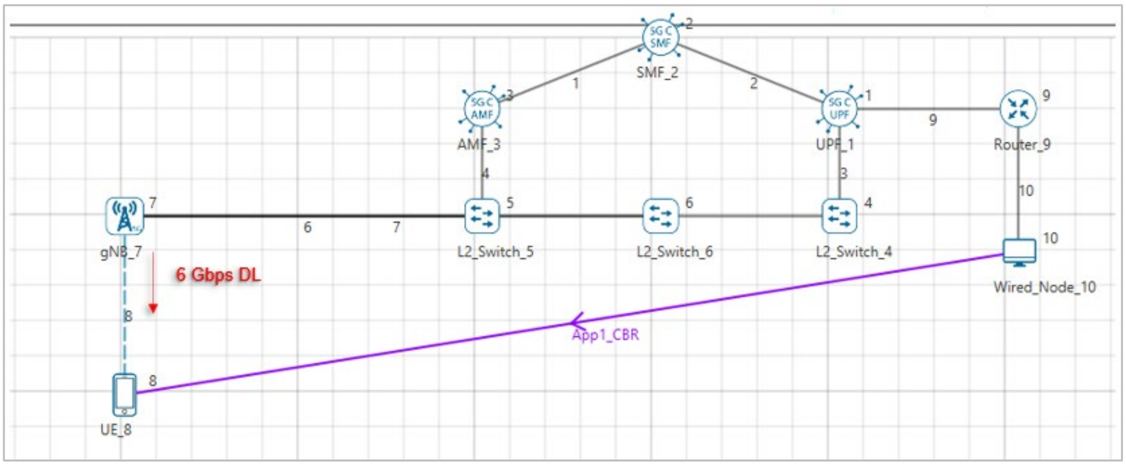


Figure 4-60: Network set up for studying the gNB cell radius for different data rates

Setting done in example config file:

1. Set the following property as shown in below Table 4-54.

gNB Properties -> Interface (5G_RAN)	
gNB Height	10m
Tx Power	40
CA Type	Single Band
CA Configuration	n78
DL: UL	4:1

Numerology	2
Channel Bandwidth	50 MHz
MCS Table	QAM256
CQI Table	TABLE2
Outdoor Scenario	Urban Macro
Pathloss Model	3GPPTR38.901-7.4.1
LOS_NLOS Selection	3GPPTR38.901-Table7.4.2-1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-54: gNB >Interface (5G_RAN) >Physical layer properties

2. Set the Tx_Antenna Count as 8 and Rx_Antenna Count as 1 in gNB> Interface 5G_RAN > Physical Layer.
3. Set the Tx_Antenna Count as 1 and Rx_Antenna Count as 8 in UE> Interface 5G_RAN > Physical Layer.
4. Set Uplink speed and Downlink speed as 100000 Mbps and BER as 0.
5. Set the following application properties:

App_1_CBR	
Source Id	10
Destination Id	8
Packet Size	1460
IAT	1.94 µs
Start time	1s
Transport Protocol	UDP
Generation Rate	6 Gbps

Table 4-55: Application properties

6. Plots are enabled in NetSim GUI.
7. Run simulation for 1.1 sec. After simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the Scenario and change distance between gNB and UE to 100m, 130m, 150m, 170m, 190m, 200m, 300m, 330m, and 350m for sample 1 to 9 and run simulation for 1.1 sec.

Result:

Cell Radius (m)	Data Rate (Mbps). Downlink
≈1500 Mbps Downlink	
100	1602.49
130	1359.32
150	1226.75
≈1000 Mbps Downlink	
170	1116.14
190	972.48

200	839.91
≈500 Mbps Downlink	
300	508.31
330	419.90
350	309.40

Table 4-56: Results Comparison

4.11.2 26 GHz n258 urban gNB cell radius for different data rates

Setting done in example config file:

1. Set the following property as shown in below given table:

gNB Properties -> Interface (5G_RAN)	
gNB Height	10m
Tx Power	40
MCS Table	QAM256
CQI Table	TABLE2
CA Type	Single Band
CA Configuration	N258
DL: UL	4:1
Numerology	2
Channel Bandwidth	200 MHz
Outdoor Scenario	Urban Macro
Pathloss Model	3GPPTR38.901-7.4.1
LOS_NLOS Selection	3GPPTR38.901-Table7.4.2-1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING
O2I Building Penetration Model	None

Table 4-57: gNB >Interface (5G_RAN) >Physical layer properties

2. Set the Tx_Antenna Count as 8 and Rx_Antenna Count as 1 in gNB> Interface 5G_RAN > Physical Layer.
3. Set the Tx_Antenna Count as 1 and Rx_Antenna Count as 8 in UE> Interface 5G_RAN > Physical Layer.
4. Set Uplink speed and Downlink speed as 100000 Mbps and BER as 0.
5. Set the following application properties:

App_1_CBR	
Source Id	10
Destination Id	8
Packet Size	1460
IAT	1.94 µs
Start time	1s

Transport Protocol	UDP
Generation Rate	6 Gbps

Table 4-58: Application properties

6. Plots are enabled in NetSim GUI.
7. Run simulation for 1.1 sec. After simulation completes go to metrics window and note down throughput value from application metrics.

Go back to the Scenario and change distance between gNB and UE to 20m, 110m, and 150m for sample 1 to 3 and run simulation for 1.1 sec.

Result:

Cell Radius (m)	Data Rate (Mbps). Downlink
≈6000 Mbps Downlink	
20	6004.34
≈1000 Mbps Downlink	
110	737.83
≈ 500 Mbps Downlink	
150	303.80

Table 4-59: Results Comparison

4.12 Impact of numerology on a RAN with phones, sensors, and cameras

Open NetSim, Select **Examples ->5G NR -> Impact of numerology on a RAN with phones sensors and cameras** then click on the tile in the middle panel to load the example as shown in below Figure 4-61.

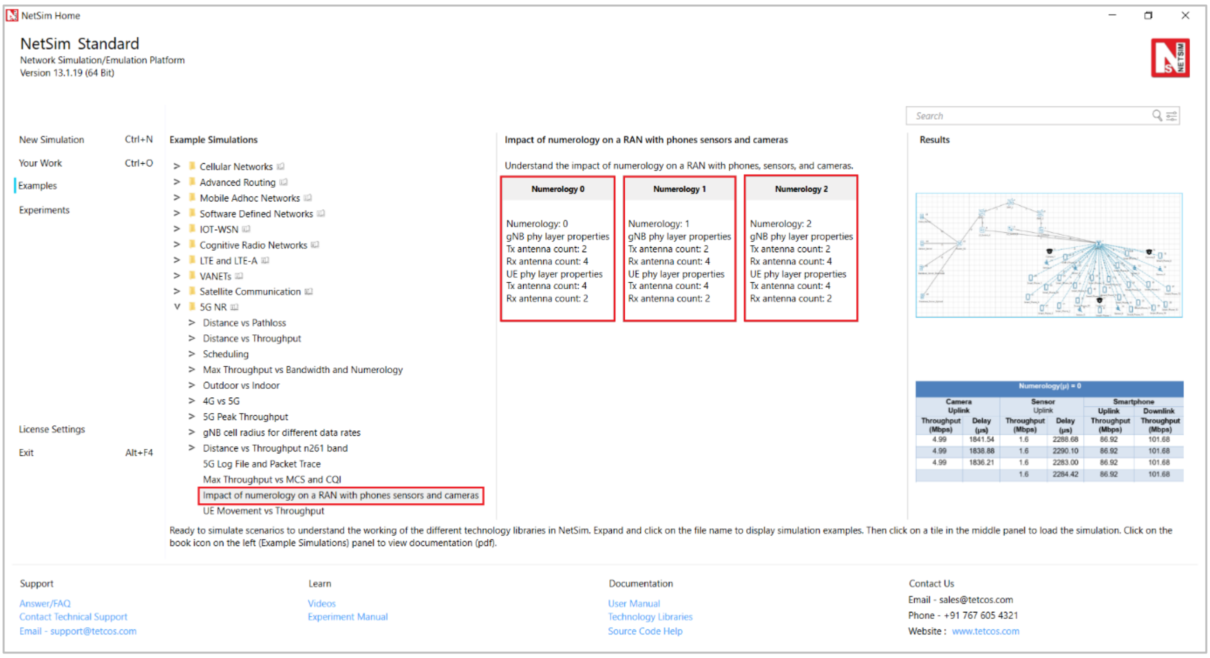


Figure 4-61: List of scenarios for the example of Impact of numerology on a RAN with phones sensors and cameras

Network Scenario[2]**:** To model a real-world scenario, we base our simulation on the setup shown in Figure 4-62. The link between the gNB and the L2_Switches that represents the Core Network (CN) is made with a point-to-point 10 Gb/s link, without propagation delay. The Radio Area Network (RAN) is served by 1 gNB, in which different UEs share the connectivity. We have 25 smartphones, 6 sensors, 3 IP cameras. The bandwidth is 100MHz and Round Robin MAC Scheduler. The position of the devices in the reference scenario depicted in Figure 4-62 is quasi-random.

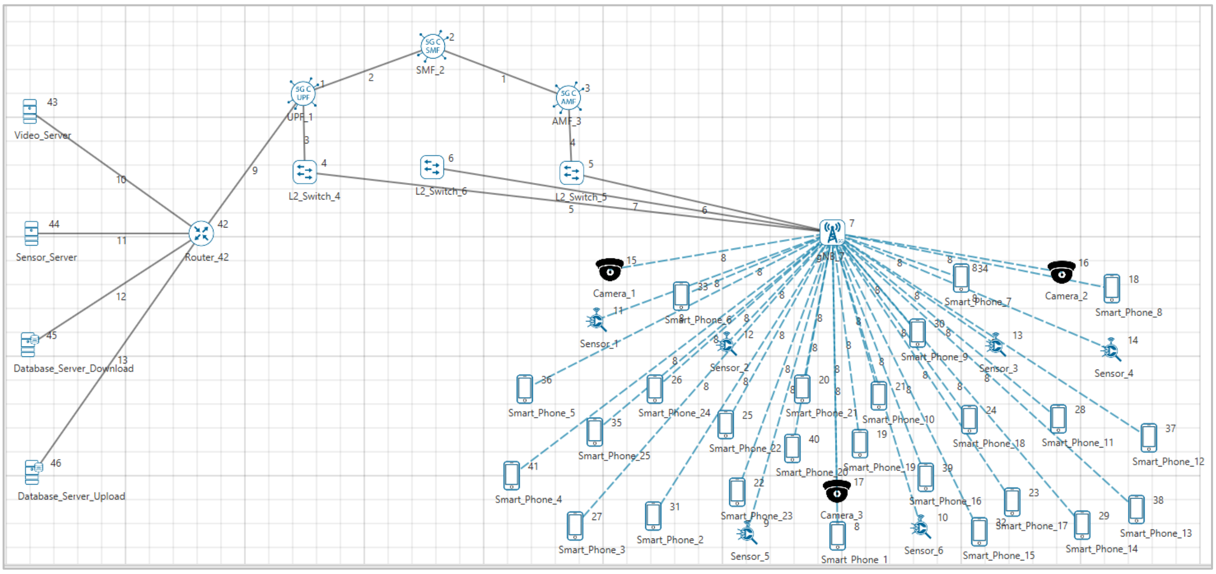


Figure 4-62: Network set up for studying the with 25 smartphones, 6 sensors and 3 cameras communicating with respective cloud servers

In terms of application data traffic, the camera (video) and sensor nodes have one UDP flow each, that goes in the UL towards a remote node on the Internet. These flows are fixed-rate flows: we have a continuous transmission of 5 Mb/s for the video nodes, to simulate a 720p24 HD video, and the sensors transmit a payload of 500 bytes each 2.5 ms, that gives a rate of 1.6 Mb/s. For the smartphones, we use TCP as the transmission protocol. These connect to data base servers. Each phone has to download a 25 MB file and to upload one file of 1.5 MB. These flows start at different times: the upload starts at a random time between the 25th and the 75th simulation seconds, while each download starts at a random time between the 1.5th and the 95th simulation seconds.

[2] This example is adapted from [3]

	Flows (No of devices)	Traffic Rate (Mbps)	Segment / File Size (B)	RAN Dir.	TCP ACK Dir.
Camera (UDP)	3	5	500	UL	-
Sensor (UDP)	6	1.6	500	UL	-
Smartphone Upload (TCP)	25	-	1,500,000	UL	DL
Smartphone Download (TCP)	25	-	25,000,000	DL	UL

Table 4-60: Various parameters of the Traffic flow models for all the devices

The numerology μ can take values from 0 to 3 and specifies an SCS of $15 \times 2^{\mu}$ kHz and a slot length of $\frac{1}{2^{\mu}}$ ms. FR1 support $\mu = 0, 1$ and 2, while FR2 supports $\mu = 2, 3$. We study the impact of different numerologies, and how they affect the end-to-end performance. The metrics measured and analysed are a) Throughput of TCP uploads & downloads, and b) Latency of the UDP uploads

Settings done in example config file:

1. For the above scenario set the following given properties:

gNB Properties -> Interface (5G_RAN)	
Pathloss Model	None
Frequency Range	FR1
CA Type	Inter Band CA
CA_Configuration	CA_2DL_2UL_n40_n41
CA1	
Numerology	0, 1, and 2
Channel Bandwidth	50 MHz
DL_UL Ratio	1:4
CA**2**	
Numerology	0, 1, and 2
Channel Bandwidth	50 MHz
DL_UL Ratio	1:4
MCS Table	QAM64
CQI Table	TABLE1

Table 4-61: gNB >Interface (5G_RAN) >Physical layer properties

Link Properties (All wired links)	
Uplink/ Downlink Speed (Mbps)	10000
Uplink/ Downlink BER	0
Uplink/ Downlink Propagation Delay (µs)	5

Table 4-62: Wired Link Properties

2. The following Application properties set to the above scenario:

Sensor UL UDP	
Generation Rate (Mbps)	1.6
Transport Protocol	UDP
Application Type	Custom
Packet Size (Bytes)	500
Inter Arrival Time (µs)	2500

Table 4-63: Sensor Application Properties for UL UDP

Camera UL UDP	
Generation Rate (Mbps)	5
Transport Protocol	UDP
Application Type	Custom
Packet Size (Bytes)	500
Inter Arrival Time (µs)	800

Table 4-64: Camera Application Properties for UL UDP

Phone DL TCP	
Transport Protocol	TCP
Start Time (s)	$1.5 + 4(t)$, Where, $i = 0, 1, 2, \ldots \ldots, 48$
Stop Time (s)	95
File Size (Bytes)	25,000,000
Inter Arrival Time (s)	200 (Simulation ends at 100s and hence only one file is sent)
Application Type	FTP

Table 4-65: Phone Application Properties for DL TCP

Phone UL TCP	
Application Type	FTP
Transport Protocol	TCP
Start Time (s)	$25 + 2(i - 1)$ Where, $i = 1, 2, \ldots \ldots, 25$
Stop Time (s)	95
File Size (Bytes)	1,500,000
Inter Arrival Time (s)	200 (Simulation ends at 100s and hence only one file is sent)

Table 4-66: Phone Application Properties for UL TCP

3. The Tx_Antenna_Count was set to 2 and Rx_Antenna_Count was set to 4 in gNB > Interface 5G_RAN >Physical Layer.
4. The Tx_Antenna_Count was set to 4 and Rx_Antenna_Count was set to 2 in UE > Interface 5G_RAN >Physical Layer.
5. Run simulation for 100 sec. After simulation completes go to metrics window and note down throughput and delay value from application metrics.

Result and Analysis:

Numerology(μ) = 0					
Camera Uplink		**Sensor** Uplink		**Smartphone**	
				Uplink	**Downlink**
Throughput (Mbps)	**Delay (μs)**	**Throughput (Mbps)**	**Delay (μs)**	**Throughput (Mbps)**	**Throughput (Mbps)**
4.99	1841.54	1.6	2288.68	86.92	101.68
4.99	1838.88	1.6	2290.10	86.92	101.68
4.99	1836.21	1.6	2283.00	86.92	101.68
		1.6	2284.42	86.92	101.68
		1.6	2285.84	86.92	101.68
		1.6	2287.26	86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
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				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68

				86.92	101.68
				86.92	101.68
				86.92	101.68
				86.92	101.68

Table 4-67: Throughput and delay for Camera, Sensors and Smartphones, When $\mu = 0$

Numerology(μ) = 1					
Camera Uplink		**Sensor Uplink**		**Smartphone**	
				Uplink	**Downlink**
Throughput (Mbps)	**Delay (μs)**	**Throughput (Mbps)**	**Delay (μs)**	**Throughput (Mbps)**	**Throughput (Mbps)**
4.99	932.39	1.60	1538.35	173.78	156.43
4.99	930.75	1.60	1539.77	173.78	156.43
4.99	929.10	1.60	1532.68	173.78	156.43
		1.60	1534.10	173.78	156.43
		1.60	1535.52	173.78	156.43
		1.60	1536.94	173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
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				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43
				173.78	156.43

Table 4-68: Throughput and delay for Camera, Sensors and Smartphones, When $\mu = 1$

Numerology(μ) = 2					
Camera Uplink		**Sensor Uplink**		**Smartphone**	
				Uplink	**Downlink**
Throughput (Mbps)	**Delay (μs)**	**Throughput (Mbps)**	**Delay (μs)**	**Throughput (Mbps)**	**Throughput (Mbps)**
5.00	477.71	1.60	782.24	347.30	151.75
5.00	476.29	1.60	783.66	347.30	151.75

5.00	474.87	1.60	776.56	347.30	151.75
		1.60	777.98	347.30	151.75
		1.60	779.40	347.30	151.75
		1.60	780.82	347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
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				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75
				347.30	151.75

Table 4-69: Throughput and delay for Camera, Sensors and Smartphones, When $\mu = 2$

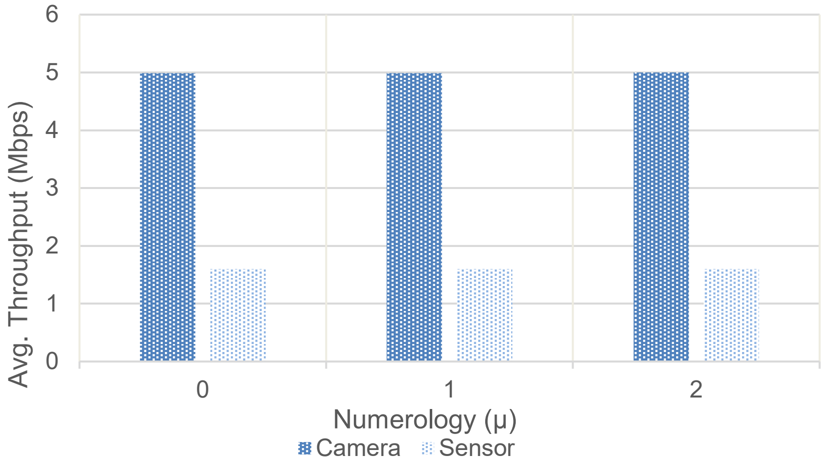

Figure 4-63: The average uplink throughput for camera and sensors remains the same as numerology is increased. This is because the flow is UDP.

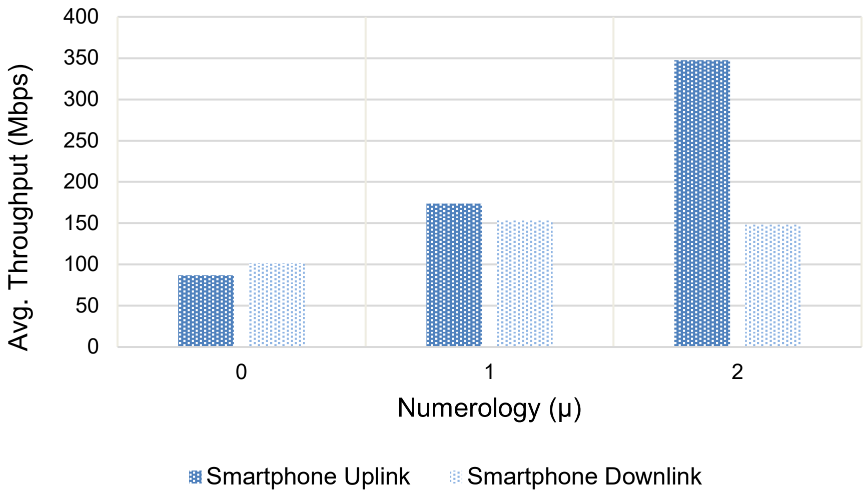

Figure 4-64: Smartphone Uplink, and Smartphone Downlink average throughput vs. Numerology (µ)

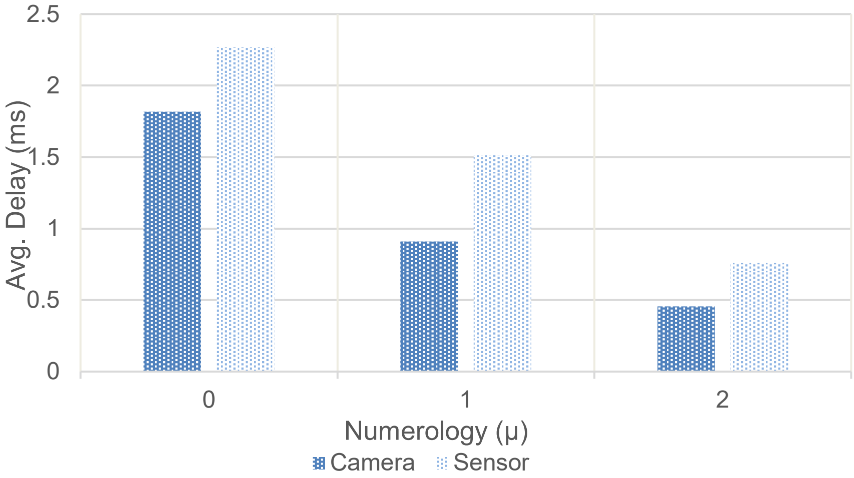

Figure 4-65: Camera Uplink, and Sensor Uplink Latency vs. Numerology. The latency drops as the numerology increases

For UDP applications the μ does not impact the throughput. However, higher μ leads to an obviously lower delay. The variation of delay vs. μ is as follows:

	Avg Delay (Camera)	Avg Delay (Sensor)
$\mu = 0$	1.838 ms	2.286 ms
$\mu = 1$	0.930 ms	1.536 ms
$\mu = 2$	0.476 ms	0.780 ms

Table 4-70: Variation of delay vs. numerology for Camera and Sensors

The TCP throughput is inversely proportional to round trip time. Therefore, for applications running over TCP the throughput increases with higher numerology. This is because higher Numerology leads to reduced round-trip (end-to-end) times.

4.13 Impact of UE movement on Throughput

Open NetSim, Select **Examples ->5G NR -> UE Movement vs Throughput** then click on the tile in the middle panel to load the example as shown in below Figure 4-66.

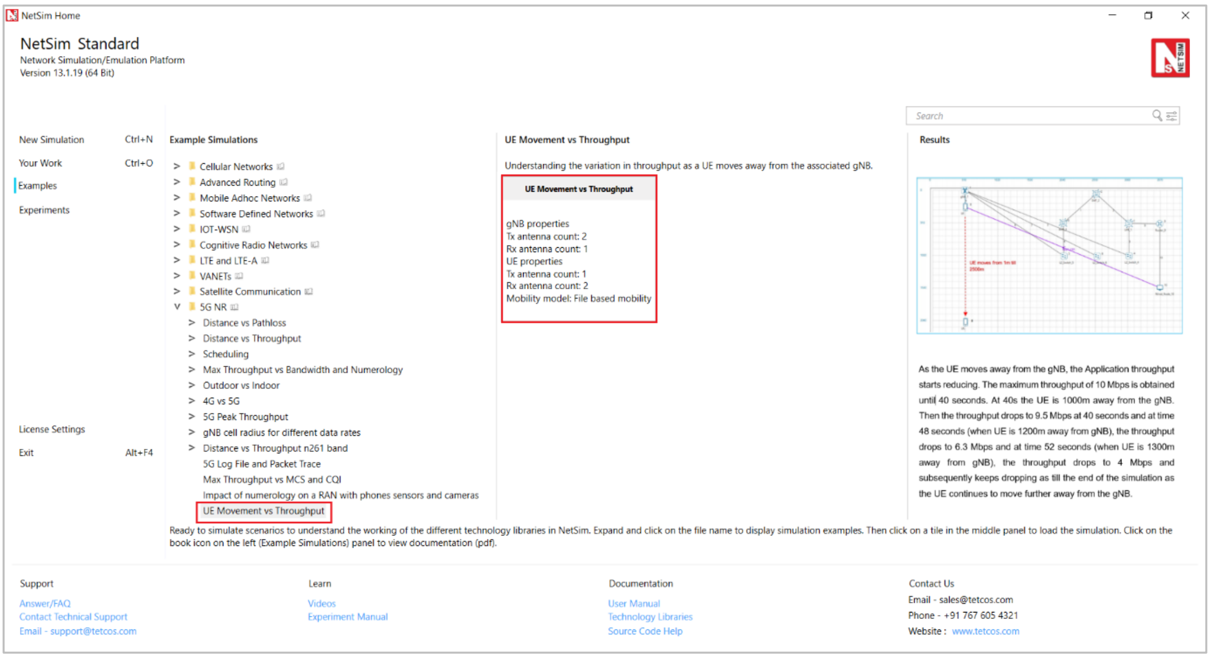

Figure 4-66: List of scenarios for the example of UE Movement vs Throughput

NetSim UI displays the configuration file corresponding to this experiment as shown below Figure 4-67.

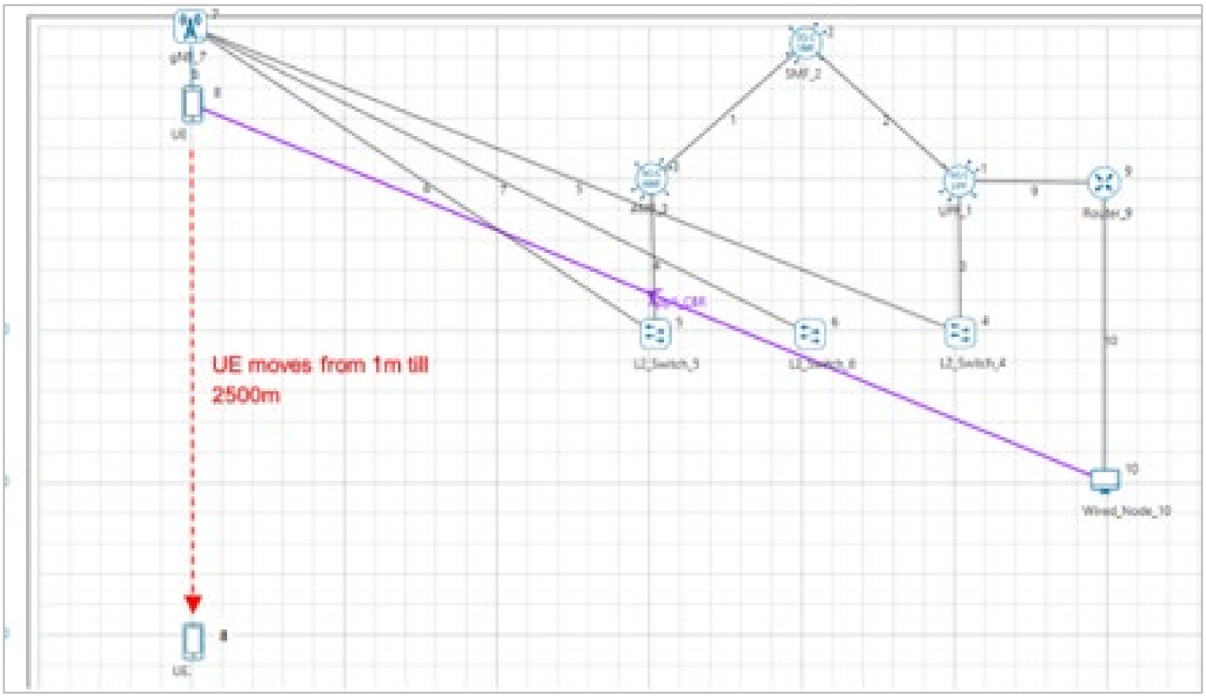

Figure 4-67: Network set up for studying the UE Movement vs Throughput

Settings done in example config file:

The following set of procedures were done to generate this sample:

Step 1: A network scenario is designed in NetSim GUI comprising of 1 gNB, 5G-Core, and 1 UE and 1 Wired Node in the **“5G NR”** Network Library.

Step 2: Grid Length was set to 5100 m x 5100 m.

Step 3: The device positions are set as per the table given below Table 4-71.

Device	UE_8	gNB_7	Wired_Node_10
x- axis	500	500	3500
y- axis	1	0	1020

Table 4-71: Device general properties

Step 4: The following properties were set in Interface (5G_RAN) of gNB

Parameter	Value
Tx_Power	40
gNB Height	10m
CA Type	Single Band
CA Configuration	n78
DL-UL Ratio	4:1
Numerology	0
Channel Bandwidth	10 MHz
MCS Table	QAM64LOWSE
CQI Table	TABLE3
Propagation Model	Urban Macro
Pathloss Model	3GPPTR38.901-7.4.1
LOS_NLOS_Selection	User Defined
LOS Probability	0
Shadow Fading Model	None
Fading and Beamforming	NO_FADING
O2I Building Penetration Model	Low Loss Model

Table 4-72: gNB >Interface (5G_RAN) >Physical layer properties

Step 5: Set Tx_Antenna_Count and Rx_Antenna_Count as 2 and 1 in gNB properties > Interface(5G_RAN) > Physical Layer.

Step 6: Set Tx_Antenna_Count and Rx_Antenna_Count as 1 and 2 in UE properties > Interface(5G_RAN) > Physical Layer.

Step 7: In the General Properties of UE 8, set Mobility Model as File Based Mobility

Step 8: A CBR Application was generated from Wired Node 10 i.e. Source to UE 8 i.e. Destination with Packet Size remaining 1460Bytes and Inter Arrival Time remaining 1168µs.

Step 9: The Transport Protocol was set to UDP.

Step 10: Additionally, the **"Start Time(s)"** parameter is set to 1s, while configuring the application.

File Based Mobility:

In File Based Mobility, users can write their own custom mobility models and define the movement of the mobile users. Create a mobility.txt file for UE's involved in mobility with each step equal to 4 sec with distance 100 m.

The NetSim Mobility File (mobility.txt) format is as follows:

$time 0.0 "$node_(7) 500.0 1.0 0.0"

```
$time 4.0 "$node_(7) 500.0 101.0 0.0"
$time 8.0 "$node_(7) 500.0 201.0 0.0"
$time 12.0 "$node_(7) 500.0 301.0 0.0"
$time 16.0 "$node_(7) 500.0 401.0 0.0"
$time 20.0 "$node_(7) 500.0 501.0 0.0"
$time 24.0 "$node_(7) 500.0 601.0 0.0"
$time 28.0 "$node_(7) 500.0 701.0 0.0"
$time 32.0 "$node_(7) 500.0 801.0 0.0"
$time 36.0 "$node_(7) 500.0 901.0 0.0"
$time 40.0 "$node_(7) 500.0 1001.0 0.0"
$time 44.0 "$node_(7) 500.0 1101.0 0.0"
$time 48.0 "$node_(7) 500.0 1201.0 0.0"
$time 52.0 "$node_(7) 500.0 1301.0 0.0"
$time 56.0 "$node_(7) 500.0 1401.0 0.0"
$time 60.0 "$node_(7) 500.0 1501.0 0.0"
$time 64.0 "$node_(7) 500.0 1601.0 0.0"
$time 68.0 "$node_(7) 500.0 1701.0 0.0"
$time 72.0 "$node_(7) 500.0 1801.0 0.0"
$time 76.0 "$node_(7) 500.0 1901.0 0.0"
$time 80.0 "$node_(7) 500.0 2001.0 0.0"
$time 84.0 "$node_(7) 500.0 2101.0 0.0"
$time 88.0 "$node_(7) 500.0 2201.0 0.0"
$time 92.0 "$node_(7) 500.0 2301.0 0.0"
$time 96.0 "$node_(7) 500.0 2401.0 0.0"
$time 100.0 "$node_(7) 500.0 2501.0 0.0"
```

Step 11: Plots is enabled in NetSim GUI.

Step 12: Run simulation for 100s.

Results:

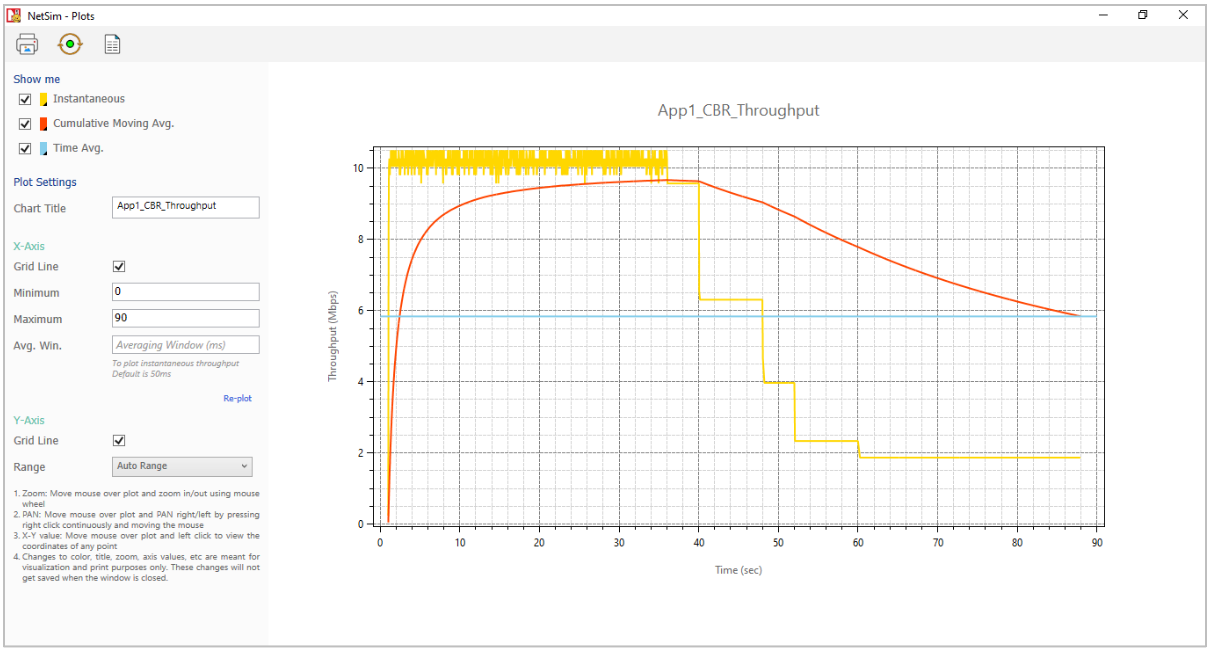

Figure 4-68 Throughput (Mbps) vs Time Plot (sec)

Discussion:

As the UE moves away from the gNB, the Application throughput starts reducing. The maximum throughput of 10 Mbps is obtained until 40 seconds. At 40s the UE is 1000m away from the gNB. Then the throughput drops to 9.5 Mbps at 40 seconds and at time 48 seconds (when UE is 1200m away from gNB), the throughput drops to 6.3 Mbps and at time 52 seconds (when UE is 1300m away from gNB), the throughput drops to 4 Mbps and subsequently keeps dropping as till the end of the simulation as the UE continues to move further away from the gNB.

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5 Omitted Features

- The omitted features in the PHY layer are mentioned in 3.9.2.
- Wireshark packet capture for 5G MAC
- Broadcast and multicast transmissions
- Implementation of ROHC (rfc 5795) for header compression and decompression of IP data flow
- Application
  - Different resource type and priority levels for applications
- RRC
  - Modification and release of RRC connection
- PDCP
  - ciphering and deciphering
  - integrity protection
  - for split bearers, routing
- MAC
  - HARQ
  - Random access procedure
  - PCH
  - BCH
  - DRx
  - S-cells
  - BWP operation
  - SUL operation
  - Beam failure detection
  - MAC CE
  - RNTI
  - MAC header
- Miscellaneous
  - In-sequence delivery of upper layer PDUs at re-establishment of lower layers
  - Duplicate elimination of lower layer SDUs at re-establishment of lower layers for radio bearers mapped on RLC AM.
  - Timer based discard.
  - Duplicate discarding.

6 5G NR Experiments in NetSim

Apart from examples, in-built experiments are also available in NetSim. Examples help the user understand the working of features in NetSim. Experiments are designed to help the user (usually students) learn networking concepts through simulation. The experiments contain objective, theory, set-up, results, and inference. The following experiments are available in the Experiments manual (pdf file).

1. Simulate and study 5G Handover procedure.

7 Reference Documents

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