NetSim®

Accelerate Network R & D

5G NR

A Network Simulation & Emulation Software

By

TETCOS LLP

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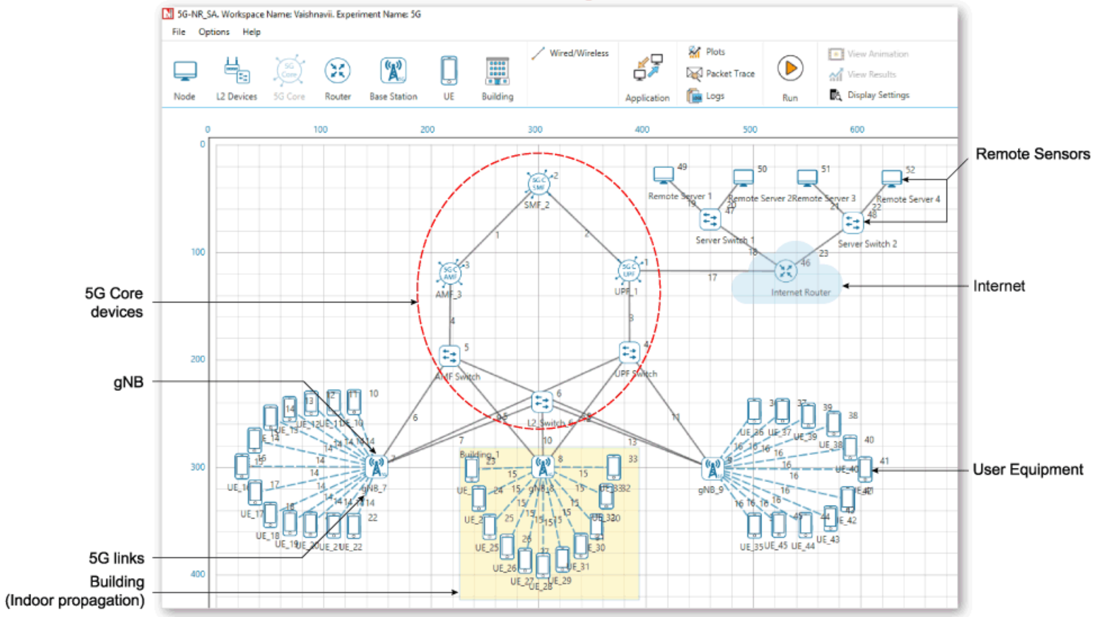
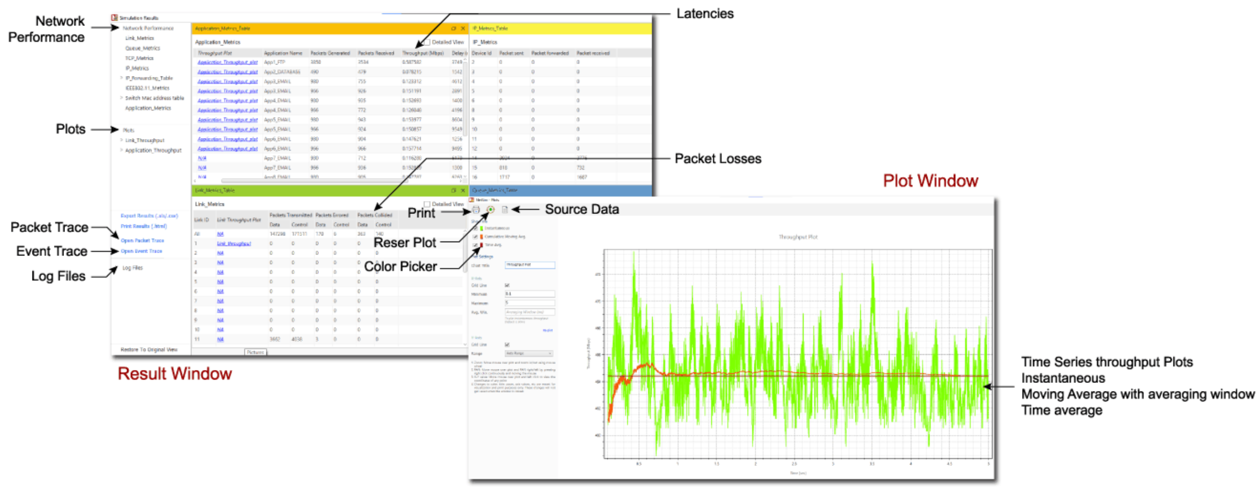
1 Introduction to 5G simulation with NetSim

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[1]. The 5G devices available in NetSim are the 5G core devices: (i) AMF, (ii) SMF, (iii) UPF, and RAN devices: (i) gNBs (ii) UEs. Simulation is discrete event and done at a packet level abstraction. This 5G library is designed to connect to the base component of NetSim (and in turn to other components), which provides functionalities such as the TCP/IP Network Stack, Routing algorithms, Mobility, Output Metrics, Traces etc. 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.

NetSim 5G NR Design Window





[1] For an introduction to 5G see Chapter 3

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

2 Simulation GUI

2.1 Create Scenario

Open NetSim and click **New Simulation** → **5G NR** as shown Figure 2-1.

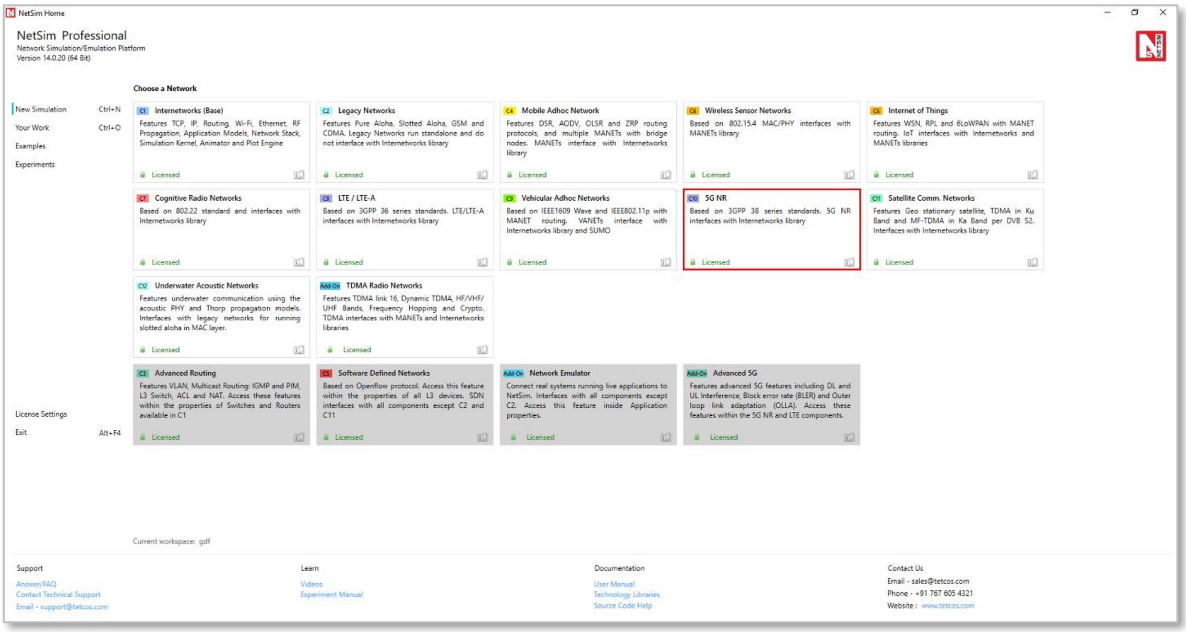

Figure 2-1: NetSim Home Screen

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. Devices are connected using 3GPP defined interfaces; O-RAN defined interfaces are not available

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2.2 NetSim 5G Network Setup

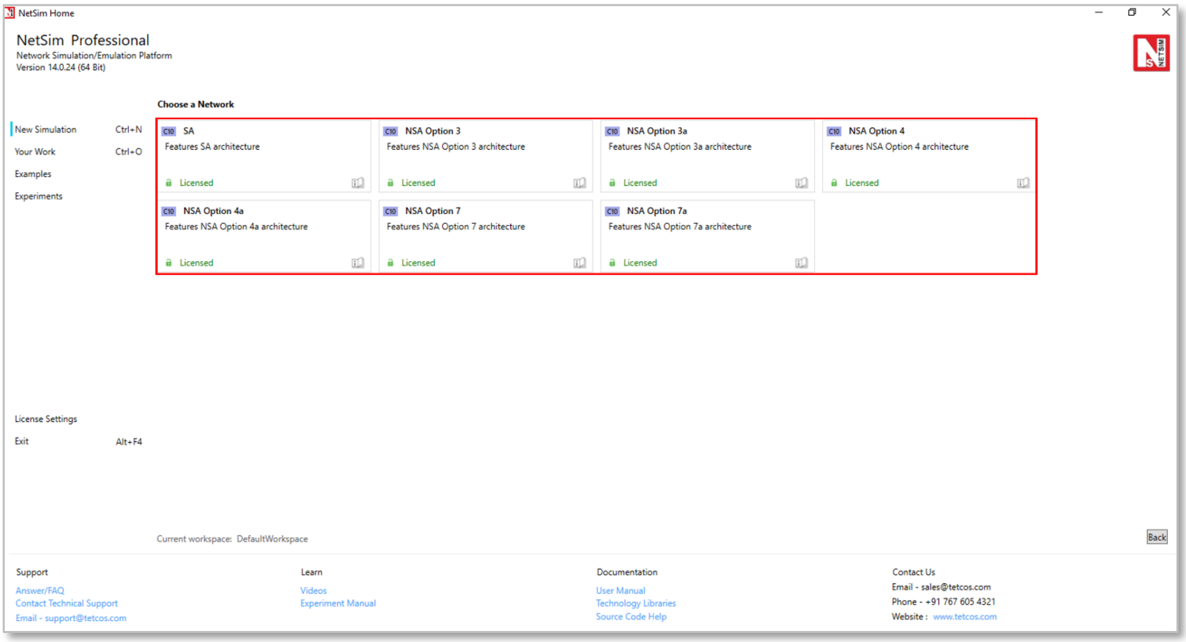

Figure 2-2: NetSim 5G Network Setup window

2.2.1 Deployment Architecture

The deployment options have been 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 (NSA)** 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 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.

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2. 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 AMF and UPF through the respective interfaces and eNB connects to all the 5G Core interfaces.

2.2.2 Device Placement

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

- Only one 5G Core and/or LTE EPC is currently supported.
- Users cannot remove 5G Core devices and/or LTE EPC, or their interconnecting links.
- 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.

2.2.3 NSA Deployment Device Connectivity

The device connectivity rules are explained below. Example screen shots are available in the section 3.16.

2.2.3.1 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

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

2.2.3.2 Option 7 / 7a

- 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.

2.2.4 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.

2.3 Devices Specific to NetSim 5G NR Library

- **UE:** User Equipment.
  - Each UE has a single LTE NR interface with an infinite buffer. It can connect to a gNB (Base Station or BS) in both FR1 (μ-Wave) and FR2 (mm-Wave) bands.
  - 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 (BS) with all the components i.e., antennas, radio, baseband, and the protocol stack. NetSim currently does not allow for the gNB to be split into RU, DU and CU.

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- NetSim supports 3 types of gNBs (i) Macro Cell gNB Omni Antenna (ii) Macro Cell gNB Sector Antenna and (iii) Small Cell gNB Omni Antenna. The macro cell gNBs by default have a transmit power setting of 40 dBm and operate in the FR1 3.5 GHz n78 band. The small cell gNBs have a transmit power setting of 30 dBm and operate in the FR2 28 GHz 261 band. Macro cell gNBs can be equipped with either omni-directional or sector antennas, and they are named based on their respective types.
- It has a 5G RAN interface for wireless connectivity to UEs.
- A gNB can be configurated as a μ-Wave (FR1, sub 6GHz) or a mm-Wave (FR2) BS by appropriately selecting the frequency of operation.
- It has a 5G_N3 interface for wired connectivity to UPF through an L2_Switch,
- It has a 5G_N1_N2 interface for wired connectivity to AMF through an L2_Switch, and
- It has a 5G_XN interface for wired connectivity between the gNBs through an L2_Switch.
- Every 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 router 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.

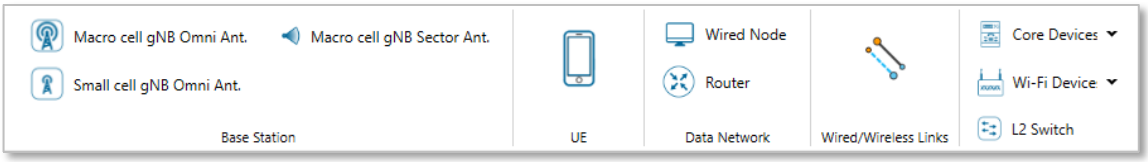

Figure 2-3: 5G NR Device Palette in GUI

2.4 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.

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gNB Properties Interface (5G RAN) – Datalink Layer			
Parameter	**Type**	**Range**	**Description**
Scheduling Type	Local	Round Robin	This is usually done to load balance and share system in circular order, handling all processes without priority
	Local	Proportional Fair	It is based upon maintaining a balance by trying to maximize total throughput while at the same time allowing all users at least a minimal level of service.
	Local	Max Throughput	Maximum throughput scheduling is a procedure to maximize the total throughput of the network by giving scheduling priority to the least "expensive" data flows.
EWMA Averaging Rate	Local	1.001 to 10000	EWMA Averaging Rate (α) determines how important the current observation is in the calculation of the EWMA. A lower alpha discounts older data faster thereby placing greater relevance on your more current data. $EWMA(t) = (1 - 1/\alpha) * EWMA(t-1) + (1/\alpha) * r(t)$ $0 < 1/\alpha <= 1.$ Default value is 50.
UE Measurement Report Interval	Local	120 ms - 40960 ms	It is a time interval between UE Measurement Report
RRC MIB Period (ms)	Local	80	The UE needs to first decode MIB for it to receive other system information. MIB is transmitted on the DL-SCH (logical channel: BCCH) with a periodicity of 80 ms and variable transmission repetition periodicity within 80 ms. MIB packets can be seen in the NetSim packet trace post simulation under Control Packet type
RRC SIB Period (ms)	Local	160	SIB1 also contains radio resource configuration information that is common for all UEs. SIB1 is transmitted on the DL-SCH (logical channel: BCCH) with a periodicity of 160 ms and variable transmission repetition periodicity within 160 ms. SIB1 is cell-specific. SIB1 packets can be seen in the NetSim packet trace post simulation under Control Packet type.
PDCP Header Compression	Local	True / False	Header compression of IP data flows using the ROHC protocol, Compresses all the static and dynamic fields.
PDCP Discard Delay Timer	Local	50/150/300/500/750/ 1500	The discard Timer expires for a PDCP SDU, or the successful

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			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	Local	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. It can be enables or disabled by setting the value "TRUE" or "FALSE".
PDCP T Reordering Timer	Local	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. Unit=ms. PDCP reordering is always enabled if in sequence delivery to layers above PDCP is needed. Reordering Timer should be in between 0 to 500 msec.
RLC T Status Prohibit	Local	0-2400ms	This timer is used by the receiving side of an AM RLC entity in order to prohibit transmission of a STATUS PDU. Unit=ms.
RLC T Reassembly	Local	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. Unit=ms.
RLC T Poll Retransmit	Local	5-4000ms	This is used by the transmitting side of an AM RLC entity in order to retransmit a poll.
RLC Poll Byte	Local	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	Local	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	Local	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.
HARQ Mode	Local	TRUE, FALSE	Hybrid automatic repeat request (hybrid ARQ or HARQ) is a combination of re transmissions and error correction. The HARQ protocol runs in the MAC and PHY layers. In the 5G PHY, a code block group (CBG) is transmitted over the air by the transmitter to the receiver. If the CBG is successfully received the receiver sends back

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			an ACK, else if the CBG is received in error the receiver sends back a NACK (negative ACK).If the transmitter receives an ACK, it sends the next CBG. However, if the transmitter receives a NACK, it re transmits the previously transmitted CBG. Large number packet errors can be observed in packet trace if HARQ is turned OFF.
MAX HARQ process count	Local	2,4,6,10,12,16	A HARQ entity is defined for each gNB-UE pair, separately for Uplink and Downlink and for each component carrier. The HARQ entity handles the HARQ processes. Max number of HARQ processes is 8 in 4G Max number of HARQ processes is 16 in 5G
Max CBG per TB	Local	2,4,6,8	Each Transport block is split into Code blocks (CBs) and CBs are grouped into Code Block Groups (CBGs). A Code Block group can have up to 2/4/6/8 CBs.
HARQ Retry Limit	Local	0-4s	HARQ Retry Limit specifies the number of retransmissions attempts that will be made whenever a Code Block fails due to error.
Handover Interruption time	Global	0-500ms	The handover process in NetSim is based on event A3 i.e., the target signal strength is offset (3 dB) higher than the source signal strength. Handover interruption time (HIT) is added at the time of handover command is delivered to the UE. During this time there is no data plane traffic flow to the UE from the source/target. Handover interruption time can be varied from 0 to 500ms.
Handover Margin	Global	0-10dB	The handover Margin is the offset in dB that is used as part of the event A3 handover process in NetSim. Handover is triggered when the target signal strength is offset higher than the source signal strength. Range for Handover margin is from 0.0 to 10.0 with 3.0 as default
Time to Trigger	Global	0-5120ms	With Time-to-Trigger, the handover is initiated only if the triggering requirement is fulfilled for a time interval specified by Time-to-Trigger (ms). This parameter can decrease the number of unnecessary handovers and effectively avoid Ping-Pong effects.

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			3GPP defines 16 valid values for time-to-trigger (all in milliseconds): 0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, and 5120. Users can enter any value between 0 to 5120 in milliseconds.

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

Interface (5G_RAN) – Physical Layer			
Parameter	**Type**	**Range**	**Description**
Protocol	Fixed		LTE NR (New Radio) is the 5G radio access technology. LTE-NR has the RLC and PDCP layers similar to LTE and has introduced a new layer named as SDAP (Service Data Adaptation Protocol). The frequency band for LTE NR is separated into two different frequency ranges: Frequency Range 1 (FR1) which includes sub-6 GHz, bands, and Frequency Range 2 (FR2) which includes mmWave bands.
3GPP series	Fixed		NetSim 5G library is based on the 3GPP 38.xxx series. Some features in NetSim are per Rel 16 and some others are per Rel 17.
Frame Duration (ms)	Fixed	10ms	The length of the frame in milliseconds. The FRAMEDURATION is a non-editable parameter whose value is fixed at 10 ms.
Sub Frame Duration (ms)	Fixed	1ms	The length of the frame in milliseconds. The SUBFRAMEDURATION is a non-editable parameter whose value is fixed at 1 ms.
Subcarrier Number Per PRB	Fixed	12	The number of Subcarriers per PRB is a non-editable parameter whose value is fixed at 12.
gNB Height (m)	Local	1-150m	Height of the base station (gNB) in meters. NetSim implements the 3GPP propagation models in which the Indoor gNB (placed within a building) range is 1 to 10 meters, while the Outdoor gNB range is 1 to 150 meters. NetSim only enforces the upper limit of 150m for both indoor and outdoor gNBs.
TX Power (dBm)	Local	-40dBm to 50dBm	In NetSim the Tx power range is -40dBm to 50dBm. The default value for Tx power is 23dBm for UEs and 40dBm for gNBs. When running in MIMO mode the transmit power is split equally amongst all the MIMO layers. The number of MIMO layers is Min (Nt, Nr).
Duplex Mode	Local	TDD FDD	Time Division Duplexing: Downlink (DL) and uplink (DL) transmissions are on the same frequency band but separated in time. Depending on the DL:UL ratio, slots are allocated for DL/UL transmissions. Frequency Division Duplexing: There are different frequency bands for UL and for DL. Hence UL and DL transmissions can occur simultaneously. NetSim supports both FDD and TDD bands and various CA configurations and Operating bands, for TDD and FDD, in FR1 and FR2 are available.

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CA Type	Local	INTER_BAND_CA INTRA_BAND_CONTIGUOUS_CA INTRA_BAND_NONCONTIGUOUS_CA SINGLE_BAND CUSTOM_BAND	In Carrier aggregation (CA) multiple component carriers (CCs) are combined to usually increase the bandwidth, and thereby increase the bit rate. CA combinations are divided into intra-band (contiguous and non-contiguous) and inter-band. Intra-band contiguous CA configuration refers to contiguous carriers aggregated in the same operating band. Intra-band non-contiguous CA configuration refers to non-contiguous carriers aggregated in the same operating band. Inter-band CA configuration refers to the aggregation of component carriers in different operating bands, where the carriers aggregated in each band can be contiguous or non-contiguous. The single band drop-down options are per TS 38.101-1 for FR1 and 38.101-2 for FR2
CA Configuration	Local	Depends on CA Type	The drop shows the frequency band options for the user to choose from.
CA Count	Fixed	Depends on CA Type	This is a non-editable parameter that shows the number of component carriers based on the CA configuration. CA count would be 1 for Single Band configuration and will be greater than or equal to 2 for carrier aggregation.
NOTE: For detailed information to Frequency Range (FR1 & FR2), Please, refer PHY Layer			
Slot Type	Local	Mixed, Downlink, Uplink,	Slot type can be Mixed, Uplink, or Downlink. Mixed: In Mixed slot type, there will be both downlink and uplink slots allocated. The DL:UL ratio will determine how many slots are to be allocated for downlink and for uplink. The default value of the DL:UL ratio is 1:1 which can be then changed by the user. The setting is of the format x: y where x and y are integers. Uplink: In uplink slot type, there are only uplink slots, and the DL:UL ratio will be fixed by NetSim as 0:1. Note that uplink applications running TCP protocol will experience zero throughputs since there will be no downlink slots available for ACK transmissions Downlink: In downlink slot type, there are only downlink slots and the DL:UL ratio will be fixed by NetSim as 1:0. Note that downlink applications running TCP protocol will experience zero throughputs since there will be no uplink slots available for ACK transmissions
Frequency Range	Local	FR1 & FR2	The frequency bands for 5G NR is separated into two frequency ranges. First, is Frequency Range 1 (FR1) which includes sub-6 GHz, frequency bands. The other is Frequency Range 2 (FR2) which includes frequency bands in the mmWave range. FR1: 410 MHz – 7125 MHz FR2-1: 24250 MHz – 52600 MHz FR2-2: 52600 MHz – 71000 MHz NetSim supports both FR1 and FR2.

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			This is a non-editable parameter shown by NetSim based on the CA configuration chosen by the user.
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, n262, n263	The operating band whose numbering is defined by 3GPP. This is a non-editable parameter (except for custom band) that is shown by NetSim based on the CA configuration chosen by the user.
F Low (MHz)	Fixed	2010-4400 MHz	The lowest frequency of the Uplink/Downlink operating band. This is a non-editable parameter (except for custom band) shown by NetSim based on the CA configuration chosen by the user
F High (MHz)	Fixed	2025-5000 MHz	The highest frequency of the Uplink/Downlink operating band. This is a non-editable parameter shown by NetSim based on the CA configuration chosen by the user
Numerology	Local	μ = 0, 1, 2, 3, 4, 5, 6	Sub carrier spacing is derived from numerology per the expression $\Delta f = 2^{\mu} \times 15kHz$. Thus, Numerology = 0 means subcarrier spacing 15 kHz Numerology = 1 means subcarrier spacing 30 kHz Numerology = 2 means subcarrier spacing 60 kHz Numerology = 3 means subcarrier spacing 120 kHz Numerology = 4 means subcarrier spacing 240 kHz Numerology = 5 means subcarrier spacing 480 kHz Numerology = 6 means subcarrier spacing 960 kHz
Channel Bandwidth (MHz)	Local	5-2000 MHz	The bandwidth can vary from 5 MHz to 100 MHz for TDD bands in FR1 frequency range and 50 MHz to 2000 MHz for TDD bands in FR2 frequency range. The bandwidth is 5MHz to 40 MHz in case of FDD bands. Unit is MHz
PRB Count	Local		PRB stands for physical resource block. The PRB count is dependent on Channel Bandwidth and automatically determined by NetSim. It cannot be edited in the GUI.
Guard Band (KHz)	Local	242.5 - 147040 kHz	Guard band is the unused part of the radio spectrum between radio bands, for the purpose of preventing interference. The minimum guard bands are calculated using the following equation: $(BWChannel\, x\, 1000\, (kHz) - NRB\;\; x\, SCS\, x\, 12)\, /\, 2 - SCS/2. Unit\ is\ kHz.$

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Subcarrier Spacing	Local	15 - 960 kHz	In 5G NR, subcarrier spacing of 15, 30, 60, 120, 240,480,960 KHz are supported. Subcarrier spacing = $15kHz$ $(\mu = 0)$ Subcarrier spacing = $30kHz$ $(\mu = 1)$ Subcarrier spacing = $60kHz$ $(\mu = 2)$ Subcarrier spacing = $120kHz$ $(\mu = 3)$ Subcarrier spacing = $240kHz$ $(\mu = 4)$ Subcarrier spacing = $480kHz$ $(\mu = 5)$ Subcarrier spacing = $960kHz$ $(\mu = 6)$.
Bandwidth PRB	Local	180 - 11520 kHz	The PRB bandwidth is dependent on numerology (μ) as shown below. $Unit = kHz$. Bandwidth= $180\ kHz\ (\mu = 0)$ Bandwidth= $360\ kHz\ (\mu = 1)$ Bandwidth= $720\ kHz\ (\mu = 2)$ Bandwidth= $1440\ kHz\ (\mu = 3)$ Bandwidth= $2880\ kHz\ (\mu = 4)$ Bandwidth= $5760\ kHz\ (\mu = 5)$ Bandwidth= $11520\ kHz\ (\mu = 6)$
Slot per Frame	Local	10, 20, 40, 80, 160, 320, 640	This represents the number of slots in a frame and is a non-editable parameter. NetSim determines the slots per frame, based on the selected numerology, in the following way When μ= 0, a subframe has only one slot, and frame has 10 slots. When μ= 1, a subframe has 2 slots, and a radio frame has 20 slots. When μ= 2, In this configuration, a subframe has 4 slots in it, it means a radio frame contains 40 slots in it. When μ= 3, In this configuration, a subframe has 8 slots in it, it means a radio frame contains 80 slots in it. When μ= 4, In this configuration, a subframe has 16 slots in it, it means a radio frame contains 160 slots in it. When μ= 5, In this configuration, a subframe has 32 slots in it, it means a radio frame contains 320 slots in it. When μ= 6, In this configuration, a subframe has 64 slots in it, it means a radio frame contains 640 slots in it.
Slot per Subframe	Local	1, 2, 4, 8, 16, 32, 64	This represents the number of slots in a sub-frame and is a non-editable parameter. NetSim determines the slots per sub-frame, based on the selected numerology, in the following way When μ= 0, a subframe has only one slot When μ= 1, a subframe has 2 slots. When μ= 2, In this configuration, a subframe has 4 slots in it. When μ= 3, In this configuration, a subframe has 8 slots in it. When μ= 4, In this configuration, a subframe has 16 slots in it. When μ= 5, In this configuration, a subframe has 32 slots in it. When μ= 6, In this configuration, a subframe has 64 slots in it.

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Slot Duration (μs)	Local	1000, 500, 250, 125, 62.5, 31.25, 15.63 μs	Slot duration is a non-editable parameter that depends on numerology selected. μ= 0, Slot Duration = 1000 μs μ= 1, Slot Duration = 500 μs μ= 2, Slot Duration = 250 μs μ= 3, Slot Duration = 125 μs μ= 4, Slot Duration = 62.5 μs μ= 5, Slot Duration = 31.25 μs μ= 6, Slot Duration = 15.63 μs
Cyclic Prefix	Local	Normal	If the cyclic prefix is set to "normal" then the number of symbols per slot is 14, if it is set to "extended" then the number of symbols per slot is 12. All carriers have the "normal" option while only certain carriers have the "extended" option.
NOTE: Cyclic Prefix is Extended only for few CA types.			
Symbol per Slot	Local	12, 14	Symbol Per Slot is dependent on Cyclic prefix. If cyclic prefix is set to "Normal" then Symbol Per Slot = 14 If cyclic prefix is set to "Extended" then Symbol Per Slot = 12
Overhead (%) per DL slot	Local	0.01-0.99	This represents the fraction of symbols in a slot used for control signalling. The remaining fraction is used for data transmission. In NetSim calculations are done over aggregated PRBs per the formula given below: Data PRB available = Total PRB available - Ceil(Total PRB available×Overhead Fraction) DL Fraction range 0.01 to 0.99 Default: 0.14 for FR1, 0.18 for FR2 In 4G Network the default value is 0.25 for both FR1 and FR2.
Overhead (%) per UL slot	Local	0.01-0.99	This represents the fraction of symbols in a slot used for control signalling. The remaining fraction is used for data transmission. In NetSim calculations are done over aggregated PRBs per the formula given below: Data PRB available = Total PRB available - Ceil(Total PRB available * Overhead Fraction) UL Fraction range 0.01 to 0.99 Default: 0.08 for FR1, 0.10 for FR2 In 4G Network the default value is 0.25 for both FR1 and FR2.
Symbol Duration (μs)	Local	71.43, 35.71, 17.86, 8.93, 4.47, 2.23, 1.12	Symbol duration is a non editable paramater that depends the numerology selected When $\mu = 0$, symbol duration = $71.43\ \mu s$ When $\mu = 1$, symbol duration = $35.71\ \mu s$ When $\mu = 2$, symbol duration = $17.86\ \mu s$ When $\mu = 3$, symbol duration = $8.93\ \mu s$ When $\mu = 4$, symbol duration = $4.47\ \mu s$ When $\mu = 5$, symbol duration = $2.23\ \mu s$ When $\mu = 6$, symbol duration = $1.12\ \mu s$
BWP	Local	Disable	A Bandwidth Part (BWP) is a contiguous set of physical resource blocks (PRBs) on a given carrier. These PRBs are selected from

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			a contiguous subset of the common resource blocks for given numerology (u). This parameter is currently reserved for future use. It therefore currently always set as disabled.
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. This parameter taken effect during MIMO operation; the number of MIMO layers would be Min (Nt, Nr), where Nt is the transmit antenna count at the transmitter and Nr is the receive antenna count at the receiver. The layer wise gains depends on the fading model chosen and is explained in the 5G NR manual, digital beamforming section.
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. This parameter taken effect during MIMO operation; the number of MIMO layers would be Min (Nt, Nr), where Nt is the transmit antenna count at the transmitter and Nr is the receive antenna count at the receiver. The layer wise gains depends on the fading model chosen and is explained in the 5G NR manual, digital beamforming section.
Antenna Type	Fixed		NetSim supports two types of Antenna, Omnidirectional and Sector Antennas.
Boresight Angle	Local	0-360°	NetSim implements a 2D parabolic sector antenna as per 3GPP TR 37.840. The boresight angle denotes the direction of maximum gain, or the highest radiated power. The angle is defined to start at 0 from the positive X-axis. If positive Y points downward, the angle increases on clockwise rotation from the positive X-axis. If positive Y points upward, the angle increases in an anti-clockwise direction from the positive X-axis. The units for the boresight angle are in degrees.
PDSCH CONFIG			
MCS Table	Local	QAM64, QAM256, QAM64LOWSE	MCS Table stands for modulation and coding scheme Table. The selection options are QAM64, QAM 256, and QAM64LOWSE. We recommend users set the same MCS table for PDSCH and PUSCH. The appropriate CQI table setting would be as follows: For QAM64 - Table1 For QAM256 - Table 2 For QAM64LOWSE - Table 3
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	QAM64, QAM256, QAM64LOWSE	MCS Table stands for modulation and coding scheme Table. The selection options are QAM64, QAM 256, and QAM64LOWSE. We recommend users set the same MCS table for PDSCH and PUSCH. The appropriate CQI table setting would be as follows: For QAM64 - Table1

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			For QAM256 - Table 2 For QAM64LOWSE - Table 3
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. This is based on 3GPP Table 5.2.2.1-2, Table 1, Table 2 and Table 3. Users must set the MCS and CQI tables in the following combination QAM64: CQI Table 1 QAM 256: CQI Table 2 QAM 64 LOWSE: CQI Table 3
CHANNEL MODEL			
Pathloss Model	Local	3GPPTR38.901-7.4.1 LOG DISTANCE NONE	NetSim computes signal attentuation per the mean pathloss model. The options currently available at None, 3GPP based and Log distance.
Outdoor Scenario	Local	Rural Macro (RMa) Urban Macro (UMa) Urban Micro (UMi)	There are three types of outdoor scenarios possible namely: Rural Macro, Urban Macro, and Urban Micro, as defined in the 3GPPTR38.900 standard. The propagation characteristics of these scenarios are provided in the 5G NR Technology library manual, section Propagation Models.
Building Height (m)	Local	5-50m	Height of building in meters. Range is 5m to 50m. The building height can be varied in scenarios where UEs are placed inside the building and where the pathloss and other parameters are to be evaluated. The impact of building height can be seen in outdoor scenarios per formulas provided in the 5G NR Technology library manual, section Propagation Models (Per 3GPPTR38.900 Channel Model)
Street Width (m)	Local	5-50m	Width of the street in meters. Range is 5 to 50 meters. The impact of street width can be seen in outdoor scenarios and will per formulas provided in the 5G NR Technology library manual, section Propagation Models (Per 3GPPTR38.900 Channel Model)
Indoor Scenario	Fixed	Indoor Office	This is a scenario where gNB and UE are within an indoor building
Indoor Office Type	Local	Mixed-Office Open-Office	There are two types of Indoor Office (InH): Mixed-Office, and Open-Office. An indoor scenarios is defined as one where we have both gNBs and UEs present within a building. Path-loss is higher than an Open-Office scenario.

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LOS/NLOS Selection	Fixed	3GPPTR38.901-Table 7.4.2-1 USER_DEFINED	3GPPTR38.901-Table7.4.2-1 The LOS mode, either Line-of-sight or Non-Line-of-sight is based on LOS probability calculated per the TR 38_901_Standard Table7.4.2-1 User Defined LOS probability is not per standard but is based on user input. NetSim will determine whether a device is in line-of-sight or non-line-of-sight based on the LOS probability value set by the user.
LOS Probability	Local	0 to 1	LOS Probability defines the LOS mode. If LOS Probability=1, the LOS mode is set to Line-of-Sight explicitly and if the LOS Probability=0, the LOS mode is set to Non-Line-of-Sight explicitly. For, any value between 0-1 LOS mode is set per the given probability, by tossing a biased coin.
Shadow Fading Model	Local	NONE 3GPPTR38.901	Models for signal attenuation due to shadowing. 3GPPTR38.901: 3GPPTR38.901 model is suitable for a scenario with mobility and obstructions within the propagation environment. In this model, the shadowing value follows a log-normal distribution with a user specified standard deviation. In general, this value should be in the range of 5 to 12 dB depending on the density of obstructions within the propagation environment. None: To disable the Shadow fading Model.
Fading and Beamforming	Local	NO_FADING_MIMO_UNIT_GAIN, NO_FADING_MIMO_ARRAY_GAIN, RAYLEIGH_WITH_EIGEN_BEAMFORMING	RAYLEIGH WITH EIGEN BEAMFORMING: When fading and beamforming is enabled, NetSim uses the rich scattering in the channel to form spatial channels. The number of spatial channels is equal to the number of layers (in turn equal to Min (Nt, Nr)). The beamforming gains in the spatial channel is equal to the eigen values of the channel covariance (wishart) matrix. NO FADING: To disable the fading and beamforming.
O2I Building Penetration Model	Local	None, Low Loss Model, High Loss Model,	A model for signal attenuation due to Path-loss combined with fading, shadowing and o2I loss. The O2I loss is the Outdoor-to-Indoor penetration loss where the signal attenuates when it penetrates through structures like concrete wall, glass, wood etc. Low-loss model is applicable to RMa. High-loss model is applicable to UMa and UMi. None to disable the O2I loss..
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. Note: NetSim Academic version does not support MATLAB.
Path Loss Exponent (η)	Local	2 to 5	Path loss exponent indicates the rate at which the path loss increases with distance. The value depends on the specific propagation environment. Set any value between 2 to 5.

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Reference Distance d0 (m)	Local	1-10m	$$PL = PL_{d_0} + 10 \times \eta \times log\left(\frac{d}{d_0}\right)$$ PL: is the path loss at the reference distance d0. Unit: Decibel (dB) d : is the distance between the transmitter and the receiver d_0: is the reference distance defined in the standard. See propagation-model.pdf for more information η: is the path loss exponent
Shadowing Model	Local	NONE, Log Normal	**Constant**: A shadowing model is used to represent the signal attenuation caused by obstructions along the propagation path. The constant shadowing model is suitable for the scenarios without mobility where the obstructions along the propagation paths remain unchanged. **Log Normal**: The lognormal shadowing model is suitable for a scenario with mobility and obstructions within the propagation environment. In this model, the shadowing value follows a log-normal distribution with a user specified standard deviation. In general, this value should be in the range of 5 to 12 dB depending on the density of obstructions within the propagation environment.
Standard Deviation (dB)	Local	5 to 12 dB	Shadowing is caused mainly by terrain features of the radio propagation environment. The mathematical model for shadowing is a log-normal distribution with standard deviation of 5 to 12 dB. Set any value between 5 to 12 dB.
INTERFERENCE MODEL			
Downlink Interference Model	Global	NO_INTERFERENCE, GRADED_DISTANCE_BASED_WYNER_MODEL, EXACT_GEOMETRIC_MODEL	DL interference options are No interference, Graded Distance based Wyner model and Exact geometric models. If no interference is chosen then in the SINR calculations, the values of I is set to zero. Wyner and geometric models compute interference. Wyner is an approximate model used by the research community while the geometric model is exact. Technical details of the two models are provided in the 5G NR/4G manual.
Uplink Interference Model	Global	NO_INTERFERENCE, INTERFERNEC_OVER_THERMAL	NetSim uses Interference-over-thermal (IoT), to model co-channel uplink interference..
IoT value (dB)	Global	0 to 20	The Uplink IoT (dB) value is used to compute the SINR, and Interference power based on the following equations: $$SINR\ (dB) = SNR(dB) - IoT(dB)$$ The interference power (dBm units), logged in the radio measurements file will be given as $$I\ (dBm) = 10 \times log_{10}\left(N \times \left(10^{IOT\ (dB)-1}\right)\right)$$ where N is thermal noise and is equal to $k \times TB$.
ERROR MODEL AND MCS SELECTION			
MCS Selection Model	Global	IDEAL_SHANNON_THEOREM_BASED_RATE,	NetSim determines the modulation and coding scheme in 5G and LTE, based on received SINR, per the following models:

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		SHANNON_RATE_WITH_ATTENUATION_FACTOR	Ideal Shannon Theorem-Based Rate: Spectral Efficiency is computed as $Spectral\ Efficiency = log(1 + SINR)$ Shannon Rate with Attenuation Factor (α): Spectral Efficiency is computed as $Spectral\ Efficiency = \alpha\ x\ log(1 + SINR)$ Then the 3GPP standards Spectral Efficiency vs MCS Table is looked up to select the MCS. This could be the 64QAM table, 256 QAM table, or the 64QAMLOWSE table depending on what was chosen by the user.
Attenuation Factor	Global	0.5-1	Attenuation factor (α) takes value between 0.5 and 1 with the default value of 0.75.
BLER Model	Global	ZERO_BLER BLER_ENABLE	Block Error Rate Model (BLER) is used to decide code block and transport block error in 5G and LTE. If set to true then NetSim looks up the SINR-CBS-MCS vs. BLER tables to decide on the code block errors rate for the chosen MCS. Here MCS will be chosen as explained in the MCS selection section. If OLLA is enabled then MCS bump up/down will be based on HARQ ACKs/NACKs.
Outer loop link adaption	Global	TRUE FALSE	The Outer Loop Link Adaptation (OLLA) technique, if enabled can improve the channel quality estimation by adjusting the value of SINR by an offset dependent on whether previous transmissions were decoded successfully or not, as captured by Hybrid Automatic Repeat Request (HARQ) feedback
Target BLER	Global	0-1	The OLLA algorithm in NetSim is designed to converge the transport BLER to the set value of the target BLER. Range: 0 to 1
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	-40 dBm to 50 dBm	In NetSim the Tx power range is -40dBm to 50dBm. The default value for Tx power is 23dBm for UEs and 40dBm for gNBs. When running in MIMO mode the transmit power is split equally amongst all the MIMO layers. The number of MIMO layers is Min (Nt, Nr).
ANTENNA			
TX Antenna Count	Local	1, 2 , 4, 8, 16	The number of transmit antennas. This parameter taken effect during MIMO operation; the number of MIMO layers would be Min (Nt, Nr), where Nt is the transmit antenna count at the transmitter and Nr is the receive antenna count at the receiver. The layer wise gains depend on the fading model chosen and is explained in the 5G NR manual, digital beamforming section.
RX Antenna Count	Local	1, 2, 4, 8, 16	The number of receive antennas. This parameter taken effect during MIMO operation; the number of MIMO layers would be Min (Nt, Nr), where Nt is the transmit

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Parameter	Type	Range	Description
			antenna count at the transmitter and Nr is the receive antenna count at the receiver. The layer wise gains depend on the fading model chosen and is explained in the 5G NR manual, digital beamforming section.
5G Logs			
Parameter	**Type**	**Range**	**Description**
LTENR Radio Measurements Log	Global	Enable or Disable	The LTENR Radio measurements csv log file records Timestamp, Device ID, Distance, Pathloss, Shadow fading loss, Received power, SNR, Interference Power, SINR, MCS, CQI, Beamforming gain and more, for each carrier on the PDSCH, PUSCH and SSB. PDSCH and PUSCH measurements are logged every sub-frame while SSB measurements are logged every UE measurement report.
LTENR Resource Allocation Log	Global	Enable or Disable	The 5G Radio Resource Allocation csv log file records information related to physical resource block (PRB) allocation such as the Total PRBs, Slot Start Time(ms), Slot End, BitsPerPRB, BufferFill, Allocated PRBs, Rank (scheduling metric) and more, in the DL and in the UL. All these parameters are written in every slot.
LTENR Handover TTT Log	Global	Enable or Disable	Records the events that occur during a handover. This contains the time stamp, serving cell ID, UE ID, target cell ID, and Handover Trigger time (time at which the handover condition was met) - when the TTT parameter is enabled. The log can be used to identify handover attempts and the impact of TTT on handovers.
LTENR Code Block Log	Global	Enable or Disable	Records parameters associated with Code Block segmentation such as Process ID, TB size, Modulation, Code Rate, CBS, BLER, CBG ID, etc. along with remarks on events associated with HARQ and PRB allocation. This will be useful to understand BLER model and Code Block segmentation in 5G.
LTENR OLLA Log	Global	Enable or Disable	Logs parameters associated with Outer Loop Link Adaptation(OLLA) such as CQI with and without OLLA, phy SINR, SINR Delta, Virtual SINR, etc along with time stamps, gNB ID, UE ID , etc. This log can be used to understand OLLA mechanism in 5G.
IEEE 802.11 Radio Measurement Log	Global	Enable or Disable	Records pathloss, shadowing loss, fading loss, transmitted power, received power, SNR, Interference Power, SINR, SNR, BER, NSS, MCS, etc. This log can be used to understand the channel model and its impact on varying channel conditions.
IEEE 802.11 Backoff Log	Global	Enable or Disable	Records details such as the Device name, Time stamp, Packet ID, BackoffTime, contention Window size and Retry Limit. This log can be used to understand the Medium access mechanism in IEEE 802.11 Protocols.
IEEE 802.11 Log	Global	Enable or Disable	Records events and states associated with IEEE 802.11 protocols along with time stamps. This file can be used for

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			understanding and debugging through the protocol internals.
OSPF Log	Global	Enable or Disable	Records events and states associated with the OSPF Protocol, such as the control message exchanges, interface state update, etc along with timestamps
OSPF Hello Log	Global	Enable or Disable	Logs the events associated with OSPF Hello messages with timestamps. This includes hello interval timer events, hello message update, hello message processing, etc.
TCP Log	Global	Enable or Disable	Records events associated with TCP connection states such as LISTEN, SYN-SENT, SYN-RECEIVED, ESTABLISHED, FIN-WAIT-1, FIN-WAIT-2, CLOSE-WAIT, CLOSING, LAST-ACK, TIME-WAIT, and CLOSED.

Table 2-1: 5G Config Properties

2.4.1 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(Macro cell gNB Omni Antenna, Small cell gNB Antenna and Sector Antenna):

- 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.

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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.

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- 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.

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3 Model Features

3.1 The 5G Frame Structure

In 5G-NR the physical time and frequency resources correspond to OFDM symbols (time) and subcarriers (frequency) respectively. The physical radio resources in each frame (or subframes) can be considered as a resource grid made up of OFDM subcarriers in the frequency domain, and OFDM symbols in the time domain. The smallest physical resource, known as the resource element (RE), comprises one subcarrier (frequency) and one OFDM symbol (time).

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.

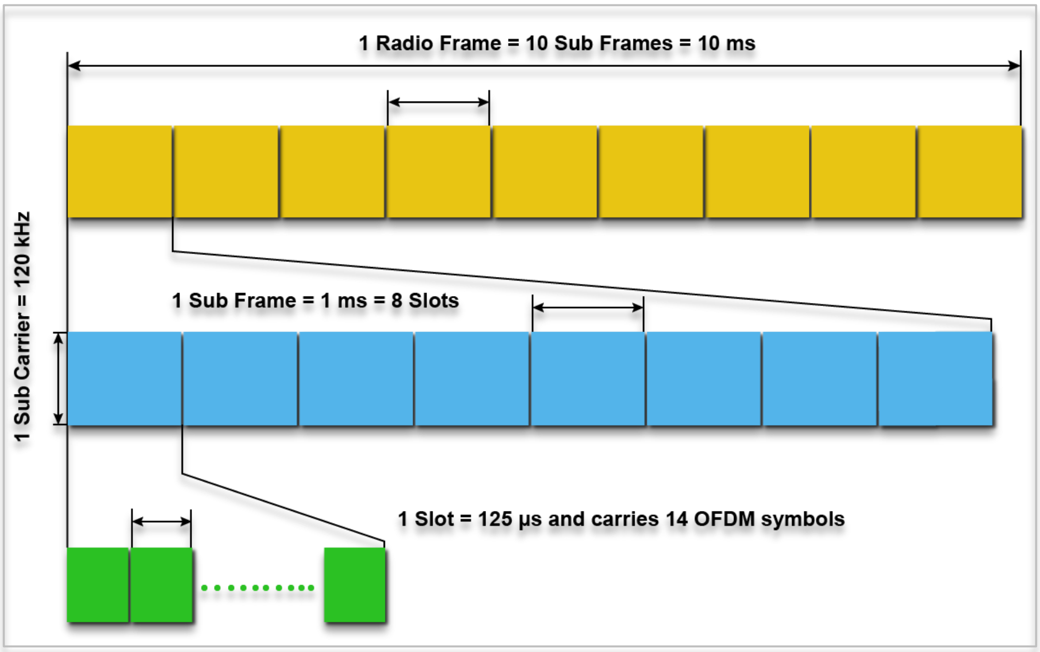

Figure 3-1: NR Frame Structure when numerology μ is set to 3

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 length 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 3.9.9.1- Numerologies, for more information.

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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.

Physical Resource Block (PRB): The PRB 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. As a formula, $PRB_{Width} = 12 \times 15 \times 2^{\mu}$ kHz.

Resource Block (RB): 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 is 1 slot in time, i.e., the duration of a resource block, and 1 PRB in frequency. One sub-carrier by one symbol is defined as a resource element.

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.
- Prior to transmission, the MAC scheduler in the gNB determines the allocation of PRBs (PHY resources) to users. In this module the Transport block size (TBS) (explained in 3.9.12) is computed using 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[2]. 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

[2] MIMO and beamforming are explained in section 3.9

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instantaneously known to the transmitter and receiver. This assumption is known as perfect 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

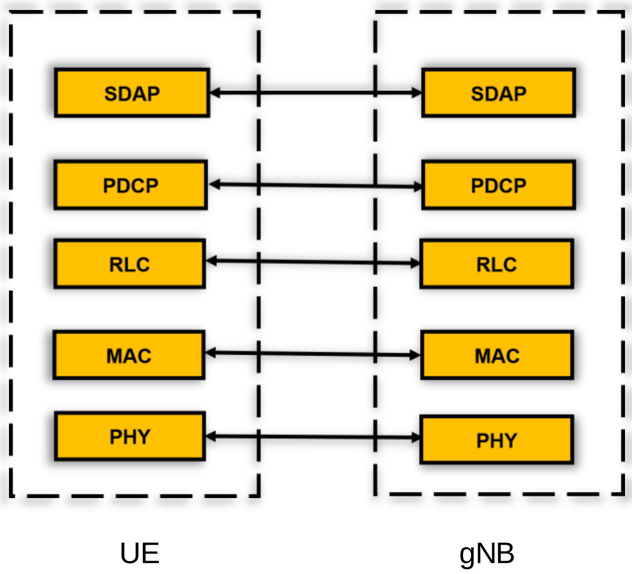

Figure 3-2: User Plane Protocol Stack

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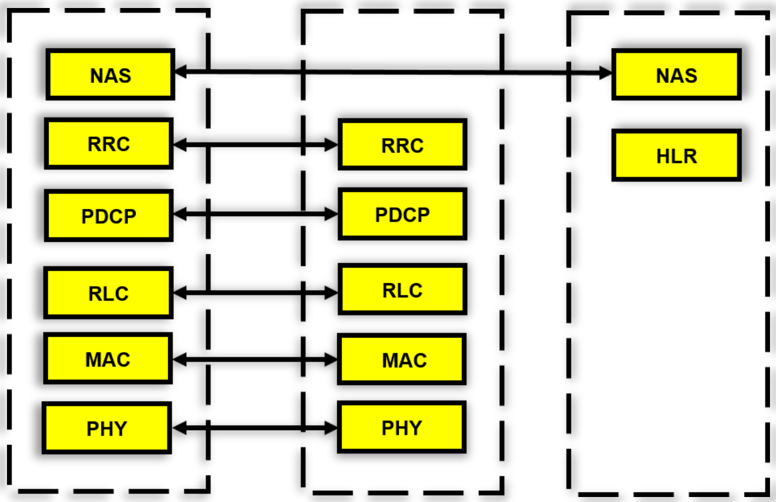

UE gNB EPC (PGW&SGW)

Figure 3-3: Control Plane Protocol Stack

3.4 SDAP (Specification: 37.324)

The features in NetSim SDAP are:

- Mapping between a QoS flow and a data radio bearer (DRB) per the new QoS framework
- Marking QoS flow ID (QFI) in both DL and UL packets.

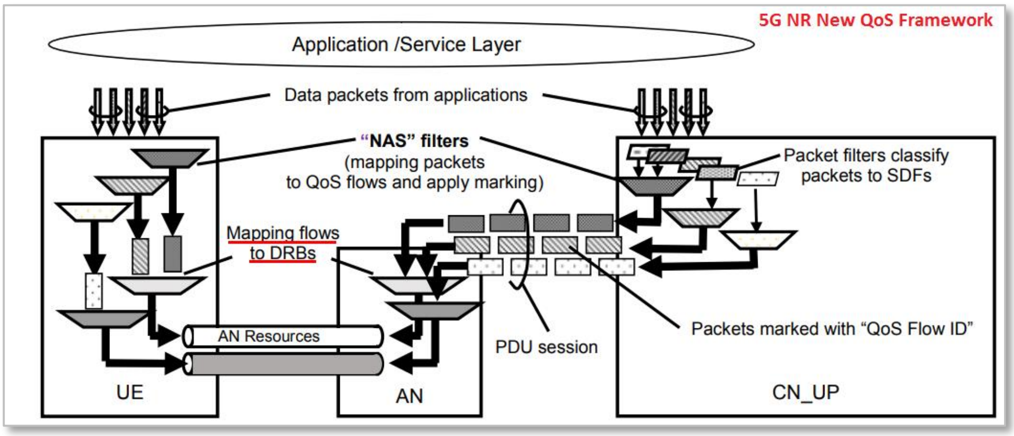

Figure 3-4: 5G Quality of Services (QoS)

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

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finds the associated UEs. The SDAP header is then added which contains the QFI. Recall that the NetSim 5G NR library only supports unicast transmissions (i.e., broadcast is not supported).

After this is the SendToNetwork function. This function is called when a packet is at MAC-IN at the receiver. 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 (if intermediate device) or sent to network layer (if end device). 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 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 (Unacknowledged Mode) and AM (Acknowledge mode) as shown in Figure 3-5.

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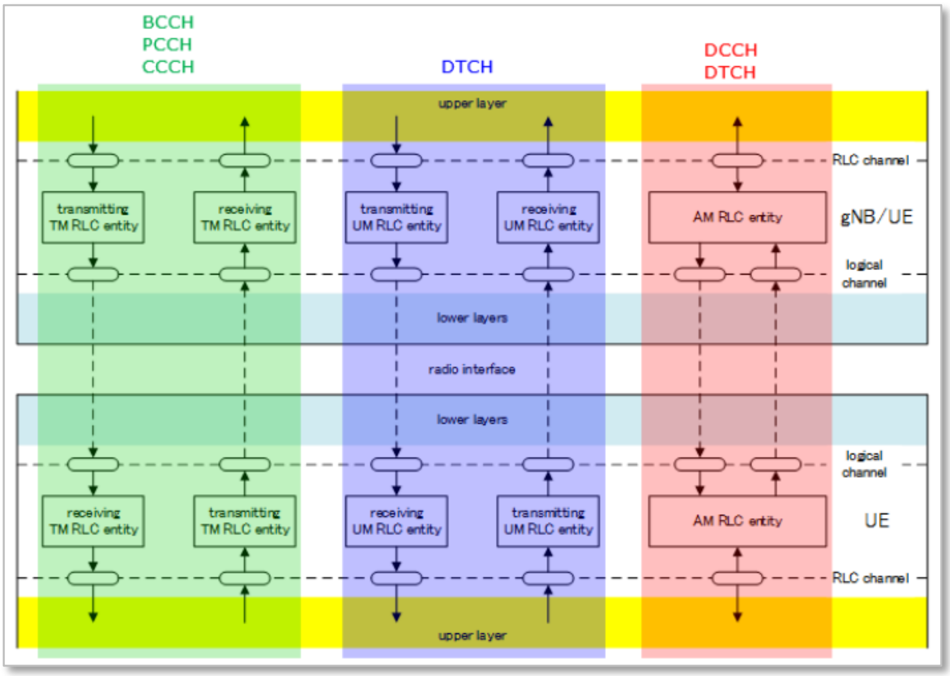

Figure 3-5: RLC Modes of operation and RLC Entities

A 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. 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.

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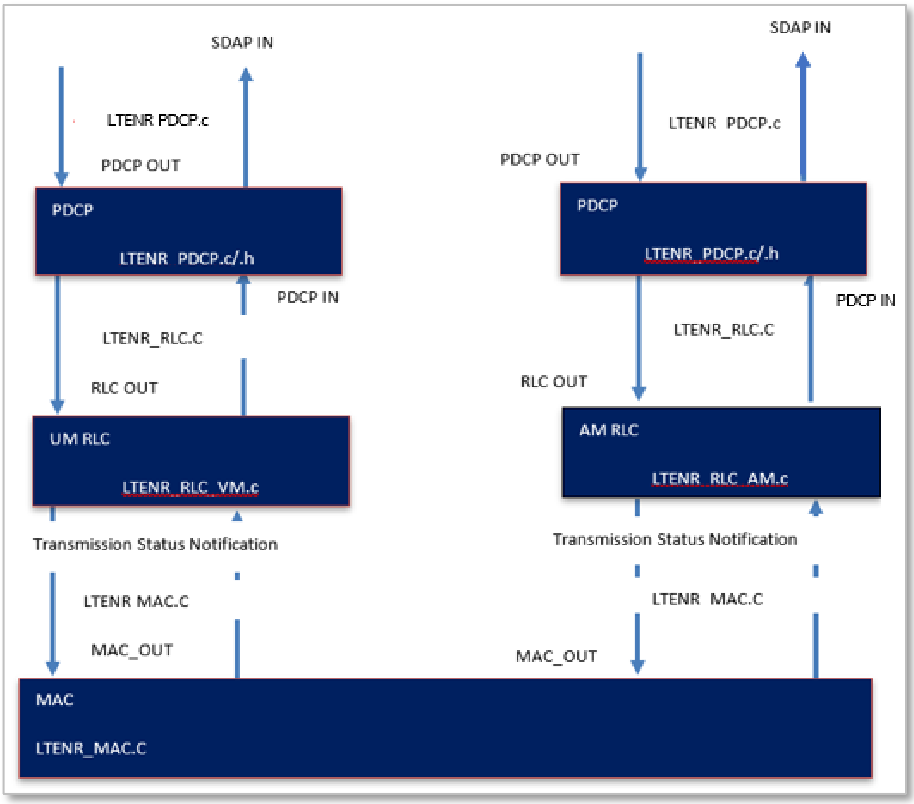

Figure 3-6: Implementation Model of PDCP, RLC and MAC entities

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()*

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- 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 the 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

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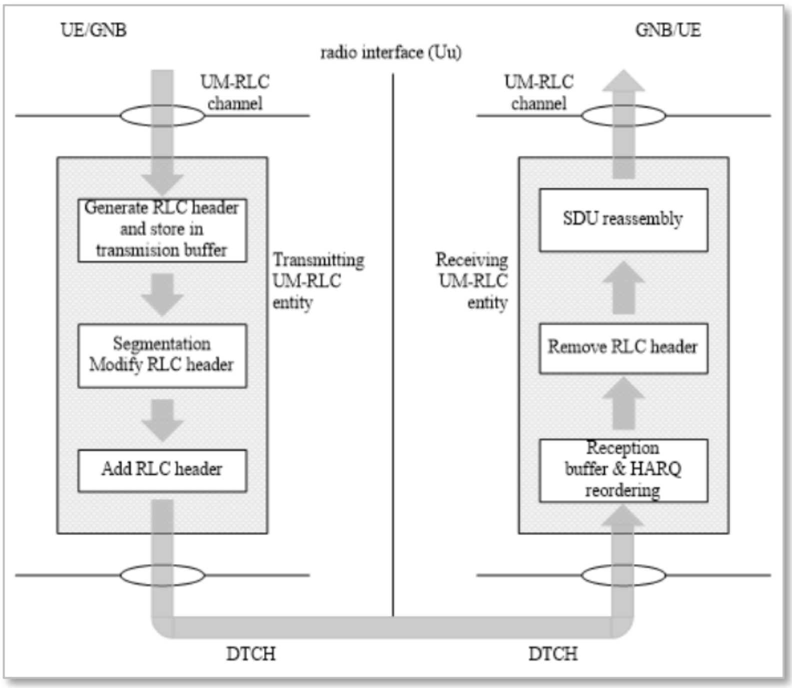

Figure 3-7: RLC UM working

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.

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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 means 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

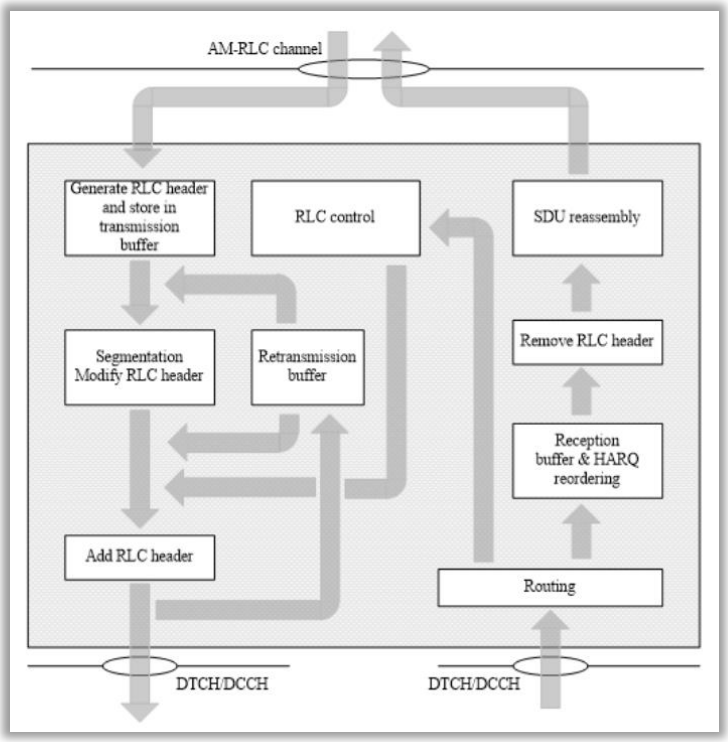

Figure 3-8: RLC AM Working

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)

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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 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.

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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.

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– 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

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  - 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.

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3.8.2 MAC Scheduler: Introduction

Base stations (gNBs) generally deal with multiple mobile stations UEs, some of which require larger bandwidths than others and some of which have better connections (signal quality) than others. In ideal circumstances the base station has plenty of resources (e.g., bandwidth) and each UE gets the resources it needs. However, usually resources are limited, and the base station needs some way of fairly allocating the resources between the UEs.

Consider the downlink of a single gNB 5G cellular system. Several UEs are receiving data from ongoing transfers, for example, TCP controlled file downloads. Assuming that the bottleneck on the transfer path for these connections is this gNB to UE wireless access, the downlink per-UE queues in the gNB will be nonempty. At the beginning of each downlink slot (TTI) the gNB scheduler has to decide which of the UEs' waiting data to transmit in that slot.

At each gNB the MAC scheduler decides the PRB allocation, per carrier, per TTI (slot), in the PDSCH (DL) and in the PUSCH (UL). 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 control packets are part of Overhead as defined in 3.9.21.

3.8.3 Round Robin Scheduler

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.

3.8.4 Proportional Fair Scheduler

For data transfers, an important performance measure is long term throughput in bits/second, say, $T_i,\ 1 \leq i \leq n,$ where n is the number of UEs. One approach to designing a scheduler is to evaluate the goodness of the throughput vector $(T_1, \cdots, T_n)$ by a network utility, which is the sum of individual user utilities. The utility (or, usefulness) of a throughput $T,$ to a user, increases with increasing throughput, but for large throughputs, increasing throughput further gives diminishing increase in usefulness. This property is modeled as a nondecreasing concave function of throughput. A common measure of utility is the log function, i.e., for the throughput vector $(T_1, \cdots, T_n),$ the utility of throughput T_i to user i is measured as $\ln T_i$. The network utility is, then, given as

$$\sum_{i=1}^{n} \ln T_i$$

A Proportional Fair (PF) scheduler works by scheduling users in slots so that the utility of their long-term throughputs is maximized. In the 5G setting, the scheduling decisions at the beginning of a TTI are based on the physical rates that each UE can get in each Resource Block (RB). If we are given statistical models of these rates, then a nonlinear optimization problem can be

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formulated and solved to obtain the schedule. This is not a practical approach, however, and a learning algorithm is desired, which, based on slot-by-slot CSI measurements, takes scheduling decisions, which lead to PF optimal throughputs.

The Proportional Fair Scheduler is such a learning scheduler, that uses the throughputs that users are expected to get in the next slot, and the average throughputs they have each obtained up to this slot, to decide which UEs to schedule in the next slot. The practical PF scheme, described below, is based on information such as a presently available data rate for each user in each RB in the next slot (obtained by CSI measurements), and an average data rate over an immediately prior predetermined interval for each user.

3.8.4.1 Implementation

Since NetSim uses a flat fading model, in each slot, each UE achieves the same MCS in every RB in that slot. In other words, different UEs achieve, possibly, different MCSs, but a single UE has the same MCS across all RBs in a slot. Under this assumption, it is optimal to schedule the same UE in every RB in that slot. Since the channel condition can stochastically vary from slot to slot, the MCSs that the UEs achieve will vary from slot to slot. Under this assumption, the following algorithm is Proportional Fair optimal.

Let i, j denote generic users and let t be the slot index. A resource block index k is required given the flat fading assumption. Let $M_i(t)$ be the MCS seen by user i at time (slot) t. The channel CQI (derived from the data channel SINR) is used by the adaptive modulation and coding (AMC) module to determine the MCS. We denote by $S(M, B)$ the TB size in bits for a given MCS, M, and a given number of physical resource blocks (PRBs), B. The achievable rate $R_i\ (t)$ in bit/s for user i in slot t is defined as

$$R_i(t) = \frac{S(M_i\ (t), 1)}{\tau}$$

where τ is the TTI, i.e., 1 slot duration. At the start of each slot t, the user index $i^*(t)$ - selected by the scheduler - to which required PRBs (per that user's demand) is assigned at time t is determined as

$$i^*(t) = \underset{j=1,\dots,N}{argmax} \left(\frac{R_j(t)}{T_j(t)} \right)$$

This selection is carried out by the scheduler till all PRBs in slot t are allocated. In the above expression, $T_j(t)$ is the past throughput performance perceived by the user j, and is defined as

$$T_j(t) = \left(1 - \frac{1}{\alpha}\right) T_j(t-1) + \frac{1}{\alpha}\ \hat{T}_j(t)$$

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where α is the time constant (in units of slots) of the exponential moving average. NetSim uses $\alpha = 50$, and $\hat{T}_j(t)$ is the actual throughput achieved by the user i in the subframe t. If $\hat{B}_j(t)$ is the number of PRBs allocated to user j, we finally get

$$\hat{T}_j(t) = \frac{S(M_j(t), \hat{B}_j(t))}{\tau}$$

The value of α can be changed by the user by editing the NetSim's source code; it cannot be changed via the GUI. The PF scheduler thus selects a user having the maximum among values obtained by dividing a present possible data rate by an average data rate during a predetermined interval at every scheduling time point.

3.8.4.2 Remarks

R1. When there is no channel variation, i.e., each UE achieves the same MCS in every RB in every slot, then the throughput of the PF scheduler equals that of the round robin scheduler.

R2. The difference between the RR and PF schedulers can be seen when the radio channel varies stochastically over the slots.

R3. Mobility cases: NetSim pathloss computations do not follow continuous math since it will mean a potentially infinite number of calculations. These PL calculations are discrete time instants i.e., every time a UE moves with the UE movement update determined per the *update interval* parameter in the UI or via a mobility file. Let us denote the time difference between updates as ΔT. The UE is assumed to instantaneously move to a point P_T at time T and stay there till just before time $(T + \Delta T)$. At the moment, $(T + \Delta T)$, the UE instantaneously moves to point $P_{T+\Delta T}$. Pathloss is computed at (P_t, T) and then at $(P_{T+\Delta T}, T + \Delta T)$. Therefore, (and again) differences between the RR and PF scheduler will be appreciable only if the update interval is of the order of milli seconds.

3.8.5 Max Throughput Scheduler

The Max Throughput (MT) scheduler aims to maximize the overall throughput of the Base station (gNB or eNB). It allocates each PRBs to the user that can achieve the maximum achievable rate in the current TTI. The highest achievable rate is calculated by wideband MCS, that is derived from the CQI which in-turn is computed from the SINR. The scheduler allocates the required PRBs to this UE in the current TTI (slot). The calculation of achievable rate similar to what is explained in PF scheduler.

We denote $S(M, B)$ as the TB size in bits for a given MCS, M, and a given number of physical resource blocks (PRBs), B. The achievable rate $R_i\ (t)$ in bit/s for user i at slot t is defined as

$$R_i(t) = \frac{S(M_i\ (t), 1)}{\tau}$$

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where τ is the TTI i.e., 1 slot duration. At the start of each slot t, the user index $i^*(t)$ - selected by the scheduler - to which required PRBs (per that user's demand) is assigned at time t is determined as

$$i^*(t) = \underset{j=1,\ldots,N}{argmax}\left(R_j(t)\right)$$

While MT can maximize cell throughput, it cannot provide fairness to the UEs that experience poor channel condition.

When there are several UEs having the same achievable rate, NetSim implements RR scheduling amongst these UEs that have the same achievable rate.

3.8.6 Special cases

C1. Carrier aggregation case: the scheduler runs on a per carrier basis.

   a. PF Scheduler: $\hat{T}_j(t)$ is computed and maintained independently for each carrier.

C2. NSA mode: Traffic is split between 4G and 5G (eNB and gNB) above the MAC. The scheduler runs independently on the eNB and gNB.

C3. Association and Handover: PF Scheduler: At time of association or handover, say t_a, NetSim sets $T_j(t_a) = 1$

C4. Application priorities and heterogenous traffic: In 5G, the types of QoS are

   a. GBR, which is transmitted in RLC UM mode. In NetSim, Applications which have UGS priority set are transmitted in UM mode.

   b. Non-GBR, which is transmitted in RLC AM mode. In NetSim, Applications which do not have UGS priority set are transmitted in AM mode.

   c. Control channel traffic, which is transmitted in RLC TM mode. NetSim assume ideal control plane behaviour and doesn't model these transmissions.

C5. The MAC scheduler allocates resources on a combined (UM plus AM) RLC requirement. Once UE wise allocation is complete, RLC would first transmit the UM mode traffic followed by the AM mode traffic, to that UE. And so on for all UEs.

3.8.7 Log File

The resource allocation and the rank, i.e., $\left(\frac{R_j(t)}{T_j(t)}\right)$ computations are logged in the Radio Resource Allocation csv file.

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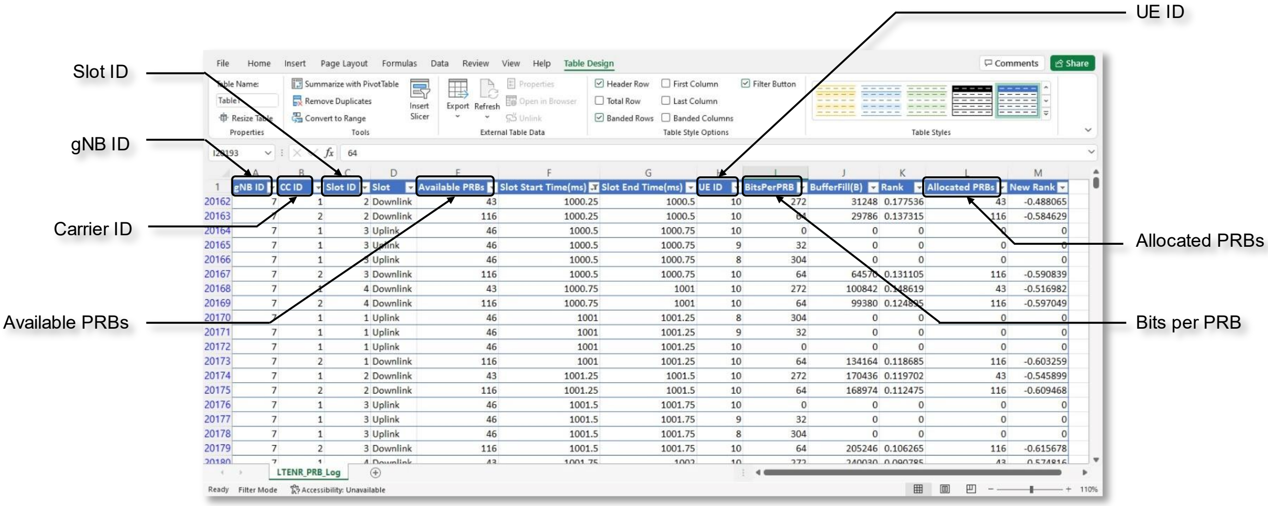

Figure 3-9: Radio resource allocation log file showing allocation per carrier per slot between each gNB and its associated UEs

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.

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:

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- 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 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 Digital Beamforming

- 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

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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 (fast fading gains) 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.
- Note that the LOS probability parameter in NetSim is solely used to compute the large scale pathloss per the 3GPP 38.901 standard. This parameter is not used in the channel rank (MIMO layers) computations.

Fading and Beamforming	No. of MIMO layers	Beamforming Gain (per layer) and Model
No fading MIMO unit gain	Min (N_t, N_r)	Unity (0 dB). A theoretical model useful for benchmarking.
No fading MIMO array gain	Min (N_t, N_r)	Max (N_t, N_r) Assumes Matched Filter Precoding (MFP) and Maximal Ratio Combining (MRC)
Rayleigh with Eigen Beamforming	Min (N_t, N_r)	Eigen values of the Wishart Matrix. Assumes MFP and MRC

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Table 3-2: Determination of (i) No. of MIMO layers and (ii) Gains in each layer using Fading and Beamforming parameters.

3.9.3 MIMO (Digital) 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 $\mathrm{LayerCount} = \mathrm{Min}\ (N_t, N_r)$ 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 $j, 1 \le j \le \mathrm{LayerCount}$,

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

  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].
- The transmit power (or total radiated power) is not split equally among the antennas. The per-antenna power depends on the beamforming vector used. For example, if the (eigen) beamforming vector is $[1, 0]^T$ in the 2-antenna case, all the power is radiated out of the first antenna. If it is $\left[\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right]^T$, then the power is split equally among the antennas ... and so on. NetSim abstracts out the actual beamforming operation and computes the received SINR when the beamforming vectors are used.

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- 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.

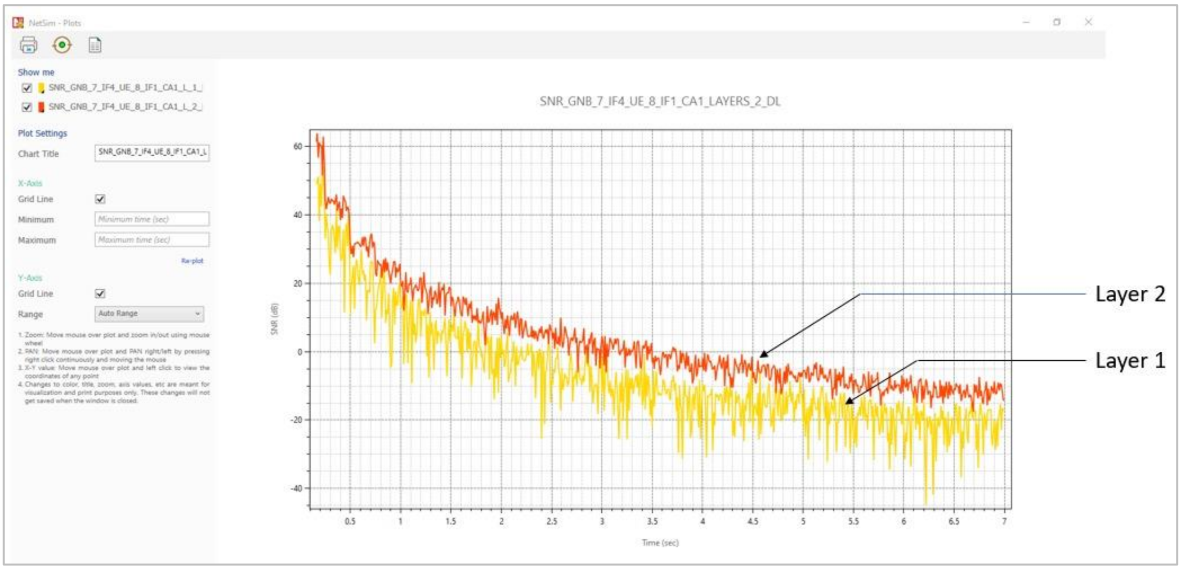

Figure 3-10: An example NetSim output showing SINR vs. time for each MIMO layer, as the UE moves away from the gNB. The beamforming gain is recalculated every coherence time

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.

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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 Analog beamforming in the SSB

1. In Analog beamforming, multiple antennas are used to concentrate the radiated power towards a particular direction (e.g., a part of a sector), thus improving the received SINR and the probability of detecting the SSB from the gNB (at a UE.)
2. Analog beamforming and digital beamforming are different as shown in the Table 3-3.

	Analog Beamforming	Digital Beamforming
Benefit	Array gain	Spatial Multiplexing/Diversity
Principle	Use the antennas to steer the main lobe towards the users in a particular area (e.g., a sector, and e.g., using a phased array) Directional (Spatial) Channel independent	Transmit and receive coding to create parallel channels Eigen vector based Channel dependent
Use Case	mmWave Short range LOS	Low and Mid Band Medium and long ranges NLOS

Table 3-3: Difference between Analog and digital beamforming

3. In NetSim, downlink Analog beamforming is implemented only in the control plane, i.e., broadcast beams for the SS/PBCH channel. If Analog beamforming is enabled in the UI then it will be used in signal strength calculations for purposes of Initial access (association) and Handovers.
4. The Analog beam forming gain computed is a wideband estimate.
5. A certain fraction of the (time-frequency) resources is deducted for control plane operations, when computing available resources in the PDSCH. This fraction is termed as overheads (OH) and the fractions are different for DL, UL and for FR1, FR2 as explained in section 3.9: Beamforming in NetSim. Analog beamforming measurements are assumed to be part of this overhead.
6. The Initial access and handover decisions are based on received SSB SNR, defined as

$$SNR = \frac{RxSignalLevel\ (dB) + AnalogBFGain(dB)}{N_0 \times W}$$

where N_0 is the noise spectral density and W is the channel bandwidth. Recall, that rate (MCS selection) is based on PDSCH SINR.

- Given the directional beamforming and the periodic transmission bursts we assume that SSB interference from other gNBs to be NIL. The probability of two SSB (directional) beams from two gNBs arriving at the same time at a UE is low. Even if this were to occur then both beams would be impacted almost equally by interference and the relative impact

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is negligible. This stems from the fact that UEs would see nearly equal powers from each gNB when H/O is occurring. Hence SNR is used.

- In the above formula

$$RxSignalLevel = gNBTxPower + Pathgain + ShadowFading$$

7. The $gNBTxPower$ is the transmit power in the SSB. This is different from the per layer transmit power that NetSim uses in PDSCH transmissions. The SSB power is set equal to the total power across all layers in the data channel (PDSCH).
8. NetSim does not (currently) implement Analog beamforming in the PDSCH or in the PUSCH. Digital beamforming can be enabled in the PDSCH/PUSCH as explained in section 3.9.
9. Analog beamforming is supported both in 5G (gNBs) as well as 4G (eNBs).

3.9.4.1 Assumptions

A1. The UE's optimal receive beam is perfectly aligned to the gNB's optimal transmit beam. As shown in the figure below, UE needs to measure RSRP based on the selected best SSB from serving cell and neighbouring cells, respectively. In the figure, UE measures the SS-RSRP from SSB with analog beamforming direction 3 from the serving cell, and from SSB from analog beamforming direction 1 from neighbouring cell. In this example, NetSim assumes beam 3 from s-gNB and beam 1 from neighbor gNB in perfectly aligned with the UE's receive beams

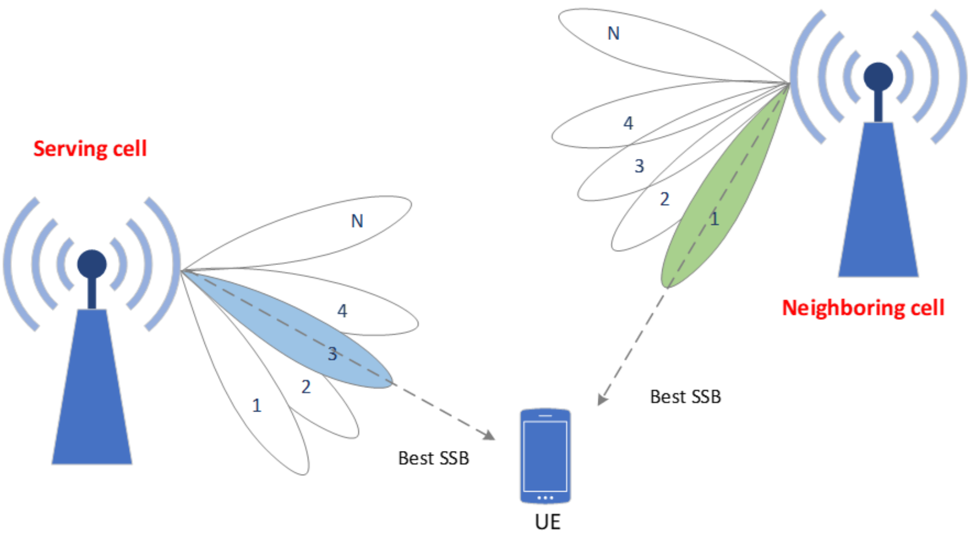

Figure 3-11: UE Measuring RSRP using Beamforming

A2. Based on A1, NetSim computes an upper bound on the average Analog beam forming gain (dB) as $10\log_{10}(N_t \times N_r)$. Here N_t is the transmit antenna count at the gNBs and N_r is the receive antenna count at the UE.

A3. The beam selection and alignment are assumed to occur instantaneously. There is no time delay to account for beam-selection, SSB burst periodicity etc. Users requiring such time

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delays can attempt modelling it using the Handover interruption time variable available in the gNB properties. In any case, the beam selection/monitoring of the best beams from both serving and neighbouring cells are assumed to be occurring in parallel with the other data processing taking place at the UE.

3.9.4.2 Logging

There is a change in radio measurements data logging in comparison with v13.1.

- The column DL/UL is being replaced as "Channel" and will have three types of entries (i) PDSCH (ii) PUSCH and (iii) SSB.
- PUSCH/PDSCH transmit/receive powers will continue to be logged on a per MIMO layer basis.
- The SSB is transmitted/received as a single stream using all Tx/Rx antennas. Hence this will have a single value for Tx-power (equal to the gNB Tx-power set in UI), for Rx-power and for AnalogBFGain.

3.9.5 Sector Antenna

NetSim implements a 2D parabolic sector antenna as per 3GPP TR 37.840.

The horizontal radiation pattern is given by

$$A_{E,H}(\varphi) = -min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right]$$

Where,

A_m is the front to back ratio (i.e., the ratio of power gain between the front and rear of a directional antenna). The default setting of 30 dB.

φ is the horizontal angle between UE and gNB

φ_{3dB} is the 3 dB, or half power, beam width of the antenna.

The sector antenna gain is,

$$A_E(\varphi,\theta) = G\,min\{-[A_{E,H}(\varphi) + A_{E,V}(\theta)], A_m\}_{E,max}$$

Where,

$G_{E,max}$ is the maximum directional gain of the radiation element (in dB) i.e., the gain along the antenna boresight. The default value is 8 dBi.

The boresight angle denotes the direction of maximum gain, or the highest radiated power.

Angle in NetSim is defined to start at 0 from the positive X-axis. If positive Y points downward, the angle increases on clockwise rotation from the positive X-axis. If positive Y points upward, the

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angle increases in an anti-clockwise direction from the positive X-axis. The unit for angle is degrees.

3.9.6 Fast fading

For a transmitter (gNB or eNB) with t antennas and a receiver with r antennas, the $N_r \times N_t$ channel gain matrix (between every transmit-receive antenna pair) on a given subcarrier has complex Gaussian elements. We assume in the standard model that the complex Gaussian elements are statistically independent across elements (which is the case the antennas are spread sufficiently far apart, e.g., of the order of a few wavelengths), and each element is a circularly symmetric Gaussian. We denote this matrix by H.

In NetSim, Fast-Fading is modeled by the elements of the H-Matrix being time-varying, with some coherence time. NetSim abstracts out the actual (digital) beamforming operation and computes the received SINR when the beamforming vectors are used. The MIMO link is modelled by parallel SISO channels, and the beamforming gain/loss would be equal to Eigenvalues of the Gram matrix of H (which would also be time-varying). This is the case when the transmitter/receiver use Eigen beamforming to precode/combine the signals across antennas, respectively. In turn, it assumes the availability of channel state information at both the transmitter and receiver. In the case where multiple layers are transmitted to different users, the interference is calculated by considering its statistics, by assuming that the channels between the base station and the different users to be independent of each other.

3.9.7 NR Frequency Bands

The definition of frequency ranges is per the table given below Table 3-4.

<table>
<tr><th colspan="2">Frequency range designation</th><th>Corresponding frequency range</th></tr>
<tr><td colspan="2">FR1</td><td>410 MHz – 7125 MHz</td></tr>
<tr><td rowspan="2">FR2</td><td>FR2-1</td><td>24250 MHz – 52600 MHz</td></tr>
<tr><td>FR2-2</td><td>52600 MHz – 71000 MHz</td></tr>
</table>

Table 3-4: NR Frequency Bands Ranges

3.9.7.1 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 single band in Duplex mode, namely n34, n38, n39, n40, n41, n50, n51, n77, n78, n79, n259, n260, n261 and n262 as shown below in Table 3-5.
- FDD Single band in Duplex mode, namely n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n66, n70, n71 and n74 as shown below in Table 3-5.

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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 – 859 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
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
n259	39500 MHz – 43500MHz	39500 MHz – 43500MHz	TDD
n260	37000 MHz – 40000MHz	37000 MHz – 40000MHz	TDD
n261	27500 MHz – 28350MHz	27500 MHz – 28350MHz	TDD
n262	47200 MHz – 48200MHz	47200 MHz – 48200MHz	TDD

Table 3-5: NR operating bands in FR1 in NetSim

3.9.7.1.1 Maximum transmission bandwidth configuration

The maximum transmission bandwidth configuration N_{RB} for each UE channel bandwidth and subcarrier spacing is specified below Table 3-6.

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 3-6: Maximum transmission bandwidth configuration NRB

3.9.7.1.2 Minimum guard band and transmission bandwidth configuration

The minimum guardband for each UE channel bandwidth and SCS is specified below Table 3-7.

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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 3-7: Minimum guard band for each UE channel bandwidth and SCS (kHz)

NOTE: The minimum guard bands have been calculated using the following equation:

$$\frac{(BW_{channel} \times 1000(kHz) - N_{RB} \times SCS \times 12) - SCS}{2}$$

where N_{RB} are from **Error! Reference source not found.**. The minimum guard band of receiving BS SCS 240 kHz for each

UE channel bandwidth is specified in Table 3-8.

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

Table 3-8: Minimum guard band (kHz) of SCS 240 kHz from Standards Table 5.3.3-2

3.9.7.2 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 3-9.

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
n259	39500 MHz	–	43500 MHz	39500 MHz	–	43500 MHz	TDD
n260	37000 MHz	–	40000 MHz	37000 MHz	–	40000 MHz	TDD
n261	27500 MHz	–	28350 MHz	27500 MHz	–	28350 MHz	TDD
n262	47200 MHz	–	48200 MHz	47200 MHz	–	48200 MHz	TDD
n263	57000 MHz	–	71000 MHz	57000 MHz	–	71000 MHz	TDD

Table 3-9: NR operating bands in FR2 in NetSim

3.9.7.2.1 Maximum transmission bandwidth configuration

The maximum transmission bandwidth configuration N_{RB} for each UE channel bandwidth and subcarrier spacing is specified in Table 3-10.

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz	800 MHz	1600 MHz	2000 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N/A	N/A	N/A	N/A
120	32	66	132	264	N/A	N/A	N/A
480	N/A	N/A	N/A	66	124	248	N/A
960	N/A	N/A	N/A	33	62	124	148

Table 3-10: Maximum transmission bandwidth configuration N_{RB} from Standards Table 5.3.2-1

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SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz	800 MHz	1600 MHz	2000 MHz
60	1210	2450	4930	N/A	N/A	N/A	N/A
120	1900	2420	4900	9860	N/A	N/A	N/A
480	N/A	N/A	N/A	9680	42640	85520	N/A
960	N/A	N/A	N/A	9440	42400	85280	147040

Table 3-11: Minimum guardband for each UE channel bandwidth and SCS (kHz) from Standards Table 5.3.3-1

3.9.8 UE channel bandwidth

3.9.8.1 General

All UEs connected to BS (gNB) have the same channel bandwidth. This is a user settable bandwidth available in the gNB properties. Bandwidth is a single parameter in TDD; in FDD users can set DL bandwidth and UL bandwidth. It is currently not possible in NetSim to configure different channel bandwidths to different UEs connected to a BS.

The above is true even in the case of carrier aggregation (CA). All component carriers (CCs) are assigned to all UEs, and the pooled OFDM resources are shared between the UEs.

3.9.9 Frame structure and physical resources

3.9.9.1 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
5	480	Normal
6	960	Normal

Table 3-12: Supported transmission numerologies from Standards Table 4.2-1

3.9.9.2 Frames and subframes

Downlink and uplink transmissions are organized into frames with $T_f = 10\text{ms}$ duration, each consisting of ten subframes of $T_{sf} = 1\text{ms}$ duration. The number of consecutive OFDM symbols per subframe is $N_{\text{symb}}^{\text{subframe},\mu} = N_{\text{symb}}^{\text{slot}} N_{\text{slot}}^{\text{subframe},\mu}$.

3.9.9.3 Slots

For subcarrier spacing configuration μ, slots are numbered $n_{\text{s}}^{\mu} \in \left\{0, \ldots, N_{\text{slot}}^{\text{subframe},\mu} - 1\right\}$ in increasing order within a subframe and $n_{\text{s,f}}^{\mu} \in \left\{0, \ldots, N_{\text{slot}}^{\text{frame},\mu} - 1\right\}$ in increasing order within a

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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 Table 3-13 and Table 3-14 The start of slot n_s^μ in a subframe is aligned in time with the start of OFDM symbol $n_s^\mu N_{\text{symb}}^{\text{slot}}$ 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 $N_{\text{Rx-Tx}} T_c$ 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 3-15.

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 $N_{\text{Tx-Rx}} T_c$ 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 3-15.

μ	$N_{\text{symb}}^{\text{slot}}$	$N_{\text{slot}}^{\text{frame},\mu}$	$N_{\text{slot}}^{\text{subframe},\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16
5	14	320	32
6	14	640	64

Table 3-13: Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix from Standards Table 4.3.2-1.

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

Table 3-14: Number of OFDM symbols per slot, slots per frame, and slots per subframe for extended cyclic prefix from Standards Table 4.3.2-2.

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

Table 3-15: Transition time N_"Rx-Tx" and N_"Tx-Rx" from Standards Table 4.3.2-3

3.9.9.4 Slot structure in NetSim

We show below the slot structure, in NetSim, for two examples of $\mu = 0$ and $\mu = 1$.

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1. If we take $\mu = 0$, the number of slots in a sub frame is 1. The total number of slots, therefore, in a frame is $1 \times 10 = 10$. For different DL:UL ratios the slot structures are as follows

Ratio 1:1		Ratio 1:4		Ratio 4:1	
Sub Frame ID	**Slot Type**	**Sub Frame ID**	**Slot Type**	**Sub Frame ID**	**Slot Type**
1	UL	1	UL	1	UL
2	DL	2	DL	2	DL
3	UL	3	UL	3	DL
4	DL	4	UL	4	DL
5	UL	5	UL	5	DL
6	DL	6	UL	6	UL
7	UL	7	DL	7	DL
8	DL	8	UL	8	DL
9	UL	9	UL	9	DL
10	DL	10	UL	10	DL

Table 3-16: The Slot structures for different DL:UL ratios when $\mu = 0$

2. For $\mu = 1$, the number of slots in a sub frame is 2. The total number of slots, therefore, in a frame is $2 \times 10 = 20$. For different DL:UL ratios the slot structures are as follows

Ratio 1:1		Ratio 1:4		Ratio 4:1	
Sub Frame ID	**Slot Type**	**Sub Frame ID**	**Slot Type**	**Sub Frame ID**	**Slot Type**
1	UL	1	UL	1	UL
1	DL	1	DL	1	DL
2	UL	2	UL	2	DL
2	DL	2	UL	2	DL
3	UL	3	UL	3	DL
3	DL	3	UL	3	UL
4	UL	4	DL	4	DL
4	DL	4	UL	4	DL
5	UL	5	UL	5	DL
5	DL	5	UL	5	DL
6	UL	6	UL	6	UL
6	DL	6	DL	6	DL
7	UL	7	UL	7	DL
7	DL	7	UL	7	DL
8	UL	8	UL	8	DL
8	DL	8	UL	8	UL
9	UL	9	DL	9	DL
9	DL	9	UL	9	DL
10	UL	10	UL	10	DL
10	DL	10	UL	10	DL

Table 3-17: The Slot structures for different DL:UL ratios when μ=1

For a DL/UL mixed configuration, the first slot in NetSim always UL and the second slot is always DL, and subsequent slots are based on the DL:UL ratio set.

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3.9.10 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).

3.9.10.1 Channel quality indicator (CQI)

The CQI indices and their interpretations are given in Table 3-18 or Table 3-20 for reporting CQI based on QPSK, 16QAM and 64QAM. The CQI indices and their interpretations are given in Table 3-19 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 are based on the table chosen by the user. In the GUI users can select “table1” (corresponding to Table 3-18), “table2” (corresponding to Table 3-19) or “table3” (corresponding to Table 3-20). 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		

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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

Table 3-18: 4-bit CQI Table 1 from Standards Table 5.2.2.1-2

CQI index	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

Table 3-19: 4-bit CQI Table 2 from Standards Table 5.2.2.1-3

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

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12	64QAM	466	2.7305
13	64QAM	567	3.3223
14	64QAM	666	3.9023
15	64QAM	772	4.5234

Table 3-20: 4-bit CQI Table 3 from Standards Table 5.2.2.1-4

3.9.11 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)

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

3.9.11.1 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 3-22 (Table 1)
- QAM256 Table 3-23 (Table 2)
- QAM64LowSE Table 3-24 (Table 3)

The UE and gNB then uses this table to determine the modulation order Q_m and Code Rate, R. The selection is based on looking up the MCS for the given spectral efficiency, which is computed as explained in 3.9.15. 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 Table 3-21.

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

Table 3-21: 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

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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	

Table 3-22: MCS index table 1 for PDSCH from Standards Table 5.1.3.1-1

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

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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	

Table 3-23: MCS index table 2 for PDSCH from Standards Table 5.1.3.1-2

MCS Ind 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

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

Table 3-24: MCS index table 3 for PDSCH from Standards Table 5.1.3.1-3

3.9.12 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 ($\mathrm{N_{RE}}$) within the slot.
   - A UE first determines the number of REs allocated for PDSCH within a PRB (N'_{RE}) by $N'_{RE} = N^{RB}_{sc} \times N^{PRB}_{symb} - N^{PRB}_{DMRS} - N^{PRB}_{oh}$, where $N^{RB}_{sc} = 12$ is the number of subcarriers in a physical resource block, $\mathrm{N^{slot}_{symb}}$ is the number of symbols of the PDSCH allocation within the slot, $\mathrm{N^{PRB}_{DMRS}}$ is the number of REs for DM-RS per PRB in the scheduled duration and $\mathrm{N^{PRB}_{oh}}$ is the overhead configured by higher layer parameter and N^{PRB}_{oh} is set to 0.
   - A UE determines the total number of REs allocated for PDSCH ($\mathrm{N_{RE}}$)) by $N_{RE} = \min(156, N'_{RE}) \times n_{PRB} \mathrm{N_{RE}} = \mathrm{\overline{N}'_{RE} {*} n_{PRB}}$, where $n_{PRB} \mathrm{N_{RE}} = \mathrm{\overline{N}'_{RE} {*} n_{PRB}}$ is the total number of allocated PRBs for the UE.
2. Intermediate number of information bits (N_{info}) is obtained by $N_{info} = N_{RE} \times R \times Q_M \times \upsilon \mathrm{TBS_{temp}} = \mathrm{N_{RE} {*} R {*} Q_m {*} \upsilon}$.
3. When $N_{info} \leq 3824$, TBS is determined as follows
   - quantized intermediate number of information bits $N'_{info} = max\left(24, 2^n \left\lfloor \frac{N_{info}}{2^n} \right\rfloor\right)$, 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		

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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		

Table 3-25: TBS for N_info ≤3824 from Standards Table 5.1.3.1-4

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 $R \leq 1/4$

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

else

if $N'_{info} > 8424$

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

else

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

end if

end if

else if Table 3-23 is used and $28 \leq I_{MCS} \leq 31$.

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3.9.13 HARQ

3.9.13.1 Introduction

We start with a brief and simplistic explanation of the HARQ mechanism.

1. Hybrid automatic repeat request (hybrid ARQ or HARQ) is a combination of retransmissions and error correction. The HARQ protocol runs in the MAC and PHY layers.
2. In the 5G PHY, a code block group (CBG) is transmitted over the air by the transmitter to the receiver. If the CBG is successfully received the receiver sends back an ACK, else if the CBG is received in error the receiver sends back a NACK (negative ACK).
3. If the transmitter receives an ACK, it sends the next CBG. However, if the transmitter receives a NACK, it retransmits the previously transmitted CBG.
4. In 5G, the incorrectly received CBG is not discarded but stored at the receiver. When the re-transmitted CBG is received, the two CBGs are combined. This is called Hybrid ARQ with chase-combining (HARQ-CC).

3.9.13.2 Implementation in NetSim

1. HARQ is implemented in 4G (eNB) and in 5G (gNB) in both downlink and uplink.
2. A HARQ entity is defined for each gNB-UE pair, separately for Uplink and Downlink and for each component carrier. The HARQ entity handles the HARQ processes.
    a. Max number of HARQ processes is 8 in 4G
    b. Max number of HARQ processes is 16 in 5G
3. Each HARQ process transmits one Transport Block (TB) at any time
4. When operating in MIMO, each layer handles a different TB. This means that one TB is not transmitted across multiple layers.
5. Each TB is split into Code blocks (CBs) and CBs are grouped into Code Block Groups (CBGs).
6. At the receiver the CBGs are given to a multiplexer which combines the CBGs into a TB.
7. CBGs are always retransmitted at the same MCS as the first transmission. This restriction comes from the specification of the rate matcher in the 3GPP TS 38.212 standard.

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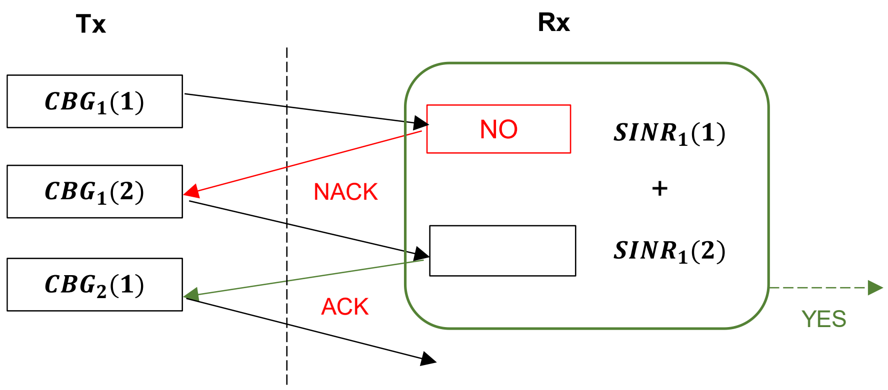

Figure 3-12: We see the HARQ transmission process. The transmitter sends CBG1 which is errored. Therefore, the receiver sends a NACK. CBG1 is then retransmitted (transmission attempt 2). The receiver then soft combines the first and second transmissions, which is successful and hence sends back an ACK

8. In HARQ-CC, every retransmission contains the same coded bits (information and coding bits). We abstract soft combining and model it by summing (in linear scale) the SINRs of transmitted and retransmitted CBGs. The BLER is then looked up for the combined SINR.
9. The New Data Indicator (NDI) flag is set (both in UL and DL) true for transmission of a new TB.
10. HARQ entity is terminated during handover-triggered de-association from a gNB and re-created at the new gNB after the handover procedure is completed.
11. HARQ retransmissions have priority over new data transmissions. Within a HARQ process, new data transmissions are not taken up when retransmission data is in the queue.
12. HARQ processes are multiplexed in time (slots) in a round robin fashion. For example, if we had a case with 4 HARQ processes then:

    Slot 1 – HARQ Process 1 > Success
    Slot 2 – HARQ Process 2 > Success
    Slot 3 – HARQ Process 3 > Error
    Slot 4 – HARQ Process 4 > Success
    Slot 5 – HARQ Process 1 > Success
    Slot 6 – HARQ Process 2 > Success
    Slot 7 – HARQ Process 3 > Retransmission Success
    ... and so on

3.9.13.3 Assumptions and limitations

1. The HARQ ACK/NACK is sent out-of-band by the receiver immediately after receipt ($\Delta t \rightarrow 0^+$). It is then instantaneously and correctly received at the transmitter. The ACK/NACKs are not logged.

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2. If DL/UL transmission can occur, then reverse direction (UL/DL respectively) ACK/NACK will be successful. Specifically, even if the UL data link is in outage, ACK/NACK transmitted in the UL will be correctly received by the gNB.

3.9.13.4 Transmission flow

1. Packets are either split or combined into transport blocks (TBs) depending on the packet size and the TB size. It is the TB that needs to be transmitted over the air.
   a. Users can set the application layer packet size in NetSim GUI > Application properties. The packet size at the MAC is the application packet size plus transport layer and IP layer overheads. Users can obtain the MAC layer packet size from the packet trace.
   b. The TB size is determined by the LTE and 5G NR protocol running in the MAC/PHY. Users can obtain the TB size from the code block log file (explained subsequently in section 3.9.12)
2. TB are then split to Code blocks (CBs). The code block size calculation and TB segmentation is explained in section 3.9.14 below.
3. CBs are grouped into code block groups (CBGs).
   a. The max number of CBGs per TB can be set in the NetSim GUI (based on RRC parameter MAX_CBG_PER_TB in the NetSim GUI)
4. TBs are transmitted by transmitting CBGs, which in turn comprises of CBs
5. BLER is applied upon CBG reception at the receiver
6. If any CB is in error, the transmitter retransmits the entire CBG to which that CB is a part of.
7. The receiver then soft combines the first transmission and all subsequent retransmissions
   a. Soft combining is modelled by adding their SINRs in the linear scale. For example, if there were 2 retransmissions, then the combined SINR would be given by

$$CombinedSINR_3^{Tx} = SINR_3^{Tx} + SINR_2^{Tx} + SINR_1^{Tx}$$

8. BLER is applied on the improved (combined) SINR by tossing a biased coin
9. If any CB is in error, go to step 6, subject to transmit limit of 4 (retransmit limit of 3).
   a. The transmit limit is user settable in NetSim, and by default is set to 4.
10. If all CBGs (in a TB) are successful, then at the receiver, the TB is sent up to the RLC
11. Else, the entire TB is dropped

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3.9.13.5 Special cases

1. If there is a retransmission scheduled in a multi-layer scenario, then the scheduler cannot retransmit data in one layer and transmit new data in another layer to the same UE. Hence during retransmissions, the scheduler allows other UEs to use the resources. The reason is: the next TB can only be sent after receiving a successful ACK or if the current TB is dropped. Therefore, another TB (to the same UE) cannot be scheduled on the remaining resources. For example, if Max-throughput scheduling is used, when a CBG is received in error the NDI flag is false. When the NDI flag is false, the UE is not passed through the scheduler function; only the CB that needs to be transmitted is Hence remaining PRBs left - after retransmitting the errored CBG - must be allocated to a not Max-SINR UE. Also note that, the not Max-SINR UE's CBGs may also be errored in which case those CBGs need to be retransmitted. This above complicating factor leads to a break down in the general belief that Max-throughput scheduler leads to Max-SINR UE getting all throughput with other UEs getting NIL throughput.
2. Again, consider a multi-layer scenario with CBG errors in 2 or more layers. How many PRBs should then be allocated for retransmissions and how many for new data from different UEs? In such cases NetSim calculates the PRBs required for retransmission as the max of PRBs required for retransmission in each layer.

3.9.13.6 Logging

Time (ms	gNBId	gNBIf	UEId	UEIf	Channel	CA	FrameId	Sub	SlotId	LayerId	ProcessId	Re	TBS	Modulation	CodeI	CBS	CBS_	SINR(Combined	BLE	CBG	CBI	NDI	Tra
13000.5	10	4	12	1	PDSCH	0	1301	1	2	1	1		888	256QAM	711	968	888	43.169552	0	1	1	TRUE	[illegible]
13000.5	10	4	12	1	PDSCH	0	1301	1	2	2	1		888	256QAM	711	968	888	50.511929	0	1	1	TRUE	[illegible]
13000.5	10	4	12	1	PDSCH	0	1301	1	2	3	1		888	256QAM	711	968	888	56.157132	0	1	1	TRUE	[illegible]
13000.5	10	4	12	1	PDSCH	0	1301	1	2	4	1		888	256QAM	711	968	888	58.955028	0	1	1	TRUE	[illegible]
13001.5	10	4	12	1	PUSCH	0	1301	2	2	1	1		888	256QAM	711	968	888	51.730194	0	1	1	TRUE	[illegible]
13003	10	4	12	1	PDSCH	0	1301	4	1	1	1		888	256QAM	711	968	888	43.169552	0	1	1	TRUE	[illegible]
13003	10	4	12	1	PDSCH	0	1301	4	1	2	1		888	256QAM	711	968	888	50.511929	0	1	1	TRUE	[illegible]
13003	10	4	12	1	PDSCH	0	1301	4	1	3	1		888	256QAM	711	968	888	56.157132	0	1	1	TRUE	[illegible]
13003	10	4	12	1	PDSCH	0	1301	4	1	4	1		888	256QAM	711	968	888	58.955028	0	1	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	1	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	1	2	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	2	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	2	2	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	3	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	4	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	5	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	6	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	7	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	8	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	1	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	1	2	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	2	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	2	2	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	3	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	4	1	TRUE	[illegible]
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	5	1	TRUE	[illegible]

Figure 3-13: HARQ log file showing code block transmission. Here CBS_ represents the information bits within a code block (CBS column).

1. Transmission attempts 1, 2, 3 and 4 are indexed as 0, 1, 2, 3. If the 4th attempt is errored, the CBG is dropped.
2. Packet trace only logs "packet" flow, and does not log flow of TBs, CBGs etc. Therefore, the packet trace logs a packet in the MAC OUT of the transmitter and subsequently if received successfully at the MAC IN of the receiver. If the packet is errored, it is also marked in the packet trace.

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3. Note that if a TB is in error than all the packets that were part of the TB will be marked as error.
4. The transmission/re-transmission of CBs is logged in the Code Block logfile.
5. The remarks column would have messages for HARQ preparation and would be blank for actual transmissions.
6. TBS is always logged on a per layer basis.
7. CBGID is also on a per layer basis
8. SINR reported in the CBG log is the post-soft combining SINR.

Time (ms)	gNBId	gNBIf	UEId	UEIf	Channel	CA	FrameId	Sub	SlotId	LayerId	ProcessId	Re	TBS	Modulation	CodeI	CBS	CBS_	SINR(Combined	BL
160.999	9	4	11	1		0	17	1	2	0	N/A	HARQ entity created							
160.999	9	4	13	1		0	17	1	2	0	N/A	HARQ entity created							
160.999	10	4	12	1		0	17	1	2	0	N/A	HARQ entity created							
160.999	10	4	14	1		0	17	1	2	0	N/A	HARQ entity created							
161	9	4	11	1	PUSCH	0	17	2	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
161	9	4	13	1	PUSCH	0	17	2	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
161	9	4	11	1	PUSCH	0	17	2	1	0	1	Allocated PRBs for new data = 0							
161	9	4	13	1	PUSCH	0	17	2	1	0	1	Allocated PRBs for new data = 0							
161	10	4	12	1	PUSCH	0	17	2	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
161	10	4	14	1	PUSCH	0	17	2	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
161	10	4	12	1	PUSCH	0	17	2	1	0	1	Allocated PRBs for new data = 0							
161	10	4	14	1	PUSCH	0	17	2	1	0	1	Allocated PRBs for new data = 0							
161.5	9	4	11	1	PUSCH	0	17	2	2	0	1	Process number = 1, NDI = True, Transmission number = 0							
161.5	9	4	13	1	PUSCH	0	17	2	2	0	1	Process number = 1, NDI = True, Transmission number = 0							
161.5	9	4	11	1	PUSCH	0	17	2	2	0	1	Allocated PRBs for new data = 0							
161.5	9	4	13	1	PUSCH	0	17	2	2	0	1	Allocated PRBs for new data = 0							
161.5	10	4	12	1	PUSCH	0	17	2	2	0	1	Process number = 1, NDI = True, Transmission number = 0							
161.5	10	4	14	1	PUSCH	0	17	2	2	0	1	Process number = 1, NDI = True, Transmission number = 0							
161.5	10	4	12	1	PUSCH	0	17	2	2	0	1	Allocated PRBs for new data = 0							
161.5	10	4	14	1	PUSCH	0	17	2	2	0	1	Allocated PRBs for new data = 0							
162	9	4	11	1	PUSCH	0	17	3	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
162	9	4	13	1	PUSCH	0	17	3	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
162	9	4	11	1	PUSCH	0	17	3	1	0	1	Allocated PRBs for new data = 0							
162	9	4	13	1	PUSCH	0	17	3	1	0	1	Allocated PRBs for new data = 0							
162	10	4	12	1	PUSCH	0	17	3	1	0	1	Process number = 1, NDI = True, Transmission number = 0							
162	10	4	14	1	PUSCH	0	17	3	1	0	1	Process number = 1, NDI = True, Transmission number = 0							

Figure 3-14: HARQ log showing HARQ working via information provided in the Remarks columns

3.9.13.7 HARQ turn off

There are ongoing discussions of abandoning of HARQ for the 1 ms end-to-end latency use case of URLLC. This decision implies that the code rate had to be lowered such that a single shot transmission, i.e., no retransmissions and no feedback, achieves the required BLER.

NetSim allows users to turn HARQ OFF via the GUI. Note that the code block log will continue to be written. Users will notice that errored CBGs are not retransmitted if HARQ is turned OFF. Since the CB/CBG is in error, that entire TB to which it belongs will be in error.

Users can inspect the packet trace and will see large numbers of packets errors if HARQ is turned OFF and if the UE is seeing a high BLER.

3.9.14 Segmentation of transport block into code blocks

1. If the transport block size is larger than 3824, a 16-bit CRC is added at the end of the transport block or 24-bit CRC is added.
2. The transport block is divided into multiple equal size code blocks when the transport block size exceeds a threshold.
3. For quasi-cyclic low-density parity-check code (QC-LDPC) base graph 1, the threshold is equal to 8448.

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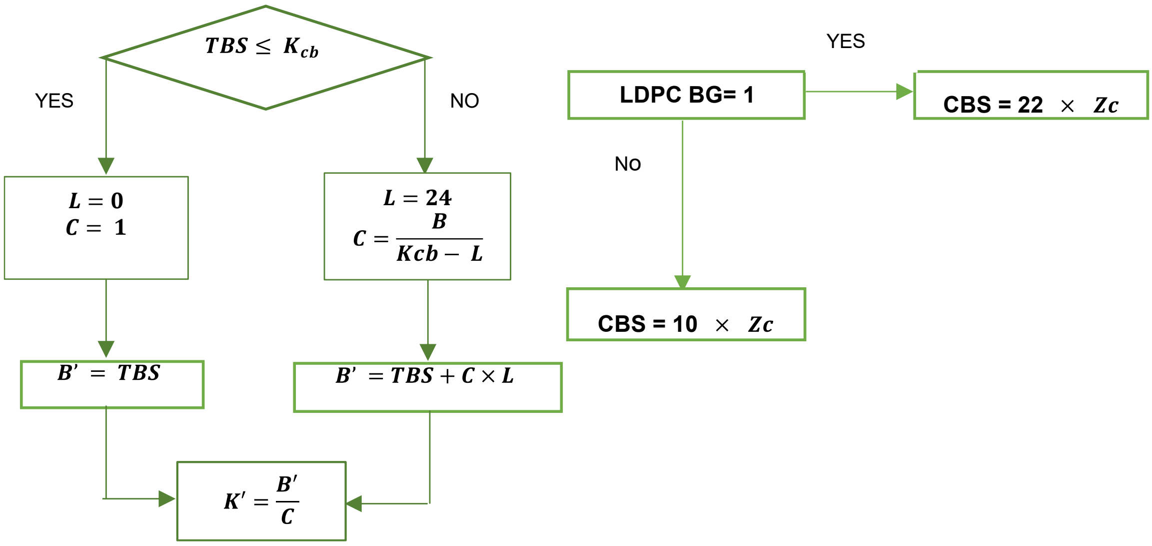
4. For QC-LDPC base graph 2, the threshold is equal to 3840. In 5G NR, the maximum code block size number is 8448.
5. An additional 24-bit CRC is added at the end of each code block when there is a segmentation.
6. A CBG can have up to 2/4/6/8 CBs.
7. Maximum transport block size - 1,277,992.

LDPC BG 1, CBS Max, (K_{cb}) = 8448, LDPC BG 2, CBS Max, (K_{cb}) = 3840



L = Extra CRC bits, C = Number of Code blocks, TBS = Size of Transport block, K' = Information bits in code block. The base matrix expansion factor Zc is calculated by selecting minimum Zc in all sets of lifting size tables, such that: $K_b \times Zc \geq K$. K_b denotes the number of information bit columns for the lifting size Zc.

3.9.15 BLER and MCS selection

NetSim GUI allows users set the BLER, via the BLER drop down option. This option has two settings, and each setting in-turn has different options for MCS selection. Both BLER and MCS selection are global options and will apply to all gNBs and UEs in both DL and UL in the network scenario.

1. Zero BLER

- MCS Selection: Ideal Shannon theorem-based rate

- MCS is chosen from the 3GPP (spectral efficiency to MCS) table assuming ideal Shannon rate whereby

$$SpectralEfficiency = \log_2(1 + SINR)$$

- Data is transmitted at this MCS with zero BLER

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- The spectral efficiency to MCS table is explained in section 3.9.11.1 (Modulation order and target code rate determination)

▪ MCS Selection: Shannon rate with attenuation factor

- MCS is chosen from the 3G (spectral efficiency to MCS) table per the following expression provided in TR 36.942:

$$SpectralEfficiency = \alpha \times \log_2(1 + SINR)$$

- α is the attenuation factor and generally $0.5 \leq \alpha \leq 1.00$. Default: 0.75
- Data is transmitted at this MCS with zero BLER.
- A more general formula, available in literature, is $SprectralEfficiency = \alpha \times \log_2(1 + \beta \times SINR)$ with $0 < \beta \leq 1$. This can be easily programmed in NetSim by modifying the code to include β and then rebuilding it.
- $SINR$ in the above expressions is in linear scale

2. BLER Enable: Within this, users can set outer loop link adaptation (OLLA) to True or False

- OLLA False: The MCS is chosen in exactly the same way as described in the Zero BLER case. Data is, however, transmitted at the chosen MCS, *with* BLER. The BLER is looked up from NetSim's proprietary BLER-MCS-SINR curves.
- OLLA True: In this case, the user needs to set a target BLER (t-BLER), for example 10%. Based upon the set t-BLER an initial MCS is "guessed". Subsequently, the MCS is dynamically adjusted based on an outer-loop link adaptation algorithm that uses HARQ ACK-NACK messages. Note that the t-BLER is based on initial transmission and not after a re-transmission.

3.9.16 BLER-MCS-SINR Curves

NetSim has exhaustive SINR-BLER data for various transport block sizes for all MCSs (1, 2, ..., 28) for Base graphs (1, 2) for all three tables (1, 2, 3). The SINR-BLER data was generated using an in-house proprietary link-level simulation program and the results have been carefully validated against published literature.

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3.9.17 Outer Loop Link Adaptation (OLLA) (Part of Adv. 5G)

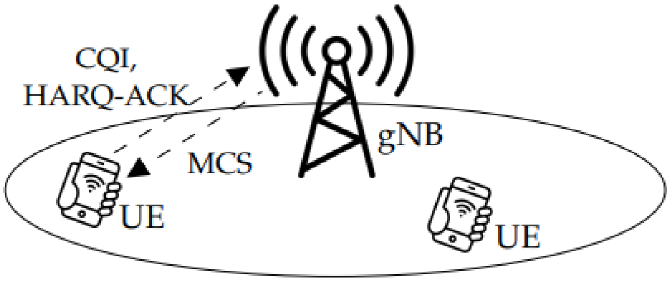

Figure 3-15: UE reports CQI based on SINR and the gNB transmits data at an MCS based on CQI

During the downlink AMC process, a user equipment (UE) reports the channel quality indicator (CQI) of the link to the gNB, as shown in Figure 3-15. This CQI is based on the received instantaneous signal to interference plus noise ratio (SINR). OLLA is a feedback loop technique that adjusts the instantaneous SINR value by adding or subtracting an offset, using positive or negative acknowledgement signals (i.e., ACK or NACK respectively). The offset is updated continuously based on the Hybrid Automatic Repeat Request (HARQ) acknowledgement feedback, such that the average Block Error Rate ($BLER_A$) converges to a predefined target ($BLER_T$)

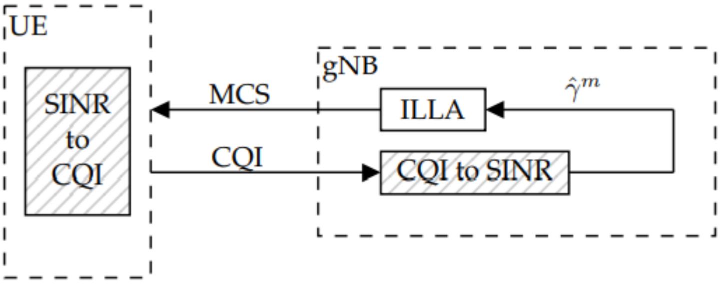

Figure 3-16: MCS selection per inner loop link adaptation (without OLLA)

Rate adaptation has two parts:

- an inner loop adaptation where the SINR measured by the user is used as an anchor to determine the transmission rate. This transmission rate is fed back, and
- OLLA is used at the base-station to make appropriate corrections to this transmission rate

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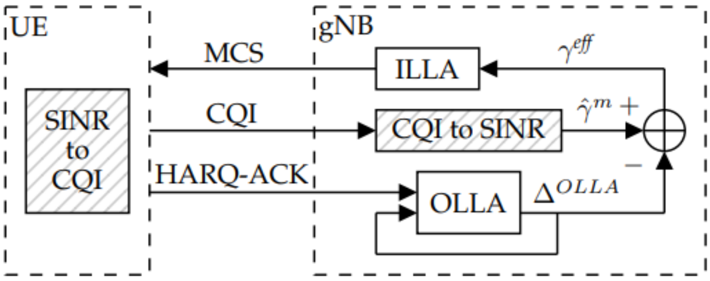

Figure 3-17: MCS selection with OLLA

The OLLA compensation is as follows:

$$\Delta_{OLLA}(k) = \Delta_{OLLA}(k-1) + \Delta_{up} \times e(k) + \Delta_{down} \times (1 - e(k))$$

Where $e(k)$ s an indicator variable whose value is 0 for ACK and 1 for NAC

$$\gamma_{eff}(k,n) = \hat{\gamma}_m(k,a) - \Delta_{olla}(k,n)$$

All terms in the above expression have units of dB. We can see that a positive value of Δ_{OLLA} leads to a lower value of γ_{eff}, which translates into a pessimistic interpretation of the reported channel conditions and the selection of a conservative MCS. Conversely, a negative value of Δ_{OLLA} leads to a higher γ_{eff}, translating into an optimistic interpretation of the channel conditions and the selection of an aggressive MCS. At the beginning of each radio resource control (RRC) connection, Δ_{OLLA} is initialized to a fixed value, Δ_{ini}, defined on a cell basis. As the connection progresses, Δ_{OLLA} is progressively modified by OLLA based on HARQ feedback.

When a positive acknowledgment (ACK) is received, Δ_{OLLA} is decreased by Δ_{down}, and when a negative acknowledgment (NACK) is received, Δ_{OLLA} is increased by Δ_{up}. The ratio $\frac{\Delta_{down}}{\Delta_{up}}$ controls the target BLER that OLLA converges to, and is given by

$$BLER_T = \frac{1}{\left(1+\frac{\Delta_{up}}{\Delta_{down}}\right)} \approx \frac{\Delta_{down}}{\Delta_{up}}, \text{ if } \Delta_{up} \gg \Delta_{down}$$

Typical values for Δ_{up} and Δ_{down} are 1 dB and 0.1 dB, respectively, to ensure quick recovery from high BLER situations and smooth convergence to equilibrium. These values yield a target BLER of 0.1 (10%).

Note that the target BLER is only reached at the end of large activity connections, for which a large number of ACKs and NACKs are received by the eNB. For these connections, OLLA reaches steady state and ∆OLLA fluctuates around the proper value due to random system errors. In contrast, for small activity connections, convergence is not guaranteed, unless ∆OLLA is properly initialized. When Δ_{ini} is too large, γ_{eff} is initially far below the actual channel

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conditions. This leads to an excessively conservative selection of the initial MCS and, therefore, user throughput is below the maximum achievable value. Considering a typical value of Δ_{down} = 0.1 dB, OLLA needs at least 10 consecutive successful transmissions (i.e., 10 ms) to compensate for a 1 dB bias in SINR reporting. On the other hand, when Δ_{ini} is too small, γ_{eff} is far above the actual channel conditions and a too aggressive MCS is initially selected. This causes high BLER figures and unnecessary retransmissions, thus lowering the net user data flow. In both cases, user throughput is negatively affected.

The target BLER for OLLA is at a transport block level and is defined as the ratio of TBs errored to the TBs transmitted. In the NetSim PHY, TBs are split into code blocks (CBs), which are sent over the air. CBs are aggregated into code block groups (CBG); the HARQ plus soft combining operates at a CBG level.

3.9.18 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 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.

3.9.19 Carrier Aggregation

In NetSim carrier aggregation (CA) is done in both DL and in the UL. When doing CA, the PHY layer is separate for each component carrier (CC). Thus, each CC will have a different pathloss, SINR and TBS. Then the resources of all component carriers (CCs) are pooled at the MAC, and scheduling is across the pooled resources. However, in practice each UE may

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be assigned resources from a particular CC. Since NetSim doesn't model frequency selective channel fading, there is generally negligible difference in network performance between allotting from a pool vs. allotting from one CC. The exception is when the data demand from any UE is greater than the capacity of a CC.

NetSim v13.3 GUI by default has options for single band and 2-band carrier aggregation. Loading all CA options – single band, 2 component carriers (CCs) and more than 2 CCs – requires the following change to be carried out.

- Go to <NetSim-Install-directory>/docs/xml (for example C:\Program Files\NetSim\Pro_v13_3\Docs\xml). Here you will find two folders (i) Properties, and (ii) Properties_5G_All_Carriers. NetSim GUI by default reads from the *Properties* folder which has only single band and 2CC CA.
- Rename the *Properties* folder as say *Properties_1CC_2CC* and then rename *Properties_5G_All_Carriers* as *Properties.* Once this is done NetSim GUI will read the new properties folder which support all CA options as explained in the section below.
- The reason for having a separate folder with single band and 2 CC is because loading all CA folder takes a long time in NetSim GUI.

3.9.20 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 than716 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 CC Configuration Table					
CC Configuration	**CC Count**	**CC Type**	**Frequency Range**	**Uplink Low (MHz)**	**Uplink High (MHz)**
INTER_BAND_CC					
CC_2DL_1UL_n39_n41	2	CC1, CC2	FR1	1880, 2496	1920, 2690
CC_2DL_2UL_n39_n41	2	CC1, CC2	FR1	1880, 2496	1920, 2690
CC_2DL_1UL_n41_n79	2	CC1, CC2	FR1	2496, 4400	2690, 5000
CC_2DL_2UL_n41_n79	2	CC1, CC2	FR1	2496, 4400	2690, 5000
CC_2DL_1UL_n40_n41	2	CC1, CC2	FR1	2300, 2496	2400, 2690
CC_2DL_2UL_n40_n41	2	CC1, CC2	FR1	2300, 2496	2400, 2690
CC_2DL_1UL_n50_n78	2	CC1, CC2	FR1	1432, 3300	1517, 3800
CC_2DL_2UL_n50_n78	2	CC1, CC2	FR1	1432, 3300	1517, 3800

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CC_2DL_1UL_n41_n50	2	CC1, CC2	FR1	2496, 1432	2690, 1517
CC_2DL_2UL_n41_n50	2	CC1, CC2	FR1	2496, 1432	2690, 1517
CC_2DL_1UL_n39_n79	2	CC1, CC2	FR1	1880, 4400	1920, 5000
CC_2DL_2UL_n39_n79	2	CC1, CC2	FR1	1880, 4400	1920, 5000
CC_2DL_1UL_n40_n78	2	CC1, CC2	FR1	2300, 3300	2400, 3800
CC_2DL_2UL_n40_n78	2	CC1, CC2	FR1	2300, 3300	2400, 3800
CC_2DL_1UL_n40_n79	2	CC1, CC2	FR1	2300, 4400	2400, 5000
CC_2DL_2UL_n40_n79	2	CC1, CC2	FR1	2300, 4400	2400, 5000
CC_2DL_1UL_n77_n258	2	CC1, CC2	FR1, FR2	3300, 24250	4200, 27500
CC_2DL_2UL_n77_n258	2	CC1, CC2	FR1, FR2	3300, 24250	4200, 27500
CC_2DL_1UL_n78_n258	2	CC1, CC2	FR1, FR2	3300, 24250	3800, 27500
CC_2DL_2UL_n78_n258	2	CC1, CC2	FR1, FR2	3300, 24250	3800, 27500
CC_2DL_1UL_n79_n258	2	CC1, CC2	FR1, FR2	4400, 24250	5000, 27500
CC_2DL_2UL_n79_n258	2	CC1, CC2	FR1, FR2	4400, 24250	5000, 27500
CC_2DL_1UL_n78_n257	2	CC1, CC2	FR1, FR2	3300, 26500	3800, 29500
CC_2DL_2UL_n78_n257	2	CC1, CC2	FR1, FR2	3300, 26500	3800, 29500
CC_2DL_1UL_n41_n260	2	CC1, CC2	FR1, FR2	2496, 37000	2690, 40000
CC_2DL_2UL_n41_n260	2	CC1, CC2	FR1, FR2	2496, 37000	2690, 40000
INTRA_BAND_CONTIGUOUS_CC					
CC_2DL_n41C_1UL_n41A	2	CC1, CC2	FR1	2496, 2496	2690, 2690
CC_2DL_n257G_2UL_n257G	2	CC1, CC2	FR2	26500, 26500	29500, 29500
CC_3DL_n257H_3UL_n257G	3	CC1, CC2, CC3	FR2	26500, 26500, 26500	29500, 29500, 29500
CC_3DL_n257H_3UL_n257H	3	CC1, CC2, CC3	FR2	26500, 26500, 26500	29500, 29500, 29500
CC_4DL_n257I_4UL_n257G	4	CC1, CC2, CC3, CC4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CC_4DL_n257I_4UL_n257H	4	CC1, CC2, CC3, CC4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500
CC_4DL_n257I_4UL_n257I	4	CC1, CC2, CC3, CC4	FR2	26500, 26500, 26500, 26500	29500, 29500, 29500, 29500

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CC_5DL_n257J_5UL_n257G	5	CC1, CC2, CC3, CC4, CC5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CC_5DL_n257J_5UL_n257H	5	CC1, CC2, CC3, CC4, CC5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CC_5DL_n257J_5UL_n257I	5	CC1, CC2, CC3, CC4, CC5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CC_5DL_n257J_5UL_n257J	5	CC1, CC2, CC3, CC4, CC5	FR2	26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500
CC_6DL_n257K_6UL_n257G	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CC_6DL_n257K_6UL_n257H	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CC_6DL_n257K_6UL_n257I	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CC_6DL_n257K_6UL_n257J	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CC_6DL_n257K_6UL_n257K	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257G	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257H	7	CC1, CC2, CC3, CC4,	FR2	26500, 26500, 26500, 26500,	29500, 29500, 29500,

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		CC5, CC6, CC7		26500, 26500, 26500	29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257I	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257J	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257K	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_7DL_n257L_7UL_n257L	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257G	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257H	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257I	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257J	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500,

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					29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257K	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257L	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_8DL_n257M_8UL_n257M	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	26500, 26500, 26500, 26500, 26500, 26500, 26500, 26500	29500, 29500, 29500, 29500, 29500, 29500, 29500, 29500
CC_n258B	2	CC1, CC2	FR2	24250, 24250	27500, 27500
CC_n258C	3	CC1, CC2, CC3	FR2	24250, 24250, 24250	27500, 27500, 27500
CC_n258D	2	CC1, CC2	FR2	24250, 24250	27500, 27500
CC_n258E	3	CC1, CC2, CC3	FR2	24250, 24250, 24250	27500, 27500, 27500
CC_n258F	4	CC1, CC2, CC3, CC4	FR2	24250, 24250, 24250, 24250	27500, 27500, 27500, 27500
CC_n258G	2	CC1, CC2	FR2	24250, 24250	27500, 27500
CC_n258H	3	CC1, CC2, CC3	FR2	24250, 24250, 24250	27500, 27500, 27500
CC_n258I	4	CC1, CC2, CC3, CC4	FR2	24250, 24250, 24250, 24250	27500, 27500, 27500, 27500
CC_n258J	5	CC1, CC2, CC3, CC4, CC5	FR2	24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500
CC_n258K	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500,

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					27500, 27500
CC_n258L	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	24250, 24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500, 27500, 27500
CC_n258M	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	24250, 24250, 24250, 24250, 24250, 24250, 24250, 24250	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500
INTRA_BAND_NONCONTIGUOUS_CC					
CC_2DL_n41(2A)_1UL_n41A	2	CC1, CC2	FR1	2496, 2496	2690, 2690
CC_n260(5A)	5	CC1, CC2, CC3, CC4, CC5	FR2	37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000
CC_n260(6A)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CC_n260(7A)	7	CC1, CC2, CC3, CC4, CC5, CC6, CC7	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000
CC_n260(8A)	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CC_n260(2D)	4	CC1, CC2, CC3, CC4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000
CC_n260(2G)	4	CC1, CC2, CC3, CC4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000
CC_n260(3G)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000,

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					40000, 40000
CC_n260(4G)	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CC_n260(2H)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CC_n260(2O)	4	CC1, CC2, CC3, CC4	FR2	37000, 37000, 37000, 37000	40000, 40000, 40000, 40000
CC_n260(3O)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CC_n260(4O)	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000
CC_n260(2P)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000
CC_n260(4P)	12	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8, CC9, CC10, CC11, CC12	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
CC_n260(2Q)	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	37000, 37000, 37000, 37000, 37000, 37000, 37000, 37000	40000, 40000, 40000, 40000, 40000, 40000, 40000, 40000

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CC_n261(2H)	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CC_n261(2I)	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CC_n261(2D)_n261A	4	CC1, CC2, CC3, CC4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CC_n261(2G)_n261A	4	CC1, CC2, CC3, CC4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CC_n261(3G)_n261A	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CC_n261(4G)_n261A	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CC_n261(2O)_n261A	4	CC1, CC2, CC3, CC4	FR2	27500, 27500, 27500, 27500	28350, 28350, 28350, 28350
CC_n261(4O)_n261A	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
CC_n261(7O)_n261A	14	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8, CC9, CC10, CC11, CC12, CC13, CC14	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350,

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					28350, 28350
CC_n261(2P)_n261A	6	CC1, CC2, CC3, CC4, CC5, CC6	FR2	27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350
CC_n261(2Q)_n261A	8	CC1, CC2, CC3, CC4, CC5, CC6, CC7, CC8	FR2	27500, 27500, 27500, 27500, 27500, 27500, 27500, 27500	28350, 28350, 28350, 28350, 28350, 28350, 28350, 28350
SINGLE_BAND					
n34	1	CC1	FR1	2010	2025
n38	1	CC1	FR1	2570	2620
n39	1	CC1	FR1	1880	1920
n40	1	CC1	FR1	2300	2400
n41	1	CC1	FR1	2496	2690
n50	1	CC1	FR1	1432	1517
n51	1	CC1	FR1	1427	1432
n77	1	CC1	FR1	3300	4200
n78	1	CC1	FR1	3300	3800
n79	1	CC1	FR1	4400	5000
n257	1	CC1	FR2	26500	29500
n258	1	CC1	FR2	24250	27500
n259	1	CC1	FR2	39500	43500
n260	1	CC1	FR2	37000	40000
n261	1	CC1	FR2	27500	28350
n262	1	CC1	FR2	47200	48200
n263	1	CC1	FR2	57000	71000

FDD Bands					
CC Configuration	**CC Count**	**CC Type**	**Frequency Range**	**F_Low (MHz)**	**F_High (MHz)**
INTER_BAND_CC					
CC_n1A_n8A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1920 880 2110 925	1980 915 2170 960
CC_n1A_n28A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1920 703 2110 758	1980 748 2170 803
CC_n3A_n8A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 880 1805 925	1785 915 1880 960
CC_n3A_n28A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 703 1805 758	1785 748 1880 803

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CC_n7A_n28A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	2500 703 2620 758	2570 748 2690 803
CC_n7A_n66A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	2500 1710 2620 2110	2570 1780 2690 2200
CC_n20A_n28A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	832 703 791 758	862 748 821 803
CC_n25A_n71A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1850 663 1930 617	1915 698 1995 652
CC_n66A_n70A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1695 2110 1995	1780 1710 2200 2020
CC_n66B_n70A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1695 2110 1995	1780 1710 2200 2020
CC_n66(2A)_n70A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1695 2110 1995	1780 1710 2200 2020
CC_n66A_n71A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 663 2110 617	1780 698 2200 652
CC_n66B_n71A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 663 2110 617	1780 698 2200 652
CC_n66(2A)_n71A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 663 2110 617	1780 698 2200 652
CC_n70A_n71A	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1695 663 1995 617	1710 698 2020 652
CC_n66A_n70A_n71A	3	CC1_UL CC2_UL CC3_UL CC1_DL CC2_DL CC3_DL	FR1	1710 1695 663 2110 1995 617	1780 1710 698 2200 2020 652
CC_n66B_n70A_n71A	3	CC1_UL CC2_UL CC3_UL CC1_DL CC2_DL CC3_DL	FR1	1710 1695 663 2110 1995 617	1780 1710 698 2200 2020 652
CC_n66(2A)_n70A_n71A	3	CC1_UL CC2_UL CC3_UL CC1_DL	FR1	1710 1695 663 2110	1780 1710 698 2200

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		CC2_DL CC3_DL		1995 617	2020 652
INTRA_BAND_CONTIGUOUS_CC					
CC_n1B	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1920 1920 2110 2110	1980 1980 2170 2170
CC_n7B	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	2500 2500 2620 2620	2570 2570 2690 2690
CC_n66B	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1710 2110 2110	1780 1780 2200 2200
CC_n71B	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	663 663 617 671	698 698 652 652
INTRA_BAND_NONCONTIGUOUS_CC					
CC_n3(2A)	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1710 1805 1805	1782 1785 1880 1880
CC_n7(2A)	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	2500 2500 2620 2620	2570 2570 2690 2690
CC_n25(2A)	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1850 1850 1930 1930	1915 1915 1995 1995
CC_n66(2A)	2	CC1_UL CC2_UL CC1_DL CC2_DL	FR1	1710 1710 2110 2110	1780 1780 2200 2200
SINGLE_BAND					
n1	1	CC1	FR1	1920	1980
n2	1	CC1	FR1	1850	1910
n3	1	CC1	FR1	1710	1785
n5	1	CC1	FR1	824	859
n7	1	CC1	FR1	2500	2570
n8	1	CC1	FR1	880	915
n12	1	CC1	FR1	699	716
n20	1	CC1	FR1	832	862
n25	1	CC1	FR1	1850	1915
n28	1	CC1	FR1	703	748
n66	1	CC1	FR1	1710	1780
n70	1	CC1	FR1	1695	1710
n71	1	CC1	FR1	663	698
n74	1	CC1	FR1	1427	1470

Table 3-26: CA Configuration Table

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3.9.21 PHY: Omitted Features

The currently omitted features include:

- 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.
- Random access procedure
- Power control

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.

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

Where,

- 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., $T_s^{\mu} = \frac{10^{-3}}{14.2^{\mu}}$.
- Note that normal cyclic prefix is assumed, which has 14 ODFM symbols per slot or $14 \times 2^{\mu}$ symbols per millisecond.

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- $N_{PRB}^{BW(j),\mu}$ 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.

$$data\ rate(in\ Mbps) = 10^{-3}\sum_{j=1}^{J} TBS_j$$

Where,

- 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.

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3.11 Propagation Models (Per 3GPPTR38.900)

3.11.1 Overview

The pathloss and channel between a UE and a BS depends on:

- **Location**: The pathloss depends on the UE's location (UE-gNB distance) and is calculated separately for each connected UE. The pathloss computations are recomputed every time a UE moves.
- **Scenario**: Rural Macro (RMa), Urban Macro (UMa), Urban Micro (Umi). This parameter is available as Outdoor Scenario in gNB properties > Interface (5G_RAN) > Physical Layer > Channel Model. Each scenario has a different pathloss model defined in the standard. This property is common for the gNB and all connected UEs.
- **Whether the UE-gNB is Line-of-sight or Non-line-of-sight (LOS/NLOS):** This parameter is available as LOS probability in gNB properties > Interface (5G_RAN) > Physical Layer > Channel Model. The pathloss models defined in the standard differ for LOS and NLOS. This property is common for the gNB and all connected UEs. However, a different (uniform) random number is sampled for each associated UE so that different UEs will see different LOS/NLOS channels. For each UE, the LOS/NLOS random variable is sampled every time a UE moves, and hence a UE may switch from LOS to NLOS if it moves.
- **Shadow fading:** This parameter is available as Shadow fading model in gNB properties > Interface (5G_RAN) > Physical Layer > Channel Model. This property is common for the gNB and all connected UEs. In this case, a different log-normal random variable is sampled for each associated UE. For each UE, the shadow fading random variable is sampled every time a UE moves.
- **Fading and beamforming:** Fast fading is enabled by turning on the parameter Fading and Beamforming in gNB properties > Interface (5G_RAN) > Physical Layer > Channel Model. Please see sections 3.9.2 and 3.9.3 for a detailed explanation. In essence, the eigen value of an $(N_r \times N_t)$ random matrix is the fast-fading gain. Since the random matrix would be different for each gNB-UE pair the gains would be different. The fast-fading gains are recomputed every (user settable) coherence time whose default value is 10ms. The coherence time is common to all UEs attached to a gNB.

NetSim also features Indoor and Outdoor pathloss (PL) models.

- NetSim GUI (gNB properties > Interface (5G_RAN) > Physical Layer > Channel Model) allows users to configure both indoor and outdoor PL models. Both indoor and outdoor options are shown in the GUI irrespective of the underlying scenario.

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- Based on gNBs/UEs placement within or outside a building NetSim automatically chooses the indoor/outdoor propagation models. The selection is as follows:
  - Outdoor gNB to Outdoor UE: Outdoor PL model
  - Outdoor gNB to Indoor UE: Outdoor PL till building, then penetration (O2I) loss, and finally indoor PL within the building
  - Indoor gNB to Indoor UE: Indoor PL model
  - An Indoor gNB cannot be connected to an Outdoor UE in NetSim

3.11.2 Pathloss formulas

The pathloss models are summarized in Figure 3-18 and the distance definitions are indicated in Figure 3-18 and Figure 3-19. Note that the distribution of the shadow fading is log-normal, and its standard deviation for each scenario is given in Figure 3-18.

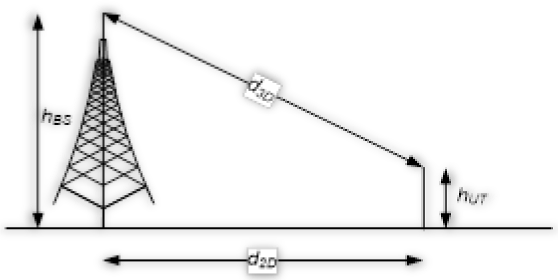

Figure 3-18: Definition of d_{2d} and d_{3d} from Standards Figure 7.4.1-1

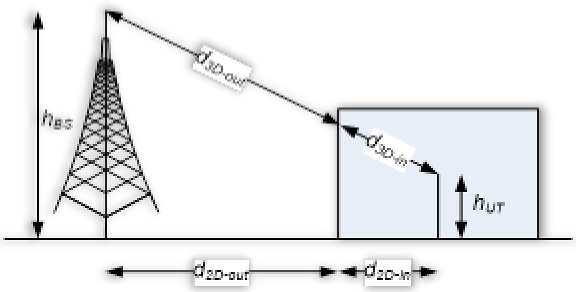

Figure 3-19: Definition of $d_{2d-out}, d_{2d-in}, and\ d_{2d-out}$ and d_{3d-out}, d_{3d-out} for indoor UTs from Standards figure 7.4.1-2

Note that,

$$d_{3D-out} + d_{3D-in} = \sqrt{(d_{2D-out} + d_{2D-in})^2 + (h_{BS} - h_{UT})^2} \qquad (7.4.1\text{-}2)$$

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

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		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 $PL'_{InH-NLOS} = 32.4 + 20\,log_{10}(f_c) + 31.9\,log_{10}(d_{3D})$	$\sigma_{SF} = 8.29$	$1m \le d_{3D} \le 150m$

Table 3-27: Pathloss model from Standards Table 7.4.1-1.

Note 1: Breakpoint distance $d'_{BP} = \frac{4 \times h'_{BS} \times h'_{UT} \times f_c}{c}$, where f_c is the centre frequency in Hz, $c = 3 \times 10^8 m/s$ 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 $\frac{1}{1+C(d_{2D}, h_{UT})}$ and chosen from a discrete uniform distribution uniform $(12, 15, \ldots, (h_{UT} - 1.5))$ otherwise. With $C(d_{2D}, h_{UT})$ given by

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

Where,

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

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

$$\mathrm{PL}_{UMa-LOS} = Pathloss\ of\ UMa\ LOS\ outdoor\ scenario.$$

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

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Note 5: Break point distance $d_{BP} = \frac{2\pi \times h_{BS} \times h_{UT} \times f_c}{c}$, where f_c is the centre frequency in Hz, $c = 3 \times 10^8 m/s$ 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.

NetSim enforces the following

- RMa, UMa, UMI: If $d_{2D} < 10m$ then $d_{2D} = 10m$
- InH: If $d_{2D} < 1m$ then $d_{2D} = 1m$

3.11.3 LOS probability

The Line-Of-Sight (LOS) probabilities are given in Table 3-28**.**

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	

Table 3-28: LOS probability from Standards Table 7.4.2-1

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3.11.4 O2I penetration loss

3.11.4.1 O2I building penetration loss

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

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

where PL_b is the basic outdoor path loss given in Subclause 7.4.1, where d_{3D} is replaced by $d_{\mathrm{3D-out}} + d_{\mathrm{3D-in}}$. 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:

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

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 3-29, 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	

Table 3-29: Material penetration losses from Standards Table 7.4.3-1

Table 3-30 gives PL_{tw}, PL_{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: $\mathrm{PL_{tw}}$ in [dB]	Indoor loss: $\mathrm{PL_{in}}$ 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

Table 3-30: O2I building penetration loss model From Standards Table 7.4.3-2

$d_{\mathrm{2D-in}}$ 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.

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

Only the low-loss model is applicable to RMa.

3.11.4.2 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 in Figure 3-21.

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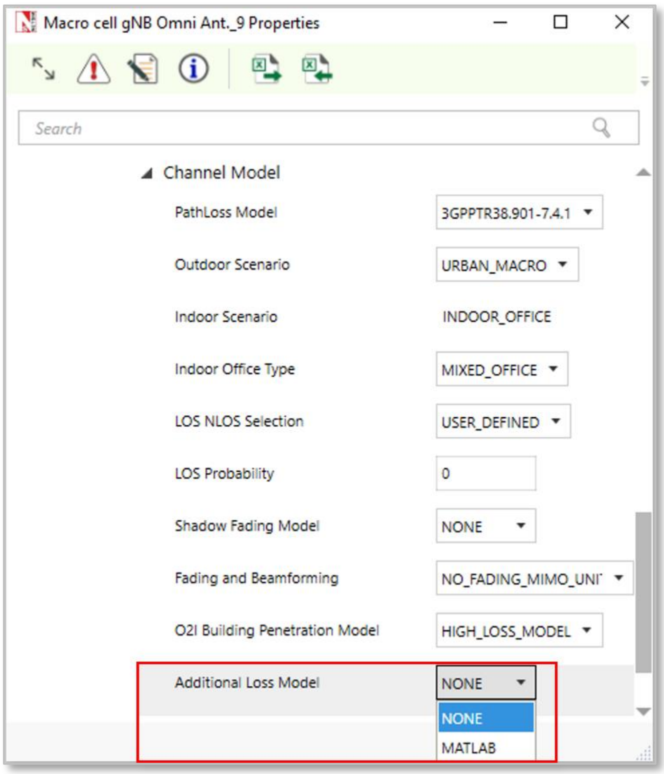

Figure 3-20: gNB >Interface (5G_RAN) >Physical layer properties

Similarly, this can be configured in the eNB's LTE interface properties under channel models section of Physical Layer as shown in Figure 3-21.

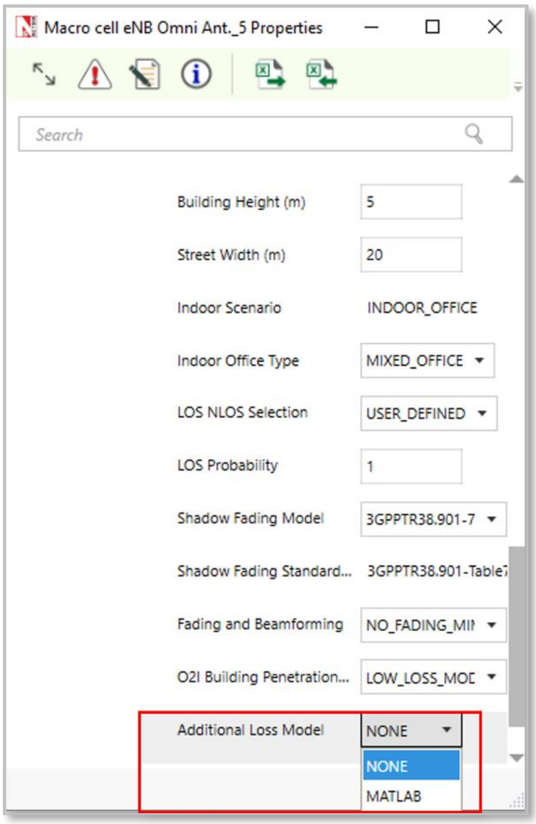

Figure 3-21: eNB >Interface (LTE) >Physical layer properties

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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 in Figure 3-22.

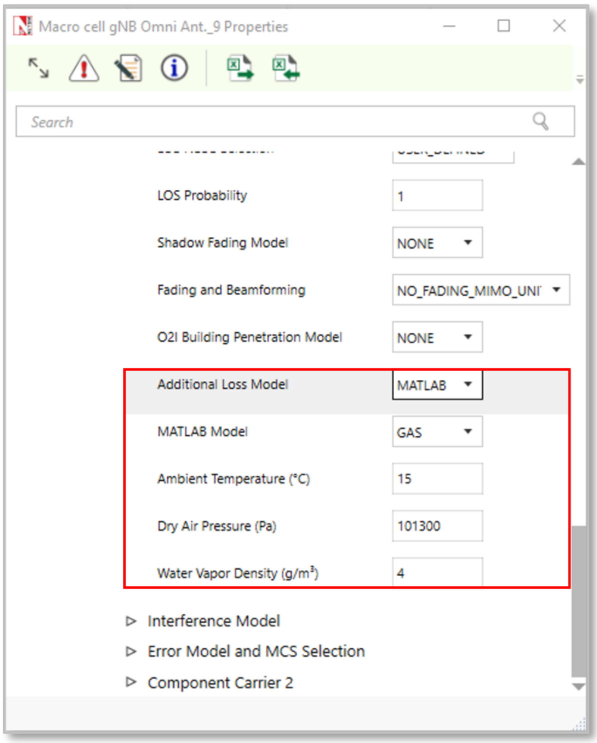

Figure 3-22: Additional Loss Model set to MATLAB in gNB >Interface (5G_RAN) >Physical layer properties

Each model has associated parameters that can be configured, which is listed in Table 3-31.

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 3-31: 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.

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3.12.2 Running Simulation

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

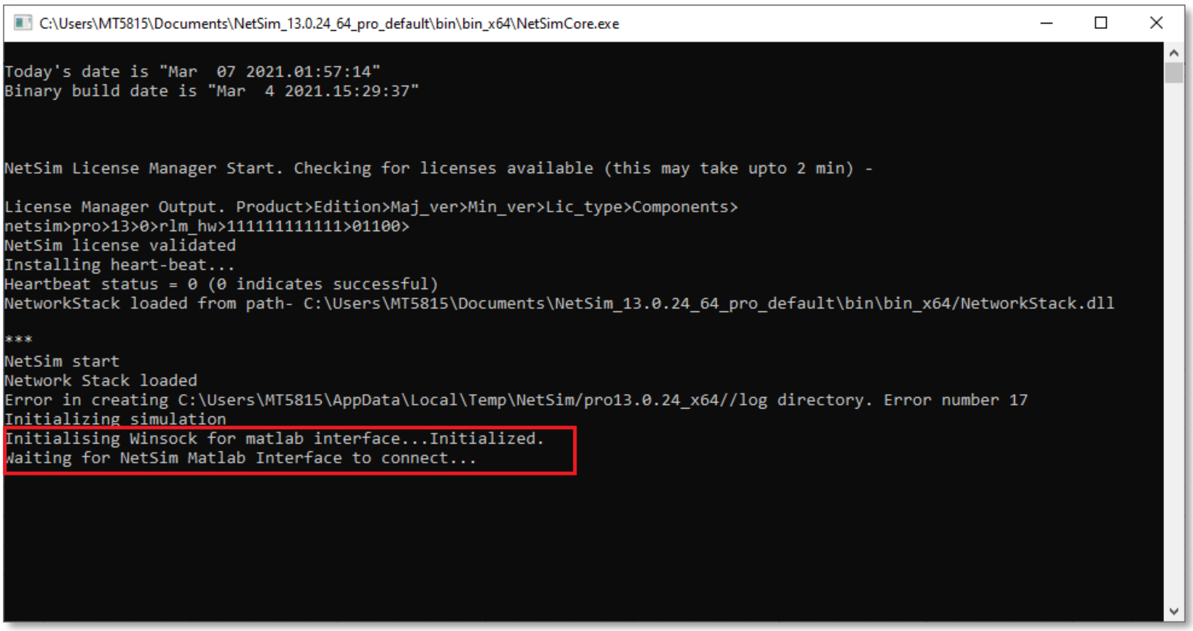

Figure 3-23: NetSim Simulation console waits for MATLAB Interface process to connect

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:

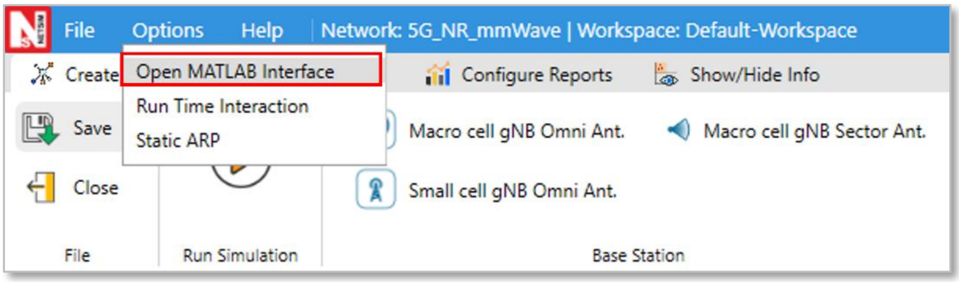

Figure 3-24: Open MATLAB Window Options

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

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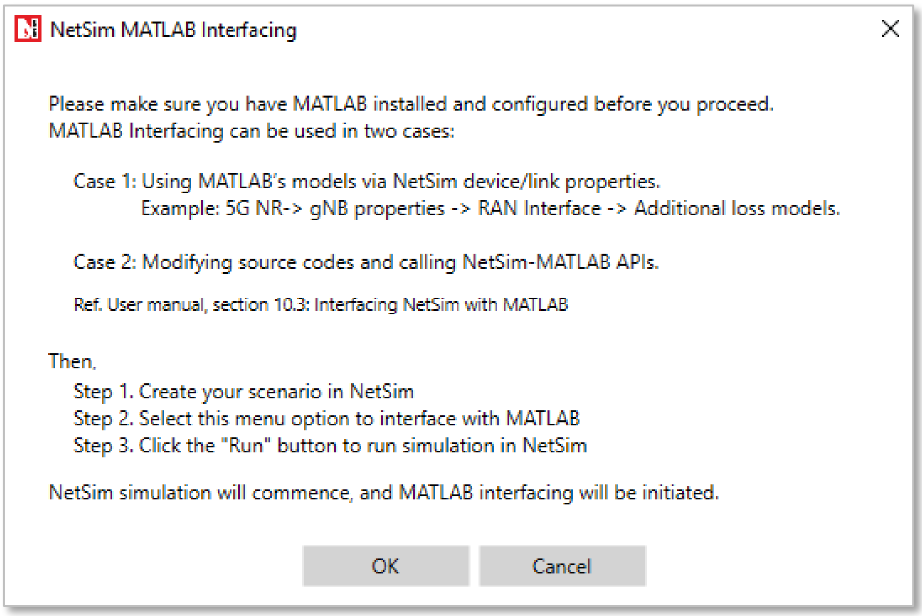

Figure 3-25: MATLAB Interface warning message

- 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:

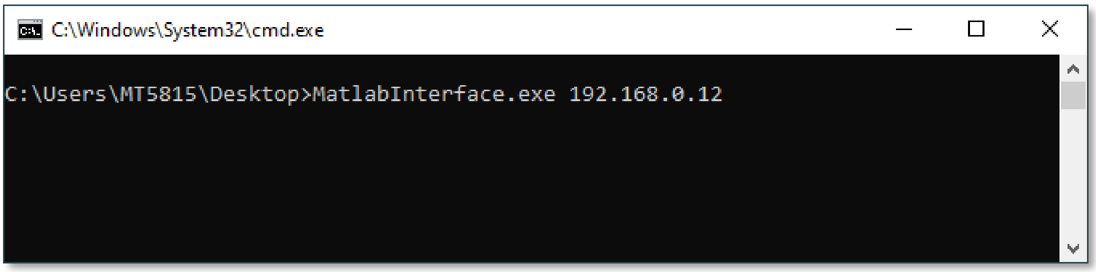

Figure 3-26: MATLAB interface over an IP address

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:

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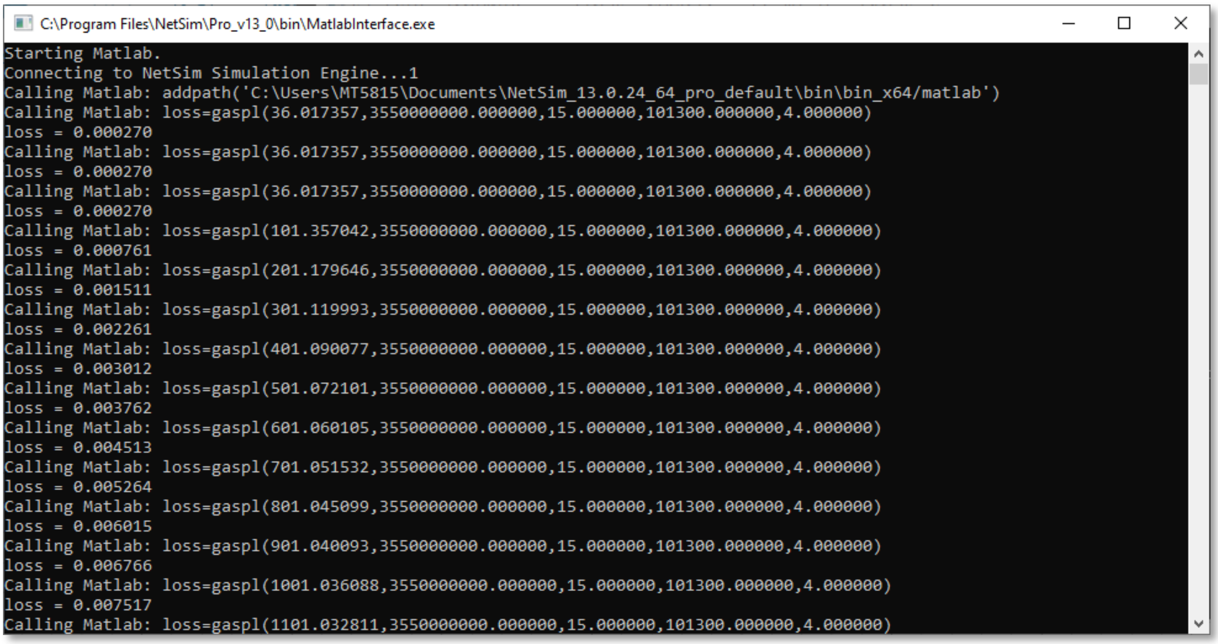

Figure 3-27: Runtime MATLAB interfacing window

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 Downlink Interference Model (Part of Adv. 5G)

3.13.1 Configuration

Downlink Interference Model can be configured in the gNB's 5G_RAN interface properties under channel models section of Physical Layer as shown Figure 3-28.

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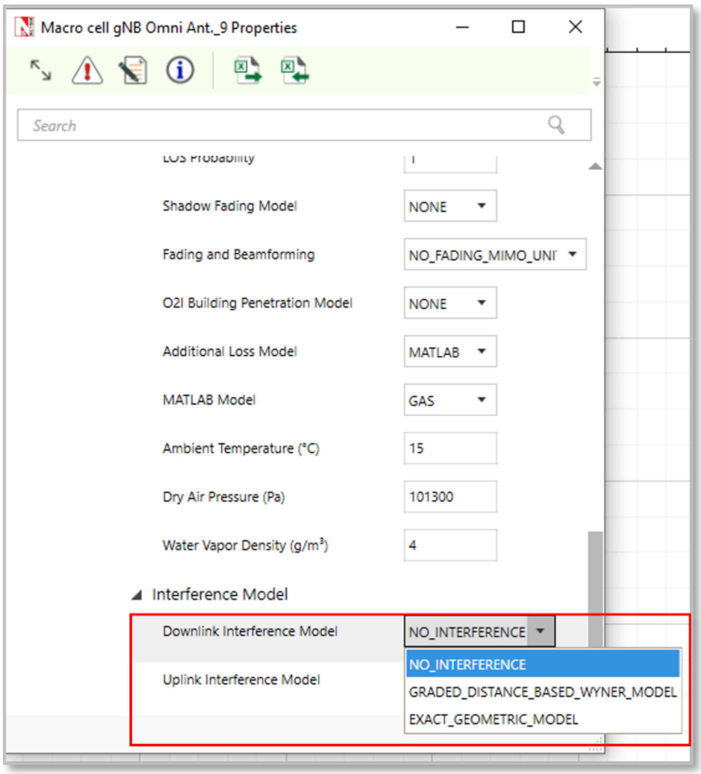

Figure 3-28: gNB >Interface (LTE) >Physical layer properties

Downlink Interference Model is set to NO_INTERFERENCE by default.

3.13.2 Graded distance-based Wyner model

The Wyner model is widely used to due to its simplicity and analytical tractability. In this model:

- Only interference from (two) adjacent cells is considered
- Random user locations and path loss variations are ignored, and
- The interference intensity from each neighbouring base station (BS) is characterized by a single fixed parameter ($0 \leq \alpha \leq 1$). The channel gain between BS and its home user is 1 and the intercell interference intensity is α. Thus, a user sees constant interference irrespective of its location.

These three simplifications lose a lot of information. We alter the Wyner model to address these flaws by:

- Considering interference from arbitrary number of BSs
- Factoring in the user location. The UEs distance from the interfering BS is an obvious factor that determines the interference intensity since the amount of interference caused depends on the signal attenuation with distance, the path loss law. Since the Wyner model uses relative interference, the ratio of a UEs distance from serving and interfering BSs is used as one of the interference parameters.

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- Using a graded interference intensity model, whereby a UE will see a different value of α at different locations, thereby modelling the effect of interference more accurately.

3.13.2.1 Technical description

- We model DL interference from any number of interfering BSs. Let BS_i be the serving BS to UE_k. Let BS_j be any other BS ($j \neq i$). Then the distance between UE_k and BS_i is denoted as $D_{UE_k}^{BS_i}$, while the distance between UE and BS_j is denoted as $D_{UE_k}^{BS_j}$.
- A UE sees interference if $\frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}}$ is within a user defined threshold (for example, 20%). This ratio is also equal to $1 - \frac{D_{UE_k}^{BS_i}}{D_{UE_K}^{BS_j}}$. When $D_{UE_K}^{BS_i} \leq D_{UE_K}^{BS_j}$, we see that $0 \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} \leq 1$. The ratio is 0 when $D_{UE_K}^{BS_i} = D_{UE_K}^{BS_j}$ and is 1 when $D_{UE_K}^{BS_i} = 0$. When $D_{UE_K}^{BS_i} = D_{UE_K}^{BS_j}$ the UE is equidistant from both BS i.e., at the cell edge. When $D_{UE_K}^{BS_i} = 0$, the UE is at the centre of the serving BS, BS_i.
- Users at the cell-edge will see out of cell interference; as the user moves closer to the cell centre, it sees lesser interference.
- We call this user defined threshold as differential distance ratio threshold and denote it by DDR_{th}. The DDR threshold is used to define K thresholds, which are in turn used to determine the out of cell interference experienced by UE_k, as explained below. First, we bin the DDR_{th}, conditional on $D_{UE_K}^{BS_i} \leq D_{UE_K}^{BS_j}$, into K steps, as follows:

$$0 \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times 1$$

$$\left(\frac{DDR_{th}}{K}\right) \times 1 \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times 2$$

...

...

$$\left(\frac{DDR_{th}}{K}\right) \times (K-1) \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times K$$

$$\left(\frac{DDR_{th}}{K}\right) \times K \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}}$$

- Where DDR_{th}, is a user input varying from 0.00 to 1.00 (default is 0.1 or 10%), and K, the number of steps, is a user input varying from 1 to 4 (default is 1). For example: if the given

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value for the DDR is 0.2 and nSteps is 4, then the range of the curves will be from 0 to $\frac{0.2}{4} = 0.05$, i.e 0 to 0.05, 0.05 to 0.10, 0.10 to 0.15, 0.15 to 0.2.

- The relative interference for each of these steps would be I_n $(0 \leq n \leq K)$ where K is the number of steps and n represents each individual step ($n = p$ if the p^{th} inequality in the above is satisfied, counting the first inequality as the zeroth inequality).
- We specify the interference power relative to the power received from BS_i. Therefore, given the value of I_n, interference power is calculated as the received power from BS_i (excluding beamforming gain) less I_n. Thus

$$InterferencePowerfromBS_j\ (dB) = ReceivedPowerfromBS_i(dBm) - I_n^j(dB)$$

- Therefore, we have $I_n^i(dB) = P_{serving}^{BS}(dBm) - P_{Interfering}^{BS}(dBm)$. This is equivalent to the Wyner model with $\alpha = \frac{P_{Interfering}^{BS}}{P_{serving}^{BS}}$ in the linear scale; however, note that in our interference model, α depends on the UE's location, because I_n depends on the distance.
- This interference powers (linear) from all interfering BSs are added to the noise power (in linear scale) and then

$$SINR = \frac{Received\ power\ from\ BS_i + BeamFormingGain}{NoisePower + \sum InterferencePower}$$

- Each I_n is a user input. It is subject to the limits $0 \leq I_n \leq 20\ dB$. NetSim will enforce the sanity check $20 \geq I_{K-1} \geq \ ... \geq I_0 \geq 0$. Here I_K is the relative interference seen when the UE is near BS_i and I_0 is the relative interference seen when the UE is nearly equidistant from its two nearest BSs (and hence far from BS_i).
- In an ideal case, when the user is at the cell edge, the received power from BS_i will be roughly equal to the received power from BS_j (since it is equidistant from the two BSs), and so $SINR_{CellEdge}$ will necessarily be less than 0 dB.
- As the UE moves away from the cell edge and towards BS_i, the received power from BS_i increases and that from BS_j decreases, and so the SINR improves. For this reason, we have the limits on I_n as $0\ dB \leq I_n \leq 20\ dB$. If the user sets I_n to a large value, it will be equivalent to having no inter-cell interference.

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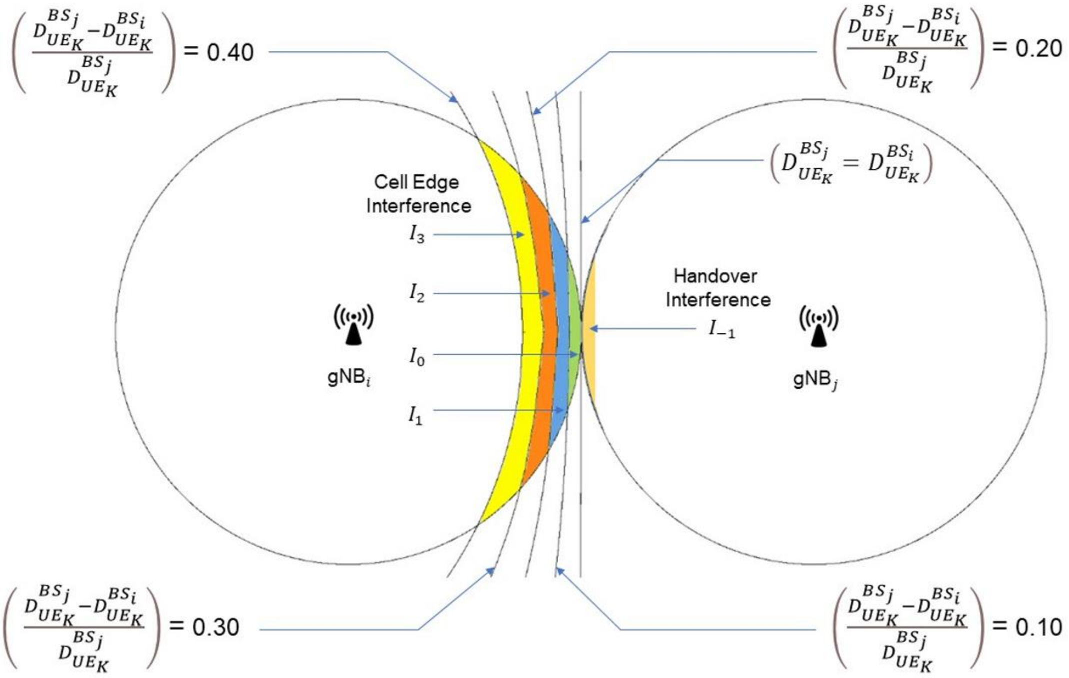

Figure 3-29: Interference zones are the regions within the four curves and the cell boundary of $\boldsymbol{gNB_i}$. This example is for a case involving just 2 BSs with $\boldsymbol{DDR = 0.4}$ and $\boldsymbol{K = 4}$. The four curves are therefore the equations where $\frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}}$ is equal to $\frac{k}{4} = \mathbf{0.1}$, $\frac{2k}{4} = \mathbf{0.2}$, $\frac{3k}{4} = \mathbf{0.3}$, and $\frac{4k}{4} = \mathbf{0.4}$. The handover interference region is also shown.

- In case $\frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} > DDR_{th}$, the out of cell interference seen at the UE is set to I_K. The default value of I_K is 0, i.e., cell centre users do not see any out of cell interference. The default values of I_k for $k = 1, 2, \ldots, K-1$ is 10 dB.
- In NetSim, handover is triggered when the signal strength from BS_j is offset (3dB by default) higher than signal strength from BS_i. A handover is not triggered when UE_k is equidistant from both BSs but only when it is slightly nearer to BS_j. Therefore, the short time when $D_{UE_K}^{BS_i} \geq D_{UE_K}^{BS_j}$ is a special case requiring a different interference power. We term this interference as “Handover interference” and is a separate user input. Handover interference is denoted as I_{-1} and $-3dB \leq I_{-1} \leq 0\ dB$.
- Sample interference file format and example:
  <gNB_i>, <gNB_j>, <DDRth>, <nSteps>,<i_-1>,<i_0>,<i_1>,<i_2> … <i_(n-1)>
  gNB_11, gNB_12, 0.2, 4, -1, 1, 2, 3, 4

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3.13.3 Exact Geometric Model

In this model NetSim computes interference from one or more interfering base-stations (BS or gNB) at a UE, based on (i) the gNB UE locations and (ii) the pathloss between the interfering gNB and the UE.

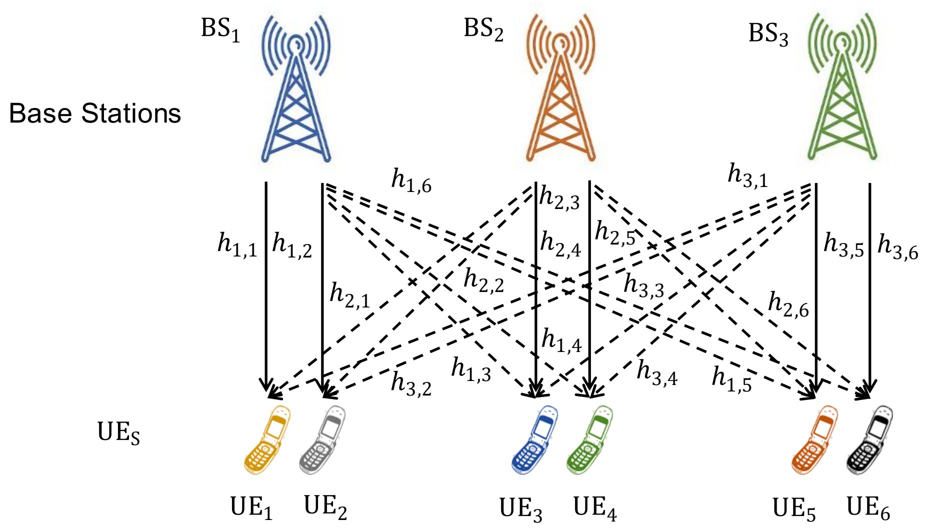

Figure 3-30: A simple scenario with 3 BSs and 6 UEs. The bold lines represent direct signal while the dashed lines represent interfering signals.

NetSim supports various 3GPP propagation models to calculate the pathloss between every BS (gNB) and every UE. One of the parameters in the pathloss equations is the distance between the BS and the UE. Some of the other user settable parameters used in the 3GPP models are (i) Centre frequency (chosen from the band selected) (ii) Rural or Urban environments (iii) UE-BS channel is in LOS or NLOS (iv) Shadow-fading in the UE-BS channel (v) Indoor or outdoor UE location, etc., Complete details of the 3GPP pathloss models supported in NetSim are given in 3.11.1.

Let BS_i be the serving BS to UE_k. Let BS_j be any other BS ($j \neq i$). UE_k communicates with BS_i while all other BSs ($j \neq i$) act as interferers. The distance between UE_k and BS_i is denoted as $D_{UE_k}^{BS_i}$, while the distance between UE and BS_j is denoted as $D_{UE_k}^{BS_j}$. The power of the interfering signal from any BS_j at any UE_k depends on (i) the transmit power of the interfering BS and (ii) pathloss between the interfering BS and the UE. It can therefore be expressed as

$$I_{UE_k}^{BS_j} = P^{BS_j} - PL_{UE_k}^{BS_j}$$

where P^{BS_j} is the transmit power of BS_j, $PL_{UE_k}^{BS_j}$ represents the 3GPP model based pathloss between BS_j and UE_k. This pathloss is dependent on $D_{UE_k}^{BS_j}$ and the channel between BS_j and UE_k. The interference powers (linear) from all interfering BSs (i.e., apart from the serving BS) are added to the noise power (in linear scale) and we get the expression

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$$SINR_{UE_k} = \frac{Received\ power\ from\ BS_i + (Eigen)BeamFormingGain}{NoisePower + \sum_j I_{UE_k}^{BS_j}}$$

SINR determines the 5G PHY rate (throughput) that the UE would get. This is because the PHY Rate depends on the CQI/MCS which is in turn depends on SINR. Section 3.2 explains the details.

The Wyner model is approximate but is computationally faster, while the geometric model is precise but computationally slower due to the calculations involved.

3.13.4 Interference modeling in OFDM in NetSim

NetSim doesn't model the allocation of specific subcarriers to individual users. The aggregate resources are divided amongst the UEs per UEs' requirements and the scheduling algorithm.

- The received power at UE_k from BS_i, with transmit power P_i is given (in the linear scale) as

$$P_{UE_k}^{BS_i} = \left(\frac{P_i}{PL_{UE_k}^{BS_i}}\right)$$

- I_{ik}^{j} or the interference in linear scale at a UE_k (associated with BS_i) from BS_j
- To normalize the power should we further multiply by the ratio given below

$$I_{ik} = \sum_j I_{ik}^{j} \times \left(\frac{RB_{UE_k}^{slot}}{RB_{total}^{slot}}\right)$$

- Assumptions:

  A1. The above formula assumes the interference seen by UE_k is proportional to the number of RBs allotted to UE_k

  A2. Fast fading is not accounted for in the interfering signal calculations since it would require too much computational time, given that it needs to be re-calculated every coherence time, not just between BS and its associated UEs but between a BS and all the UEs in all cells. Hence NetSim calculates average interfering signal power and not instantaneous interfering signal power, which is a well-accepted assumption in multi-cell MIMO literature. Recall that NetSim accounts for fast fading in the direct signal power calculations.

- The total noise seen will be

$$k \times T \times RB_{UE_k}^{slot}$$

- The signal power $P_{UE_k}^{BS_i} \times \left(\frac{RB_{UE_k}^{slot}}{RB_{total}^{slot}}\right)$

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Therefore,

$$SINR = \frac{P_{UE_k}^{BS_i} \times \left(\frac{RB_{UE_k}^{slot}}{RB_{total}^{slot}}\right)}{k \times T \times\ RB_{UE_k}^{slot} + \Sigma_j\ I_{ik}^{j} \times \left(\frac{RB_{UE_k}^{slot}}{RB_{total}^{slot}}\right)} = \frac{P_{UE_k}^{BS_i}}{k \times T \times\ RB_{total}^{slot} + \Sigma_j\ I_{ik}^{j}}$$

3.13.4.1 Interference in MIMO

- If UE_k is receiving from BS_i in multiple layers, the interference power I_{ik}^{j} is the same for all layers.

$$SINR_L = \frac{P_{UE_k}^{BS_i} \times \lambda_L}{k \times T \times\ RB_{total}^{slot} + \Sigma_j\ I_{ik}^{j}}$$

- Where L represents a MIMO layer.
- Note that neither the noise nor the interference is divided by the layer count, because the combining vector has unit norm.

3.13.4.2 Fast fading component of interfering signals

NetSim accounts for the Rx power from neighboring cells, in a statistical sense, as explained below. Let us consider an example of two BSs and two UEs with BS1 transmitting to UE1 and BS2 transmitting to UE2. The BSs employ digital (Eigen) beamforming to the UE they are transmitting to, so there is no channel-dependent beamforming between BS1 and UE2 or BS2 and UE1.

Due to this, the interference seen by UE2 due to BS1's transmission will depend on the inner product between the beamforming vector employed by BS1 (which depends only on the channel between BS1 and UE1) and the channel between BS1 and UE2 (which is independent of the channel between BS1 and UE1.)

Now, since we model the fast-fading component of the channel as having i.i.d. circularly symmetric complex Gaussian entries, the expected interference power at UE2 is simply the transmit power by BS1 times the path loss between BS1 and UE2. This because the *long-term statistical average* of the square of the magnitude inner product between the (unit-norm) beamforming vector employed by BS1 and the channel between BS1 and UE2 is unity.

3.13.4.3 Limitations

- In the above interference formula NetSim assumes that all interfering BSs transmit data in that slot.
- The interference calculations need to be done for each slot. Enabling interference will slow down the simulation.

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3.14 Uplink Interference Model (Part of Adv. 5G)

NetSim uses Interference-over-thermal (IoT), to model uplink interference. Modeling uplink interference as IoT (also called as rise over thermal noise) allows for the calculation of the interference level relative to the thermal noise level. This can provide insight into the performance of the system and the impact of uplink interference on the signal-to-noise ratio (SNR). For example, if the uplink interference level is 10 dB higher than the thermal noise level, this indicates that the interference is significantly affecting the SNR and the performance of the system.

Users can input IoT in the NetSim GUI and is available in the eNB/gNB properties. The expression for the signal to interference noise ratio is given by

$$SINR\ (dB) = SNR(dB) - IoT(dB)$$

$$IoT\ (dB) = SNR\ (dB) - SINR\ (dB)$$

Converting to linear

$$10 \times \log_{10}(IoT(linear)) = 10 \times \log_{10}\left(\frac{SNR}{SINR}\right)$$

$$IoT\ (linear) = \frac{I + N}{N}$$

Therefore, interference power in linear is

$$I = N \times (IoT\ (linear) - 1)$$

We thus get the Interference power in dBm as

$$I\ (dBm) = 10 \times \log_{10}\left(N \times \left(10^{IOT(dB)} - 1\right)\right)$$

This value of I in dBm units is logged in the Radio Measurements csv file (if turned on). An example table is provided in Table 3-32.

Bandwidth (MHz)	Noise (dBm)	IoT (dB)	Interference (dBm)
100	-93.82	3	-63.83
100	-93.82	2	-73.87
50	-96.83	2	-76.88
50	-96.83	2	-87.29
10	-103.82	1	-94.28

Table 3-32: Example table showing interference in dBm that will logged in radio measurements file for a different IoT (dB) and Bandwidth (MHz) settings

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3.15 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.

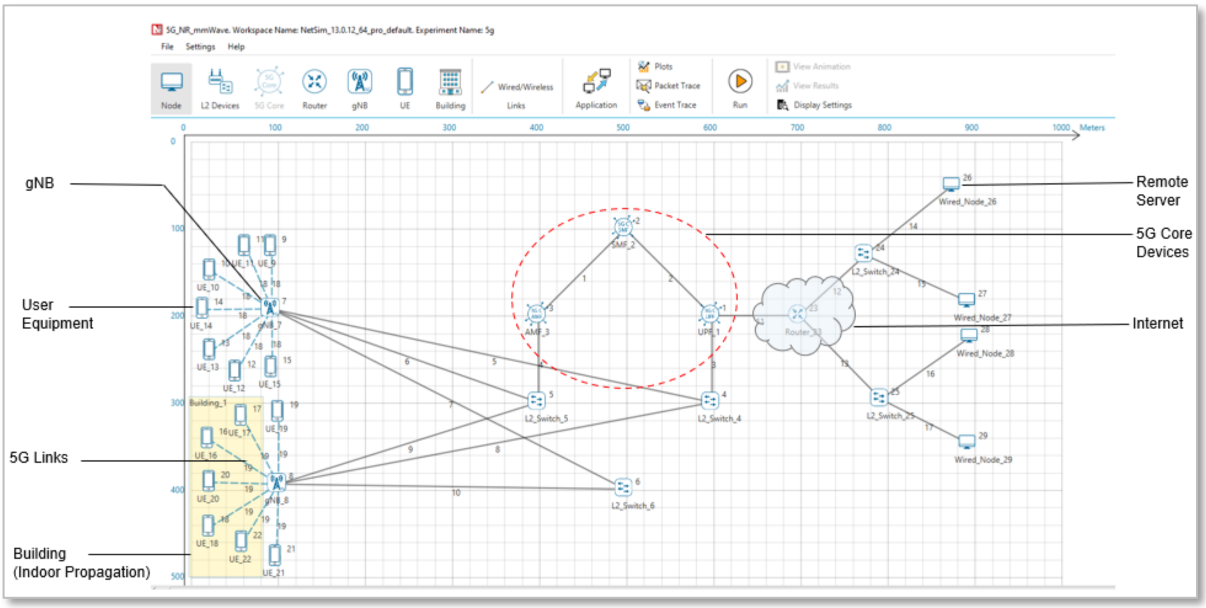

Figure 3-31: 5G Network scenario consisting of multiple UEs and gNBs connected to 5G Core - AMF, SMF and UP. The UPF is connects out to the Data Network/ Internet.

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:

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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.

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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).

3.15.1 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.

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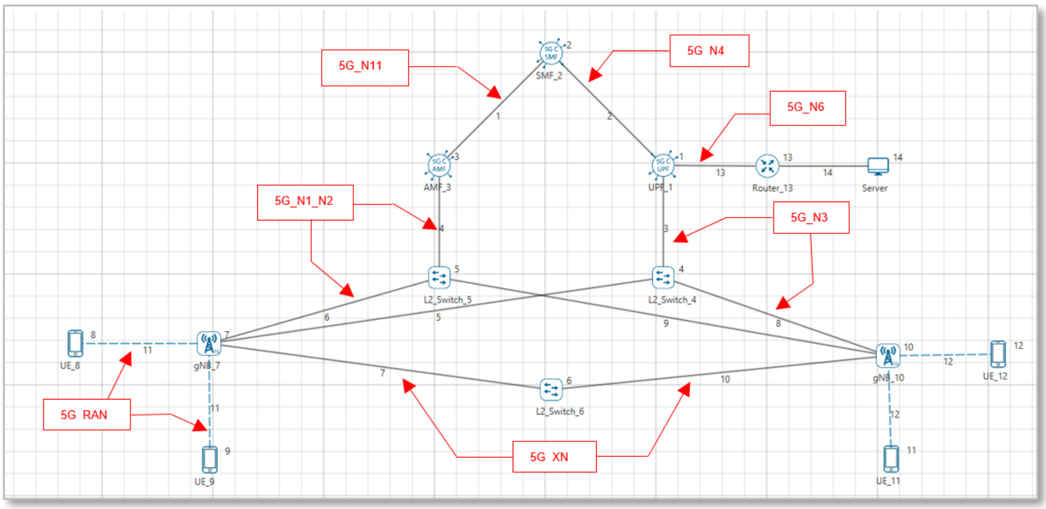

Figure 3-32: 5G Network scenario depicting the 5G Interfaces in NetSim

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 because of the reception by the AMF of a PATH SWITCH REQUEST NG-AP message.

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3.15.2 Cell Selection and UE attach procedure

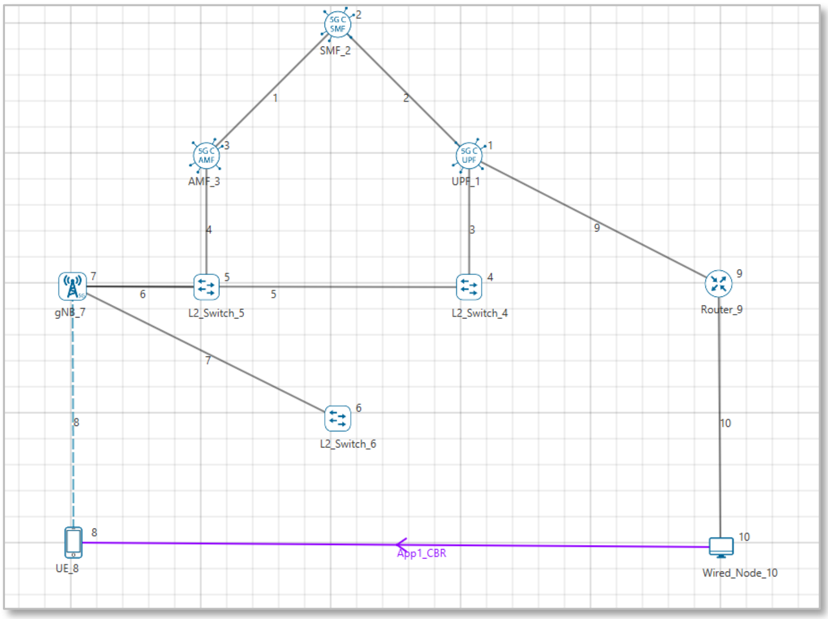

Figure 3-33: A 5G network scenario with a Single UE connected to a gNB which is connected to the 5G Core and the UE downloads data from the Server (Wired Node)

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.

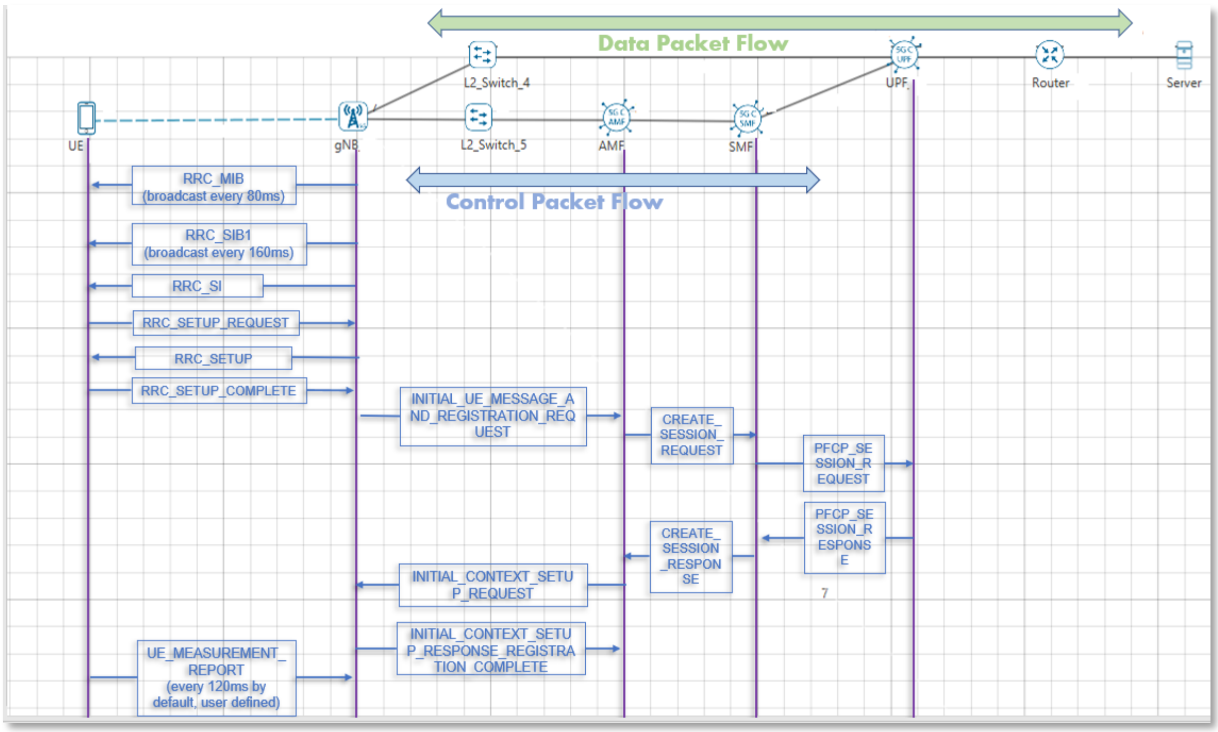

Figure 3-34: UE Attach Procedure

The attachment process is as follows:

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1. Radio Resource Control (RRC) Master Information Block (MIB) 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 SIB 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 SSB SNR.
   - If SNRs from multiple gNBs are 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 to which gNB the UE will eventually be attached.
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.

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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 3-35: RRC connection establishment in Packet Trace

3.15.3 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.

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2. The gNB will send Initial UE message and Registration request to the selected AMF (currently NetSim supports 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 3-36: 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.

3.16 5G Non-Stand Alone (NSA)

3.16.1 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

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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 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.
2. 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.

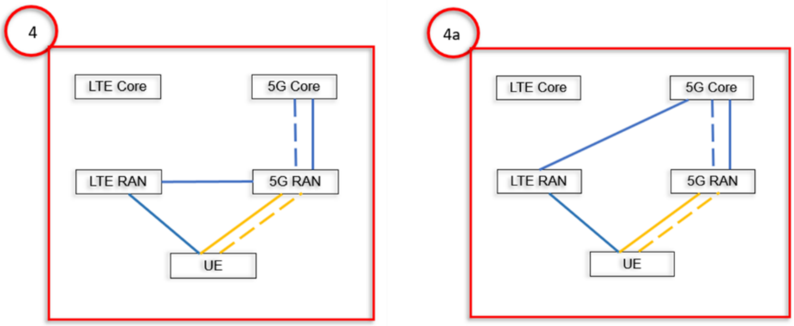

Figure 3-37: NSA deployment - Option 4, Option 4a Networking modes

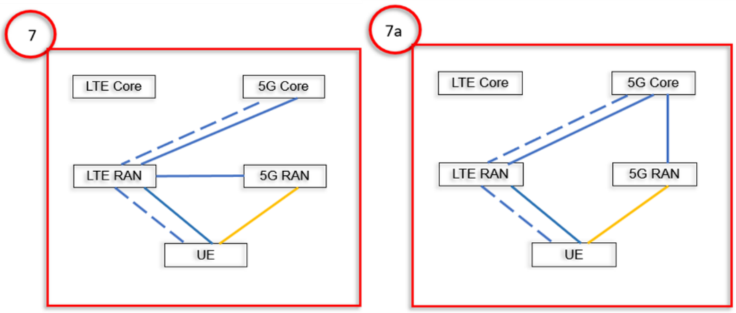

Figure 3-38: NSA deployment - Option 7, Option 7a Networking modes

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

3.16.2 Option 4/4a

Option 4 consists of a 5G Core. The master node is the LTE NR cell or gNB and the secondary node is LTE cell or eNB.

3.16.2.1 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_5 using the 5G_N3 interface and to the AMF via Switch_4 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.

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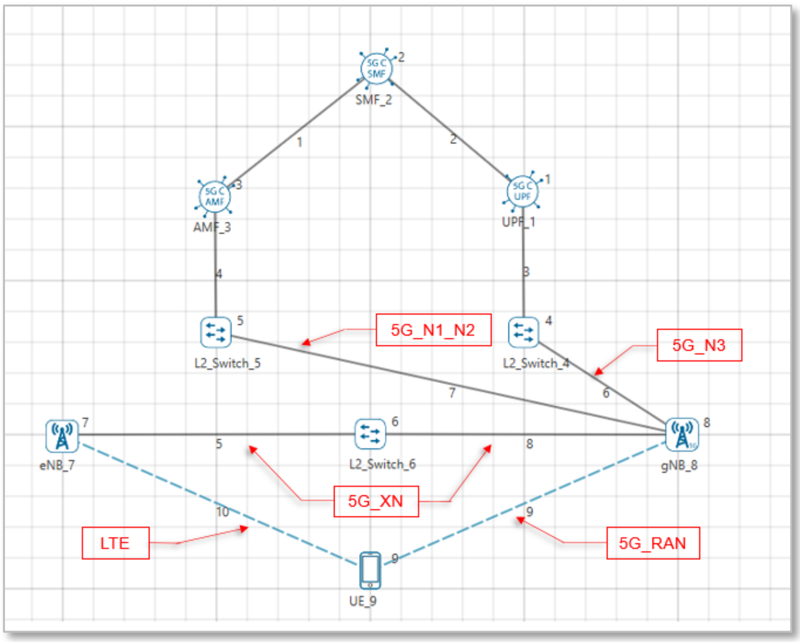

Figure 3-39: NSA deployment- Option 4 networking mode in NetSim

3.16.2.2 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.

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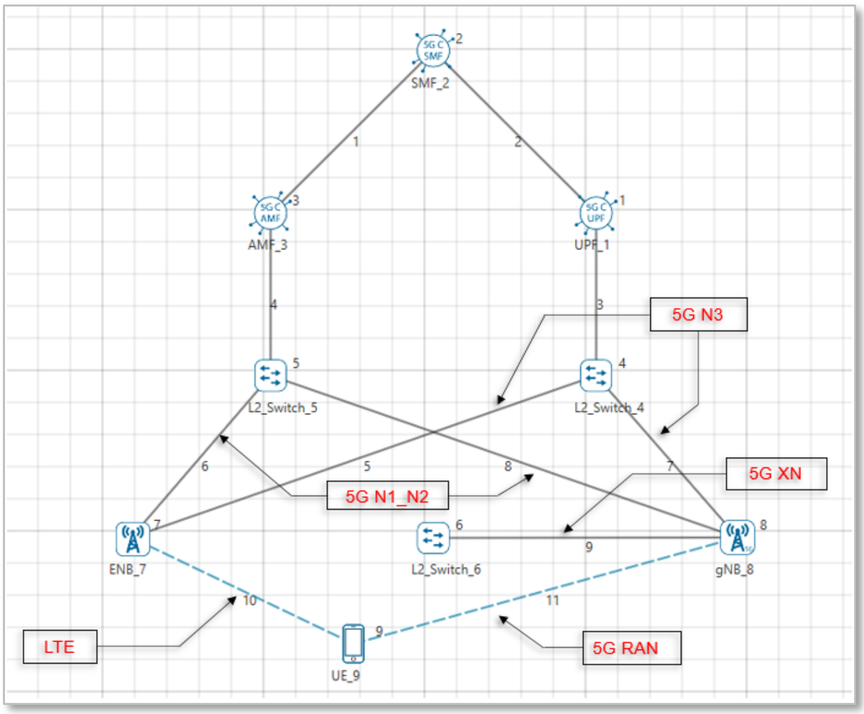

Figure 3-40: NSA deployment- Option 4a networking mode in NetSim

3.16.3 Option 7/7a

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.

3.16.3.1 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.

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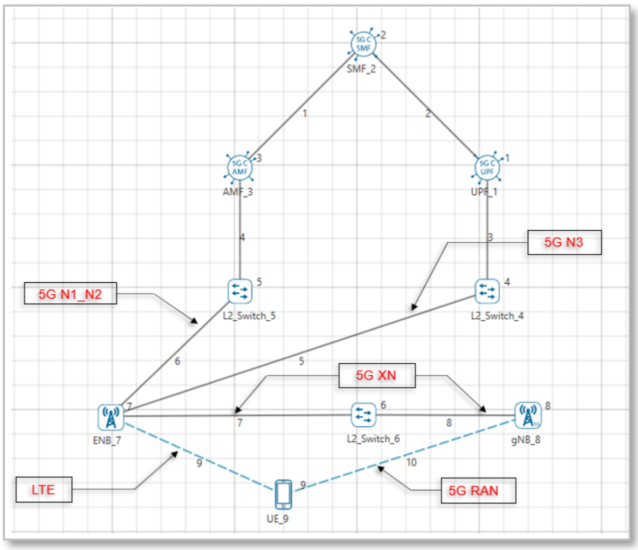

Figure 3-41: NSA deployment- Option 7 networking mode in NetSim

3.16.3.2 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.

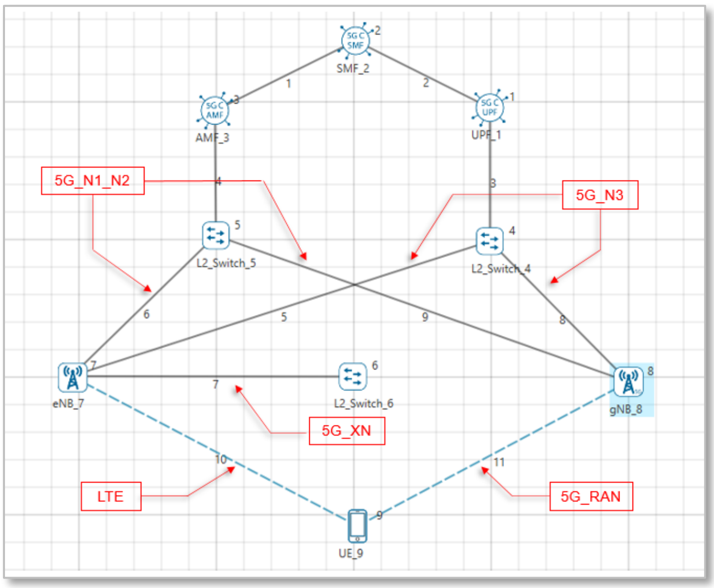

Figure 3-42: NSA deployment- Option 7a networking mode in NetSim

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3.17 NSA Packet Flow

3.17.1 Option 4

Consider the following network scenario:

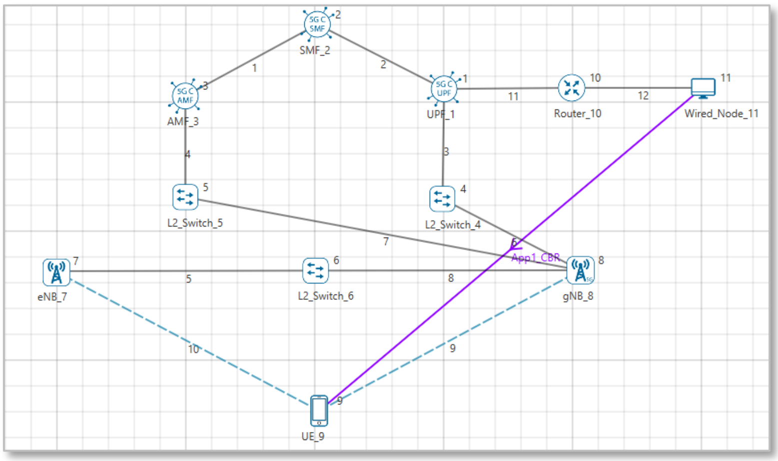

Figure 3-43: NSA deployment - Option 4 networking mode in NetSim

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.

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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 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(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 3-44: Packet flow can be analyzed using the Packet Trace

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3.17.2 Option 4a

Consider the following network scenario:

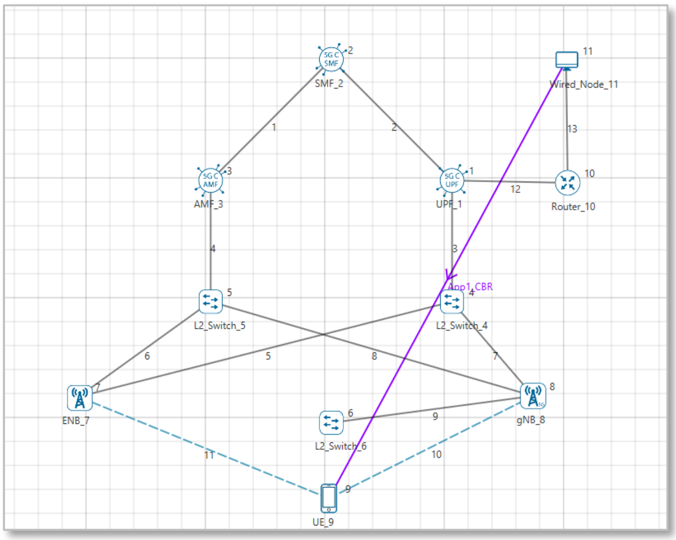

Figure 3-45: NSA deployment - Option 4a networking mode in NetSim

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.

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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
15. DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_4.
16. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
17. 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.
18. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
19. 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.
20. The second data packet will flow from UPF to the eNB via Switch_4 and then to the UE.
21. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

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)
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 3-46: Packet flow can be analyzed using the Packet Trace

3.17.3 Option 7

Consider the following network scenario:

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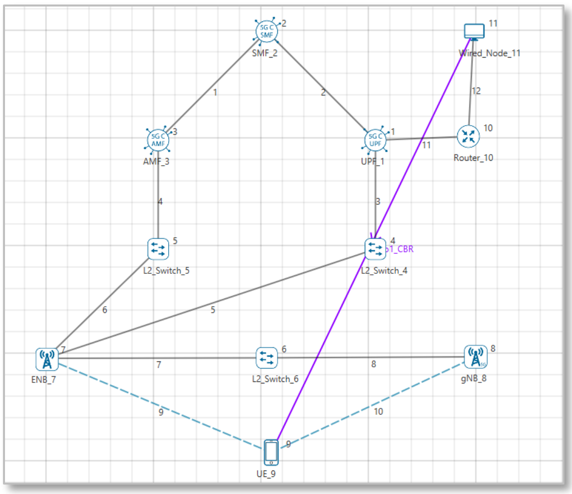

Figure 3-47: NSA deployment - Option 7 networking mode in NetSim

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.

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.,
11. CREATE_SESSION_RESPONSE.
12. AMF will send the INITIAL_CONTEXT_SETUP_REQUEST to the eNB via Switch_5.
13. 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.

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14. This marks the completion of UE registration process.
15. After the UE registration, the MN node will send DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_6.
16. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e., DC_SEC_CELL_ADDITION_RESPONSE.
17. 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.
18. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
19. 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.
20. 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.
21. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

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_ARRI
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	

Figure 3-48: Packet flow can be analyzed using the Packet Trace

3.17.4 Option 7a

Consider the following network scenario:

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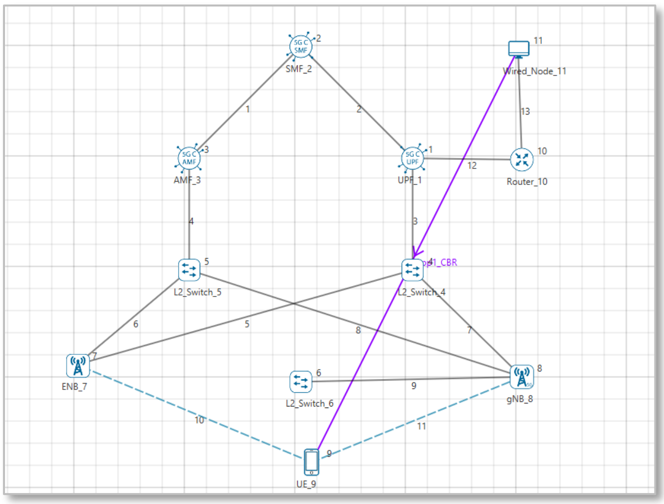

Figure 3-49: NSA deployment - Option 7a networking mode in NetSim

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
15. DC_SEC_CELL_ADDITION_REQUEST to the SN via the Switch_4.

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16. On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC_SEC_CELL_ADDITION_RESPONSE.
17. 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.
18. After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
19. 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.
20. The second data packet will flow from UPF to the gNB via Switch_4 and then from gNB to the UE.
21. Similarly, the third packet will flow through the MN, fourth through the SN and so on.

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
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 3-50: Packet flow can be analyzed using the Packet Trace

3.18 Handover

3.18.1 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.

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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. Since the noise power would be the same at s-gNB and t-gNB, in effect the handover is based on received signal level on the PDSCH.

3.18.2 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. If carrier aggregation and MIMO is enabled then the SNR is averaged over all carriers and over all layers.

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. Note that:

- The signal strength compared is the average of all layers across all carriers.
- NetSim assumes that admission control during handover is always successful. Hence there are no handover failures on this count.

3.18.3 Ping pong handovers

The above 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.

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Users may also be interested in measuring Ping pong handovers. For this, users should log the gNB to which the UE is attached. Users can then simulate scenarios where UE would attach to gNB1 then to gNB2, back to gNB1, again to gNB2 ... and so on, within a short time frame. Ping pong handovers can then be calculated per some (user-defined) criteria. Such scenarios can be simulated by enabling shadow-fading and fading-and-beamforming (fast fading). These phenomena would cause SINR to fluctuate over short distances and even over time at the same location.

Custom coding is required to log the "attached gNB" for each UE. NetSim radio measurements workspace (available in file-exchange/ GitHub) can serve as the base for this development effort.

3.18.4 Packet flow during handover

NetSim implements 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).

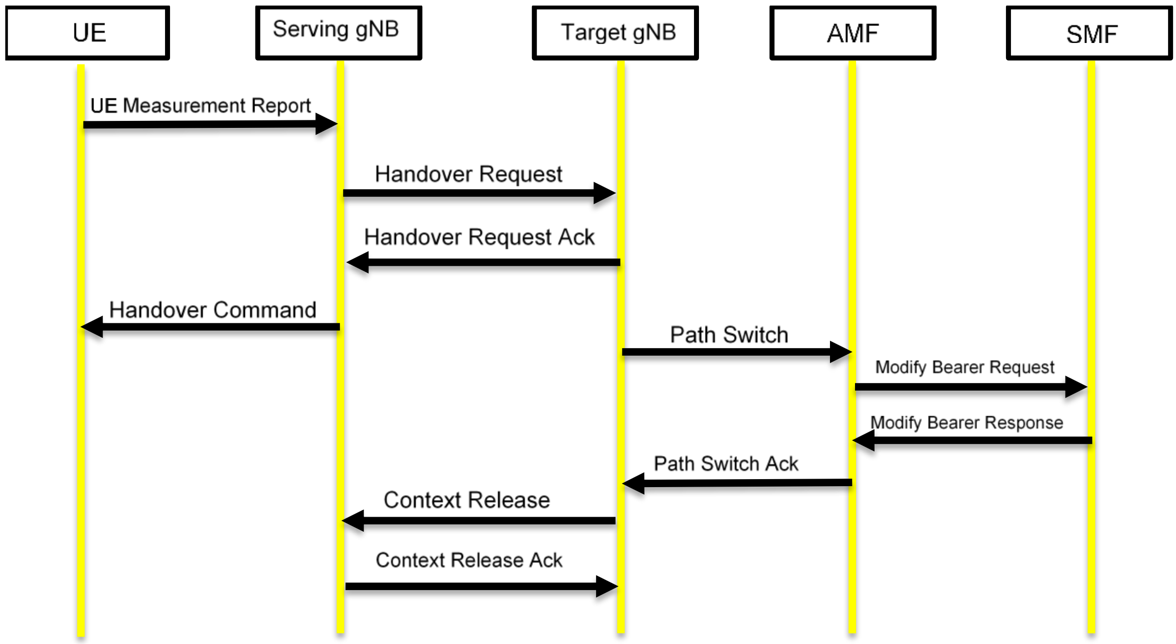

Figure 3-51: Control packet flow in the 5G handover process

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.

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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

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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_ARF
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 3-52: Screen shot of NetSim packet trace file showing the control packets involved in handover. Some columns have been hidden before the last column.

3.18.5 Handover Interruption Time

During this period the UE can neither transmit nor receive user data. Handover Interruption time can be configured in the Datalink layer properties of the gNB as shown below

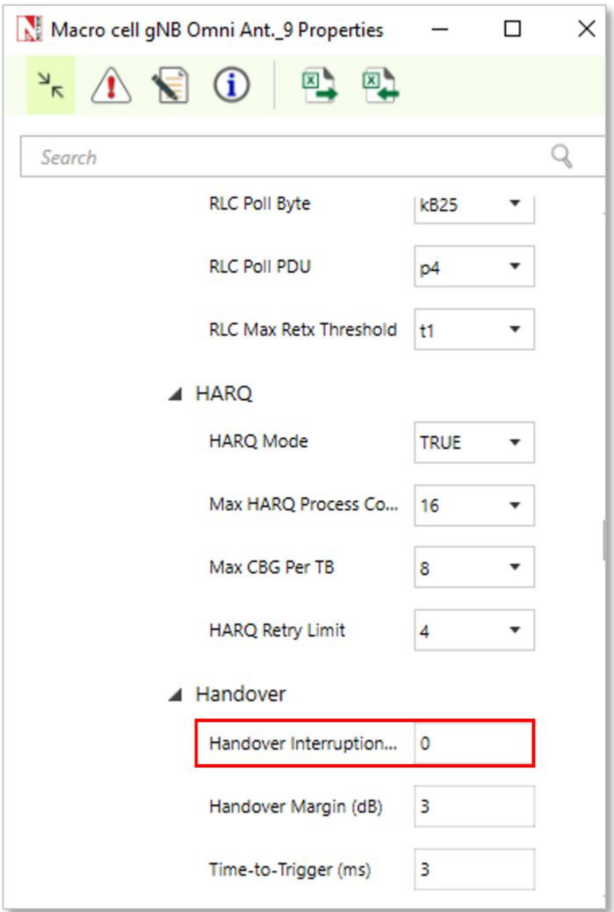

Figure 3-53: Screen shot showing handover interruption time in gNB properties

The value can range from 0.0 to 500.0 milliseconds. The handover process in NetSim is based on event A3 i.e., the target signal strength is offset (3 dB) higher than the source signal

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strength. Handover interruption time (HIT) is added at the time of handover command is delivered to the UE. During this time there is no data plane traffic flow to the UE from the source/target. The time at which the path switch is sent from the target cell to the AMF will get delayed by the Handover interruption time. This can be observed in the packet trace log file.

3.18.6 Time-to-Trigger

Cellular networks can suffer from Ping-pong (or rapid) handovers. In such handovers one successful handover is followed by a handover back to the original cell within short rapid handover time, $\mathrm{T_{RH}}$, e.g., within 3 seconds. Both handovers could potentially have been saved. Equivalently, if a successful handover is followed by another successful handover to a third cell within $\mathrm{T_{RH}}$, one could a single handover directly to this third cell would have served the purpose.

In the current version of NetSim, A3 based handover event is triggered the instant received SNR (on the downlink in the SSB) from target gNB, $SNR_{UE(SSB)}^{t-gNB}$ is offset, Δ, higher than received signal strength (on the downlink in the SSB) from serving gNB $SNR_{UE(SSB)}^{s-gNB}$. This offset, Δ, is also known as the Hand Over Margin (HOM). Thus, A3 event is triggered when, in dB scale,

$$SNR_{UE(SSB)}^{t-gNB}(t) - SNR_{UE(SSB)}^{s-gNB}(t) \geq \Delta \qquad (1)$$

where t is a discrete time instant.

Given the way NetSim measures power, SNR is used to account for differences in the bandwidth between serving and target gNBs. If their bandwidths are equal, then, in dB scale

$$SNR_{UE(SSB)}^{t-gNB}(t) - SNR_{UE(SSB)}^{s-gNB}(t) = RSRP_{UE(SSB)}^{t-gNB}(t) - RSRP_{UE(SSB)}^{s-gNB}(t)$$

In NetSim, SSB power between all UE-gNB pairs are computed.

a. when a measurement report is sent, which is every measurement interval T_{MI} (default 120 ms), and
b. at every mobility event i.e., whenever a UE moves. Recall here that in NetSim mobility is discretised over instants of time and movement is not continuous over time i.e., a UE moves to (x_1, y_1) at time t_1, remains at (x_1, y_1) till just before time t_2, and then instantly moves to (x_2, y_2) at t_2.

Hence, the A3 trigger occurs at the instant power levels at t-gNB and s-gNB satisfy (1). This could occur at a measurement report event or at a mobility event.

By definition of time to trigger, T_{TTT}, a handover event should only be triggered if (1) holds true for a duration equal to T_{TTT} .

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Since NetSim is a discrete event simulator its internal virtual clock progresses (virtual) time at events. Therefore, NetSim cannot check for (1) continuously over time. The test of whether (1) would continue to hold true can only be carried out at subsequent measurement report events and mobility events.

TTT condition will be successfully met only if powers from t-gNB and s-gNB meet condition (1) at all mobility and measurements events within the TTT period. If condition (1) fails to hold at any event during TTT, then TTT condition will have failed. The A3 trigger will be removed.

NetSim does not (recursively) average, or filter, $SNR_{UE(SSB)}^{t-gNB}$, or $SNR_{UE(SSB)}^{s-gNB}$ within the T_{TTT} window and (1) is evaluated on instantaneous powers at all events.

NetSim Time-to-trigger variable

a. is global scope; it remains the constant across the network, and

b. can be set by the user in the rage [0 ms, 5120 ms] as defined in the standards.

Algorithm

1. When A3 condition is met AddTrigger event is added
2. Check (1) at all measurement report events and mobility events.
3. If at any event (1) doesn't hold remove the AddTrigger event
4. Else, if (1) holds at all events within the TTT, initiate H/O trigger upon expiry of TTT interval.

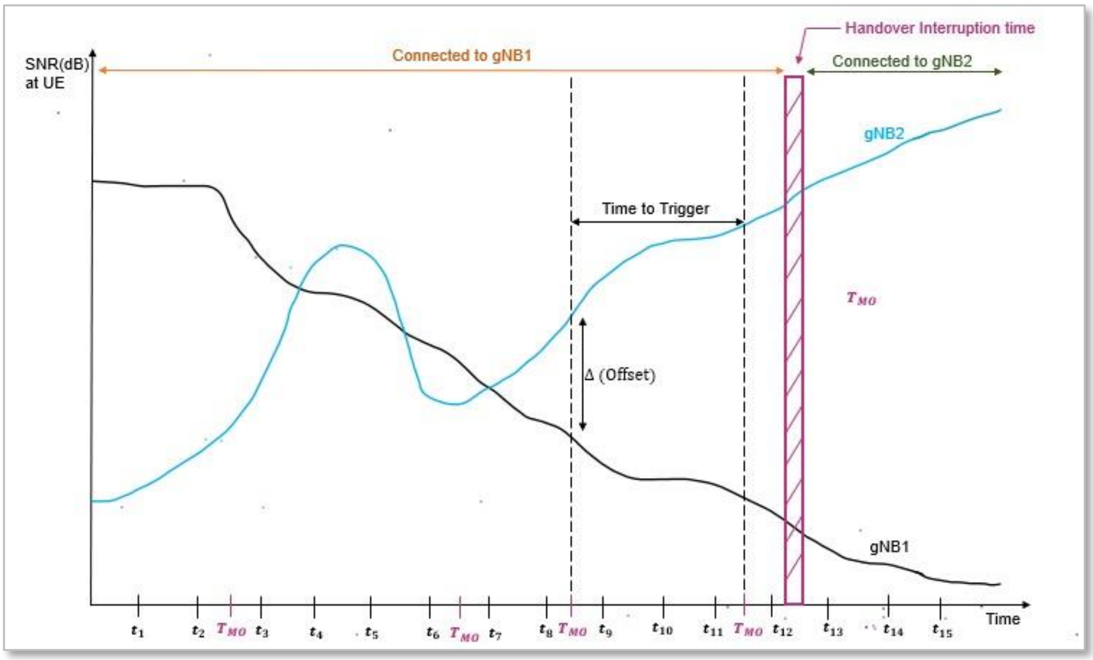

Figure 3-54: We see the SNR variation with time measured by UE from gNB1 (black) and gNB2 (blue). Time to trigger starts the instant $SNR_{UE}^{gNB2} - SNR_{UE}^{gNB1} > \Delta$. Once this condition holds for a duration equal to time-to-trigger, handover is initiated. Users can also configure a handover interruption time during which the UE is not connected to either gNB. Post this the UE gets associated with gNB2.

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3.18.6.1 Assumptions and limitations

1. Time to trigger (T_{TTT}) will be implemented for 5G Standalone (SA) mode. Non-stand alone (NSA) mode will not support T_{TTT}
2. NetSim assumes non failure of:
   a. Measurement reports
   b. Handover messages
3. Handovers are always successful. There are no handover failures on account of admission control at t-gNB.
4. In NetSim, UEs can be handed over to gNBs of different frequencies as long as (1) is met. There is no difference in handover functionality when the t-gNB and s-gNb operate in (i) the same frequency (say s-gNb and t-gNB in C-band) and (ii) different frequencies (say s-gNB in C-band and t-gNB in mmWave).
5. Time-to-trigger implementation is based on Rel 15. Enhancements added in Rel 16 namely (i) Dual active protocol stack (DAPS) and (ii) Conditional handovers, are not yet supported in NetSim.

3.18.6.2 Algorithm for implementation in NetSim

- Each gNB maintains a matrix named as the Conditional HO TTT Matrix
- The rows are the associated UEs, and the columns are all other gNBs in the scenario
- Whenever a UE_i associates with a gNB
  - Initialize all the matrix entries for all j (i.e., for all gNBs) for the given row i as follows
    - $T^j_{trigger}$to -1 for all j // #define TTT_not_set = -1
- Whenever a measurement report from an associated UE_i is received
  - If the condition ($SNR^{gNB}_{UE(SSB)} - SNR^{s-gNB}_{UE(SSB)} > \Delta$) is met
    - If matrix entry $T^j_{trigger}$ is currently -1, then // i is fixed
      – Update the matrix entry, $T^j_{trigger} = T_{current}$, where $T_{current}$ is current simulation time
    - Else (matrix entry is not -1)
      – If $T_{current} - T^j_{trigger} \geq TTT$
        - Initiate handover procedure
  - Else

- If the matrix entry, $T_{trigger}^{j}$ is not -1
  - Set it equal to -1
- Whenever a UE_i disassociates with a gNB, delete the row i

3.18.6.3 Configuring Time-to-Trigger

The desired TTT value in milliseconds can be configured in the Datalink layer properties of the gNB as shown below.

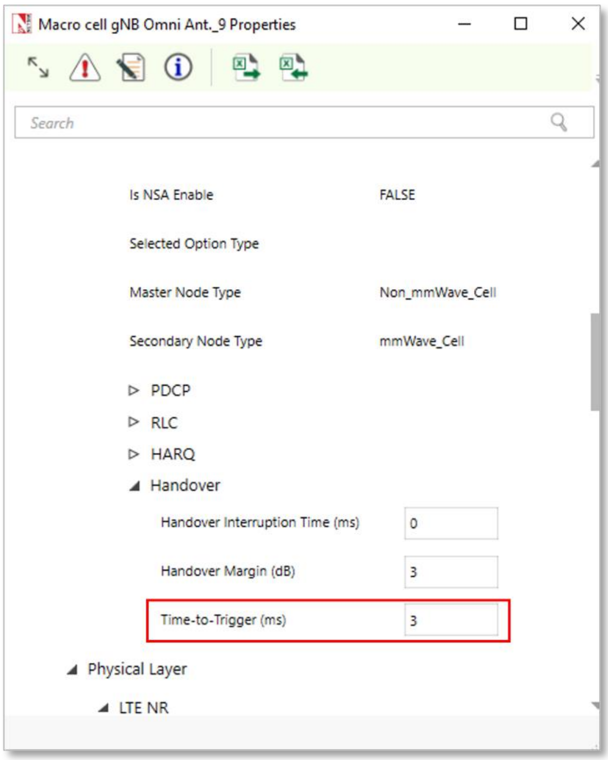

Figure 3-55: Time-to-Trigger configuration in gNB/eNB Data Link layer properties

This value is common for all gNBs in a network i.e., TTT parameters is global in scope. Setting TTT to 0 is equivalent to disabling Time-to-Trigger.

3.18.6.4 Enabling the TTT Log

The LTENR Handover TTT log can be enabled by clicking on Enable Logs under Configure Reports option.

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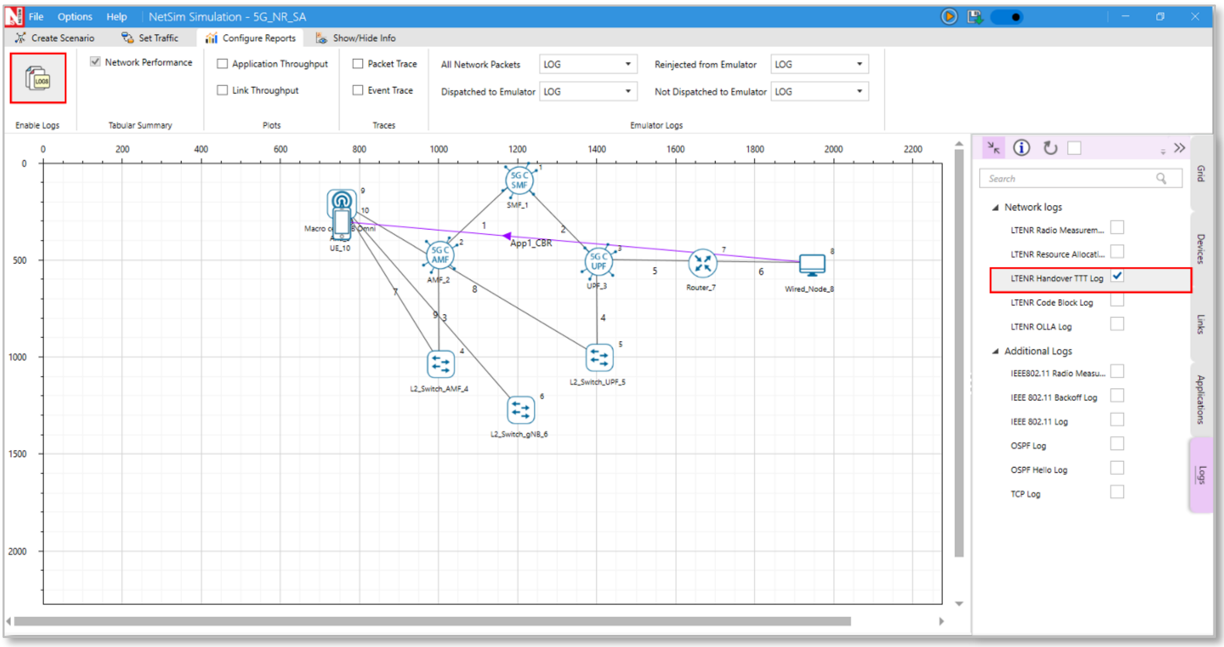

Figure 3-56: Enabling the LTENR Handover TTT log

Upon running simulations with this log enabled, a LTENR_TTT_Log.csv file is written and can be accessed from the results dashboard as shown below:

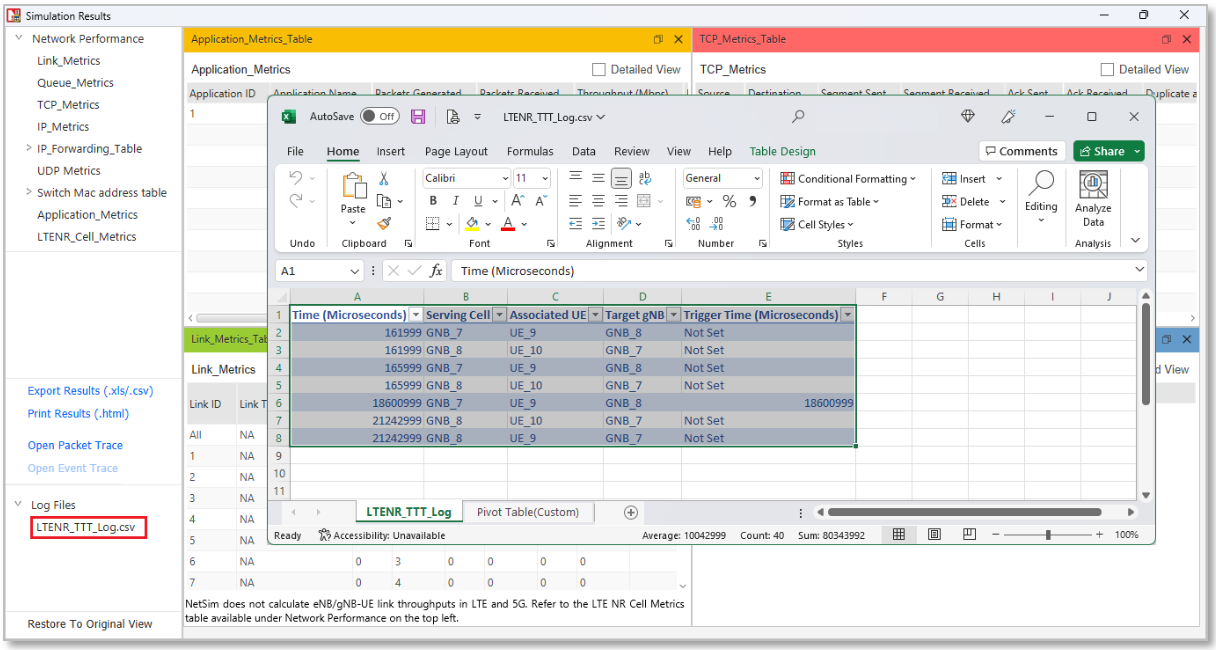

Figure 3-57: Accessing TTT log from NetSim results dashboard

The log file consists of time stamps in Microseconds, the serving cell name, associated UE name, target cell name, and the trigger time in Microseconds.

Entries to the file are written (i) for initial UE association (will have two entries) (ii) when handover condition is hit (iii) when UE is handed over (iv) when TTT is reset

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For example, upon running the inbuilt 5G-Handover example with TTT set to 2560 milliseconds (or 2.56 s), we get the following entries in the log file.

Time (Microseconds)	Serving Cell	Associated UE	Target gNB	Trigger Time (Microseconds)
161999	GNB_7	UE_9	GNB_8	Not Set
161999	GNB_8	UE_10	GNB_7	Not Set
165999	GNB_7	UE_9	GNB_8	Not Set
165999	GNB_8	UE_10	GNB_7	Not Set
18600999	GNB_7	UE_9	GNB_8	18600999
21242999	GNB_8	UE_10	GNB_7	Not Set
21242999	GNB_8	UE_9	GNB_7	Not Set

Figure 3-58: TTT log showing entries with handover condition met at 18.6 seconds, and handover at 21.24 seconds.

- From the log file we can see that, around 162 milliseconds, UE 9 gets associated with gNB 7 and UE10 gets associated with gNB 8.
- UE 9 is configured with mobility such that it moves away from gNB 7 and towards gNB 8.
- At 18.6 seconds, the handover condition is met for UE 9 with the SNR from gNB 8 greater than the SNR from gNB 7 by the default margin of 3 dB.
- Trigger Time for UE 9 gNB 8 pair is set to the time at which the condition is met.
- The condition ($SNR_{UE(SSB)}^{gNB} - SNR_{UE(SSB)}^{s-gNB} > \Delta$) continues to hold.
- At time 21.24 seconds, UE 9 gets handed over to gNB 8 after a duration greater than or equal to the TTT (2560000 μs) successfully.

3.18.7 Buffer transfer and timers

During handover buffer is transferred from s-gNB to t-gNB, and active timers such as t-poll retransmit are stopped in the s-gNB.

3.19 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 3-33: LTENR results Packet trace parameter descriptions

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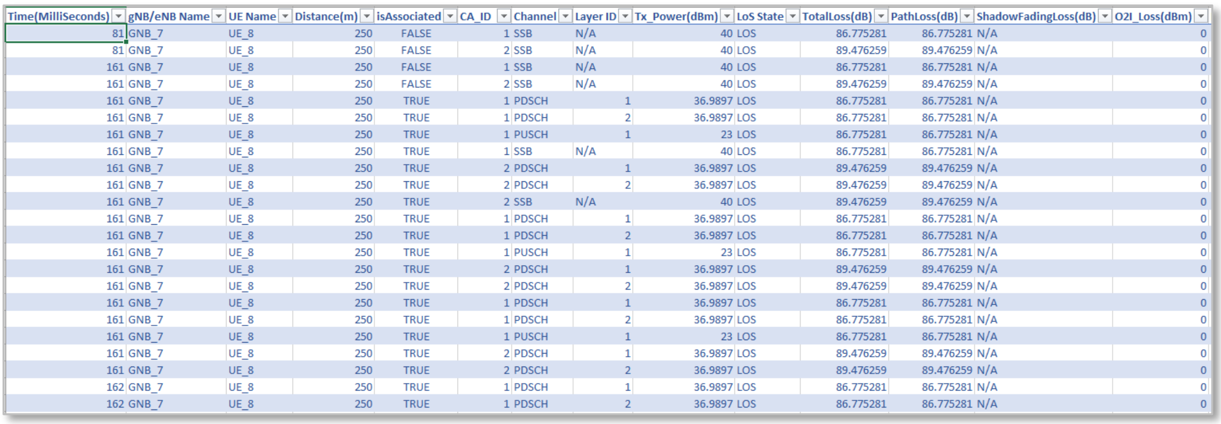
3.19.1 LTE NR Packet trace

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.



Time(MilliSeconds)	gNB/eNB Name	UE Name	Distance(m)	isAssociated	CA_ID	Channel	Layer ID	Tx_Power(dBm)	LoS State	TotalLoss(dB)	PathLoss(dB)	ShadowFadingLoss(dB)	O2I_Loss(dBm)
81	GNB_7	UE_8	250	FALSE	1	SSB	N/A	40	LOS	86.775281	86.775281	N/A	0
81	GNB_7	UE_8	250	FALSE	2	SSB	N/A	40	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	FALSE	1	SSB	N/A	40	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	FALSE	2	SSB	N/A	40	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	1	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	2	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PUSCH	1	23	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	SSB	N/A	40	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	1	36.9897	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	2	36.9897	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	2	SSB	N/A	40	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	1	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	2	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PUSCH	1	23	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	1	36.9897	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	2	36.9897	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	1	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PDSCH	2	36.9897	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	1	PUSCH	1	23	LOS	86.775281	86.775281	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	1	36.9897	LOS	89.476259	89.476259	N/A	0
161	GNB_7	UE_8	250	TRUE	2	PDSCH	2	36.9897	LOS	89.476259	89.476259	N/A	0
162	GNB_7	UE_8	250	TRUE	1	PDSCH	1	36.9897	LOS	86.775281	86.775281	N/A	0
162	GNB_7	UE_8	250	TRUE	1	PDSCH	2	36.9897	LOS	86.775281	86.775281	N/A	0

Figure 3-59: 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.

3.19.2 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 3-34.

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 3-34: 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,

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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 indicates that the Status report is not requested, while 1 indicates that the Status report is requested.

3.19.3 LTENR Event Trace

3.19.3.1 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

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- 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.

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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

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- 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.

3.20 Radio measurements log file

NetSim LTENR Radio measurements csv log file records pathloss, shadow fading loss, received power, SNR, Interference Power, SINR, MCS, CQI, and Beamforming gain.

The LTENR Radio measurement log can be enabled by clicking on icon present in the tool bar as shown below.

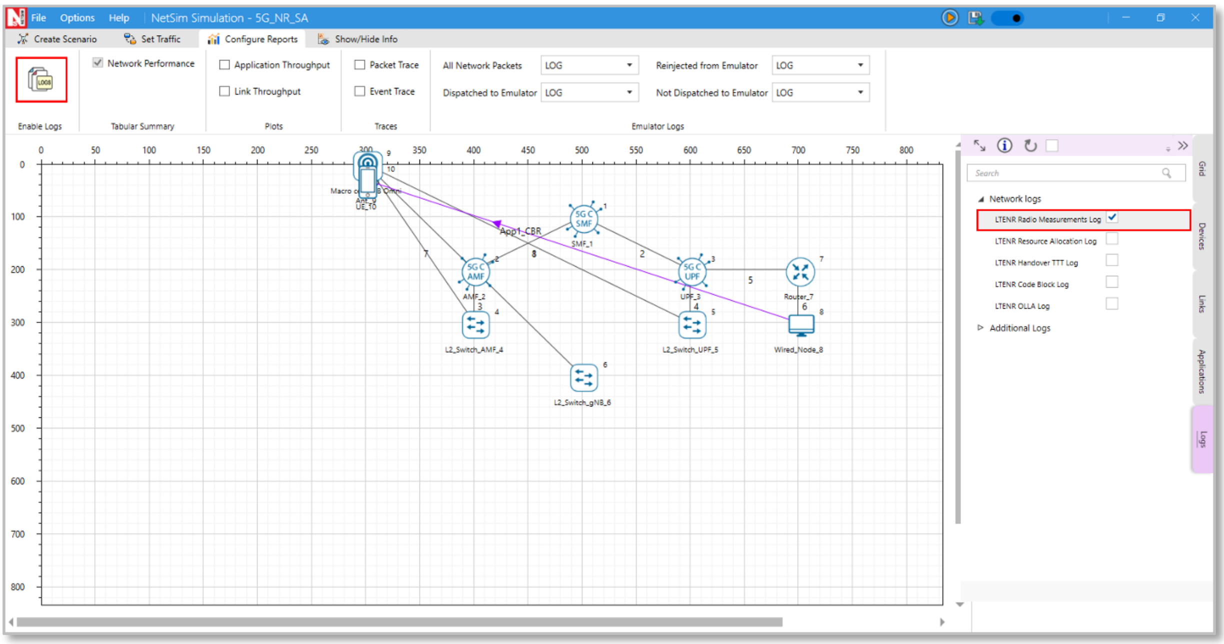

Figure 3-60: Enabling LTENR Radio Measurement logs

The LTENR_Radio_Measurement_Log.csv file will contain the following information:

- Time in Milliseconds

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- gNB/eNB Name
- UE Name
- Distance between the gNB/eNB and the UE in meters
- Association Status (True/False)
- Carrier ID (CC ID)
- Channel Type (PDSCH/PUSCH/SSB)
- MIMO Layer ID
- Transmitter Power in dBm
- LoS State
- Total Loss in dB
- Pathloss in dB
- Shadow Fading Loss in dB
- Additional loss dB
- Received Power in dBm
- SNR in dB
- SINR in dB
- O2I (Outdoor to indoor) penetration loss in dBm
- Interference Power in dBm
- Beamforming gain in dB
- CQI Index
- MCS Index

The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

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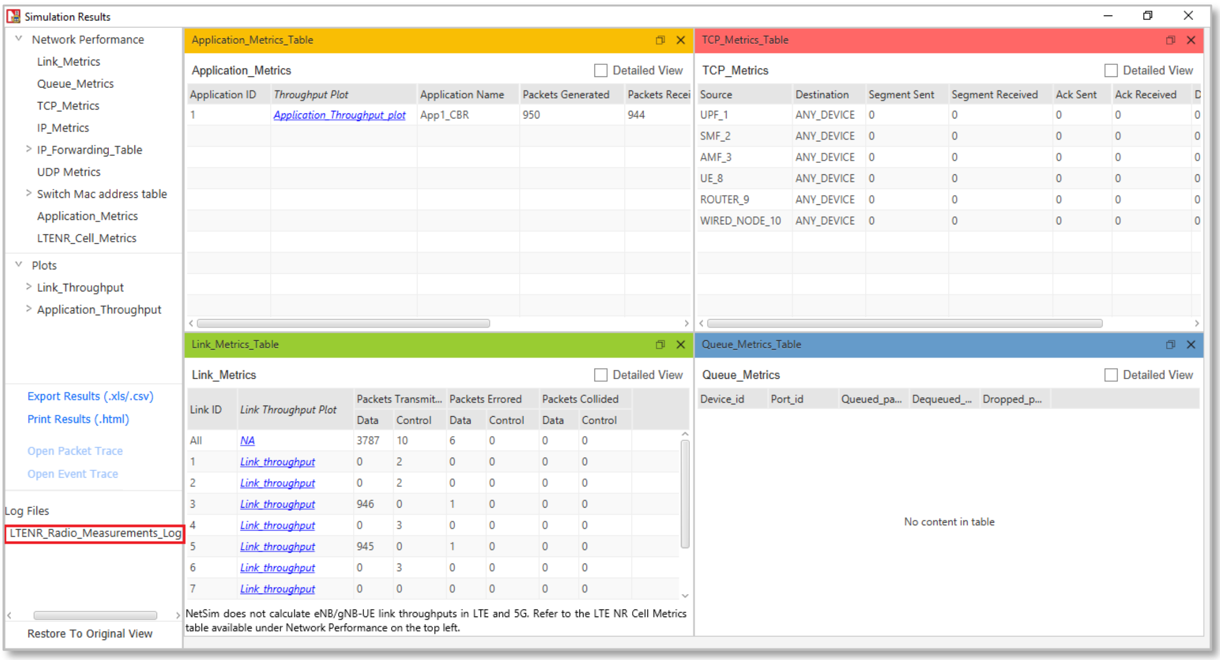
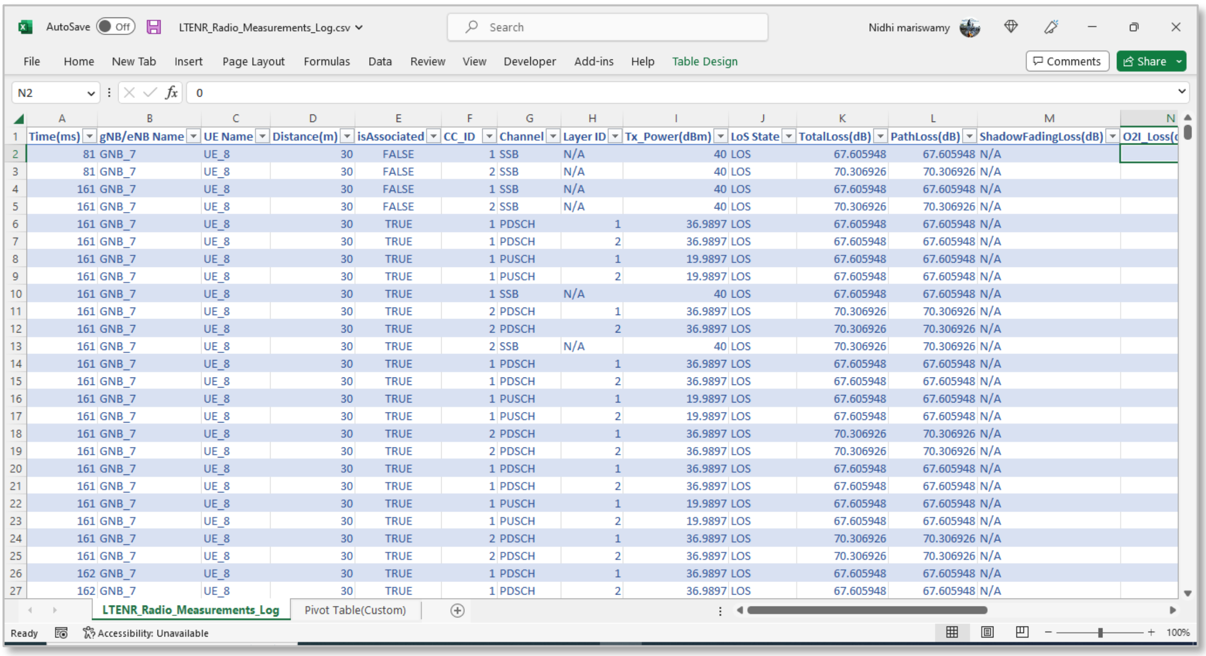


Figure 3-61: LTENR_Radio_Measurement_Log file highlighted in the Results window.



Time(ms)	gNB/eNB Name	UE Name	Distance(m)	isAssociated	CC_ID	Channel	Layer ID	Tx_Power(dBm)	LoS State	TotalLoss(dB)	PathLoss(dB)	ShadowFadingLoss(dB)	O2I_Loss(
81	GNB_7	UE_8	30	FALSE	1	SSB	N/A	40	LOS	67.605948	67.605948	N/A	
81	GNB_7	UE_8	30	FALSE	2	SSB	N/A	40	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	FALSE	1	SSB	N/A	40	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	FALSE	2	SSB	N/A	40	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	SSB	N/A	40	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	2	SSB	N/A	40	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	LOS	67.605948	67.605948	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	LOS	70.306926	70.306926	N/A	
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	LOS	70.306926	70.306926	N/A	
162	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	LOS	67.605948	67.605948	N/A	
162	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	LOS	67.605948	67.605948	N/A	

Figure 3-62: LTENR_Radio_Measurement_Log.csv file

Implementation details and Assumptions:

- The PDSCH channel corresponds to downlink.
- The PUSCH channel corresponds to uplink.
- The SSB channel corresponds to the control channel.
- Parameters associated with PDSCH and PUSCH channels are logged at every slot only for associated gNB-UE pairs.

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- Parameters associated with SSB channel are logged once at initialization and further during each mobility event.
- Initially only SSB channel entries will be found in the log since gNB-UE association takes time.
- Interference is not modelled for uplink.
- The SSB control channel transmission is over a single layer. Analog Beamforming gain is logged for this channel and is used for SSB received power computation.
- Interference is not modelled for the SSB channel and hence SINR and Interference Power parameters are not logged.
- The SNR computed for SSB channel is used for control decisions such as Association and Handover. It is not used to calculate the MCS/CQI Index which is used to determine PDSCH/PUSCH rate.

3.21 Radio resource allocation log file

NetSim 5G Radio Resource Allocation csv log file records information related to physical resource block allocation such as the Total PRBs, Slot Start Time(ms), Slot End, BitsPerPRB, BufferFill, Allocated PRBs, etc.

The LTENR Radio Resource allocation can be enabled by clicking on the icon present in the tool bar as shown below.

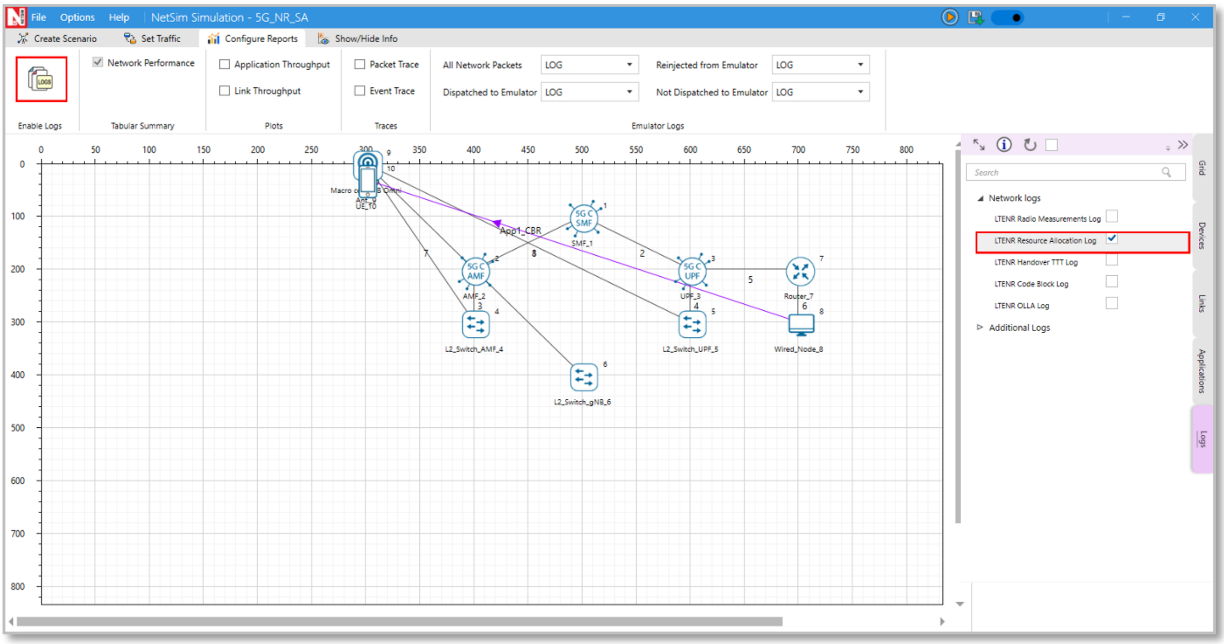

Figure 3-63: Enabling LTENR Resource Allocation logs

The LTE_Radio_Resource_Allocation.csv file will contain the following information:

- gNB ID

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- Component Carrier ID
- Slot ID
- Slot
- Total PRBs
- Slot Start Time(ms)
- Slot End Time(ms)
- UE ID
- BitsPerPRB
- BufferFill(B)
- Rank
- Allocated PRBs
- New Rank

The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

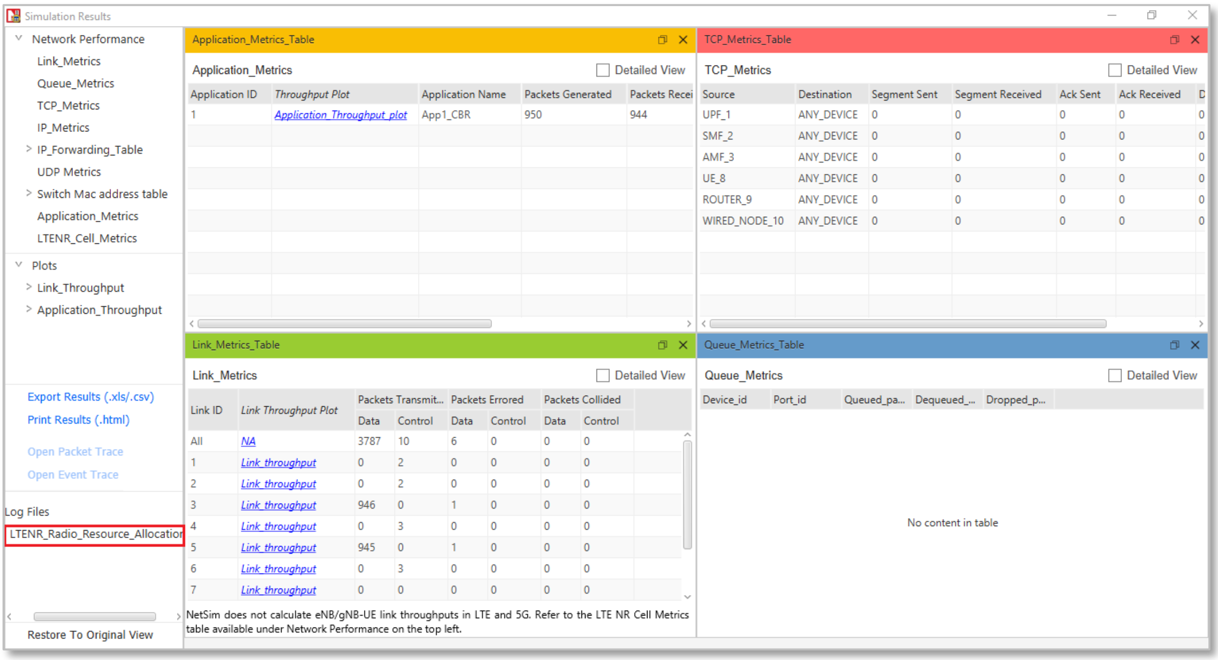

Figure 3-64: LTENR_Radio_Resource_Allocation_Log file highlighted in the Results window

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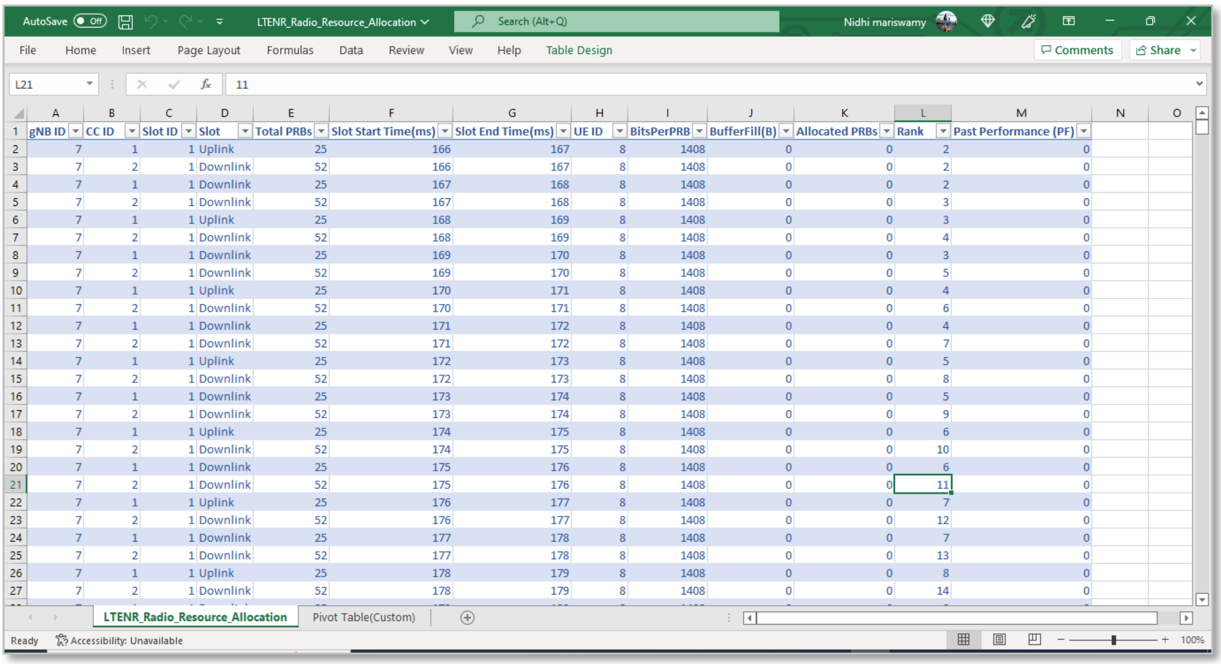

gNB ID	CC ID	Slot ID	Slot	Total PRBs	Slot Start Time(ms)	Slot End Time(ms)	UE ID	BitsPerPRB	BufferFill(B)	Allocated PRBs	Rank	Past Performance (PF)
7	1	1	Uplink	25	166	167	8	1408	0	0	2	0
7	2	1	Downlink	52	166	167	8	1408	0	0	2	0
7	1	1	Downlink	25	167	168	8	1408	0	0	2	0
7	2	1	Downlink	52	167	168	8	1408	0	0	3	0
7	1	1	Uplink	25	168	169	8	1408	0	0	3	0
7	2	1	Downlink	52	168	169	8	1408	0	0	4	0
7	1	1	Downlink	25	169	170	8	1408	0	0	3	0
7	2	1	Downlink	52	169	170	8	1408	0	0	5	0
7	1	1	Uplink	25	170	171	8	1408	0	0	4	0
7	2	1	Downlink	52	170	171	8	1408	0	0	6	0
7	1	1	Downlink	25	171	172	8	1408	0	0	4	0
7	2	1	Downlink	52	171	172	8	1408	0	0	7	0
7	1	1	Uplink	25	172	173	8	1408	0	0	5	0
7	2	1	Downlink	52	172	173	8	1408	0	0	8	0
7	1	1	Downlink	25	173	174	8	1408	0	0	5	0
7	2	1	Downlink	52	173	174	8	1408	0	0	9	0
7	1	1	Uplink	25	174	175	8	1408	0	0	6	0
7	2	1	Downlink	52	174	175	8	1408	0	0	10	0
7	1	1	Downlink	25	175	176	8	1408	0	0	6	0
7	2	1	Downlink	52	175	176	8	1408	0	0	11	0
7	1	1	Uplink	25	176	177	8	1408	0	0	7	0
7	2	1	Downlink	52	176	177	8	1408	0	0	12	0
7	1	1	Downlink	25	177	178	8	1408	0	0	7	0
7	2	1	Downlink	52	177	178	8	1408	0	0	13	0
7	1	1	Uplink	25	178	179	8	1408	0	0	8	0
7	2	1	Downlink	52	178	179	8	1408	0	0	14	0

Figure 3-65: LTENR_Radio_Resource_Allocation_Log.csv file

Implementation details and assumptions:

- In the case of scheduling algorithms such as Max Throughput when all PRB's are allocated to one UE, the entries for the other UEs for which allocation did not happen is not written to the log file.
- Rank is a metric used for resource allocation.

3.22 Handover TTT Log file

NetSim Handover TTT Log records the events that occur during a handover. This contains the time stamp, serving cell ID, UE ID, target cell ID, and Handover Trigger time (time at which the handover condition was met) - when the TTT parameter is enabled. The log can be used to identify handover attempts and the impact of TTT on handovers.

The LTENR Handover TTT Log can be enabled by clicking on the icon present in the tool bar as shown below.

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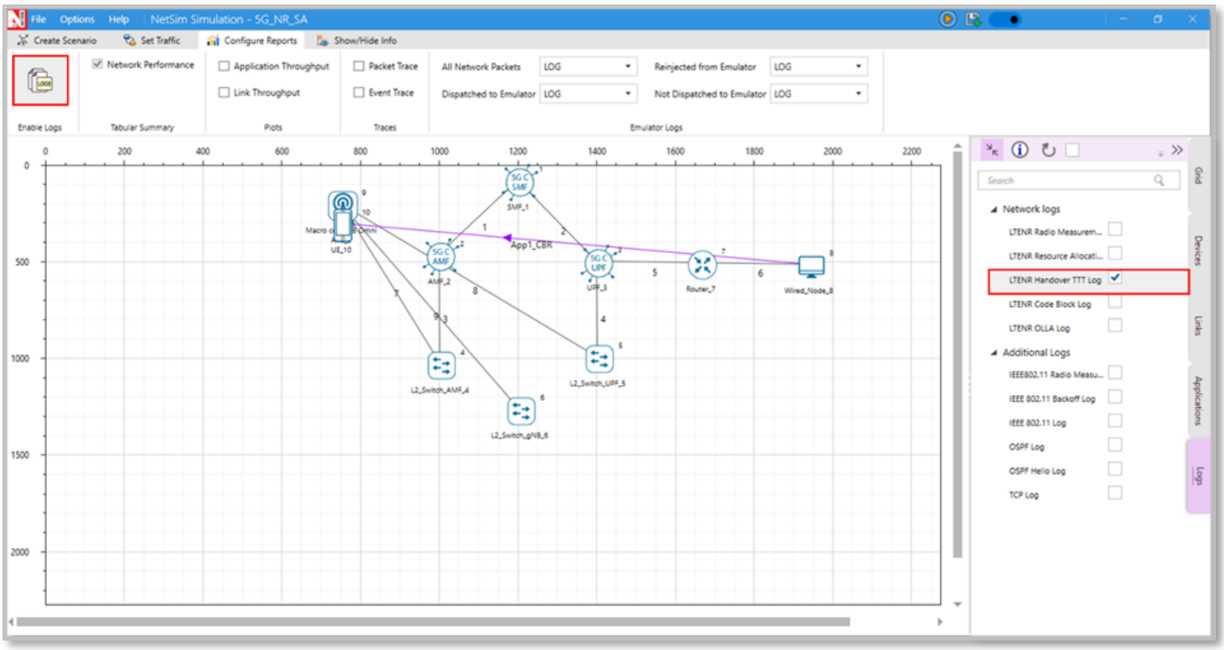

Figure 3-66: Enabling LTENR Handover TTT Log

The LTE_Handover_TTT.csv file will contain the following information:

- Time in microseconds
- Serving cell
- Associated UE
- Target Cell
- Trigger Time in microseconds

The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

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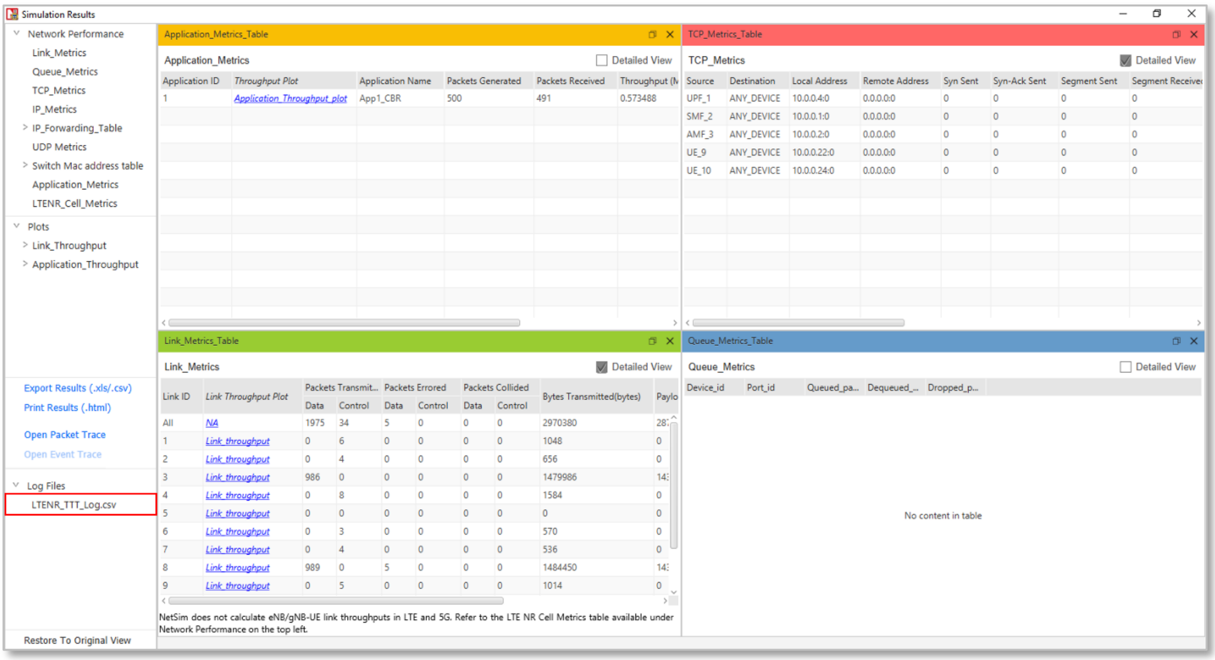

Figure 3-67: LTENR_TTT_Log.csv file highlighted in the Results window

Time (Microseconds)	Serving Cell	Associated UE	Target gNB	Trigger Time (Microseconds)
161999	GNB_7	UE_9	GNB_8	Not Set
161999	GNB_8	UE_10	GNB_7	Not Set
165999	GNB_7	UE_9	GNB_8	Not Set
165999	GNB_8	UE_10	GNB_7	Not Set
18600999	GNB_7	UE_9	GNB_8	18600999
21242999	GNB_8	UE_10	GNB_7	Not Set
21242999	GNB_8	UE_9	GNB_7	Not Set

Figure 3-68: LTENR_TTT_Log.csv file

3.23 Code Block Log file

NetSim Code Block Log Records parameters associated with Code Block segmentation such as Process ID, TB size, Modulation, Code Rate, CBS, BLER, CBG ID, etc. along with remarks on events associated with HARQ and PRB allocation. This will be useful to understand BLER model and Code Block segmentation in 5G.

The LTENR Code Block Log can be enabled by clicking on the icon present in the tool bar as shown below.

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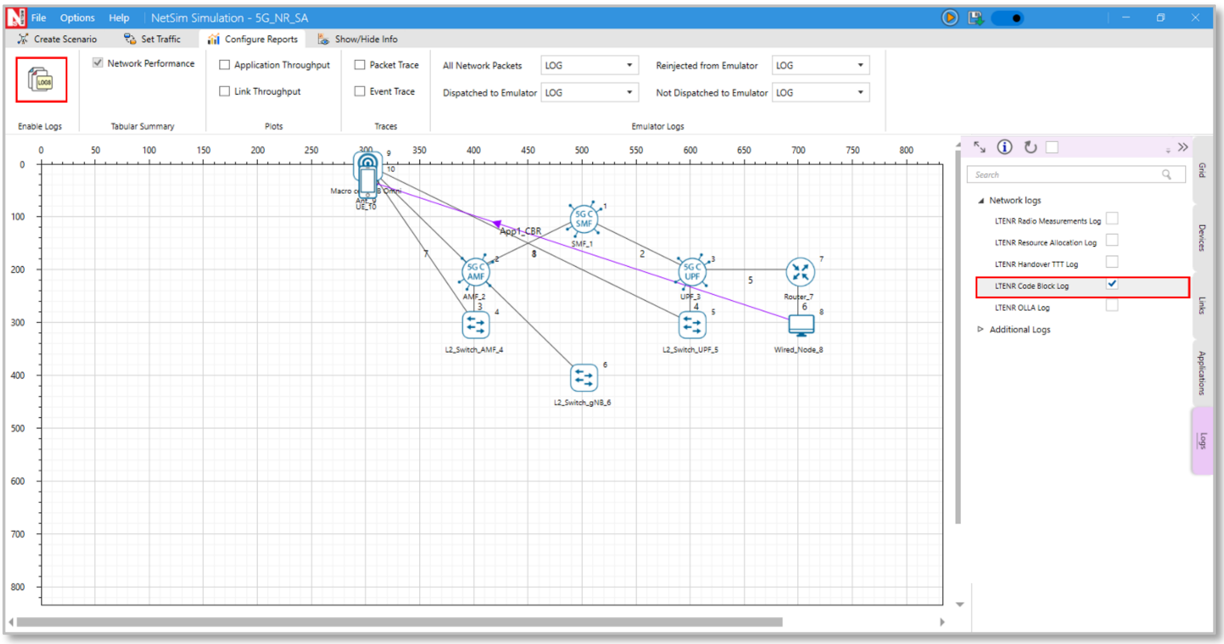

Figure 3-69: Enabling LTENR Code Block Log

The LTE_CodeBlock_Log.csv file will contain the following information:

- Time in milliseconds
- gNB/eNB ID
- gNB/eNB I/F (Interface)
- UE ID
- UE I/F (Interface)
- Channel Type (PDSCH/PUSCH)
- Carrier ID (CC ID)
- Frame ID
- Subframe ID
- Slot ID
- Layer ID
- Process ID
- Remarks
- Transport Block Size
- Modulation
- Code Rate
- Code Blocks
- SINR
- BLER
- CBG ID

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- CB ID
- NDI
- Transmission Number
- Status

The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

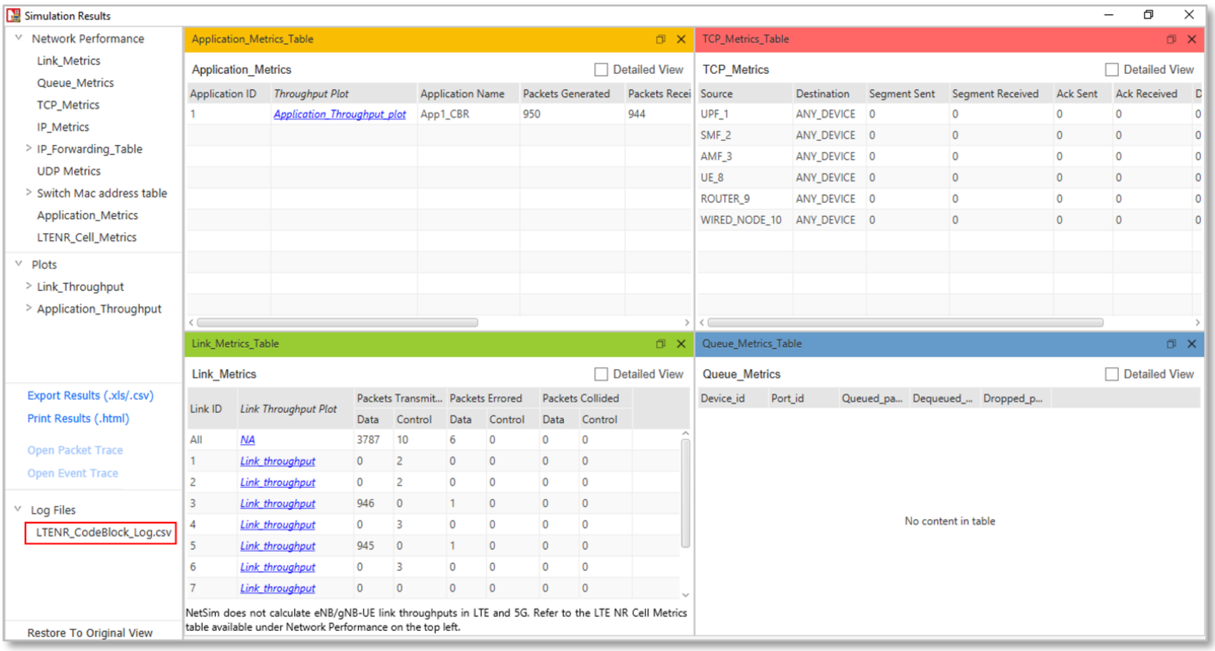

Figure 3-70: LTENR_CodeBlock_Log.csv file highlighted in the Results window

Time (ms)	gNB/eNB ID	gNB/eNB I/F	UE ID	UE I/F	Channel	CC ID	Frame ID	SubFrame ID	Slot ID	Layer ID	Process ID
160.999	7	4	8	1		1	17	1	1	0	N/A
161	7	4	8	1	PDSCH	0	17	2	1	0	1
161	7	4	8	1	PDSCH	0	17	2	1	0	1
161	7	4	8	1	PDSCH	1	17	2	1	0	1
161	7	4	8	1	PDSCH	1	17	2	1	0	1
162	7	4	8	1	PUSCH	0	17	3	1	0	1
162	7	4	8	1	PUSCH	0	17	3	1	0	1
162	7	4	8	1	PDSCH	1	17	3	1	0	1
162	7	4	8	1	PDSCH	1	17	3	1	0	1
162.999	7	4	8	1		1	17	3	1	0	N/A
162.999	7	4	8	1		1	17	3	1	0	N/A
163	7	4	8	1	PDSCH	0	17	4	1	0	1
163	7	4	8	1	PDSCH	0	17	4	1	0	1
163	7	4	8	1	PDSCH	1	17	4	1	0	1
163	7	4	8	1	PDSCH	1	17	4	1	0	1
164	7	4	8	1	PUSCH	0	17	5	1	0	1
164	7	4	8	1	PUSCH	0	17	5	1	0	1
164	7	4	8	1	PDSCH	1	17	5	1	0	1
164	7	4	8	1	PDSCH	1	17	5	1	0	1

Figure 3-71: LTENR_CodeBlock_Log.csv file

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3.24 OLLA Log file

NetSim OLLA Log Records Logs parameters associated with Outer Loop Link Adaptation (OLLA) such as CQI with and without OLLA, Phy SINR, SINR Delta, Virtual SINR, etc. along with time stamps, gNB ID, UE ID, etc. This log can be used to understand OLLA mechanisms in 5G. The LTENR Code Block Log can be enabled by clicking on the icon present in the tool bar as shown below.

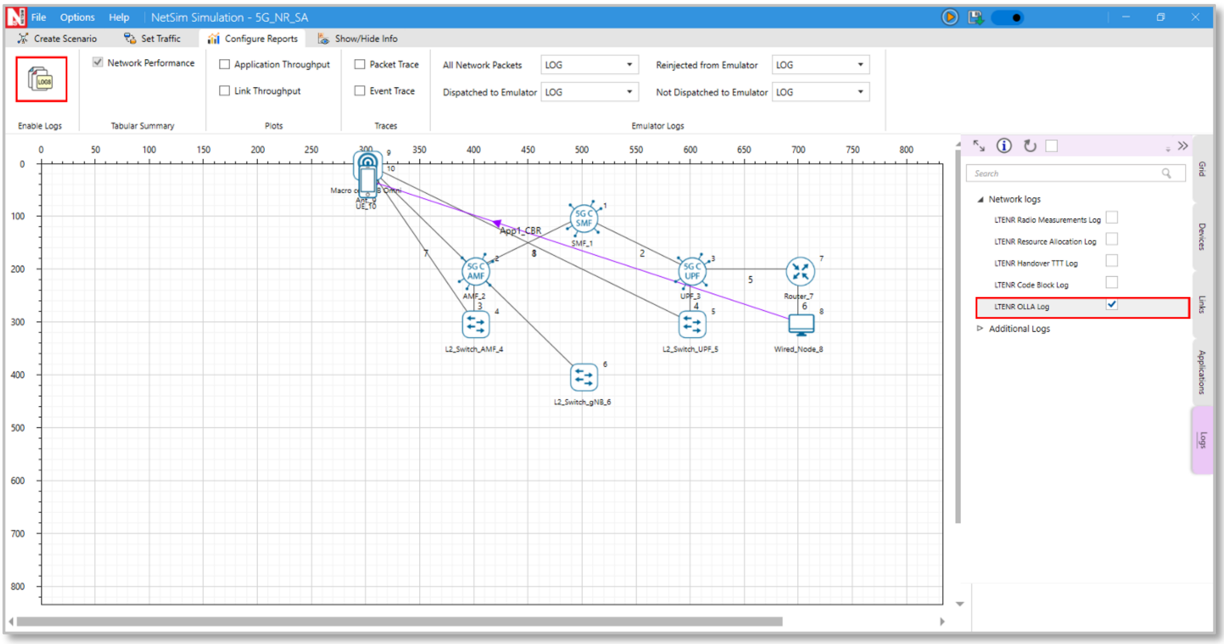

Figure 3-72: Enabling LTENR Code Block Log

The LTENR_OLLA_Log.csv file will contain the following information:

- UE Name
- Carrier ID
- Layer ID
- Frame ID
- Sub-Frame ID
- Slot ID
- Channel
- Phy SINR in dB
- SINR Delta in dB
- Virtual SINR in dB
- CQI without OLLA
- CQI with OLLA

The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

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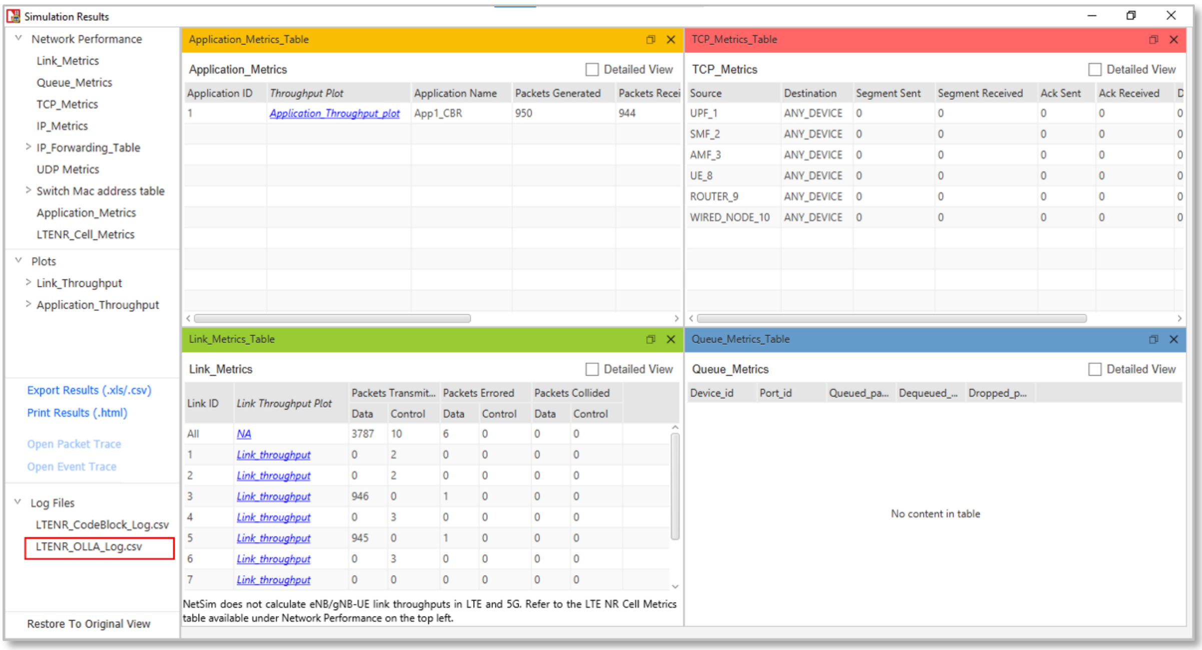

Figure 3-73: LTENR_OLLA_Log.csv file highlighted in the Results window

UE Name	Carrier ID	Layer ID	Frame Id	Sub-Frame Id	Slot Id	Channel	Phy SINR(dB)	SINR Delta(dB)	Virtual SINR(dB)	CQI without OLLA	CQI with OLLA
UE_8	1	1	17	1	1	PDSCH	76.222008	0	76.222008	15	15
UE_8	1	2	17	1	1	PDSCH	76.222008	0	76.222008	15	15
UE_8	1	1	17	1	1	PUSCH	59.222008	0	59.222008	15	15
UE_8	1	2	17	1	1	PUSCH	59.222008	0	59.222008	15	15
UE_8	2	1	17	1	1	PDSCH	70.51073	0	70.51073	15	15
UE_8	2	2	17	1	1	PDSCH	70.51073	0	70.51073	15	15
UE_8	2	1	17	1	1	PUSCH	53.51073	0	53.51073	15	15
UE_8	2	2	17	1	1	PUSCH	53.51073	0	53.51073	15	15
UE_8	1	1	17	2	1	PDSCH	76.222008	0	76.222008	15	15
UE_8	1	2	17	2	1	PDSCH	76.222008	0	76.222008	15	15
UE_8	1	1	17	2	1	PUSCH	59.222008	0	59.222008	15	15
UE_8	1	2	17	2	1	PUSCH	59.222008	0	59.222008	15	15
UE_8	2	1	17	2	1	PDSCH	70.51073	0	70.51073	15	15
UE_8	2	2	17	2	1	PDSCH	70.51073	0	70.51073	15	15
UE_8	2	1	17	2	1	PUSCH	53.51073	0	53.51073	15	15
UE_8	2	2	17	2	1	PUSCH	53.51073	0	53.51073	15	15

Figure 3-74: LTENR_OLLA_Log.csv file

3.25 Enable detailed logs in 5G NR

A detailed 5G NR log can be enabled by a user, by going to the file LTE_NR.h, and then uncommenting the #define LTENR_LOG and #define LTENR_LOG_DEV.

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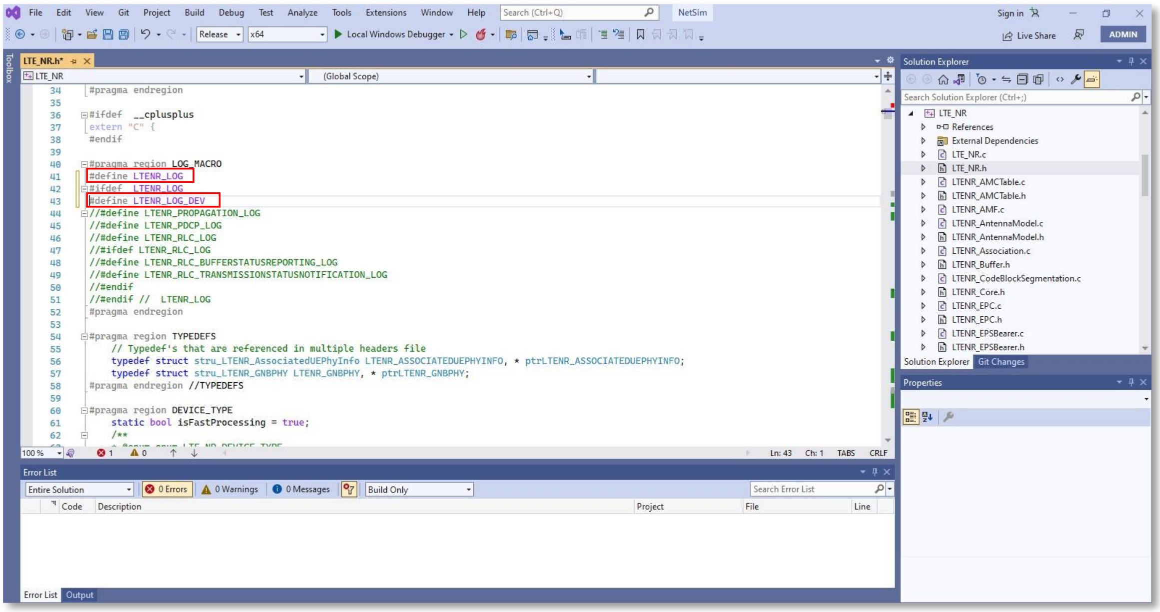

Figure 3-75: Enable LTE_NR log file in visual studio

Then rebuild the code and run the simulation.

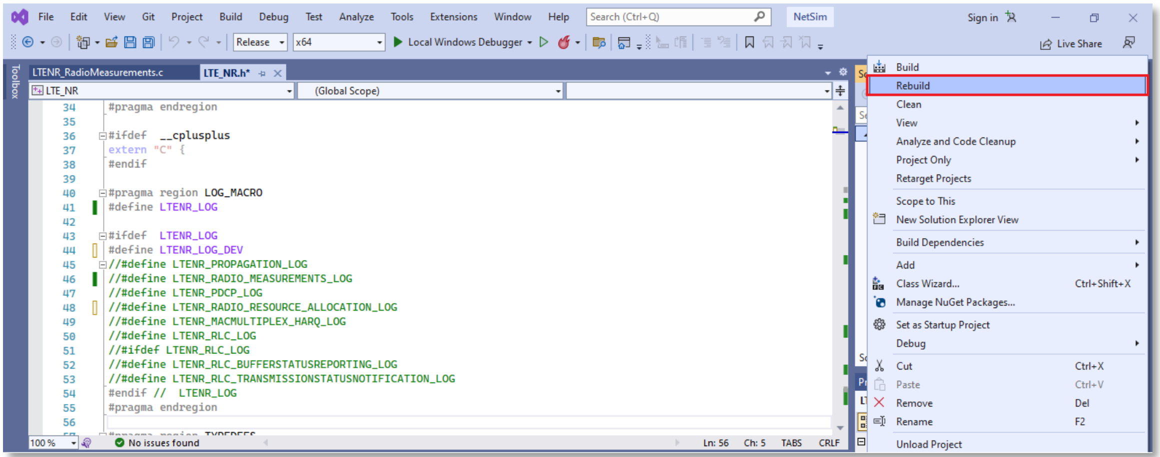

Figure 3-76: Rebuild 5G Project

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

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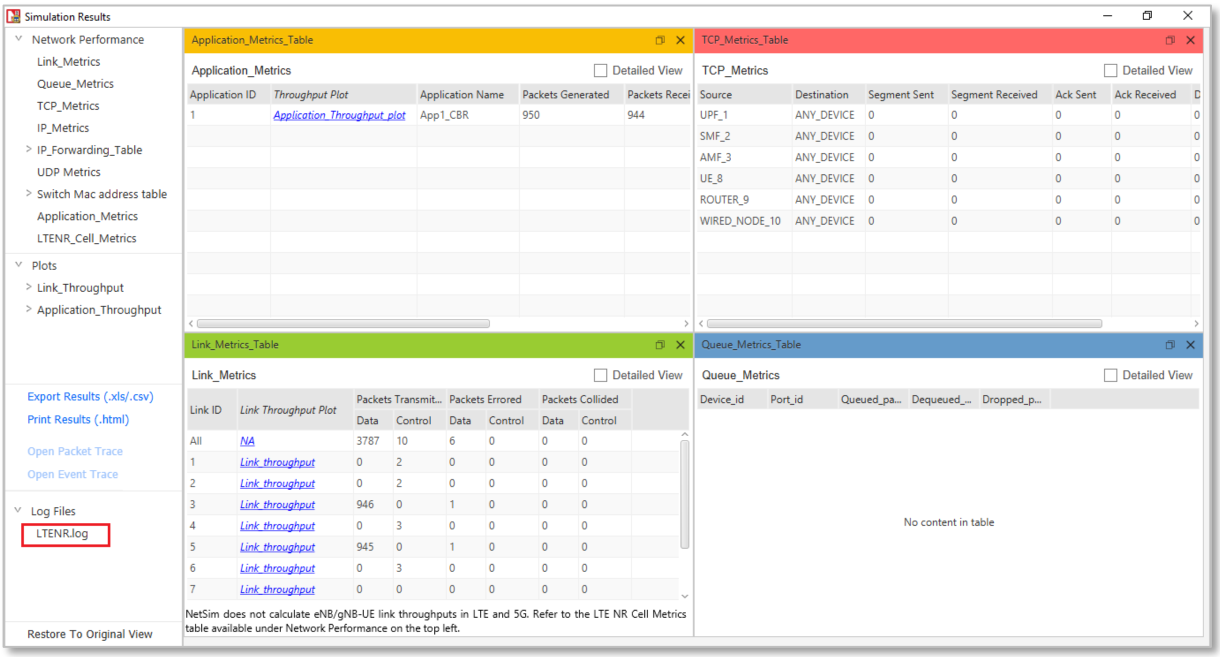

Figure 3-77: Results Window

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

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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.

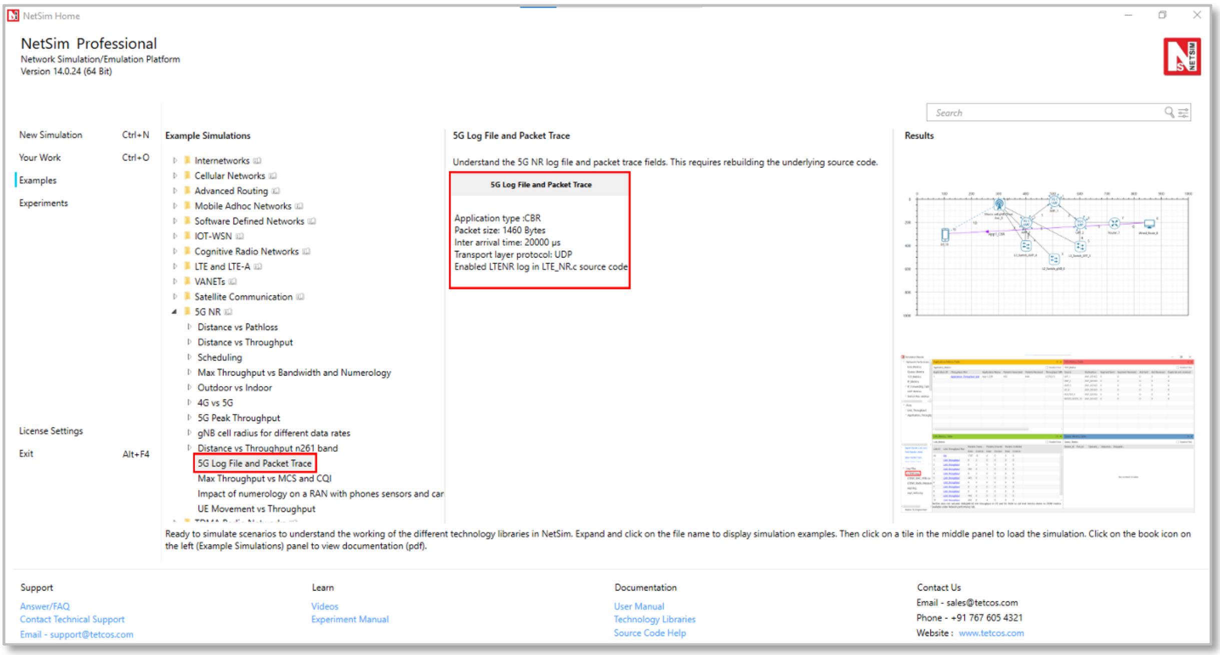

Figure 4-1: List of scenarios for the example: 5G Log File and Packet Trace

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

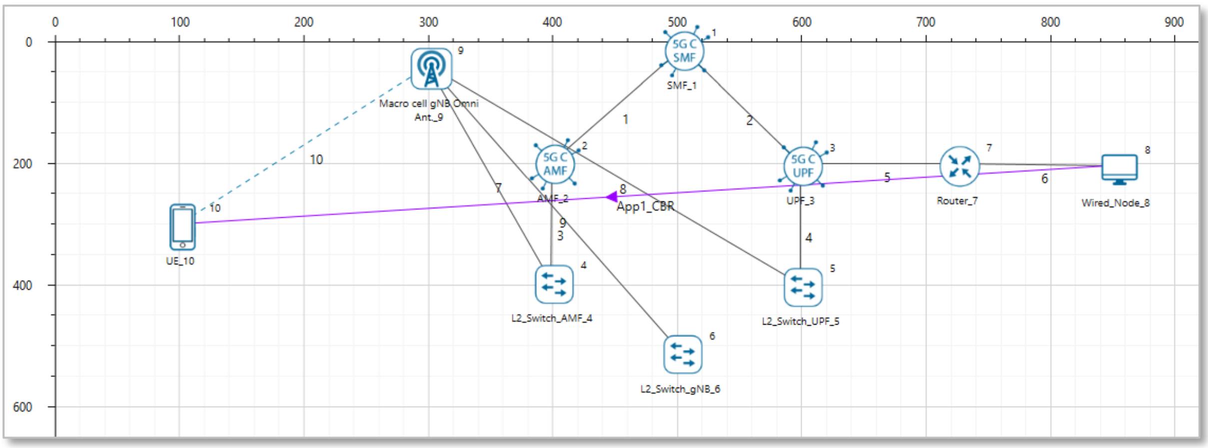

Figure 4-2: Network set up for studying the 5G Log File and Packet Trace

Settings done in example config file:

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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 be enabled per the information provided in Section 3.22.
4. Enable Plots, Packet Trace 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, open the source code and inside the LTE NR project, uncomment the lines given below in LTE_NR.h

LTE_NR.h

```
#define LTENR_LOG_DEV

#define LTENR_PDCP_LOG

#define LTENR_RLC_BUFFERSTATUSREPORTING_LOG
```

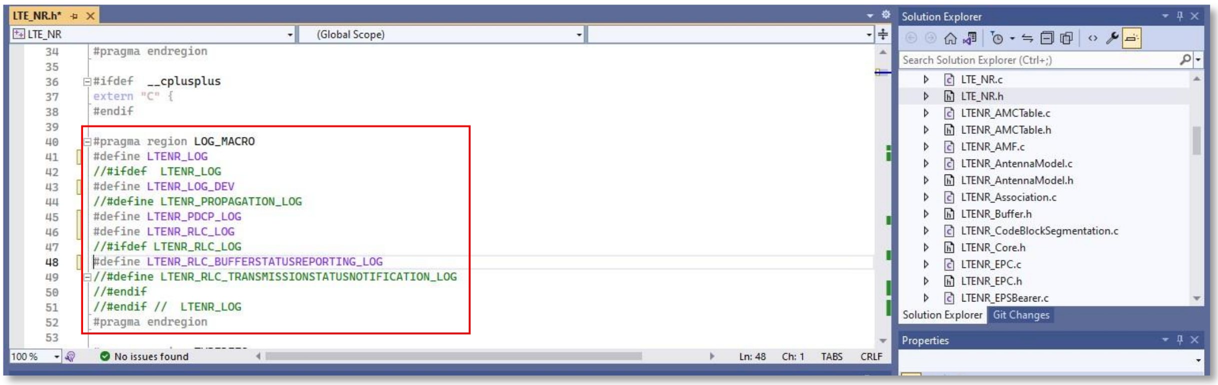

Figure 4-3: LTENR code uncomment to log Buffer-status-notification and Transmission-status-notification

Rebuild the code to enable logs per Section 3.22 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.

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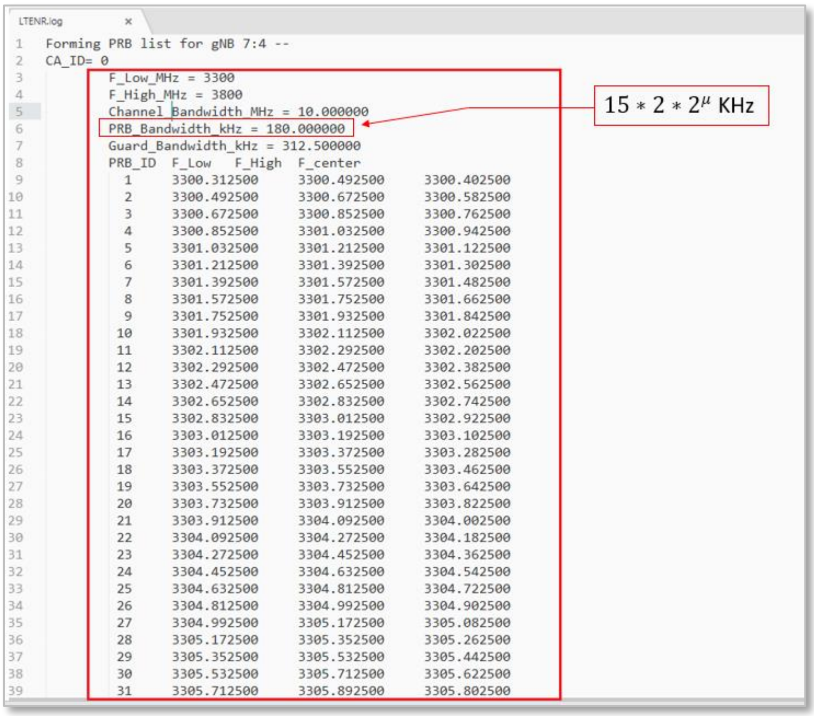


```
Forming PRB list for gNB 7:4 --
CA_ID= 0
        F_Low_MHz = 3300
        F_High_MHz = 3800
        Channel_Bandwidth_MHz = 10.000000
        PRB_Bandwidth_kHz = 180.000000
        Guard_Bandwidth_kHz = 312.500000
        PRB_ID  F_Low   F_High  F_center
          1     3300.312500     3300.492500     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
```

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.

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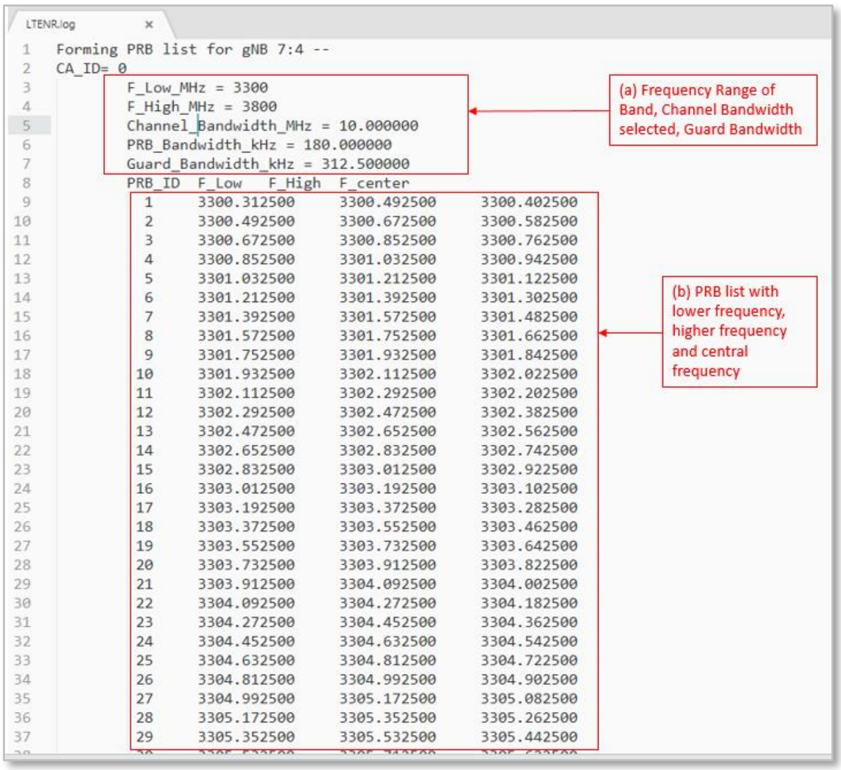

```
LTENR.log
Forming PRB list for gNB 7:4 --
CA_ID= 0
        F_Low_MHz = 3300
        F_High_MHz = 3800
        Channel_Bandwidth_MHz = 10.000000
        PRB_Bandwidth_kHz = 180.000000
        Guard_Bandwidth_kHz = 312.500000
        PRB_ID  F_Low   F_High  F_center
        1       3300.312500     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.

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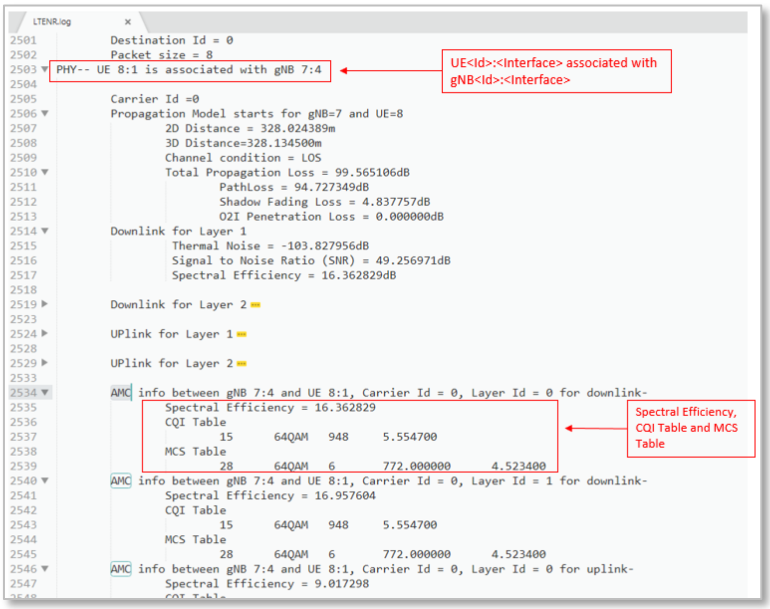

Figure 4-6: LTE NR Log File: UE Association

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.

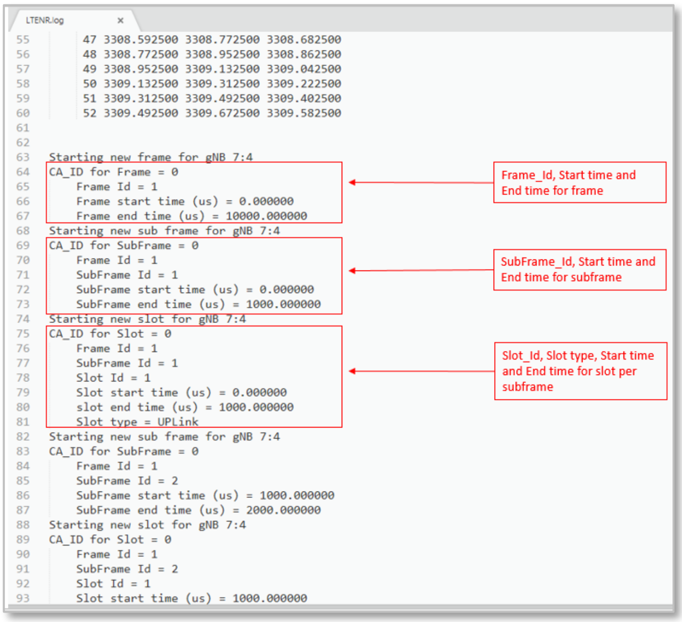

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Figure 4-7: LTE NR Log File: Frame and Sub Frame list with start time and end time

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.

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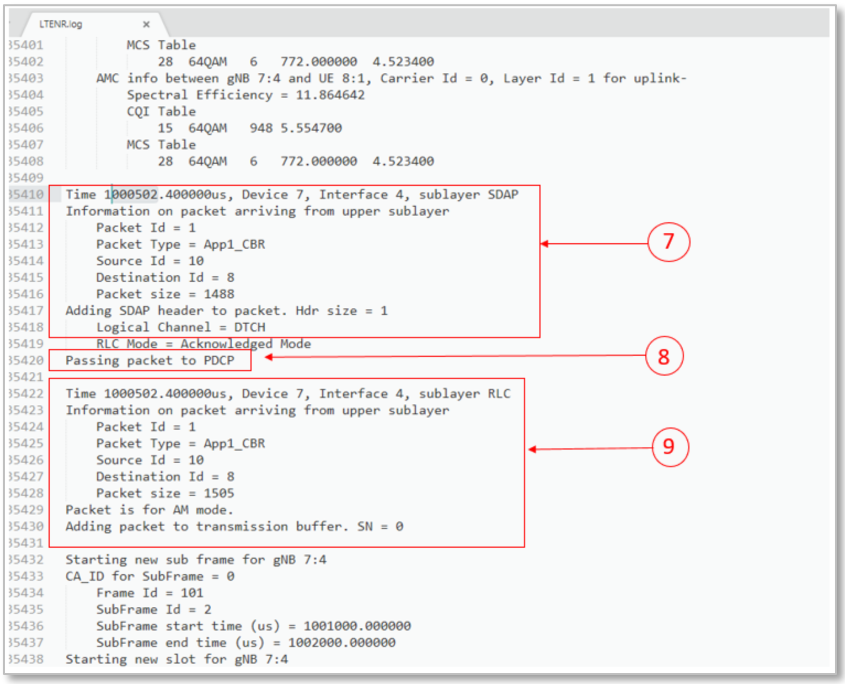
9. The packet is then passed to the Radio Link Control (RLC) sub-layer at gNB and is added to the transmission buffer.


```
LTENR.log
        MCS Table
            28  64QAM   6   772.000000  4.523400
    AMC info between gNB 7:4 and UE 8:1, Carrier Id = 0, Layer Id = 1 for uplink-
        Spectral Efficiency = 11.864642
        CQI Table
            15  64QAM   948 5.554700
        MCS Table
            28  64QAM   6   772.000000  4.523400

Time 1000502.400000us, Device 7, Interface 4, sublayer SDAP
Information on packet arriving from upper sublayer
    Packet Id = 1
    Packet Type = App1_CBR
    Source Id = 10
    Destination Id = 8
    Packet size = 1488
Adding SDAP header to packet. Hdr size = 1
    Logical Channel = DTCH
    RLC Mode = Acknowledged Mode
Passing packet to PDCP

Time 1000502.400000us, Device 7, Interface 4, sublayer RLC
Information on packet arriving from upper sublayer
    Packet Id = 1
    Packet Type = App1_CBR
    Source Id = 10
    Destination Id = 8
    Packet size = 1505
Packet is for AM mode.
Adding packet to transmission buffer. SN = 0

Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 101
    SubFrame Id = 2
    SubFrame start time (us) = 1001000.000000
    SubFrame end time (us) = 1002000.000000
Starting new slot for gNB 7:4
```


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)

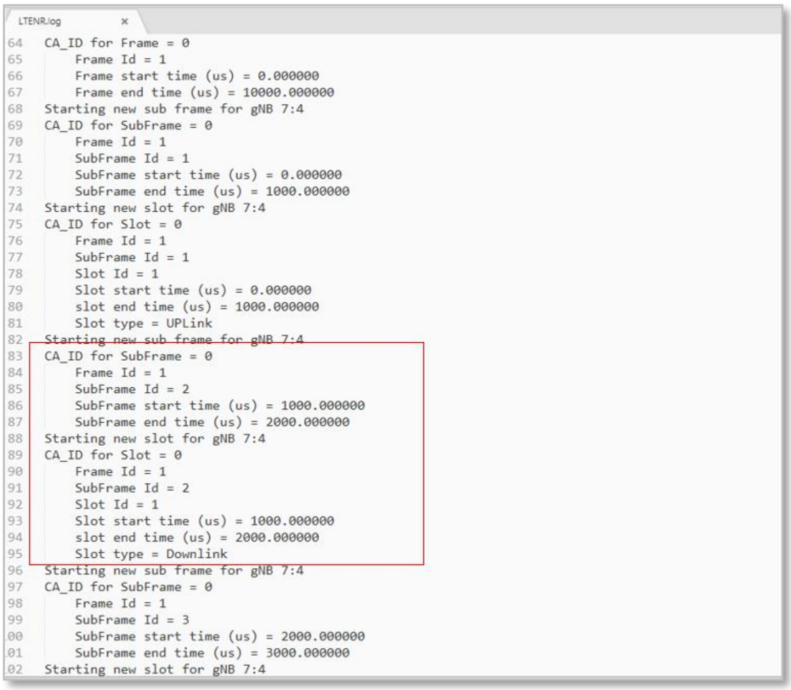

```
LTENR.log
CA_ID for Frame = 0
    Frame Id = 1
    Frame start time (us) = 0.000000
    Frame end time (us) = 10000.000000
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 1
    SubFrame Id = 1
    SubFrame start time (us) = 0.000000
    SubFrame end time (us) = 1000.000000
Starting new slot for gNB 7:4
CA_ID for Slot = 0
    Frame Id = 1
    SubFrame Id = 1
    Slot Id = 1
    Slot start time (us) = 0.000000
    slot end time (us) = 1000.000000
    Slot type = UPLink
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 1
    SubFrame Id = 2
    SubFrame start time (us) = 1000.000000
    SubFrame end time (us) = 2000.000000
Starting new slot for gNB 7:4
CA_ID for Slot = 0
    Frame Id = 1
    SubFrame Id = 2
    Slot Id = 1
    Slot start time (us) = 1000.000000
    slot end time (us) = 2000.000000
    Slot type = Downlink
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 1
    SubFrame Id = 3
    SubFrame start time (us) = 2000.000000
    SubFrame end time (us) = 3000.000000
Starting new slot for gNB 7:4
```

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.

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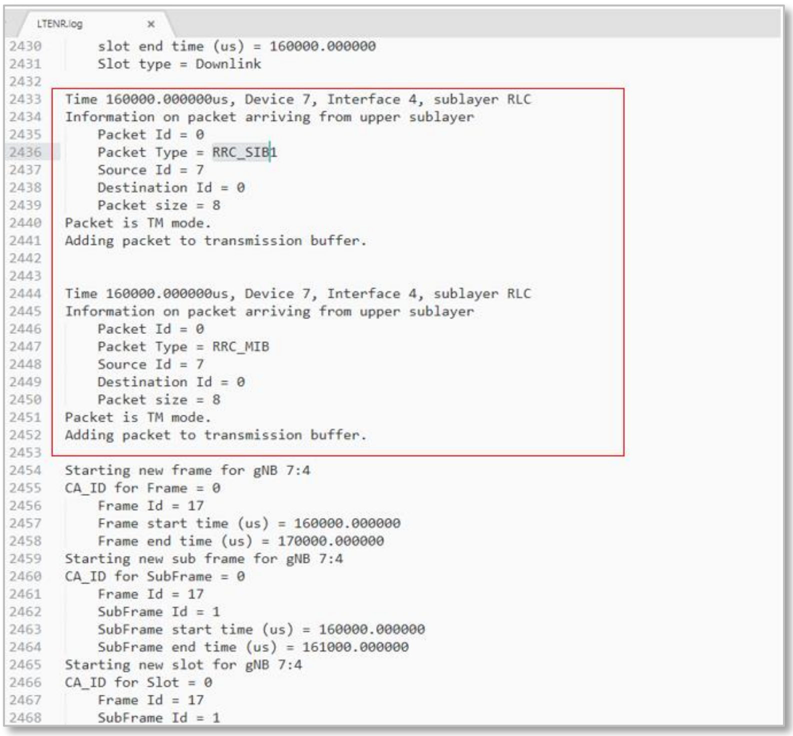

```
LTENR.log
    slot end time (us) = 160000.000000
    Slot type = Downlink

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.

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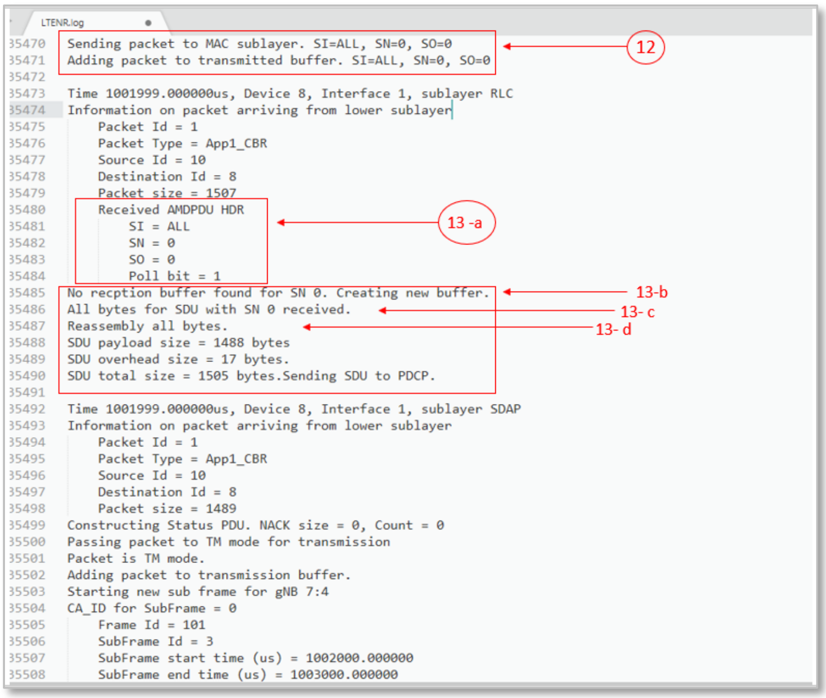


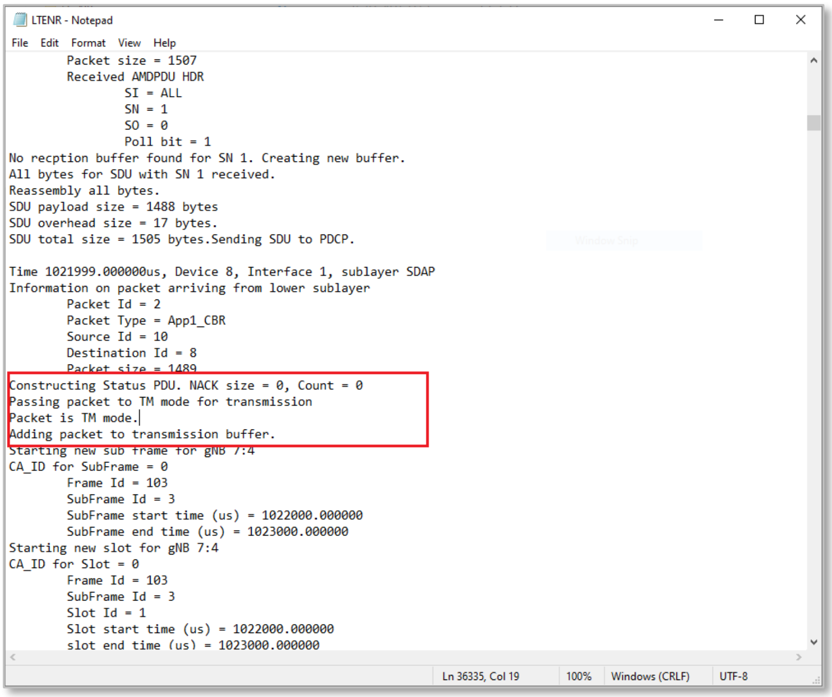

```
Sending packet to MAC sublayer. SI=ALL, SN=0, SO=0
Adding packet to transmitted buffer. SI=ALL, SN=0, SO=0

Time 1001999.000000us, Device 8, Interface 1, sublayer RLC
Information on packet arriving from lower sublayer
    Packet Id = 1
    Packet Type = App1_CBR
    Source Id = 10
    Destination Id = 8
    Packet size = 1507
    Received AMDPDU HDR
        SI = ALL
        SN = 0
        SO = 0
        Poll bit = 1
No recption buffer found for SN 0. Creating new buffer.
All bytes for SDU with SN 0 received.
Reassembly all bytes.
SDU payload size = 1488 bytes
SDU overhead size = 17 bytes.
SDU total size = 1505 bytes.Sending SDU to PDCP.

Time 1001999.000000us, Device 8, Interface 1, sublayer SDAP
Information on packet arriving from lower sublayer
    Packet Id = 1
    Packet Type = App1_CBR
    Source Id = 10
    Destination Id = 8
    Packet size = 1489
Constructing Status PDU. NACK size = 0, Count = 0
Passing packet to TM mode for transmission
Packet is TM mode.
Adding packet to transmission buffer.
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
    Frame Id = 101
    SubFrame Id = 3
    SubFrame start time (us) = 1002000.000000
    SubFrame end time (us) = 1003000.000000
```

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.




```
        Packet size = 1507
        Received AMDPDU HDR
                SI = ALL
                SN = 1
                SO = 0
                Poll bit = 1
No recption buffer found for SN 1. Creating new buffer.
All bytes for SDU with SN 1 received.
Reassembly all bytes.
SDU payload size = 1488 bytes
SDU overhead size = 17 bytes.
SDU total size = 1505 bytes.Sending SDU to PDCP.

Time 1021999.000000us, Device 8, Interface 1, sublayer SDAP
Information on packet arriving from lower sublayer
        Packet Id = 2
        Packet Type = App1_CBR
        Source Id = 10
        Destination Id = 8
        Packet size = 1489
Constructing Status PDU. NACK size = 0, Count = 0
Passing packet to TM mode for transmission
Packet is TM mode.
Adding packet to transmission buffer.
Starting new sub frame for gNB 7:4
CA_ID for SubFrame = 0
        Frame Id = 103
        SubFrame Id = 3
        SubFrame start time (us) = 1022000.000000
        SubFrame end time (us) = 1023000.000000
Starting new slot for gNB 7:4
CA_ID for Slot = 0
        Frame Id = 103
        SubFrame Id = 3
        Slot Id = 1
        Slot start time (us) = 1022000.000000
        slot end time (us) = 1023000.000000
```

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.

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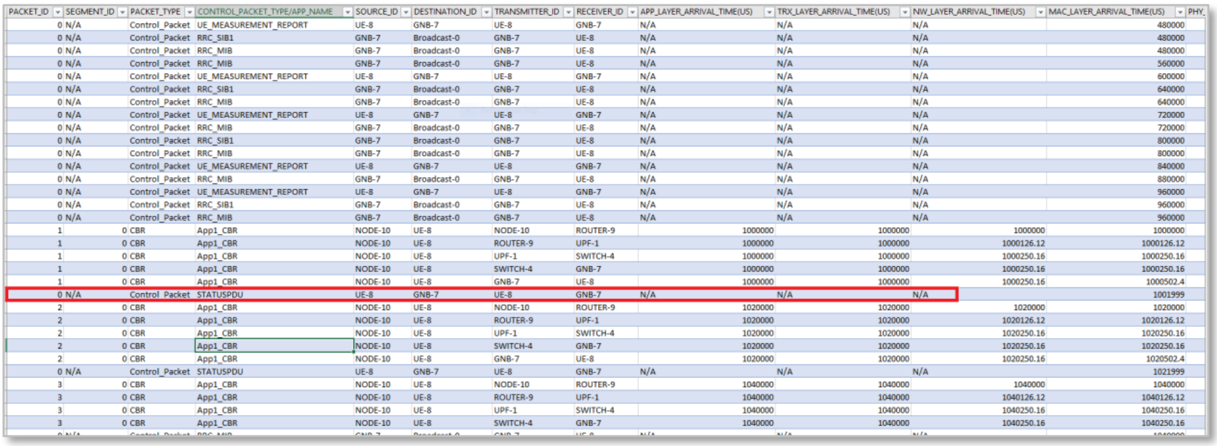
16. Next the STATUSPDU gets transmitted from the UE to the gNB (See Packet Trace)



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)
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.

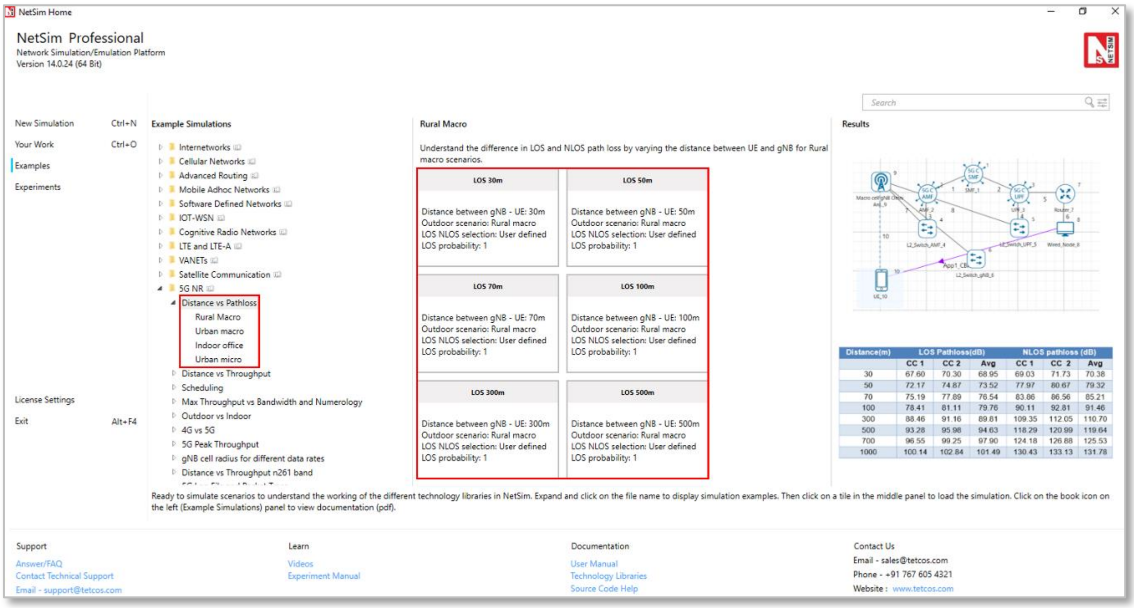


Figure 4-14: List of scenarios for the example of Distance vs Pathloss

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

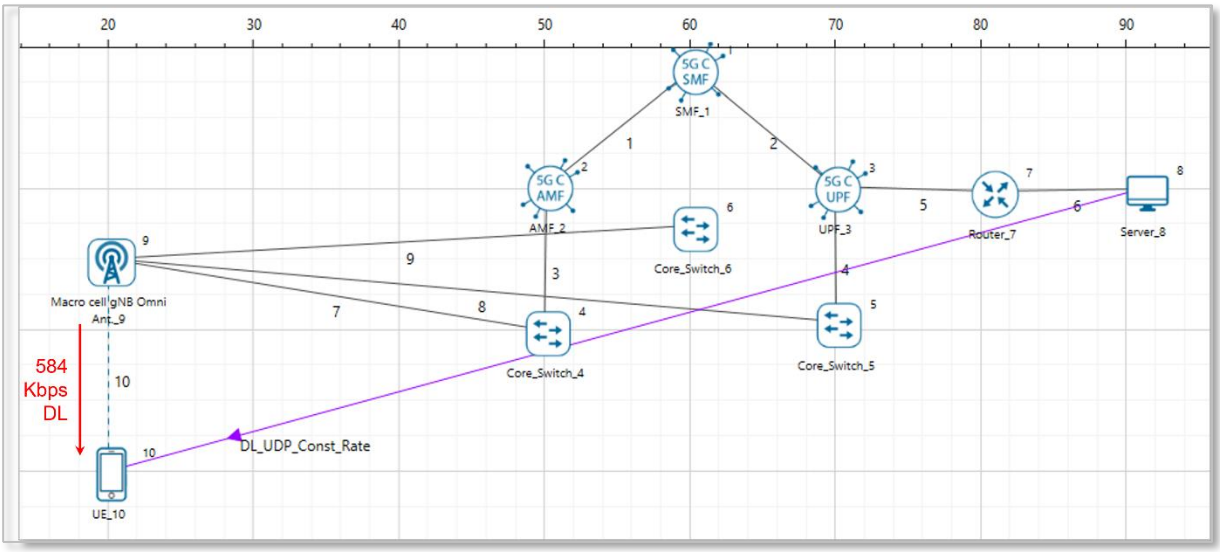


Figure 4-15: Network set up for studying the Distance vs Pathloss

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 Probability	1
Shadow Fading Model	None
Fading and Beamforming	NO_FADING_MIMO_UNIT_GAIN

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

NOTE: HARQ mode in gNB properties à Interface (5G_RAN) a Datalink layer is disabled in all 5G featured examples.

1. 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.
2. Set UE height as 10m.
3. Set other properties to default.

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4. The LTENR Radio measurement log file must be enabled from the design window.
    - Logs can be enabled by clicking on the icon in Configure Reports option as shown below.

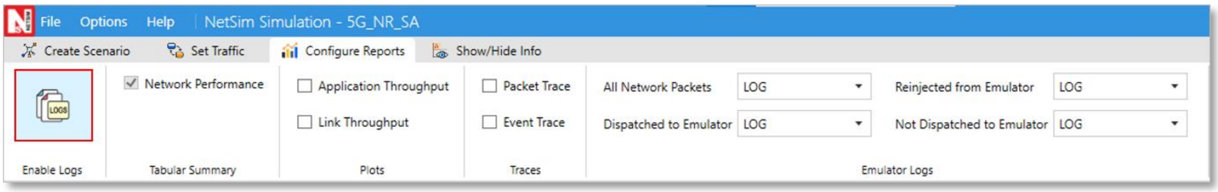

Figure 4-16: Enabling log files in NetSim GUI.

- Select the LTENR Radio Measurements log and click on OK.

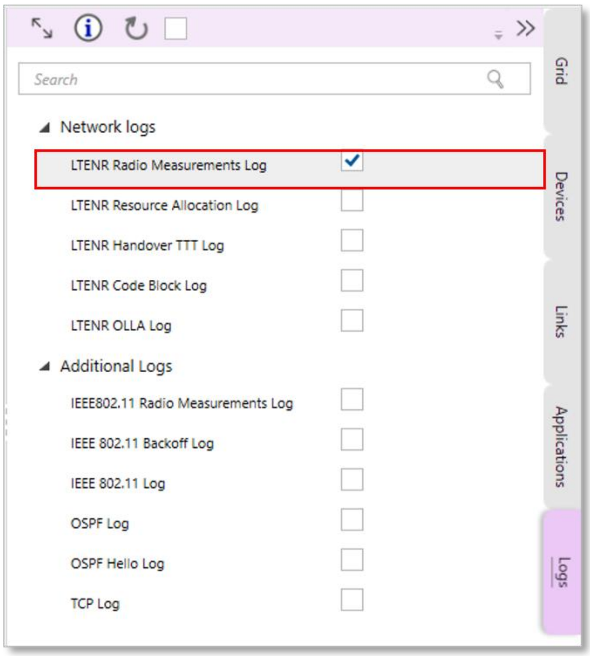

Figure 4-17: Enabling LTENR Radio Measurements Log

5. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the Pathloss.

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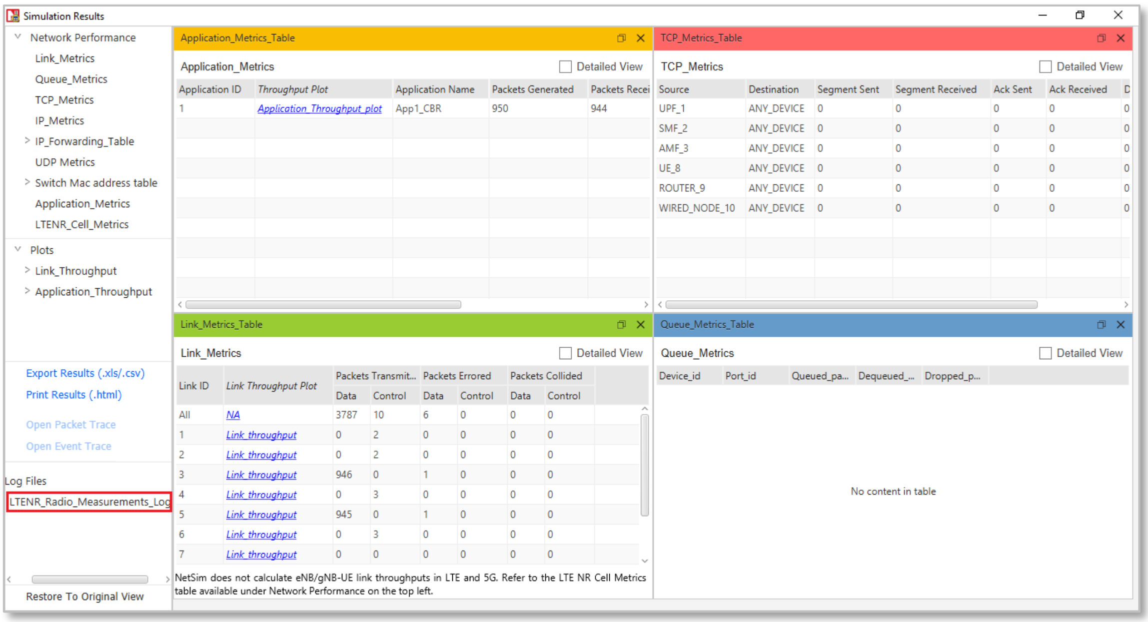
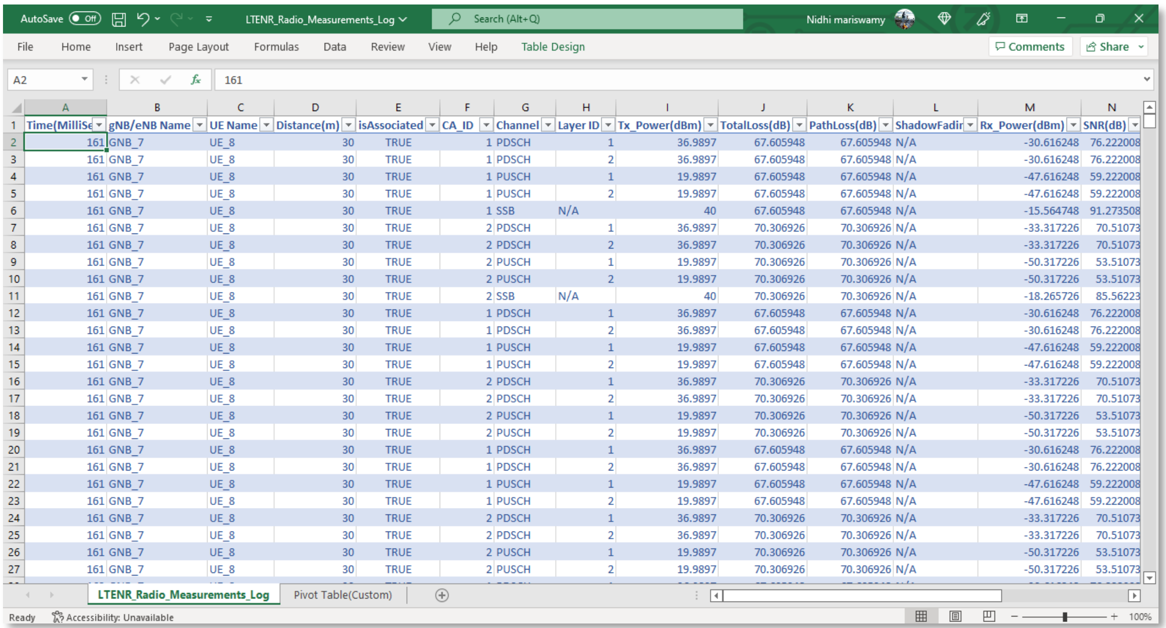


Figure 4-18: Results window



Time(MilliSe	gNB/eNB Name	UE Name	Distance(m)	isAssociated	CA_ID	Channel	Layer ID	Tx_Power(dBm)	TotalLoss(dB)	PathLoss(dB)	ShadowFadir	Rx_Power(dBm)	SNR(dB)
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	1	SSB	N/A	40	67.605948	67.605948	N/A	-15.564748	91.273508
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073
161	GNB_7	UE_8	30	TRUE	2	SSB	N/A	40	70.306926	70.306926	N/A	-18.265726	85.56223
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073
161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	67.605948	67.605948	N/A	-30.616248	76.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	67.605948	67.605948	N/A	-47.616248	59.222008
161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	70.306926	70.306926	N/A	-33.317226	70.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073
161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	70.306926	70.306926	N/A	-50.317226	53.51073

Figure 4-19: LTENR Radio Measurement log.csv 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

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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_MIMO_UNIT_GAIN

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

3. Set all other properties same as LOS example.
4. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20.
5. Run Simulation for 20s.

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)		
	CC 1	CC 2	Avg	CC 1	CC 2	Avg
30	67.60	70.30	68.95	69.03	71.73	70.38
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

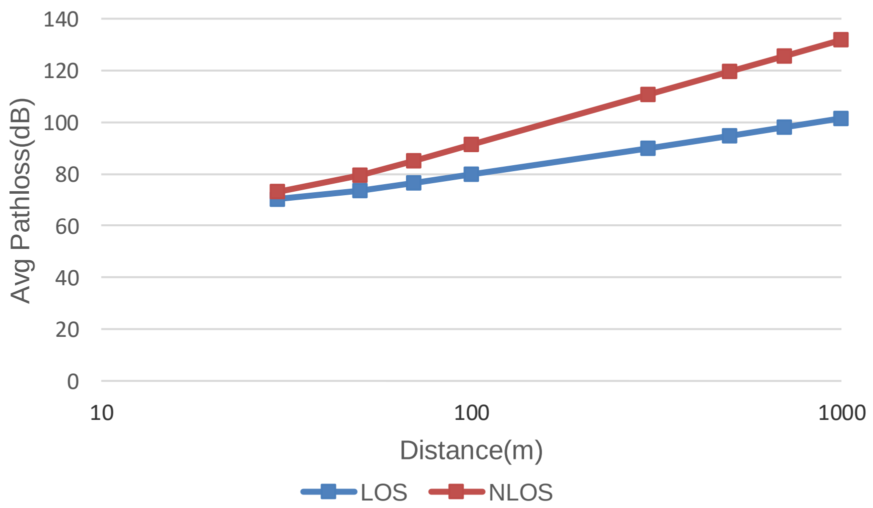

Figure 4-20: Plot of Distance vs. Avg Pathloss

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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_MIMO_UNIT_GAIN

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. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20
7. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the pathloss.

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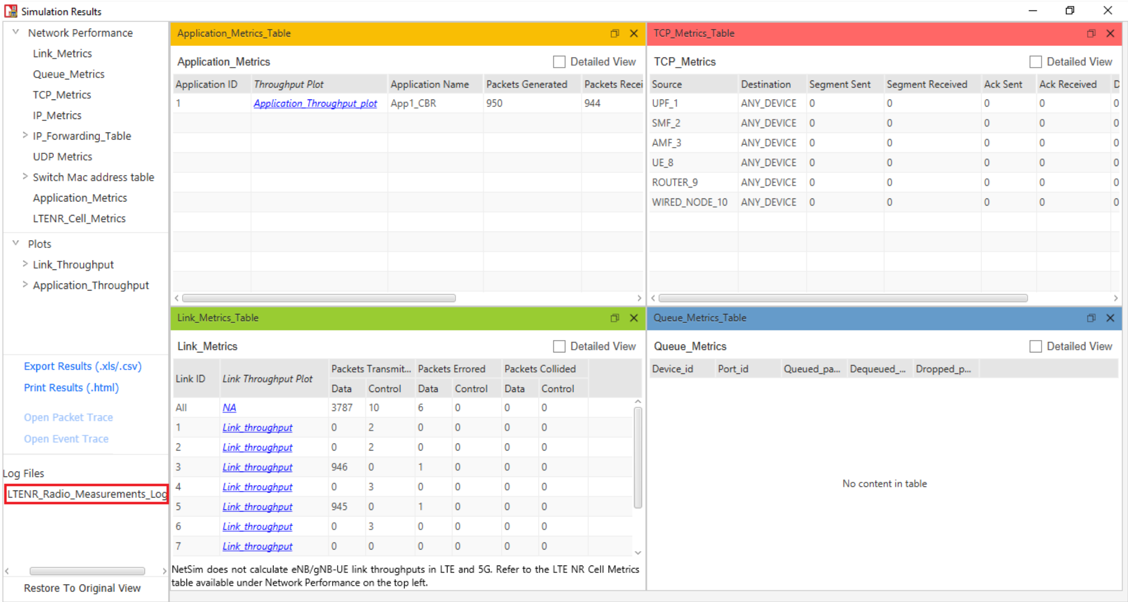

Figure 4-21: Result window

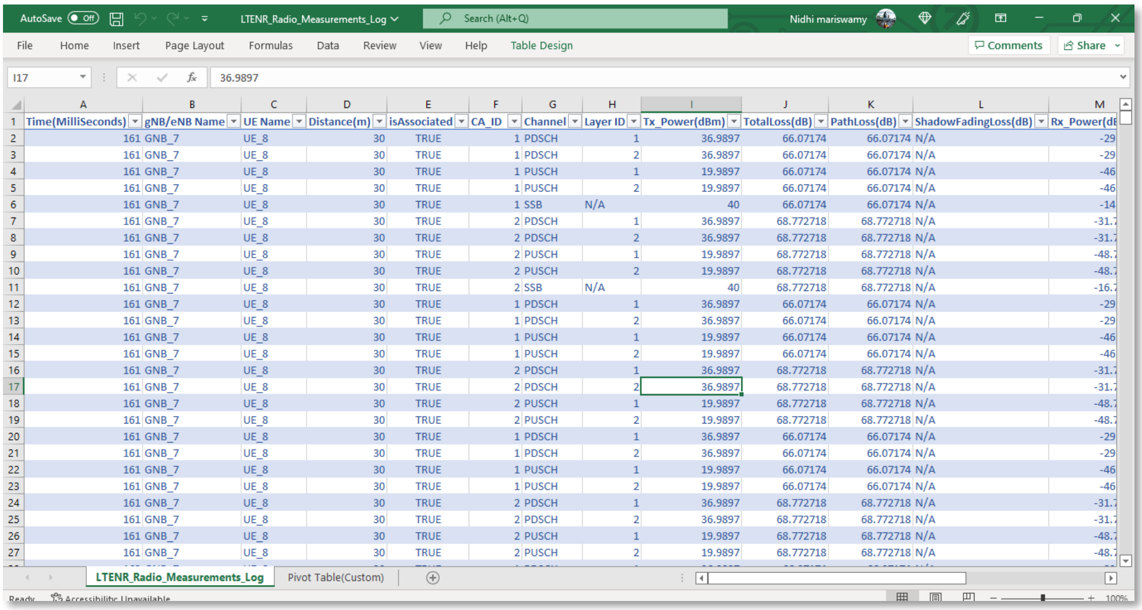

Figure 4-22: LTENR Radio Measurement log.csv file

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 considered as 10m.

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 à Interface (5G_RAN) à PHYSICAL_LAYER

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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	0
Shadow Fading Model	None
Fading_and_Beamforming	NO_FADING_MIMO_UNIT_GAIN

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

3. Set all other properties same as LOS example.
4. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20.
5. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the pathloss.
6. 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)		
	CC 1	CC 2	Avg	CC 1	CC 2	Avg
30	66.07	68.77	67.42	71.74	74.44	73.09
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

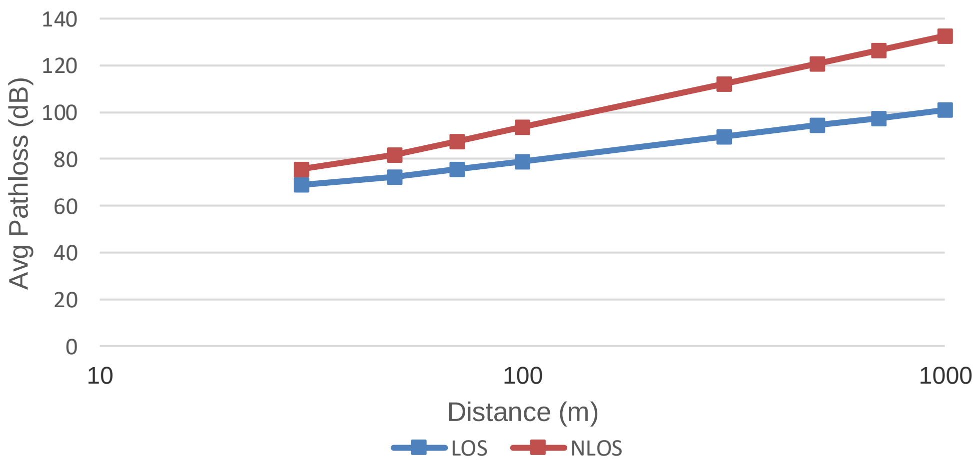

Figure 4-23: Plot of Distance vs. Avg Pathloss

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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_MIMO_UNIT_GAIN

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. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20
7. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the Pathloss.

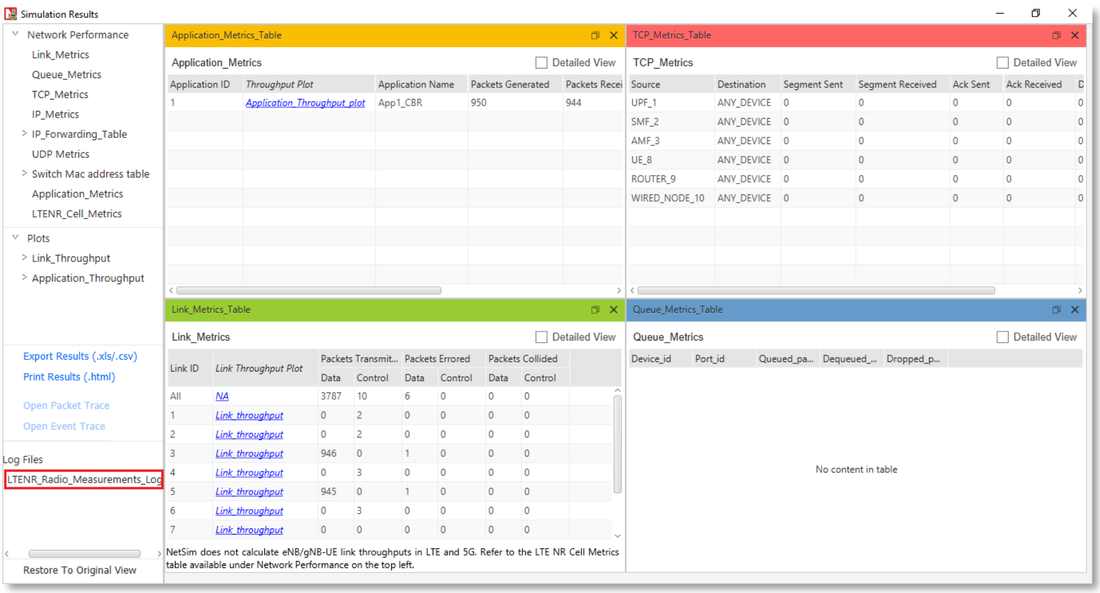

Figure 4-24: Result window

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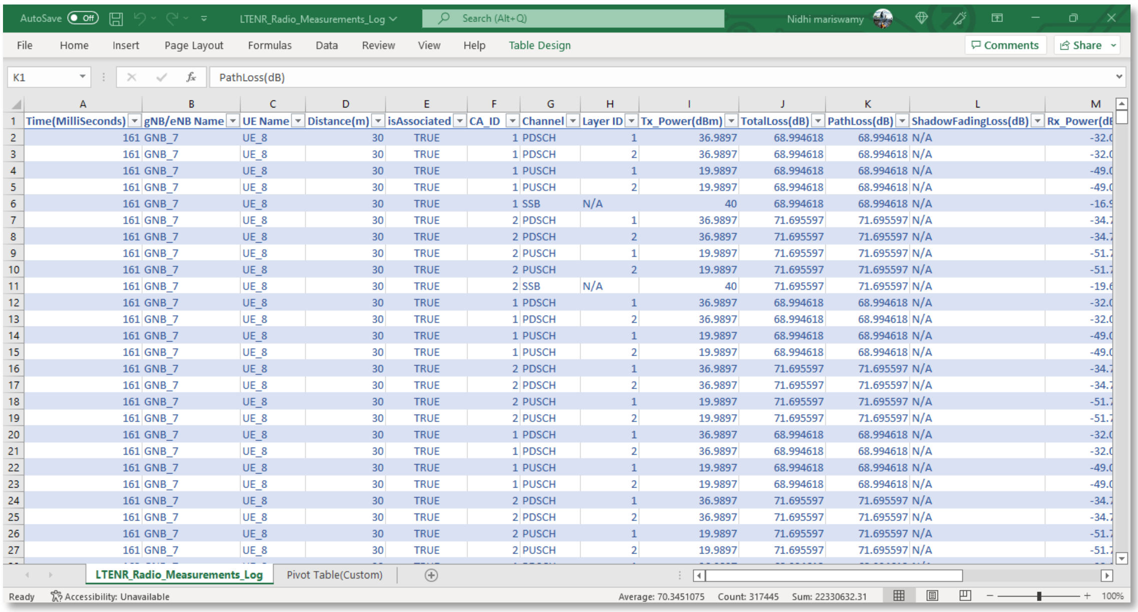

	Time(MilliSeconds)	gNB/eNB Name	UE Name	Distance(m)	isAssociated	CA_ID	Channel	Layer ID	Tx_Power(dBm)	TotalLoss(dB)	PathLoss(dB)	ShadowFadingLoss(dB)	Rx_Power(dE
2	161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	68.994618	68.994618	N/A	-32.0
3	161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	68.994618	68.994618	N/A	-32.0
4	161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	68.994618	68.994618	N/A	-49.0
5	161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	68.994618	68.994618	N/A	-49.0
6	161	GNB_7	UE_8	30	TRUE	1	SSB	N/A	40	68.994618	68.994618	N/A	-16.9
7	161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	71.695597	71.695597	N/A	-34.7
8	161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	71.695597	71.695597	N/A	-34.7
9	161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	71.695597	71.695597	N/A	-51.7
10	161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	71.695597	71.695597	N/A	-51.7
11	161	GNB_7	UE_8	30	TRUE	2	SSB	N/A	40	71.695597	71.695597	N/A	-19.6
12	161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	68.994618	68.994618	N/A	-32.0
13	161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	68.994618	68.994618	N/A	-32.0
14	161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	68.994618	68.994618	N/A	-49.0
15	161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	68.994618	68.994618	N/A	-49.0
16	161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	71.695597	71.695597	N/A	-34.7
17	161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	71.695597	71.695597	N/A	-34.7
18	161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	71.695597	71.695597	N/A	-51.7
19	161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	71.695597	71.695597	N/A	-51.7
20	161	GNB_7	UE_8	30	TRUE	1	PDSCH	1	36.9897	68.994618	68.994618	N/A	-32.0
21	161	GNB_7	UE_8	30	TRUE	1	PDSCH	2	36.9897	68.994618	68.994618	N/A	-32.0
22	161	GNB_7	UE_8	30	TRUE	1	PUSCH	1	19.9897	68.994618	68.994618	N/A	-49.0
23	161	GNB_7	UE_8	30	TRUE	1	PUSCH	2	19.9897	68.994618	68.994618	N/A	-49.0
24	161	GNB_7	UE_8	30	TRUE	2	PDSCH	1	36.9897	71.695597	71.695597	N/A	-34.7
25	161	GNB_7	UE_8	30	TRUE	2	PDSCH	2	36.9897	71.695597	71.695597	N/A	-34.7
26	161	GNB_7	UE_8	30	TRUE	2	PUSCH	1	19.9897	71.695597	71.695597	N/A	-51.7
27	161	GNB_7	UE_8	30	TRUE	2	PUSCH	2	19.9897	71.695597	71.695597	N/A	-51.7

Figure 4-25: LTENR Radio Measurement log.csv 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_MIMO_UNIT_GAIN

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

3. Set all other properties same as LOS example.
4. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20.
5. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the pathloss.
6. 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.

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4.2.3.3 Result

Distance(m)	LOS Pathloss (dB)			NLOS pathloss (dB)		
	CC 1	CC 2	Avg	CC 1	CC 2	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

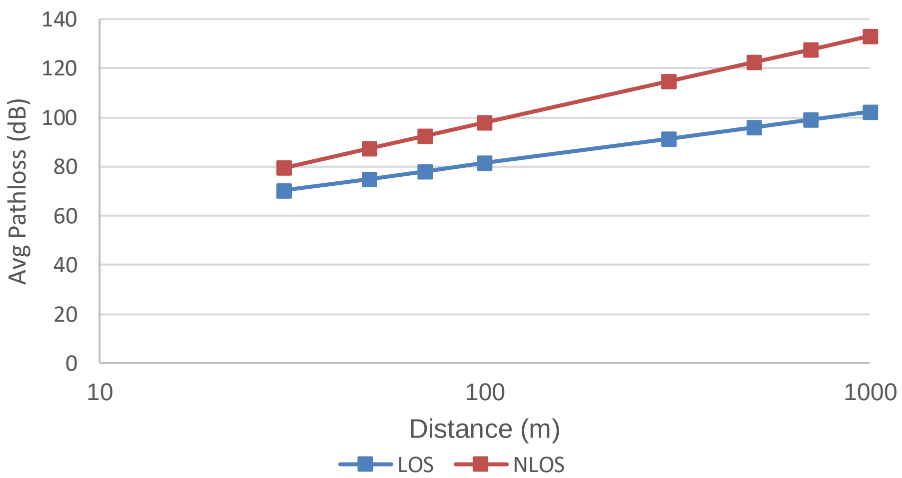

Figure 4-26: Plot of Distance vs. Avg Pathloss

4.2.4 Indoor-Office

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

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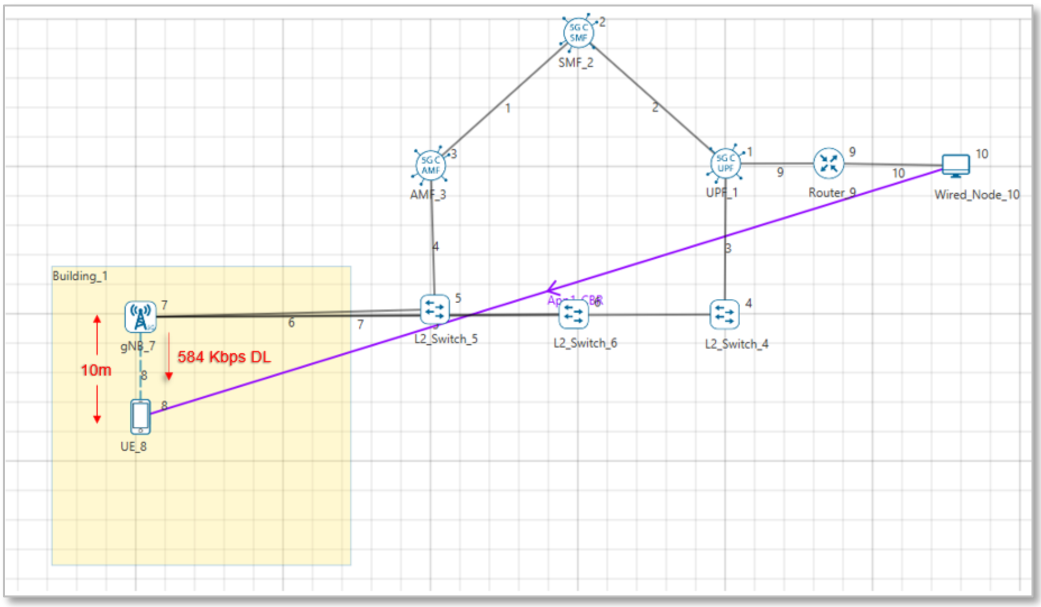

Figure 4-27: Network Topology for this experiment

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_MIMO_UNIT_GAIN
O2I Building Penetration Model	LOW_LOSS_MODEL

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. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20.

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8. Run Simulation for 20s, after the simulation completes Go to metrics window expand Log Files option and open LTENR Radio Measurement Log.csv and note down the Pathloss.

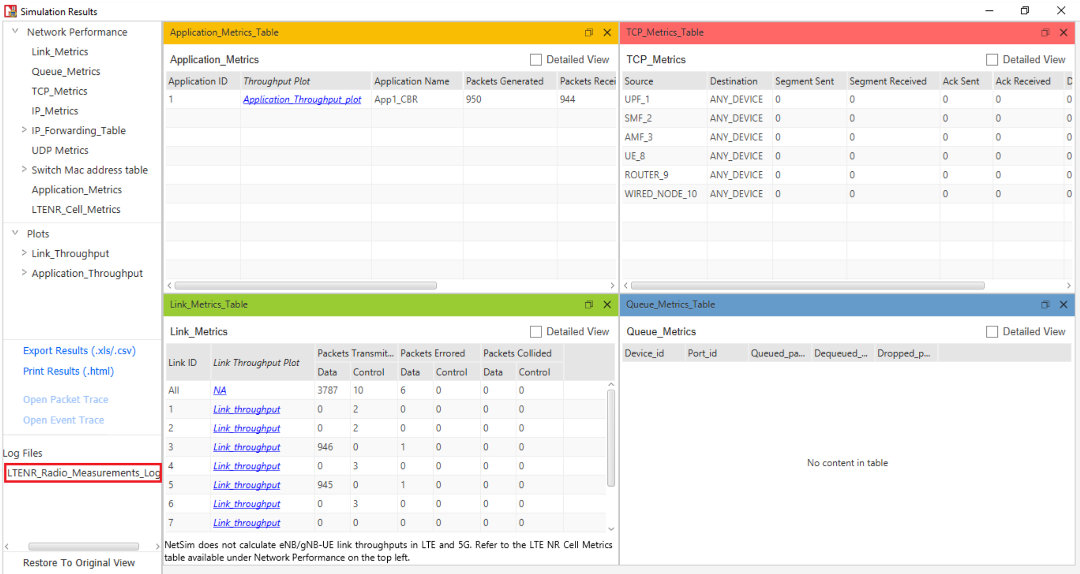

Figure 4-28: Results Window

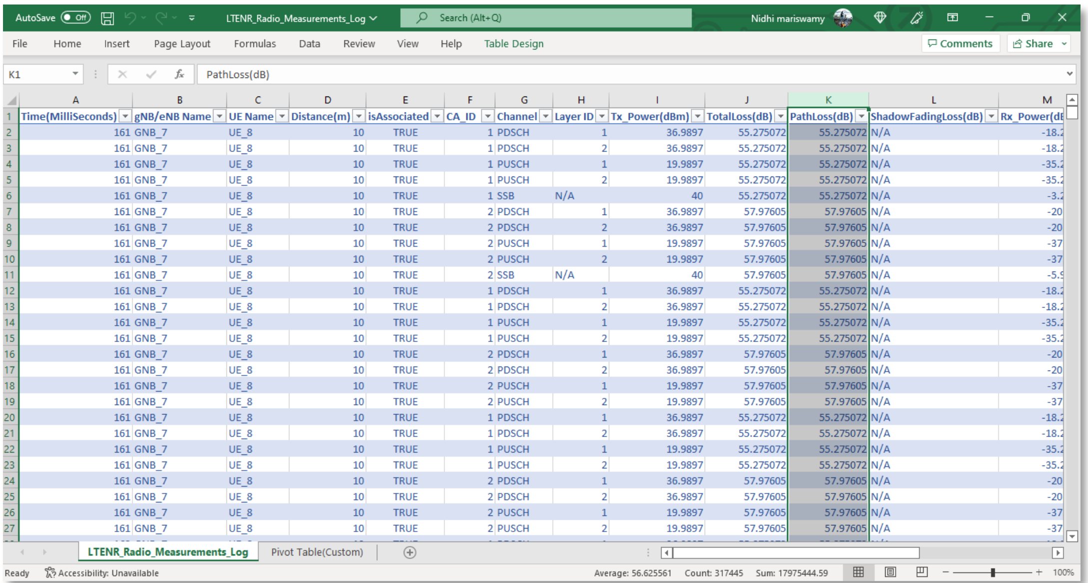

Figure 4-29: LTENR Radio Measurement log.csv file

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.

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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_MIMO_UNIT_GAIN
O2I Building Penetration Model	LOW_LOSS_MODEL

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

4. Set all other properties same as LOS example.
5. The LTENR Radio measurement log file can be enabled as per information provided in the section 3.20.
6. Run Simulation for 20s, after the simulation completes Go to metrics expand Log Files option and open LTENR Radio Measurement Log.csv and note down the pathloss.
7. 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)		
	CC 1	**CC 2**	**Avg**	**CC 1**	**CC 2**	**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

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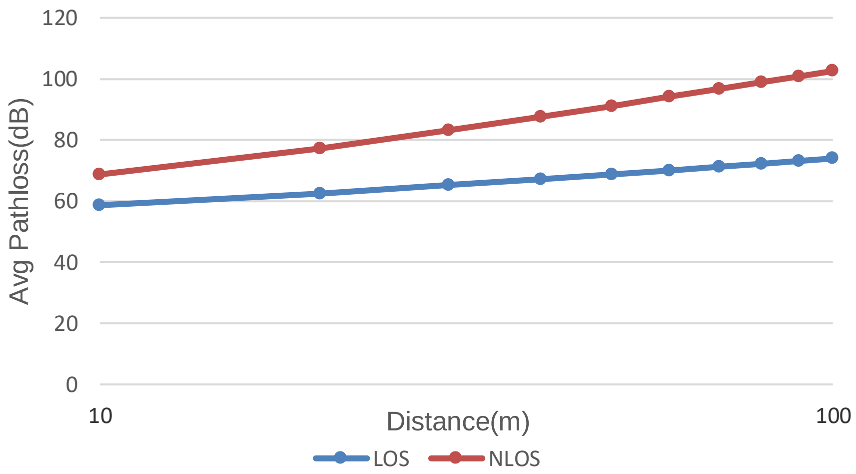

Figure 4-30: Plot of Distance vs. Avg Pathloss

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 3.20 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.

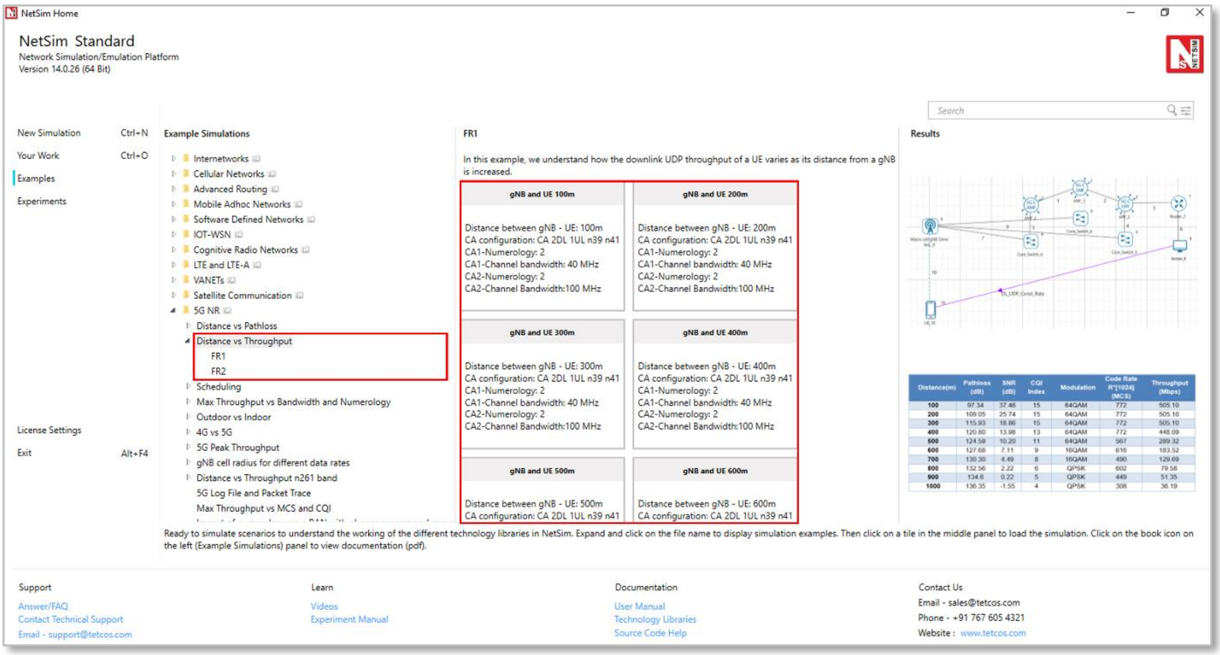

Figure 4-31: List of scenarios for the example of Distance vs Throughput

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

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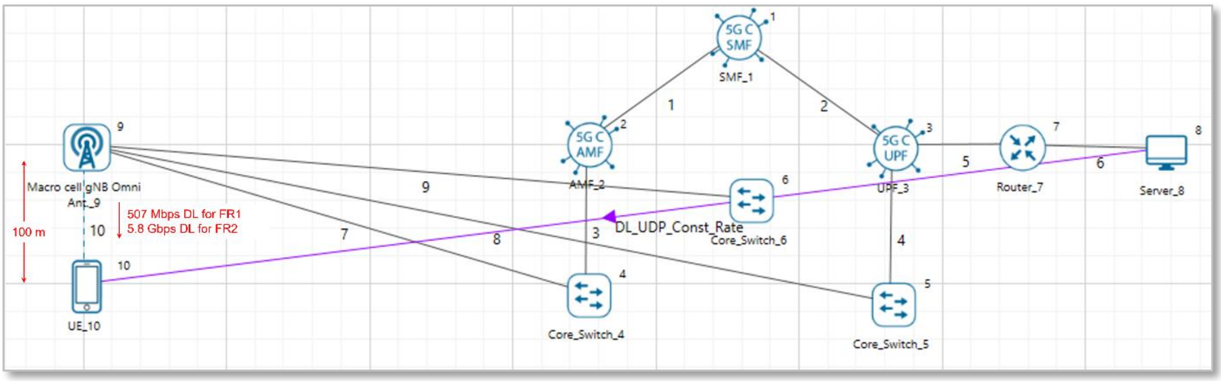

Figure 4-32: Network set up for studying the Distance vs Throughput

4.3.1 Frequency Range - FR1

Settings done in example config file.

1. Set grid length as 2000m from Environment setting.
2. Set distance between gNB_7 and UE_8 as 100m.
3. Go to gNB properties → Interface (5G_RAN) → PHYSICAL_LAYER, set the following properties as shown below Table 4-14.

Properties	
CA_Type	INTER_BAND_CA
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	NO_FADING_MIMO_UNIT_GAIN
Outdoor_Scenario	URBAN_MACRO
LOS_NLOS_Selection	USER_DEFINED
LOS_Probabillity	0
MCS Table	QAMLOWSE
CQI Table	TABLE3

Table 4-13: gNB >Interface (5G_RAN) >Physical layer properties

4. Set Tx_Antenna_Count and Rx_Antenna Count in gNB as 2 and 2.
5. Set Tx_Antenna_Count and Rx_Antenna_Count in UE as 2 and 2.
6. 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

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Packet_Size	1460Bytes
Inter_Arrival_time	23µs
Start_Time	1s

Table 4-14: Application properties

7. The LTENR Radio measurement log file must be enabled from the design window.
    - Logs can be enabled by clicking on the icon in Configure Reports option as shown below.

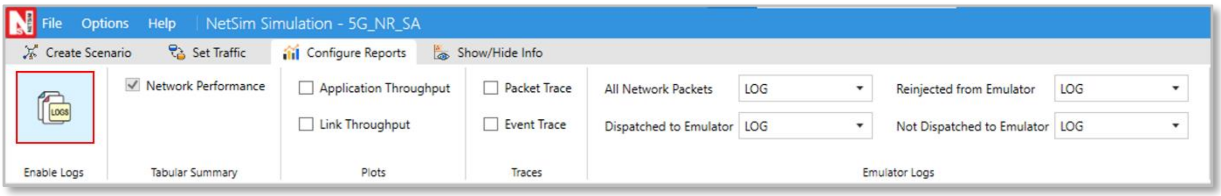

Figure 4-33: Enabling log files in NetSim GUI.

- Select the LTENR Radio Measurements log and click on OK.

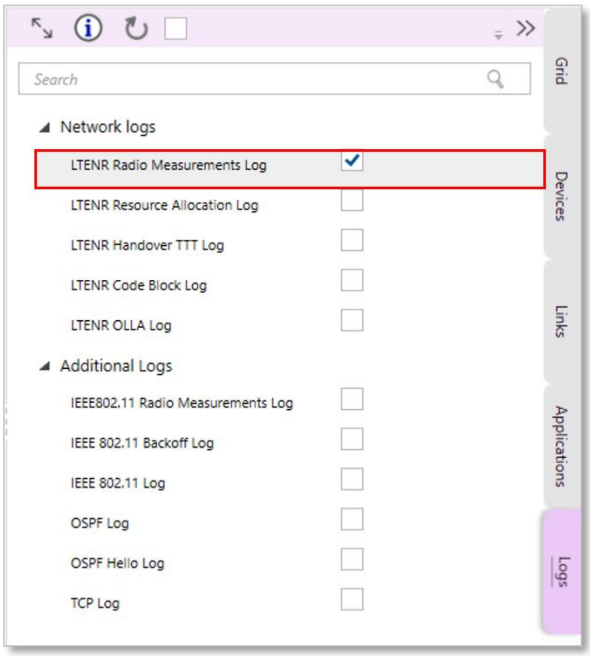

Figure 4-34: Enabling LTENR Radio Measurements Log

8. 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 Radio measurement logs.

4.3.2 Frequency Range - FR2

Settings done in example config file

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1. Set grid length as 2000m from Environment setting.
2. Set distance between gNB_7 and UE_8 as 50m.
3. 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_CONTIGUOUS_CA
CA Configuration		CA_n258G
	Numerology	**Channel Bandwidth (MHz) per carrier**
CA1, CA2	3	400
Pathloss Model		3GPPTR38.901-7.4.1
Shadow Fading Model		None
Fading and Beamforming		NO_FADING_MIMO_UNIT_GAIN
Outdoor Scenario		URBAN_MACRO
LOS NLOS Selection		USER_DEFINED
LOS Probability		0
MCS Table		QAM256
CQI Table		TABLE2

Table 4-15: gNB >Interface (5G_RAN) >Physical layer properties

4. Set Tx_Antenna_Count and Rx_Antenna Count in gNB as 2 and 2.
5. Set Tx_Antenna_Count and Rx_Antenna_Count in UE as 2 and 2.
6. 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 4-16: Application properties

7. The LTENR Radio measurement log file can be enabled as per the information provided in Section 3.20.
8. 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 Radio Measurement log.csv

Results

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NOTE: Filter the CC_ID to 1 in the LTENR Radio measurement log file and same values have been considered in the tables given below. (SNR and CQI are shown for downlink Layer1).

Distance(m)	Pathloss (dB)	SNR (dB)	CQI Index	Modulation	Code Rate R*[1024] (MCS)	Throughput (Mbps)
100	97.33	37.46	15	64QAM	772	507.57
200	109.05	25.74	15	64QAM	772	507.57
300	115.92	18.86	15	64QAM	772	507.57
400	120.80	13.98	15	64QAM	772	448.12
500	124.59	10.20	13	64QAM	567	289.32
600	127.68	7.11	11	16QAM	616	183.52
700	130.30	4.49	10	16QAM	490	129.69
800	132.56	2.22	8	QPSK	602	79.58
900	134.56	0.22	7	QPSK	449	51.35
1000	136.35	-1.55	6	QPSK	308	36.19

Table 4-17: FR1 - Variation of pathloss, SNR, CQI, Modulation, code rates and throughput as the distance of the UE from the gNB is increased.

Distance(m)	Pathloss (dB)	SNR (dB)	MCS Index	Modulation	Code Rate R*[1024] (MCS)	Throughput (Mbps)
50	108.43	16.36	19	64QAM	873	2692.94
100	120.01	4.77	7	16QAM	490	1013.12
150	126.86	-2.06	1	QPSK	308	186.41
200	131.73	-6.94	0	QPSK	120	106.52

Table 4-18: FR 2 - Variation of pathloss, SNR, MCS, 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 UEs 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

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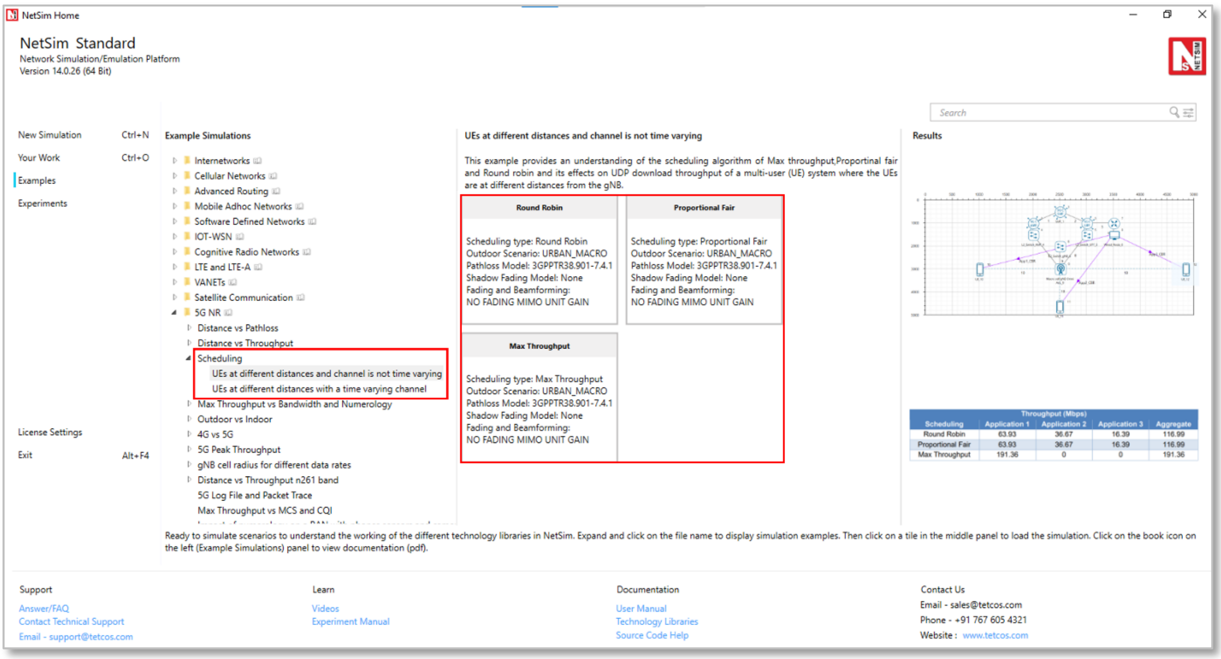

Figure 4-35: List of scenarios for the example of Scheduling

4.4.1 Multi UE throughput with UEs at different distances and channel is not time varying.

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

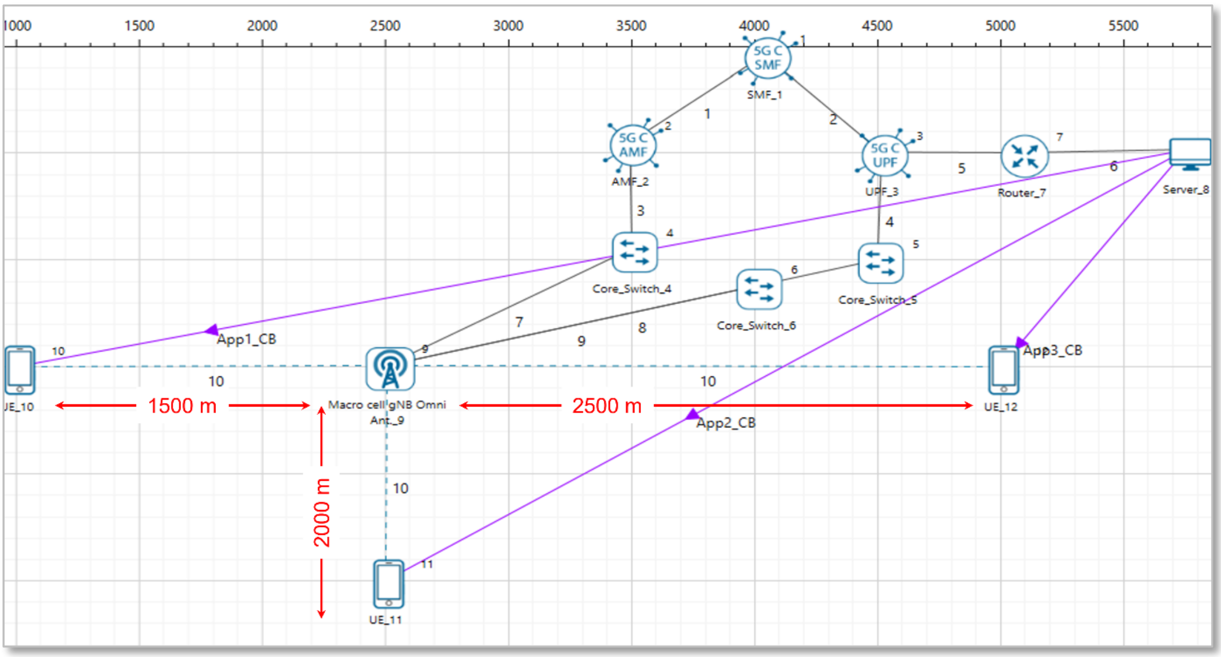

Figure 4-36: Network set up for studying the Scheduling example.

Configuring the scheduling algorithm, and parameter settings in example config files

1. Set grid length as 5000m from Environment setting.
2. Set distance as follows.

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a. gNB_7 to UE_8 = 1500m

b. gNB_7 to UE_11 = 2000m, and

c. gNB_7 to UE_12 = 2500m

3. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below Table 4-22. In the first sample the scheduling type is set to Round Robin, in the second to Proportional fair, and in the third to Max throughput.

Properties	
Data Link Layer Properties	
Scheduling Type	Varies: Proportional Fair, Max throughput, Round Robin
Physical Layer Properties	
CA Type	SINGLE_BAND
CA Configuration	n78
CC1	
Numerology	1
Channel Bandwidth	100 MHz
Outdoor Scenario	URBAN_MACRO
LOS NLOS Selection	USER_DEFINED
LOS Probability	1
Pathloss Model	3GPPTR38.901-7.4.1
Shadow Fading Model	None
Fading and Beamforming	NO_FADING_MIMO_UNIT_GAIN

Table 4-19: gNB >Interface (5G_RAN) >Data Link layer properties

4. Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in gNB properties.
5. Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in all the UEs.
6. 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	10	10	10
Destination ID	8	11	12
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 4-20: Application properties

7. Run Simulation for 1.5s and note down throughput value in the results window in each sample. Recall that each sample has a different scheduling algorithm configured.

Results and discussions

The results with all the three UEs simultaneously downloading data is as given below.

Throughput (Mbps)

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Scheduling	Application 1	Application 2	Application 3	Aggregate
Round Robin	63.93	36.67	16.39	116.99
Proportional Fair	63.93	36.67	16.39	116.99
Max Throughput	191.36	0	0	191.36

Table 4-21: UDP download throughputs for different scheduling algorithms when all three 3 UEs simultaneously downloading data

Next, consider a scenario with only one of the UEs seeing DL traffic (we don't provide inbuilt configuration file for this, and since it is a simple exercise for a user) First, run for the UE at 1500m, then for UE at 2000m and finally for UE at 2500m. This gives the maximum achievable throughput per node since the gNB resources (bandwidth) is not shared between 3 UEs and is fully dedicated to just one UE. The results are below.

Distance from gNB (m)	Application ID	Throughput (Mbps)	Remarks
1500	1	191.36	UE 1 alone has full buffer DL traffic
2000	2	110.16	UE 2 alone has full buffer DL traffic
2500	3	49.26	UE 3 alone has full buffer DL traffic

Table 4-22: UE throughputs if they were run standalone (without the other UEs downloading data)

The PHY rate is decided per the received SNR. Therefore, 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 4-22.The PF scheduler results will match that of the RR scheduler since the channel is not time varying. In Max throughput scheduling the PRBs are allocated such that the system gets the maximum download throughput. The nearest UE will get all the resources and its throughput will be 3 times the throughput of the UE which got the max throughout in RR.

4.4.2 Multi UEs at different distances with a time varying channel

Configuring the scheduling algorithm, and parameter settings will remain the same for the case below.

Changes in the gNB properties are as follows.

1. Go to gNB properties à Interface (5G_RAN), set the following properties as shown below. In the first sample the scheduling type is set to Round Robin, in the second to Proportional fair, and in the third to Max throughput.

Properties
Data Link Layer Properties

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Scheduling Type	Varies: Proportional Fair, Max throughput, Round Robin
Physical Layer Properties	
CA Type	SINGLE_BAND
CA Configuration	n78
CC1	
Numerology	1
Channel Bandwidth	100 MHz
Outdoor Scenario	URBAN_MACRO
LOS NLOS Selection	USER_DEFINED
LOS Probability	1
Pathloss Model	3GPPTR38.901-7.4.1
Shadow Fading Model	None
Fading and Beamforming	RAYLIEGH_WITH_EIGEN_BEAMFORMING

Table 4-23: gNB >Interface (5G_RAN) >Data Link layer properties

2. Run Simulation for 1.5s and note down throughput value in the results window in each sample.

Results and discussions

The results with all the three UEs simultaneously downloading data are as given below.

	Throughput (Mbps)			
Scheduling	**Application 1**	**Application 2**	**Application 3**	**Aggregate**
Round Robin	50.38	29.69	18.73	98.81
Proportional Fair	64.91	37.98	23.12	126.01
Max Throughput	131.25	31.69	0.00	163.94

Table 4-24: UDP download throughputs for different scheduling algorithms when all three 3 UEs simultaneously downloading data with time varying channel.

A difference in the performance of the RR and PF schedulers can be seen when the channel is time varying (of the order of the coherence time which is 10ms). To induce time varying randomness in the channel we enable fading and beamforming. Thus, after every 10ms, NetSim draws an i.e. fading random variable, as the additional loss. Under these conditions, the RR scheduler would allot resources to the UEs in a round robin fashion, whereas the PF scheduler would give preference to the UE which sees the best channel (highest SINR). The reason why the RR scheduler yields lower throughputs than the PF scheduler is that the RR scheduler is not “opportunistic,” i.e., it does not take advantage of the knowledge that a UE has a good channel in the next slot and continues to serve the UEs cyclically. The results are shown in Table 4-24; observe how this is different from Table 4-22 where the channel is not time varying.

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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 Figure 4-37.

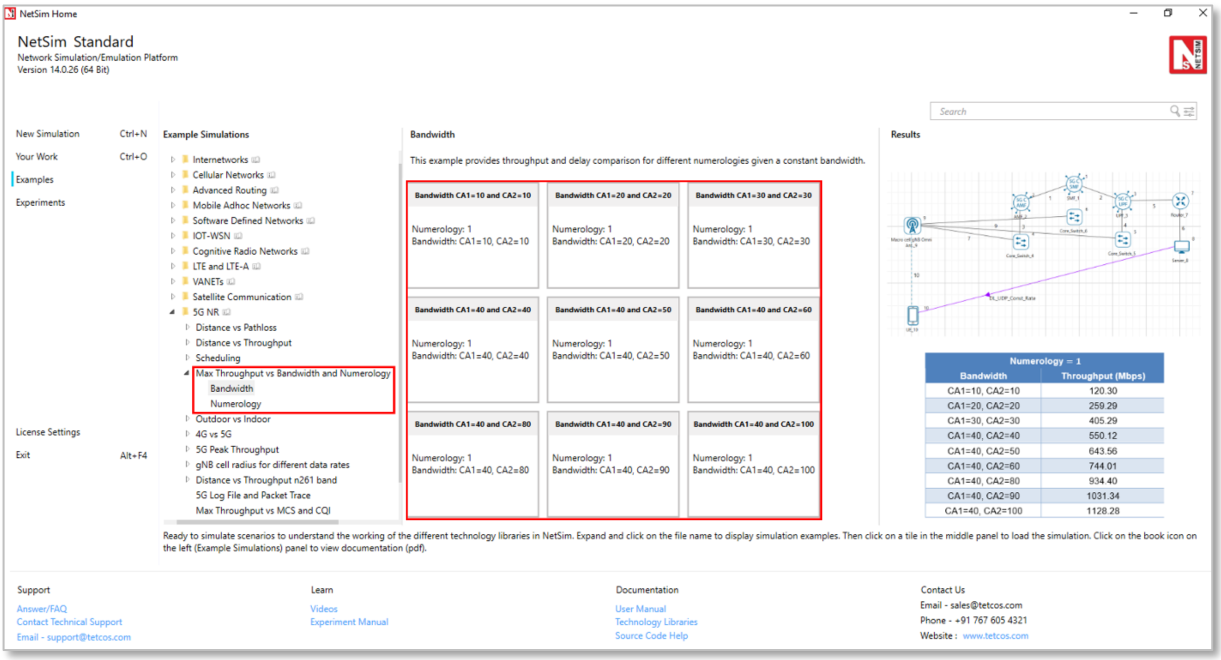

Figure 4-37: List of scenarios for the example of Max Throughput vs Bandwidth and Numerology

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

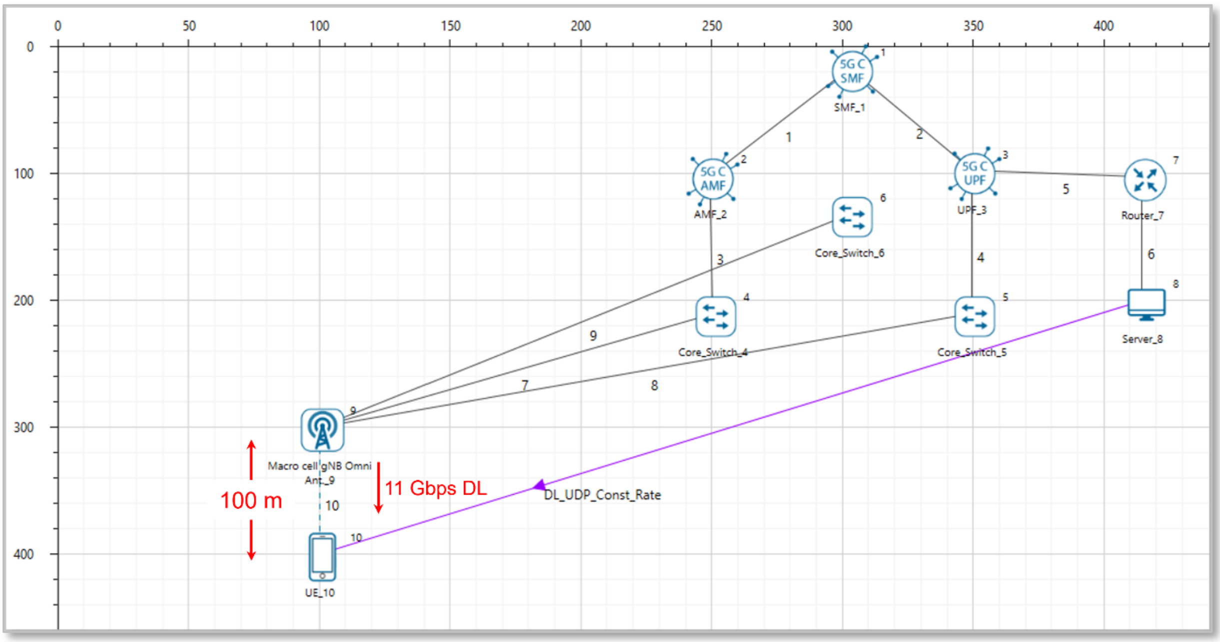

Figure 4-38: Network set up for studying the Max Throughput vs Bandwidth and Numerology

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 in Table 4-25

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

Table 4-25: 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 Application properties and set the following properties as shown below Table 4-26.

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 4-26: Application properties

6. 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)**

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CA1=10, CA2=10	120.30
CA1=20, CA2=20	259.29
CA1=30, CA2=30	405.29
CA1=40, CA2=40	550.12
CA1=40, CA2=50	643.56
CA1=40, CA2=60	744.01
CA1=40, CA2=80	934.40
CA1=40, CA2=90	1031.34
CA1=40, CA2=100	1128.28

Table 4-27: Results Comparison with constant Numerology vs. Bandwidth and throughput

Bandwidth	Numerology	Throughput (Mbps)	Delay (µs)
CA1=40, CA2=50	0	581.66	5104.65
CA1=40, CA2=50	1	643.56	4903.86
CA1=40, CA2=50	2	650.57	4808.65

Table 4-28: 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.

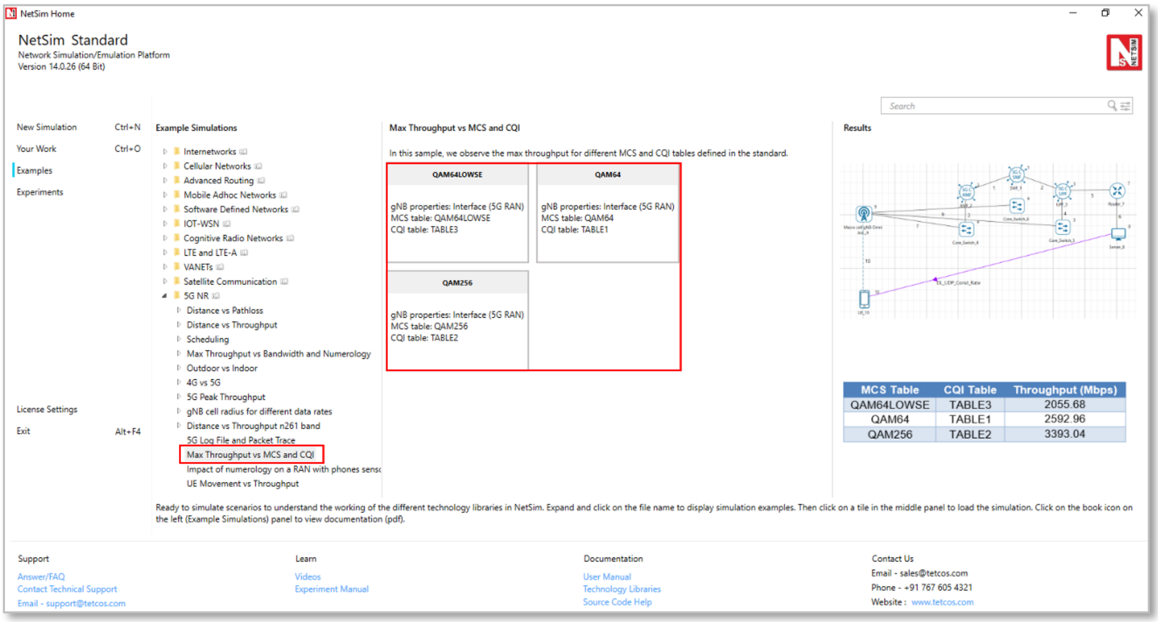

Figure 4-39: List of scenarios for the example of Max Throughput vs MCS and CQI

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

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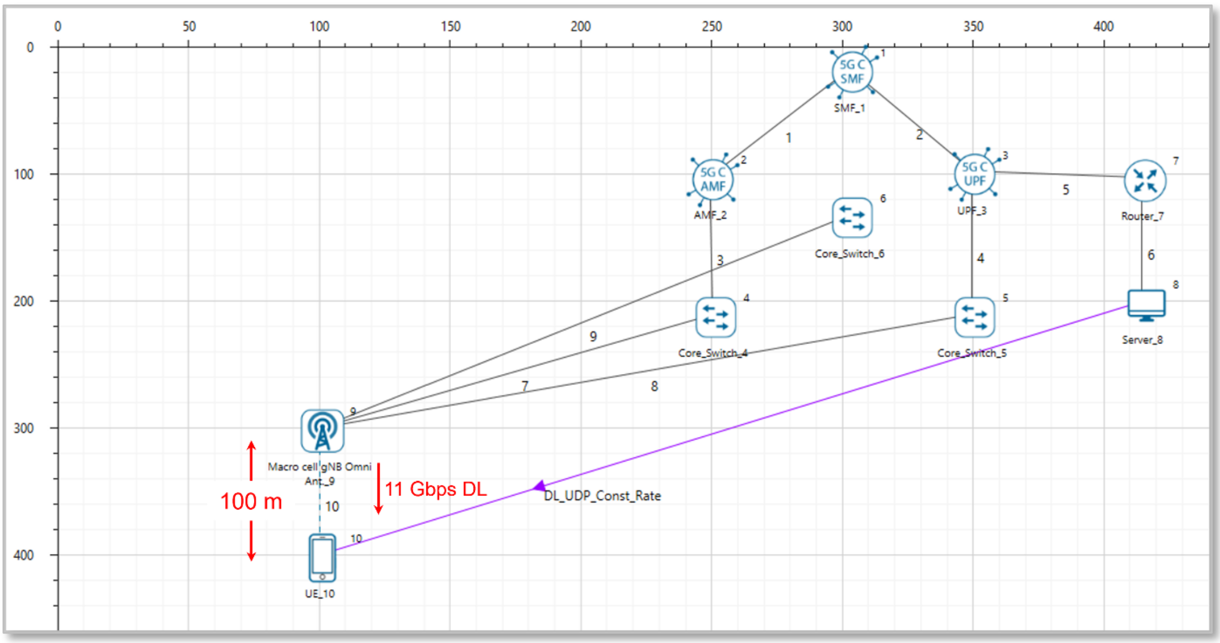

Figure 4-40: Network set up for studying the Max Throughput vs MCS and CQI

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 4-29.

Properties		
Physical Layer Properties		
Frequency Range		FR2
CA_TYPE		INTER_BAND_CONTIGUOUS_CA
CA_Configuration		CA_n258G
	Numerology	**Channel Bandwidth (MHz)**
CA1	3	400
CA2	3	400
Pathloss Model		None

Table 4-29: gNB >Interface (5G_RAN) >Physical layer properties

3. Go to Application properties and set the following properties as shown below Table 4-30.

Application Properties	
Source_Id	10
Destination_Id	8
Transport Protocol	UDP
Start_Time	1s
Packet_Size	1460Bytes
Inter_Arrival_time	1µs
Generation Rate	11680Mbps

Table 4-30: Application 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 UE properties.

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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	2055.68
QAM64	TABLE1	2592.96
QAM256	TABLE2	3393.04

Table 4-31: 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.

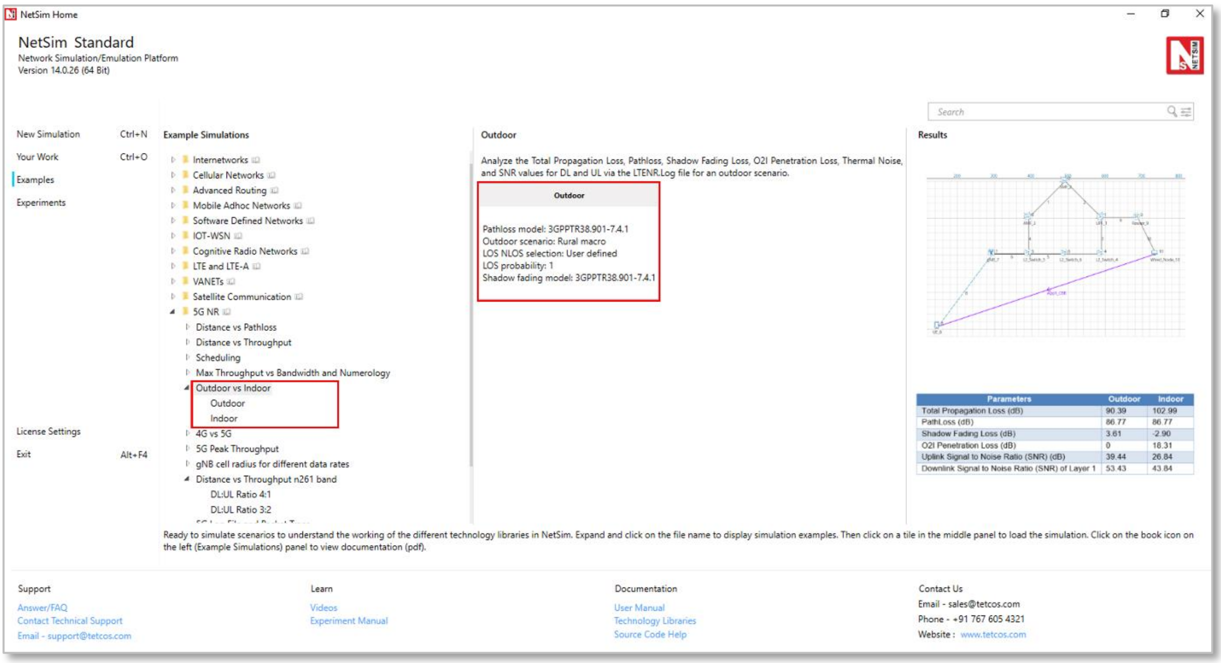

Figure 4-41: List of scenarios for the example of Outdoor vs Indoor

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

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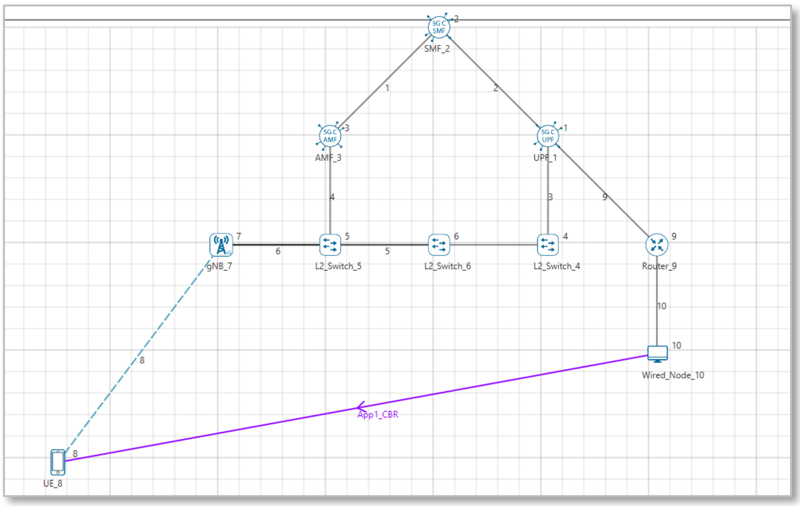

Figure 4-42: Network set up for studying the Outdoor

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 4-32

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

Table 4-32: Device Positions

3. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below Table 4-33.

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

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Shadow Fading Model	3G99TR38.901-7.4.1
ShadowFading_Standard_Deviation	3G99TR38.901-Table7.4.1-1
Fading _and_Beamforming	NO_FADING_MIMO_UNIT_GAIN

Table 4-33: 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 UE 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.
   - Logs can be enabled by clicking on the icon in Configure Reports option as shown below.

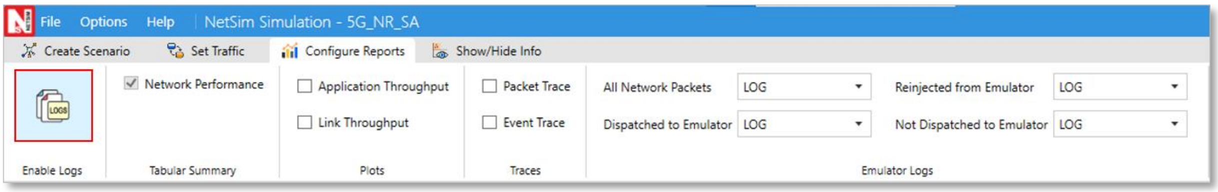

Figure 4-43: Enabling log files in NetSim GUI.

   - Select the LTENR Radio Measurements log and click on OK.

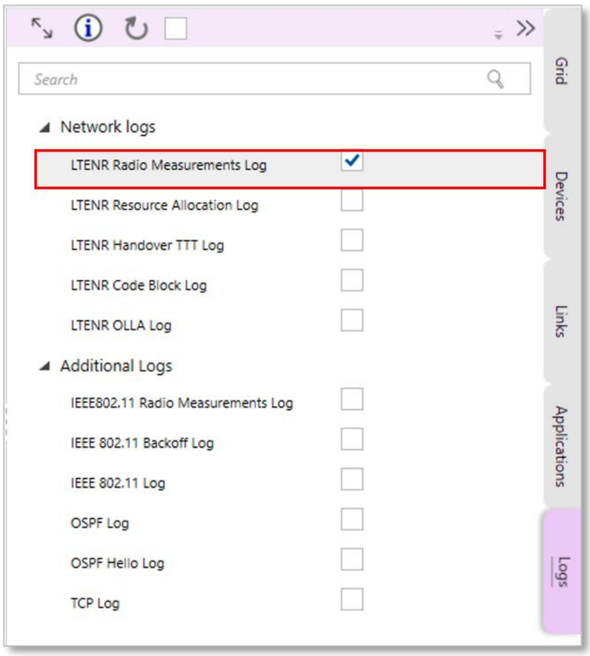

Figure 4-44: Enabling LTENR Radio Measurements Log

8. Run simulation for 11 sec.

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

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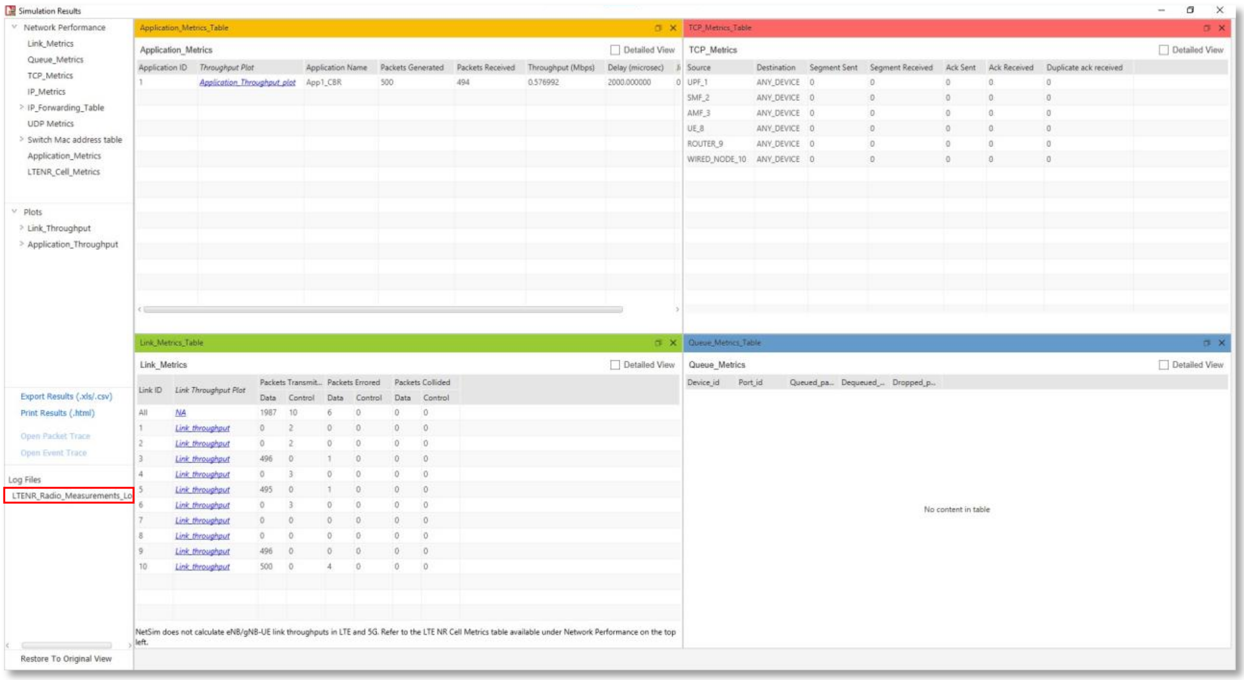

Figure 4-45: Results Window

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

gNB/eNB I	UE Name	TotalLoss(dB)	PathLoss(dB)	ShadowFadingLoss(	O2I_Loss(	Rx_Power(	SNR(dB)	SINR(dB)	Interferen	BeamForm	CQI Index	MCS Index
GNB_7	UE_8	90.162699	86.775281	3.387418	0	-44.1421	62.6962	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	89.415503	89.476259	-0.060757	0	-43.3949	60.4331	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	90.162699	86.775281	3.387418	0	-44.1421	62.6962	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	89.415503	89.476259	-0.060757	0	-43.3949	60.4331	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-53.4026	53.4357	53.4357	-1000	N/A	15	28
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-53.4026	53.4357	53.4357	-1000	N/A	15	28
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-67.3923	39.446	39.446	-1000	N/A	15	27
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-44.3717	62.4666	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	94.314017	89.476259	4.837757	0	-57.3243	46.5036	46.5036	-1000	N/A	15	28
GNB_7	UE_8	94.314017	89.476259	4.837757	0	-57.3243	46.5036	46.5036	-1000	N/A	15	28
GNB_7	UE_8	94.314017	89.476259	4.837757	0	-48.2934	55.5345	N/A	N/A	6.0206	N/A	N/A
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-53.4026	53.4357	53.4357	-1000	N/A	15	28
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-53.4026	53.4357	53.4357	-1000	N/A	15	28
GNB_7	UE_8	90.392254	86.775281	3.616973	0	-67.3923	39.446	39.446	-1000	N/A	15	27
GNB_7	UE_8	94.314017	89.476259	4.837757	0	-57.3243	46.5036	46.5036	-1000	N/A	15	28
GNB_7	UE_8	94.314017	89.476259	4.837757	0	-57.3243	46.5036	46.5036	-1000	N/A	15	28

LTENR_Radio_Measurements_Log

Figure 4-46: LTENR Radio Measurement log.csv file

4.7.2 Indoor

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

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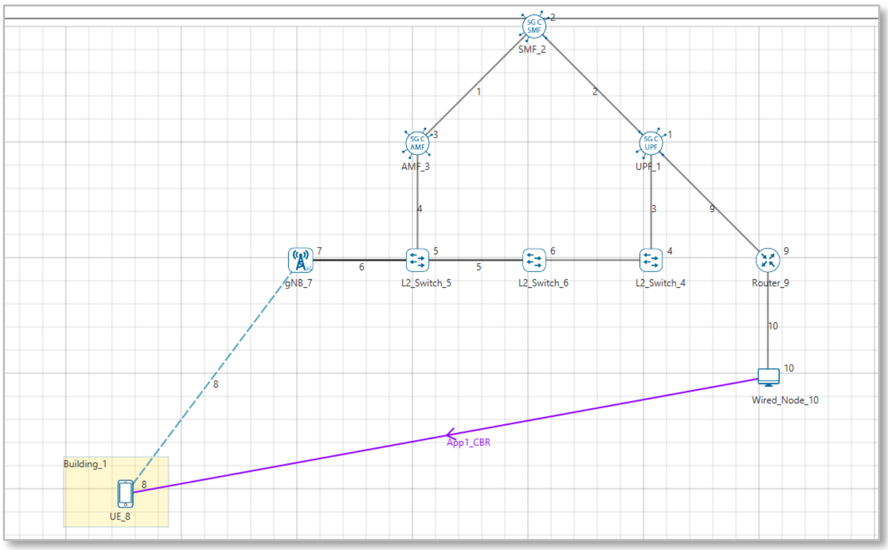

Figure 4-47: Network set up for studying the Indoor

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 4-34.

General Properties		
	X Coordinate	**Y Coordinate**
Building Properties	50	100
gNB Properties	300	200
UE Properties	150	400

Table 4-34: Devices Positions

3. Go to the building properties, set Length_X as 105.52m and Breadth_Y as 118.51m.
4. Go to gNB properties → Interface (5G_RAN), set the following properties as shown below Table 4-35.

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

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LOS Probability	1
Shadow Fading Model	3G99TR38.901-7.4.1
ShadowFading_Standard_Deviation	3G99TR38.901-Table7.4.1-1
Fading _and_Beamforming	NO_FADING_MIMO_UNIT_GAIN
O2I Building Penetration Model	LOW_LOSS_MODEL

Table 4-35: 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 LTENR Radio measurement log file can be enabled as per information provided in the section 3.20
10. 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 CC ID =1 and layer ID = 1 present in the log file have been considered in the tables given below. (To check SNR values for downlink, filter the channel as PDSCH and for uplink as PUSCH with Layer ID as 1).

Parameters	Outdoor	Indoor
Total Propagation Loss (dB)	90.39	102.99
Pathloss (dB)	86.77	86.77
Shadow Fading Loss (dB)	3.61	-2.09
O2I Penetration Loss (dB)	0	18.31
Uplink Signal to Noise Ratio (SNR) (dB)	39.44	26.84
Downlink Signal to Noise Ratio (SNR) of Layer 1	53.43	43.84

Table 4-36: 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.

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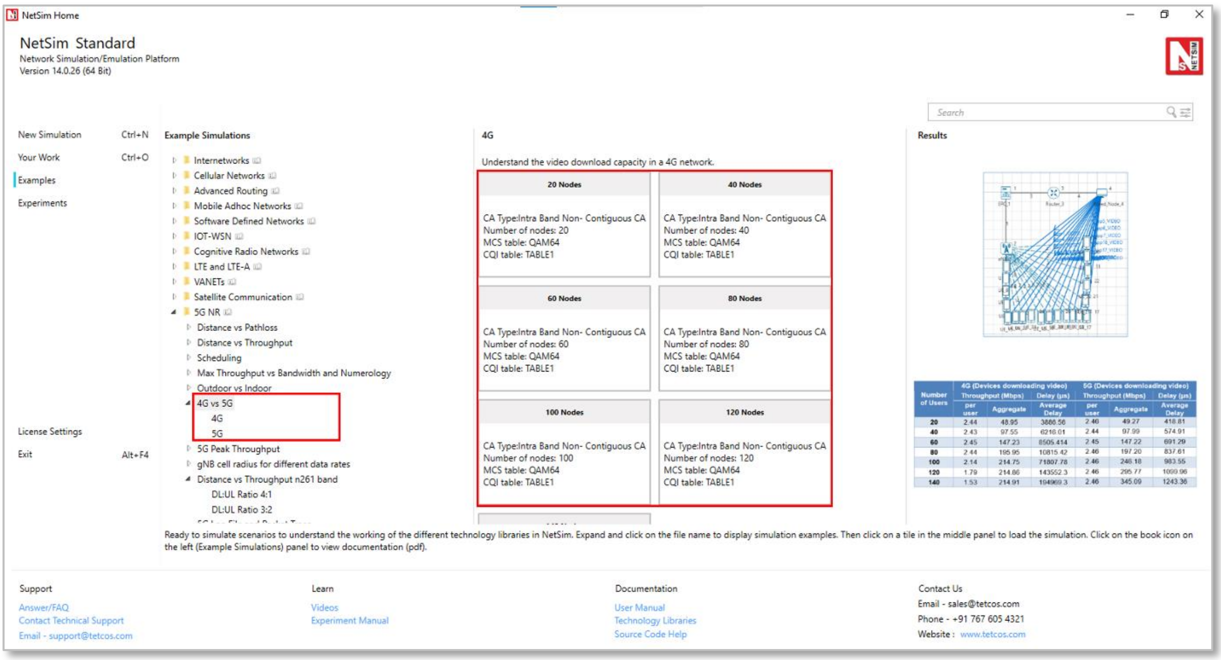

Figure 4-48: List of scenarios for the example of 4G vs 5G

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.

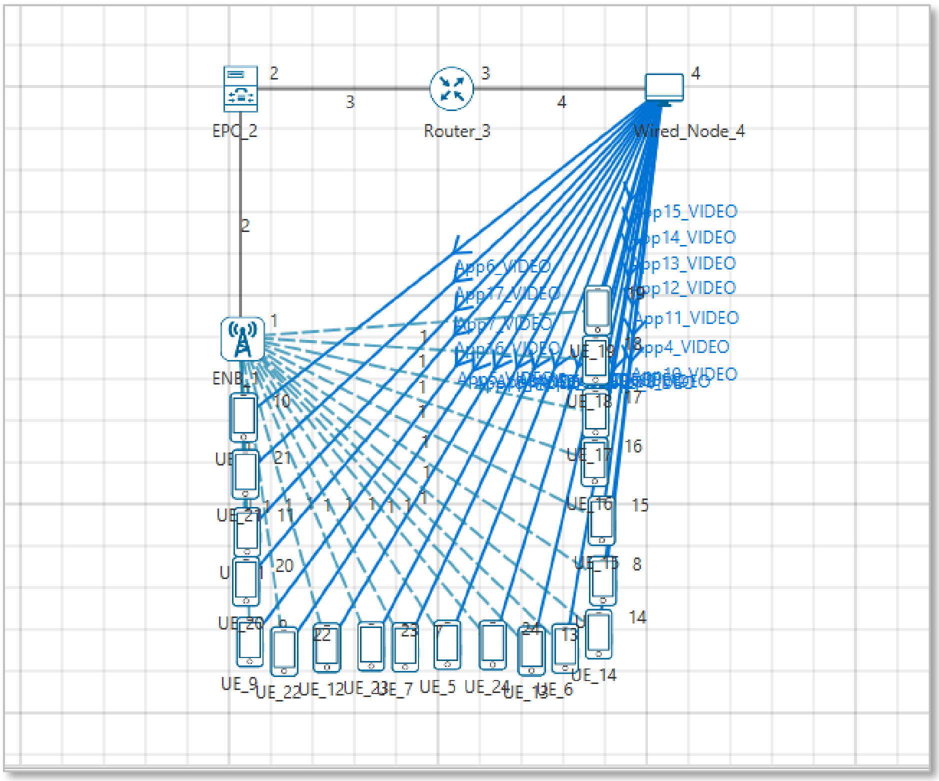

Figure 4-49: Network set up for studying the 4G

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 4-37.

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 4-37: 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. 'Configure the 20 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 4-38: Application properties

8. 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.

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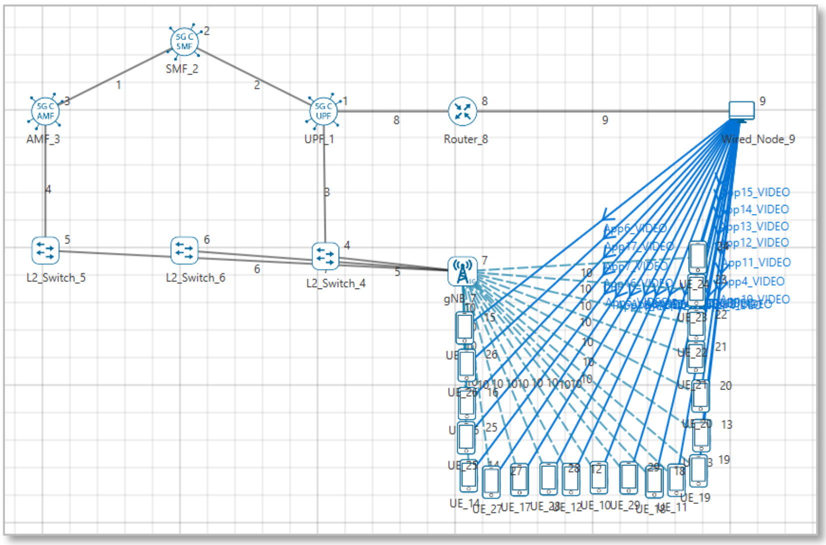

Figure 4-50: Network set up for studying the 5G

Settings done in example config file:

1. For the above 5G scenario set the following given properties Table 4-39.

gNB Properties -> Interface (5G_RAN)		
Pathloss Model	None	
DL_UL_Ratio	1:1	
Frequency Range	FR2	
CA_Type	INTRA_BAND_CONTIGUOUS_CA	
CA_Configuration	CA_n258G	
	Numerology	**Channel Bandwidth (MHz)**
CA1, CA2	3	400
MCS Table	QAM256	
CQI Table	TABLE2	

Table 4-39: 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 as 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.

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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	2.44	48.80	2682.81	2.46	49.38	423.41
40	2.42	97.19	3856.27	2.45	98.08	599.83
60	2.44	146.75	5115.11	2.44	146.99	709.73
80	2.44	195.24	6240.86	2.44	195.69	835.06
100	2.42	242.46	6549.66	2.44	244.50	973.40
120	2.44	292.98	8750.25	2.44	293.28	1085.11
140	2.44	342.10	9945.99	2.42	339.27	1193.823

Table 4-40: 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.

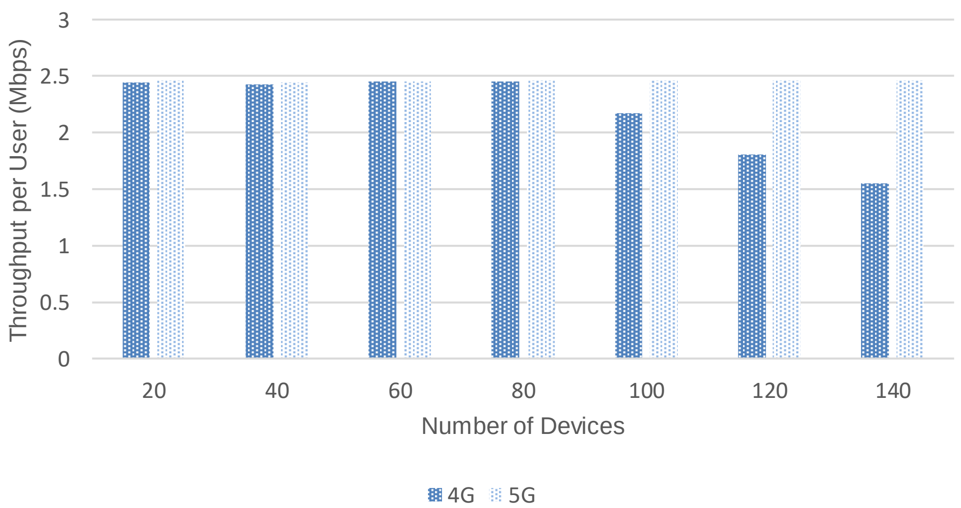

Figure 4-51: Throughput vs Number of Devices for 4G and 5G. The 4G per user throughput starts falling after 80 devices.

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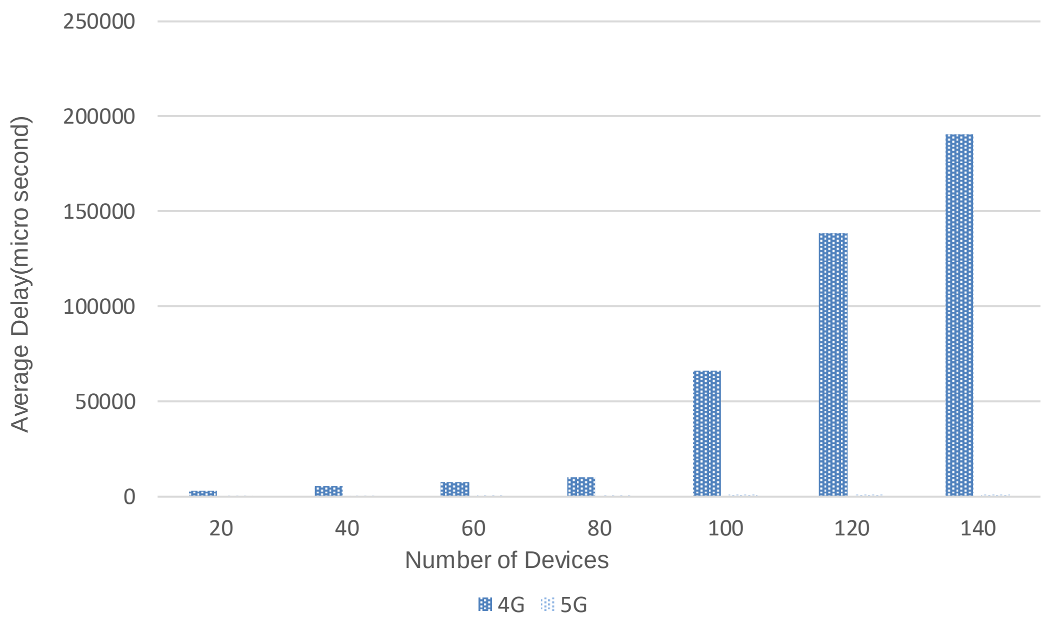

Figure 4-52: Plot of Latency vs Number of Devices. The 5G Network average delay is insignificant i.e., many orders of magnitude lower, and hence not visible in the plot.

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

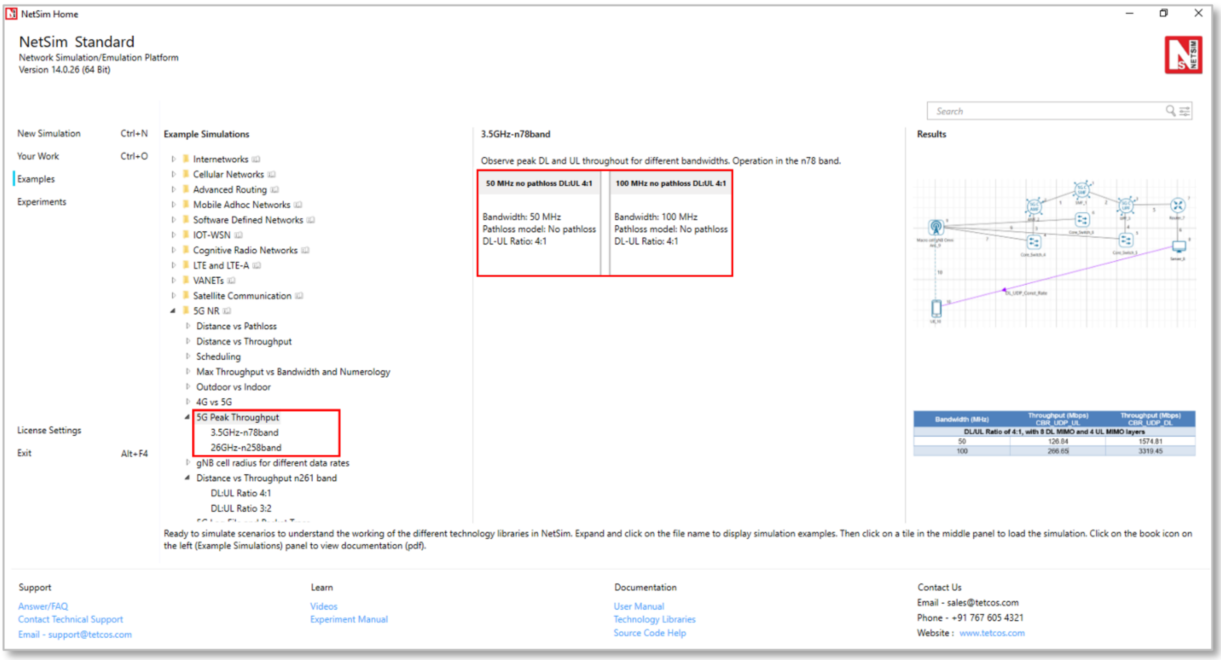

Figure 4-53: List of scenarios for the example of 5G Peak Throughput

4.9.1 3.5 GHz n78 band

The following network diagram illustrates, what the NetSim UI displays on clicking.

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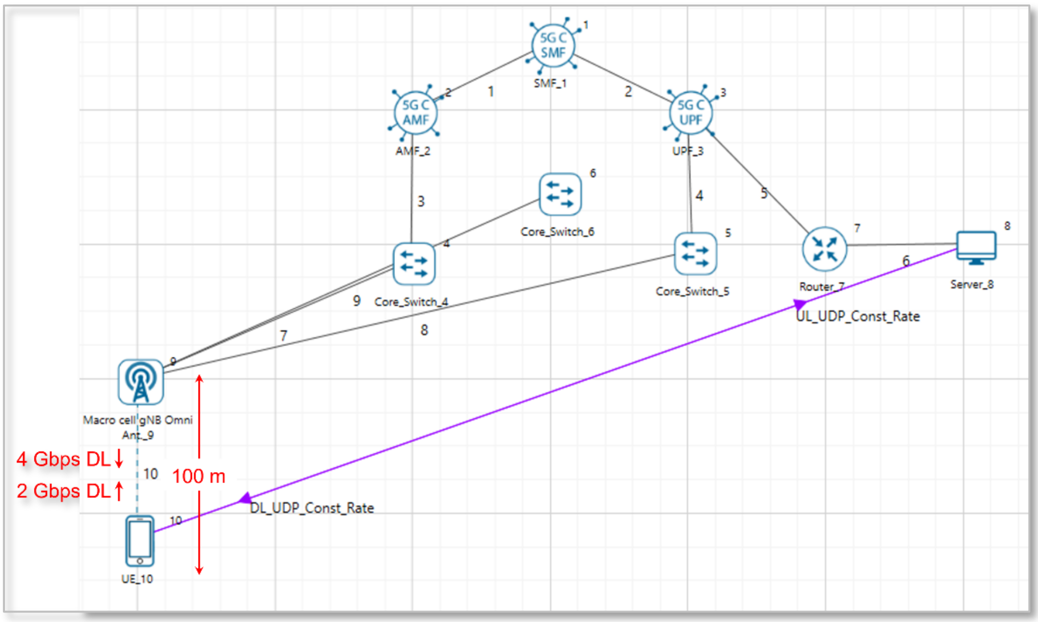

Figure 4-54: Network set up for studying the 5G Peak Throughput

Settings done in example config file:

1. Set the following property as shown in below given Table 4-41.

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 4-41: 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. 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

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App_CBR_UDP_UL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (µs)	5.84

Table 4-42: Application properties

5. Plots are enabled in NetSim GUI.
6. 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	126.84	1574.81
100	266.65	3320.04

Table 4-43: Results Comparison

4.9.2 26 GHz n258 band

The following network diagram illustrates, what the NetSim UI displays on clicking.

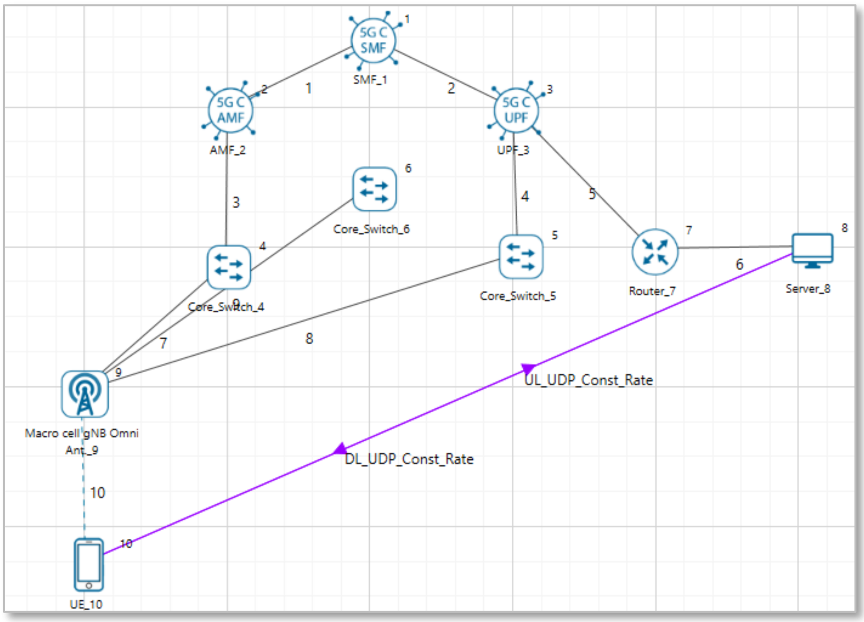

Figure 4-55: Network set up for studying the 5G Peak Throughput

Settings done in example config file:

1. Set the following property as shown in below Table 4-44.

gNB Properties -> Interface (5G_RAN)	
Pathloss Model	None

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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 4-44: 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. 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 4-45: Application properties

5. 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	510.88	6195.35
400	1026.43	10773.51

Table 4-46: Results Comparison

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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 4-56.

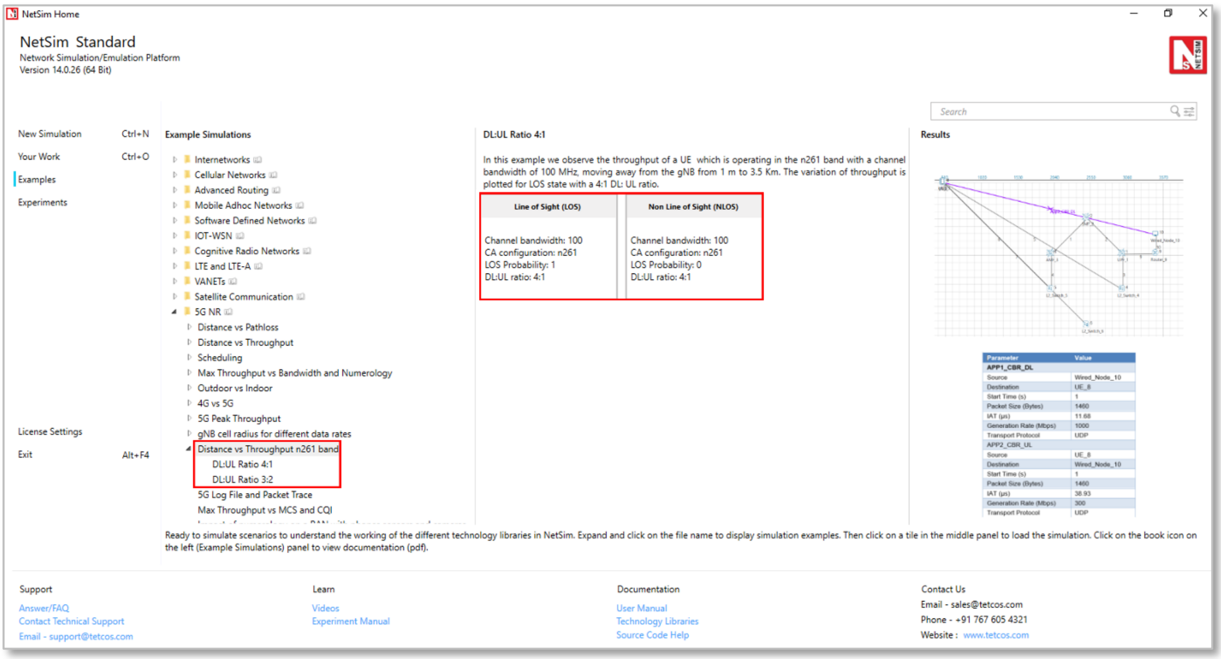

Figure 4-56: List of scenarios for the example of Distance vs Throughput n261 band

NetSim UI displays the configuration file corresponding to this experiment as shown below in Figure 4-57.

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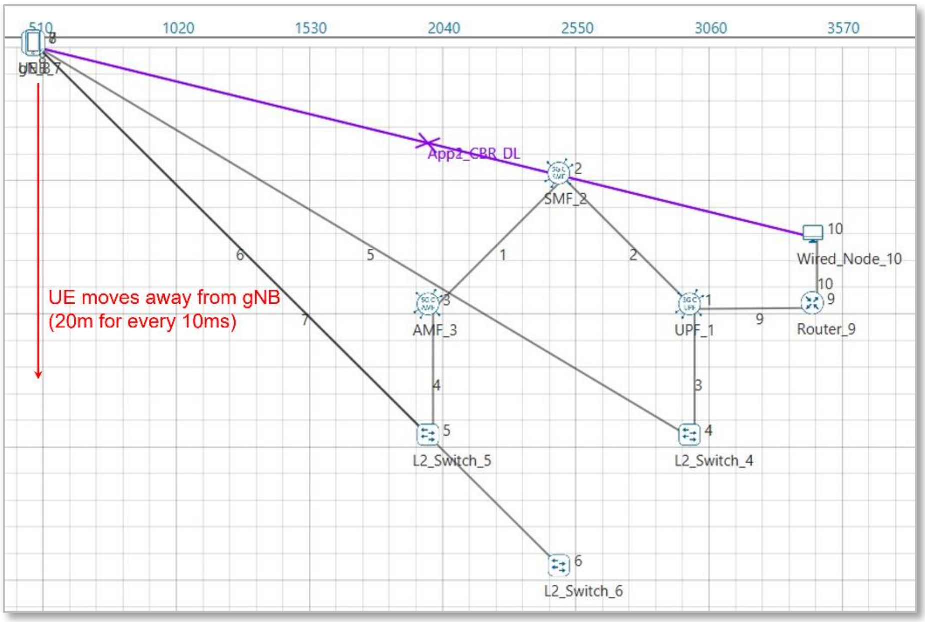

Figure 4-57: Network set up for studying the Distance vs Throughput n261 band

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 4-47: 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	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

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LOS_NLOS_Selection	User Defined
LOS Probability	1
Shadow Fading Model	None
Fading _and_Beamforming	NO_FADING_MIMO_UNIT_GAIN

Table 4-48: 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 4-49: 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.csv file for UE's involved in mobility with each step equal to 4 sec with distance 100 m. The NetSim Mobility File (mobility.csv) format is as follows:

#Time(s)	Device ID	X	Y	Z
1	8	500	50	0
1.01	8	500	70	0
..				
..				
2.72	8	500	3490	0

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2.73 8 500 3510 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

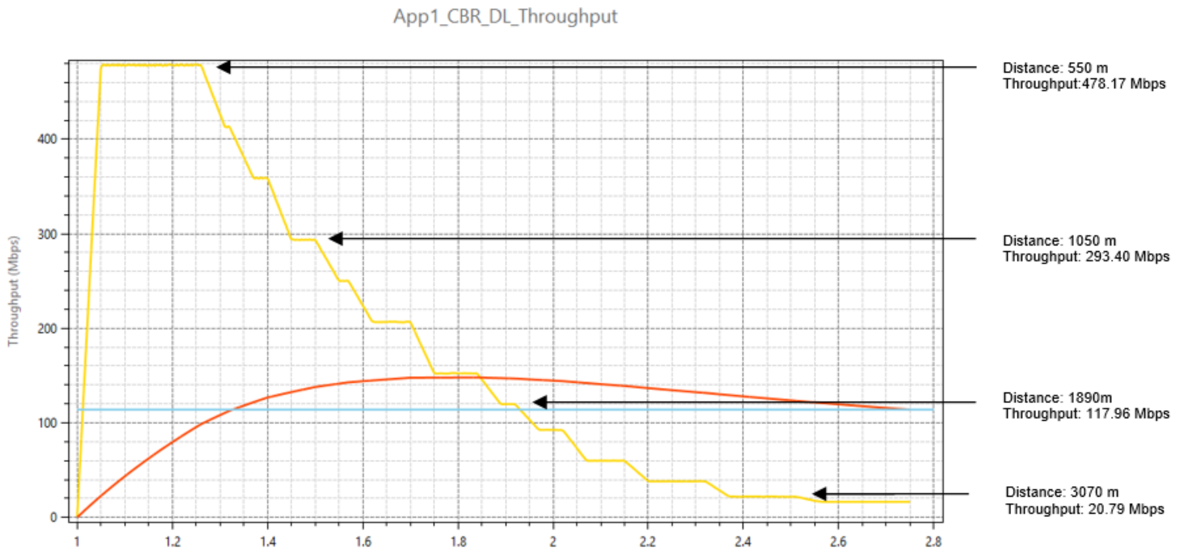

Figure 4-58: Downlink Application Throughput Plot in LOS mode

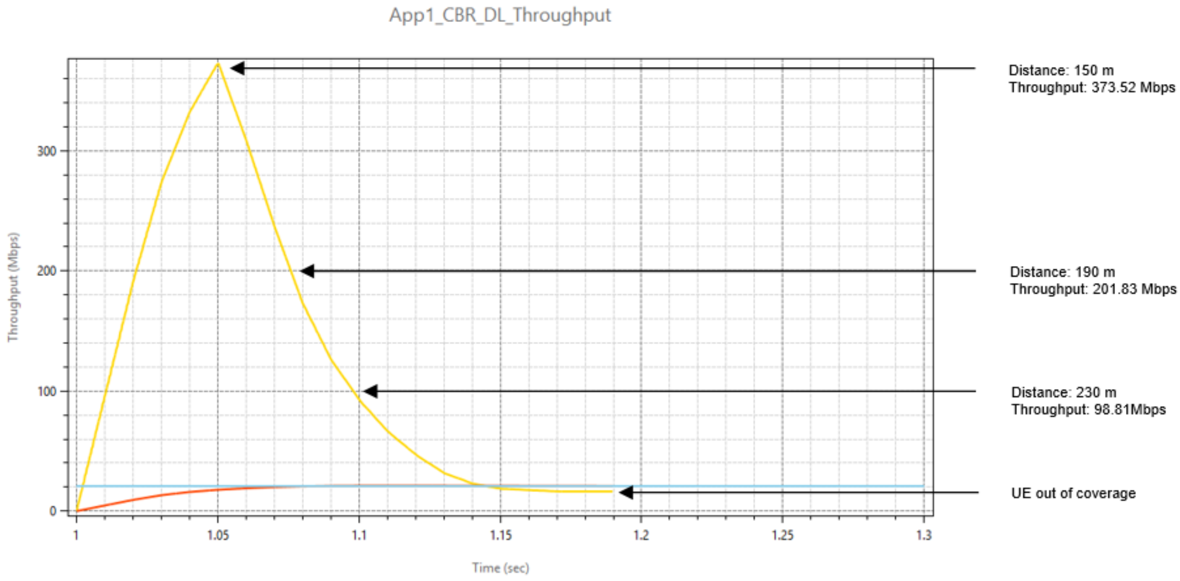

Figure 4-59: Downlink Application Throughput Plot in NLOS mode

Uplink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

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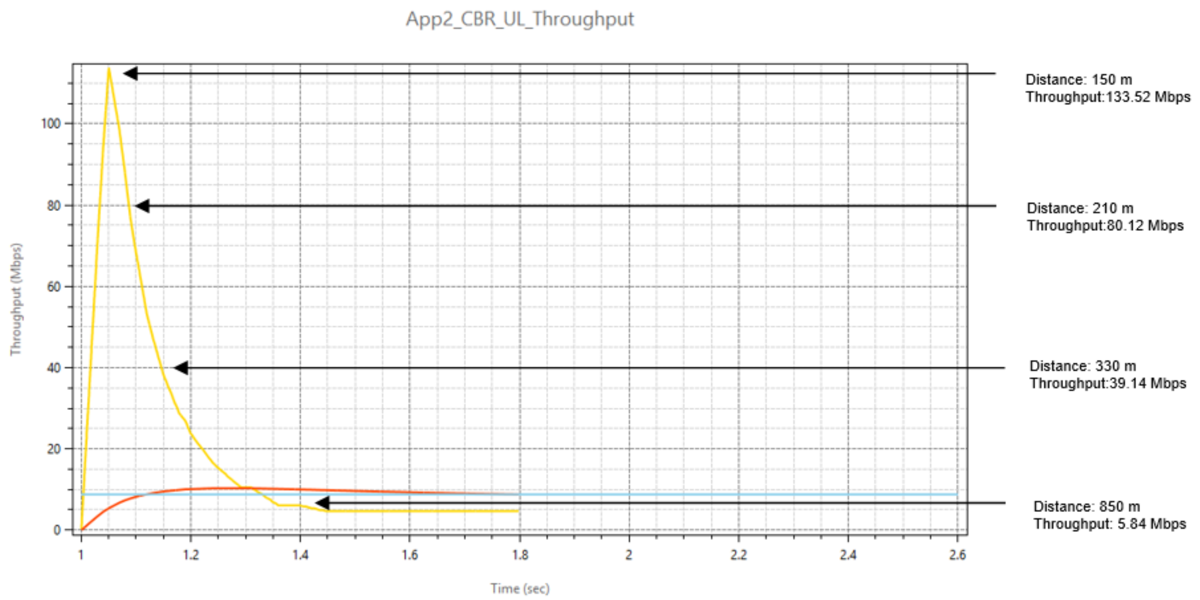

Figure 4-60: Uplink Application Throughput Plot in LOS mode

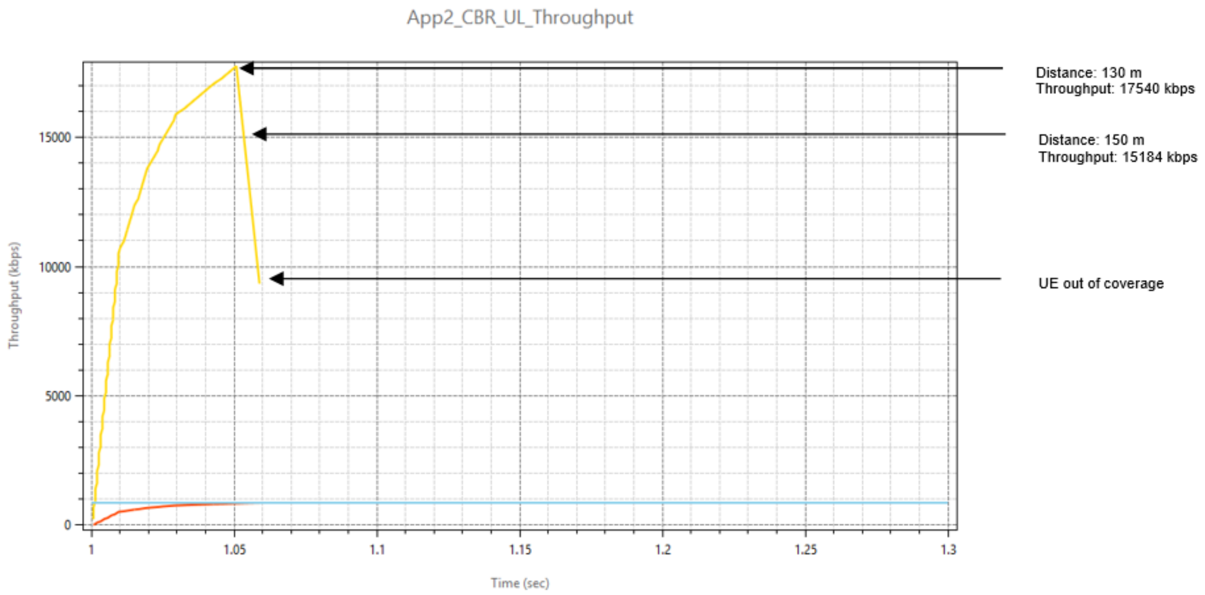

Figure 4-61: Uplink Application Throughput Plot in NLOS mode

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.

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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 4-50: 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

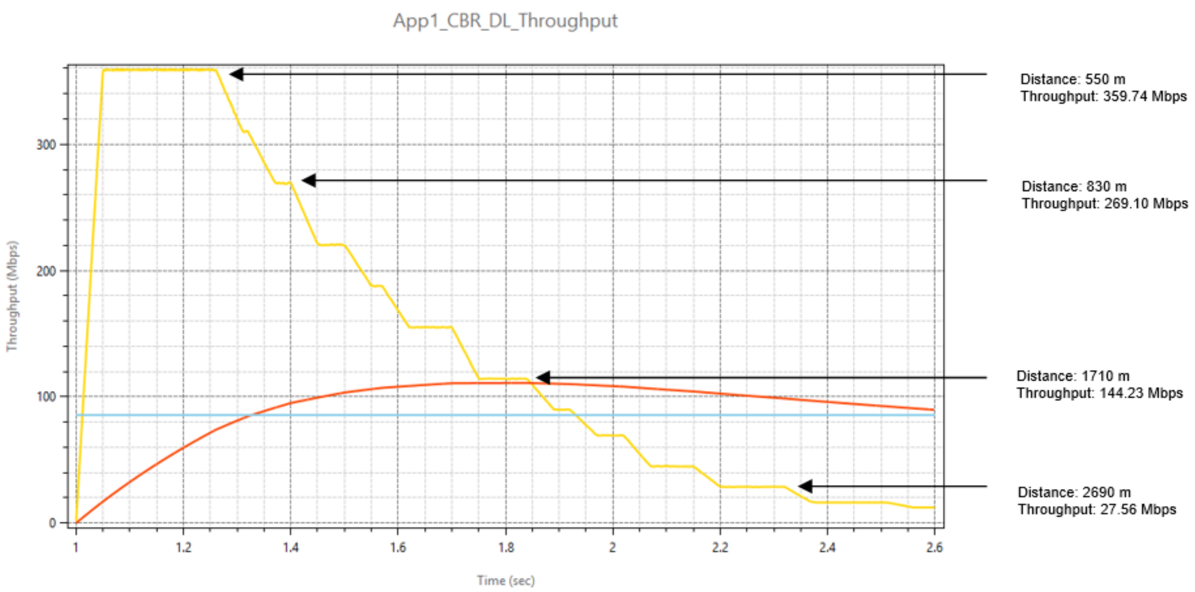

Figure 4-62: Downlink Application Throughput Plot in LOS mode

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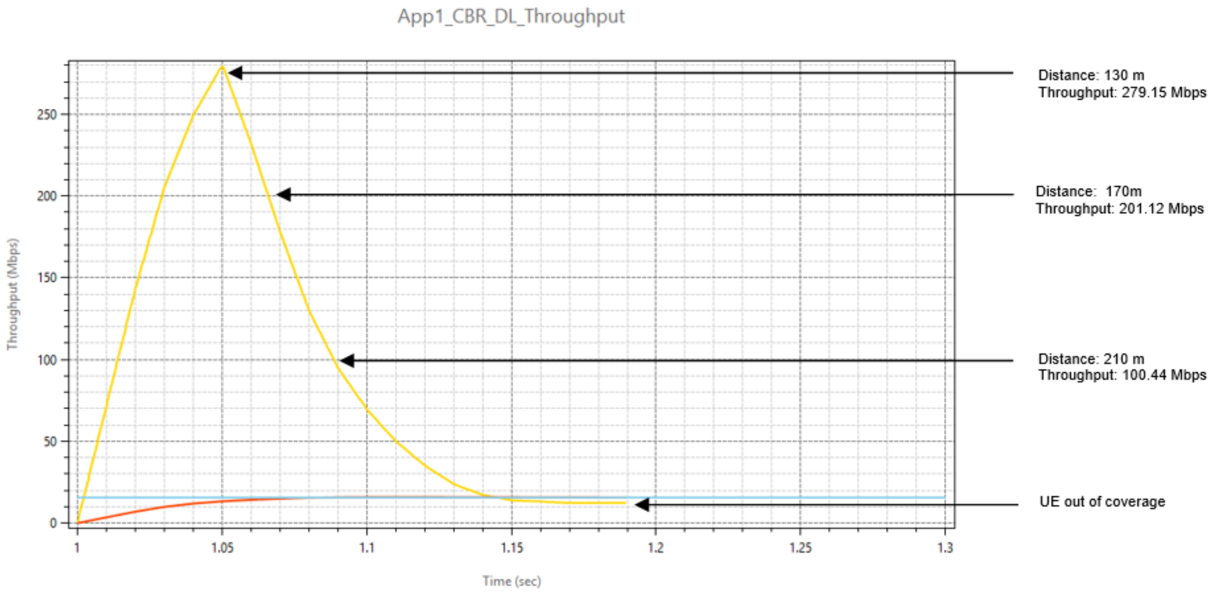

Figure 4-63: Downlink Application Throughput Plot in NLOS mode

Uplink Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) Plots

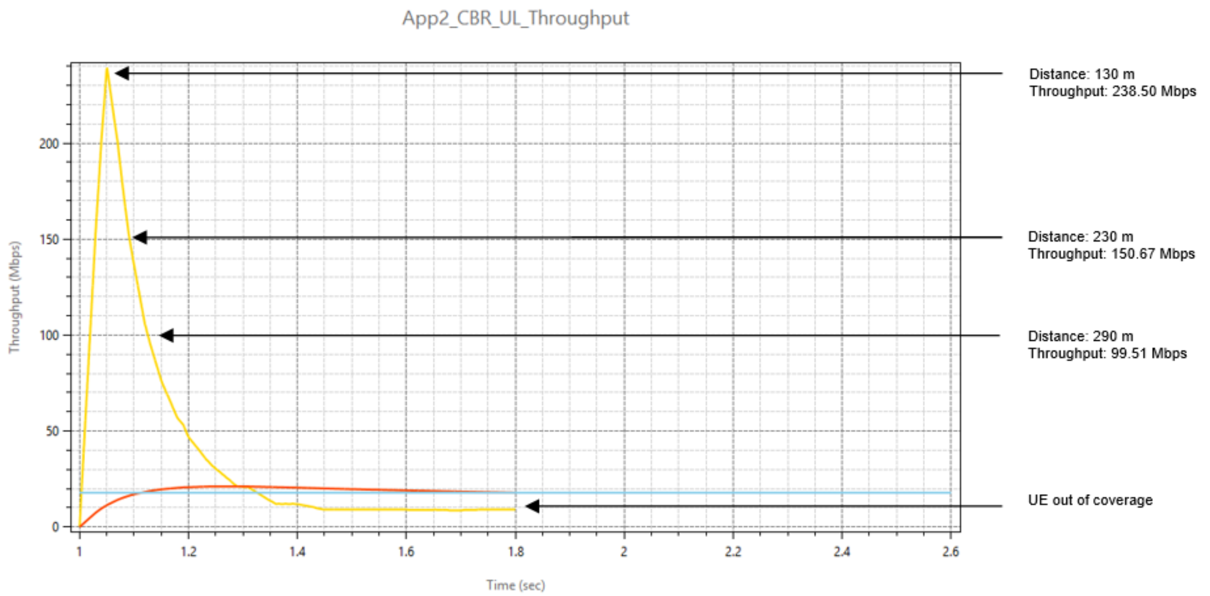

Figure 4-64: Uplink Application Throughput Plot in LOS mode

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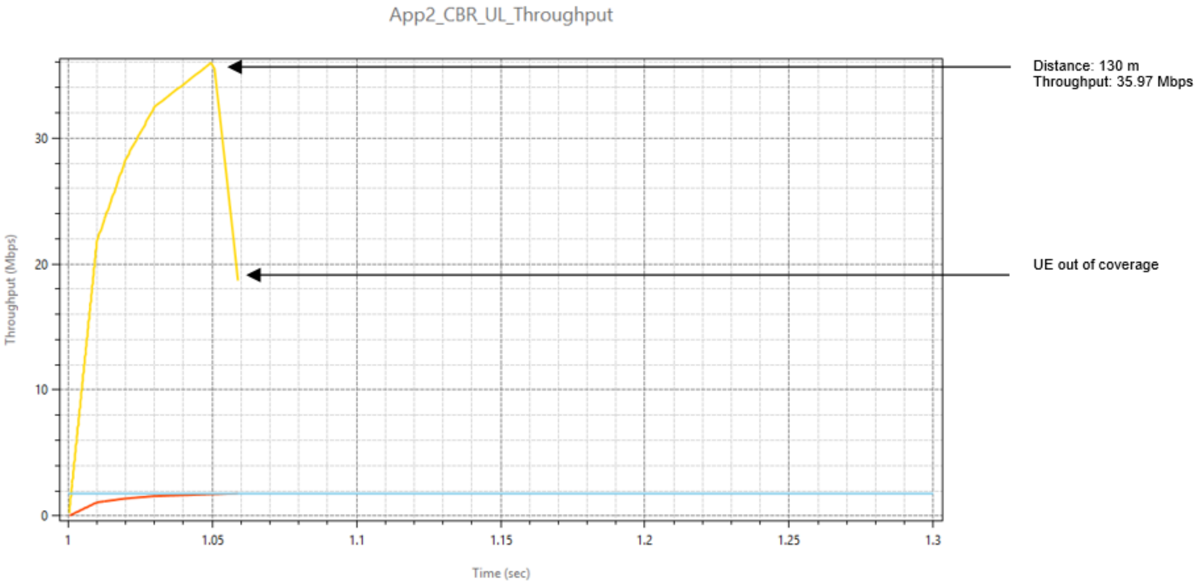

Figure 4-65: Uplink Application Throughput Plot in NLOS mode

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 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

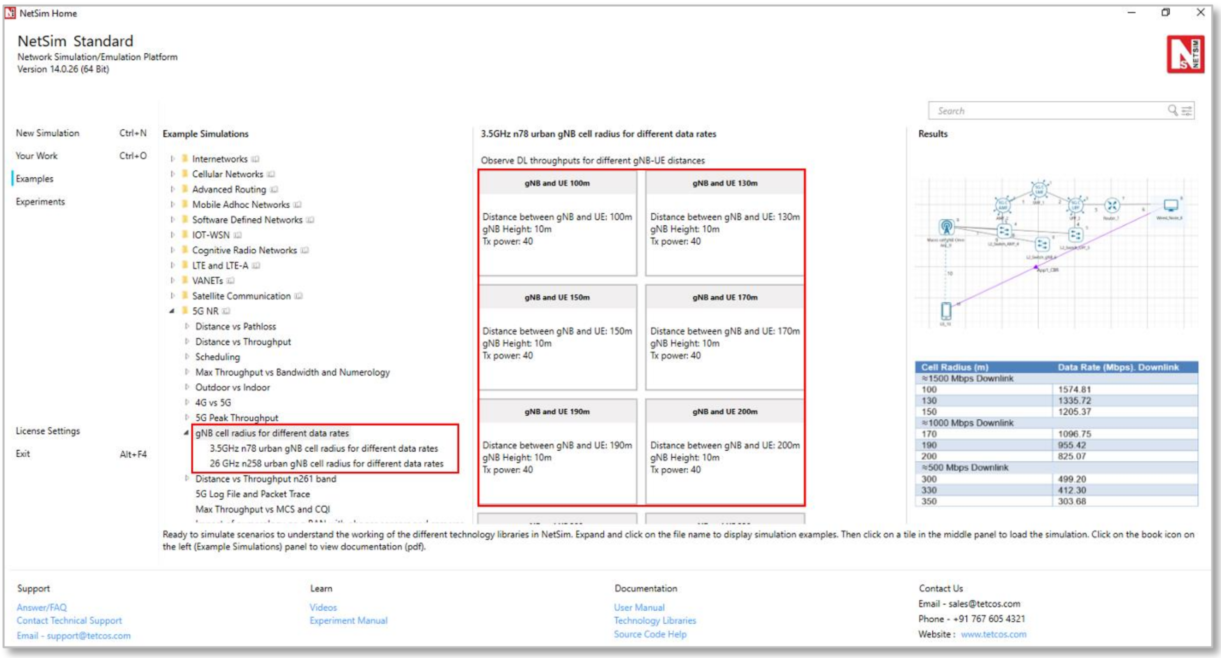

Figure 4-66: List of scenarios for the example of gNB cell radius for different data rates

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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.

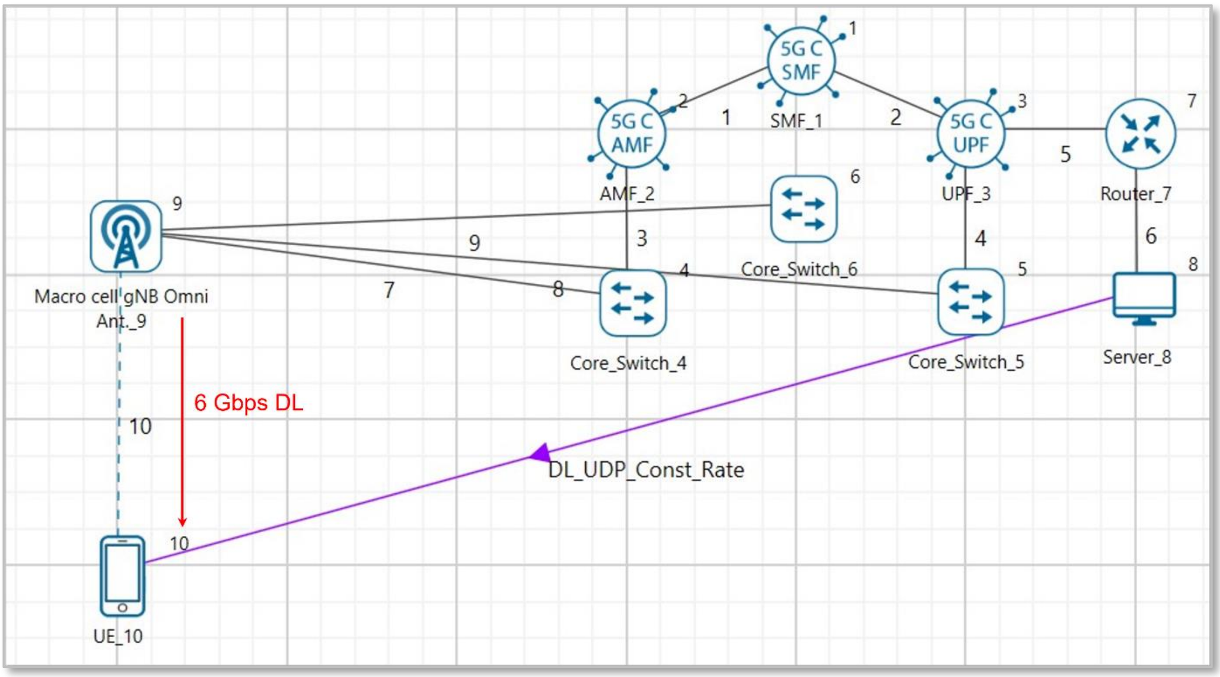

Figure 4-67: Network set up for studying the gNB cell radius for different data rates

Setting done in example config file:

1. Set the following property as shown in below Table 4-51.

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_MIMO_UNIT_GAIN

Table 4-51: 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.

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4. 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 4-52: Application properties

5. Plots are enabled in NetSim GUI.
6. 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 and run simulation for 1.1 sec.

Result:

Cell Radius (m)	Data Rate (Mbps). Downlink
≈1500 Mbps Downlink	
100	1574.81
130	1335.72
150	1205.37
≈1000 Mbps Downlink	
170	1096.75
190	955.42
200	825.07
≈500 Mbps Downlink	
300	499.20
330	412.30
350	303.68

Table 4-53: 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

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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_MIMO_UNIT_GAIN

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 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

5. 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 and run simulation for 1.1 sec.

Result:

Cell Radius (m)	Data Rate (Mbps). Downlink
≈6000 Mbps Downlink	
20	3092.74
≈1000 Mbps Downlink	
110	362.08
≈ 500 Mbps Downlink	
150	149.03

Table 4-56: 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 4-68.

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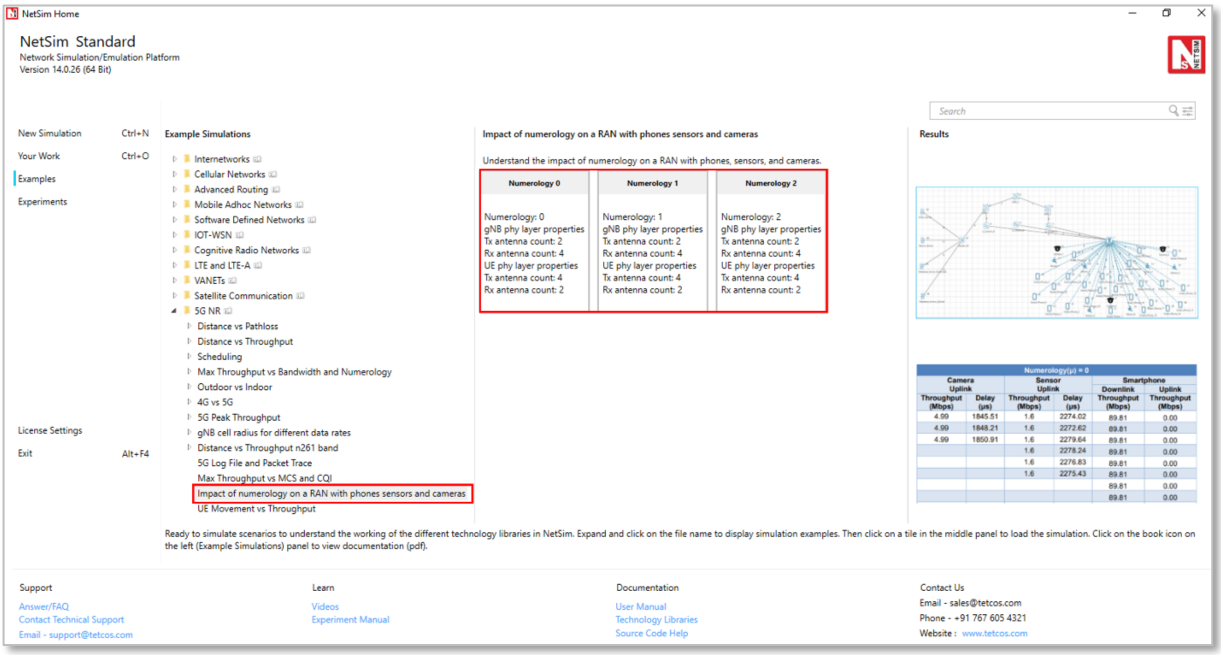

Figure 4-68: List of scenarios for the example of Impact of numerology on a RAN with phones sensors and cameras

Network Scenario[3]**:** To model a real-world scenario, we base our simulation on the setup shown in Figure 4-69. 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 4-69 is quasi-random.

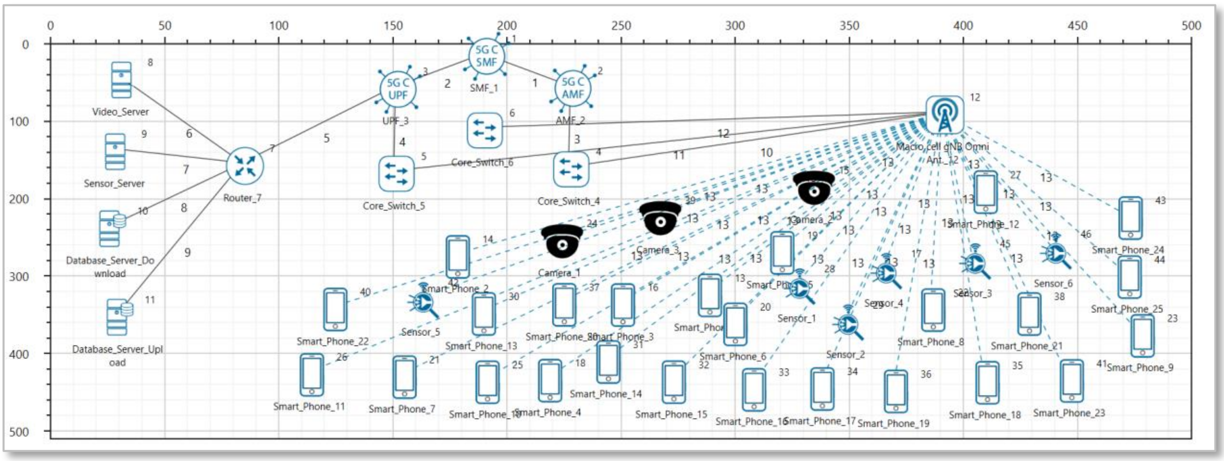

Figure 4-69: Network set up for studying the with 25 smartphones, 6 sensors and 3 cameras communicating with respective cloud servers.

[3] This example is adapted from [3]

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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.

	Flows (No of devices)	TrafficRate (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 4-57: 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
CA2	
Numerology	0, 1, and 2
Channel Bandwidth	50 MHz
DL_UL Ratio	1:4
MCS Table	QAM64
CQI Table	TABLE1

Table 4-58: gNB >Interface (5G_RAN) >Physical layer properties

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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 4-59: 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 4-60: Camera Application Properties for UL UDP

Phone DL TCP	
Transport Protocol	TCP
Start Time (s)	$1.5 + 4(t)$, Where, $i = 0, 1, 2, \dots \dots, 48$
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 4-61: Phone Application Properties for DL TCP

Phone UL TCP	
Application Type	FTP
Transport Protocol	TCP
Start Time (s)	$25 + 2(i - 1)$ Where, $i = 1, 2, \dots \dots, 25$
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 4-62: 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:

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Numerology(μ) = 0					
Camera Uplink		Sensor Uplink		Smartphone	
				Downlink	Uplink
Throughput (Mbps)	Delay (μs)	Throughput (Mbps)	Delay (μs)	Throughput (Mbps)	Throughput (Mbps)
4.99	1845.51	1.6	2274.02	89.81	0.00
4.99	1848.21	1.6	2272.62	89.81	0.00
4.99	1850.91	1.6	2279.64	89.81	0.00
		1.6	2278.24	89.81	0.00
		1.6	2276.83	89.81	0.00
		1.6	2275.43	89.81	0.00
				89.81	0.00
				89.81	0.00
				89.81	0.00
				89.81	80.50
				89.81	85.70
				90.01	75.44
				3.64	86.28
				0.23	86.26
				0.36	86.28
				0.18	86.28
				0.26	86.28
				0.38	86.28
				1.35	86.28
				1.52	86.28
				0.68	86.28
				2.61	86.28
				2.26	86.28
				2.64	86.28
				2.89	86.28

Table 4-63: Throughput and delay for Camera, Sensors and Smartphones, when $\mu = 0$

Numerology(μ) = 1					
Camera Uplink		Sensor Uplink		Smartphone	
				Downlink	Uplink
Throughput (Mbps)	Delay (μs)	Throughput (Mbps)	Delay (μs)	Throughput (Mbps)	Throughput (Mbps)
4.99	35801.95	1.60	1523.71	154.02	0.00
4.99	35720.37	1.60	1522.31	154.02	0.00
4.99	35948.6	1.60	1529.33	154.02	0.00
		1.60	1527.92	154.02	0.00
		1.60	1526.52	154.02	0.00
		1.60	1525.12	154.02	0.00
				154.02	0.00
				154.02	0.00
				154.02	0.00
				154.02	0.00

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				154.02	172.52
				154.02	172.52
				153.73	171.38
				0.52	171.38
				0.55	171.38
				0.66	171.38
				0.63	171.38
				0.69	171.38
				4.56	171.38
				7.14	171.38
				6.61	171.38
				1.11	171.38
				5.58	171.38
				5.69	171.38
				2.09	171.38

Table 4-64: Throughput and delay for Camera, Sensors and Smartphones, when $\mu = 1$

Numerology(μ) = 2					
Camera Uplink		Sensor Uplink		Smartphone	
				Downlink	Uplink
Throughput (Mbps)	Delay (µs)	Throughput (Mbps)	Delay (µs)	Throughput (Mbps)	Throughput (Mbps)
5.00	78284.11	1.6	773.58	149.34	0.00
5.00	79995.75	1.6	772.17	149.34	0.00
5.00	52688.4	1.6	779.19	149.34	0.00
		1.6	777.79	149.34	0.00
		1.6	776.38	149.34	0.00
		1.6	774.98	149.34	0.00
				149.34	0.00
				149.34	0.00
				149.34	0.00
				149.34	0.00
				149.34	344.74
				149.34	344.74
				149.34	342.62
				4.62	342.62
				4.64	342.62
				5.50	342.62
				6.60	342.62
				8.56	342.62
				10.33	342.62
				11.48	342.62
				11.46	342.62
				11.41	342.62
				11.44	342.62
				11.44	342.62

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				11.41	342.62

Table 4-65: Throughput and delay for Camera, Sensors and Smartphones, when $\boldsymbol{\mu} = \mathbf{2}$

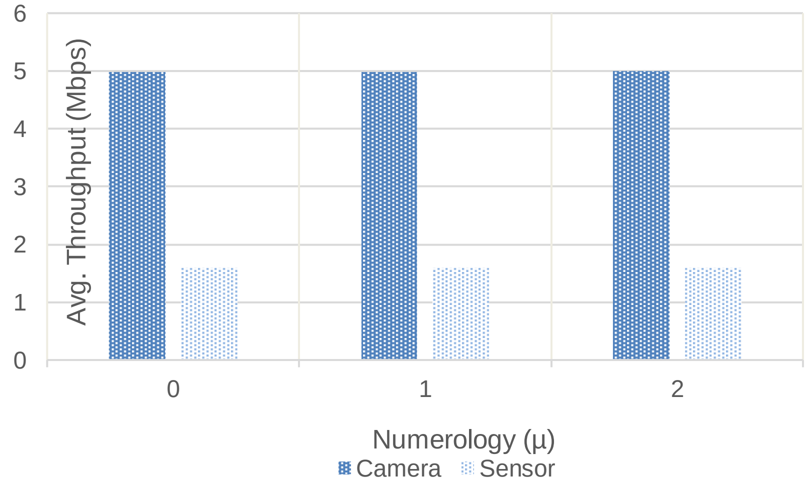

Figure 4-70: The average uplink throughput for camera and sensors remains the same as numerology is increased. This is because the flow is UDP.

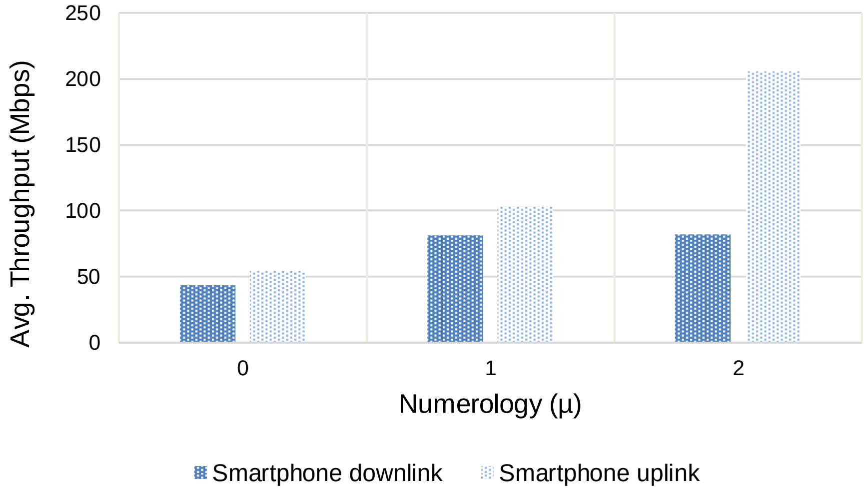

Figure 4-71: Smartphone Uplink, and Smartphone Downlink average throughput vs. Numerology (µ)

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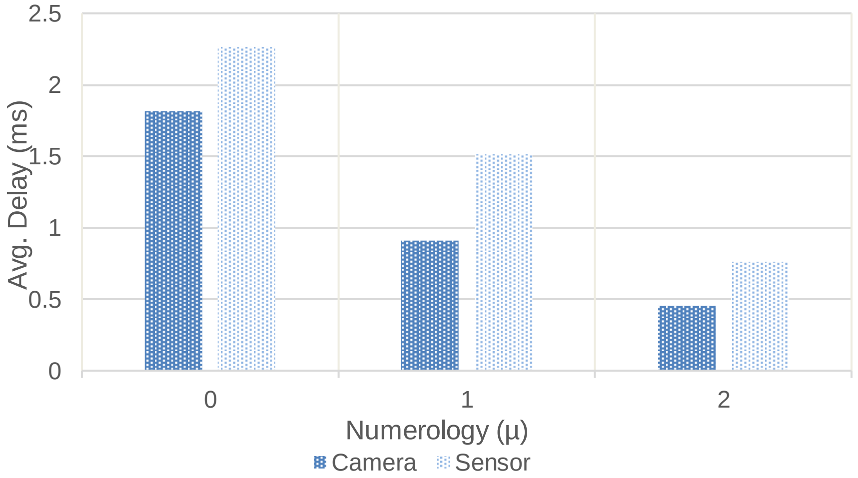

Figure 4-72: Camera Uplink, and Sensor Uplink Latency vs. Numerology. The latency drops as the numerology increases

For UDP applications the μ does not impact the throughput. This is because throughput of UDP over 5G only depends on the "capacity" of the OFDM time-frequency grid. Changing the numerology does not change the OFDM capacity, given the inverse relationship between subcarrier spacing and numerology. 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 4-66: 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 4-73.

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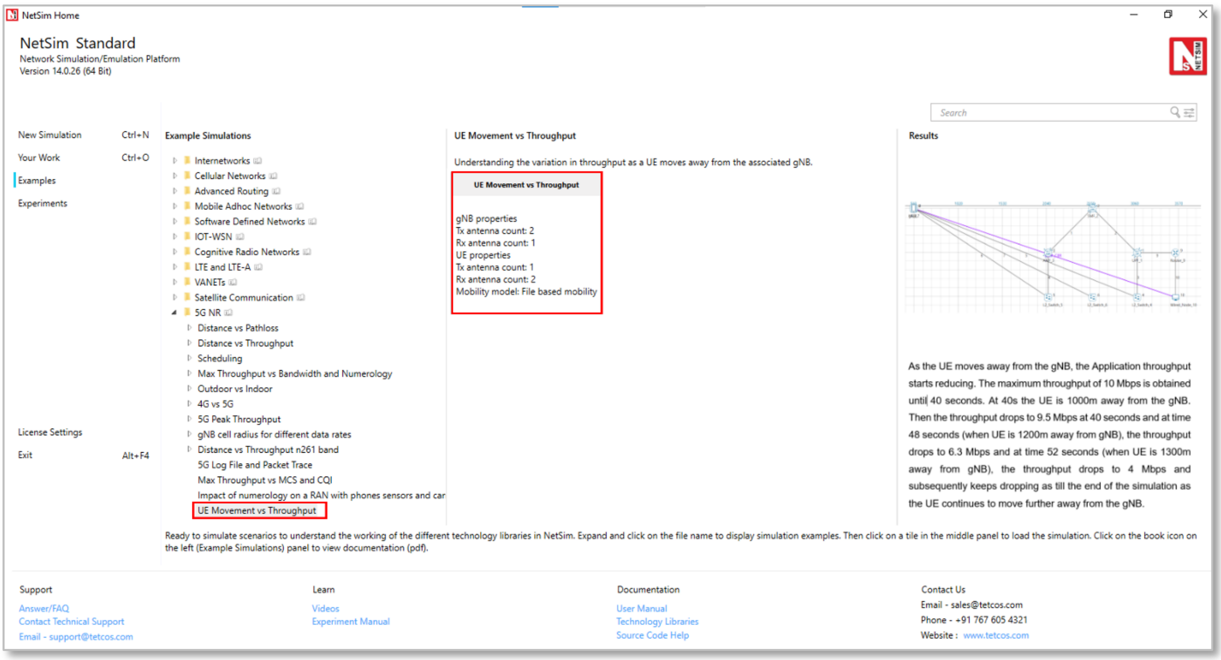

Figure 4-73: List of scenarios for the example of UE Movement vs Throughput

NetSim UI displays the configuration file corresponding to this experiment as shown below in Figure 4-74.

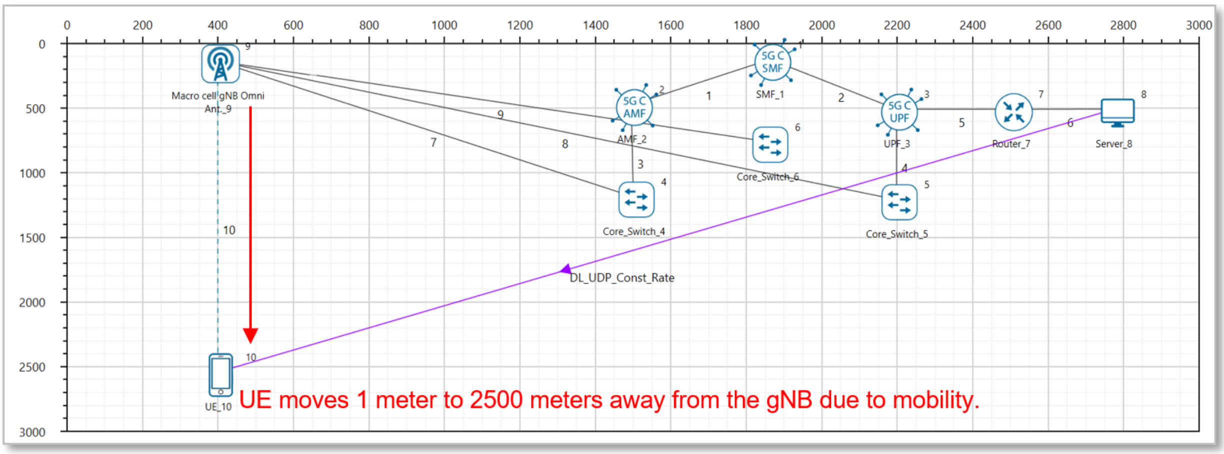

Figure 4-74: Network set up for studying Throughput vs. UE Movement

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 3000 m x 3000 m.

Step 3: The device positions are set as per the table given below Table 4-67.

Device	UE_8	gNB_7
x- axis	500	500
y- axis	1	0

Table 4-67: Device general properties

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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_MIMO_UNIT_GAIN

Table 4-68: 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.csv file for UE's involved in mobility with each step equal to 4 sec with distance 100 m.

The NetSim Mobility File (mobility.csv) format is as follows:

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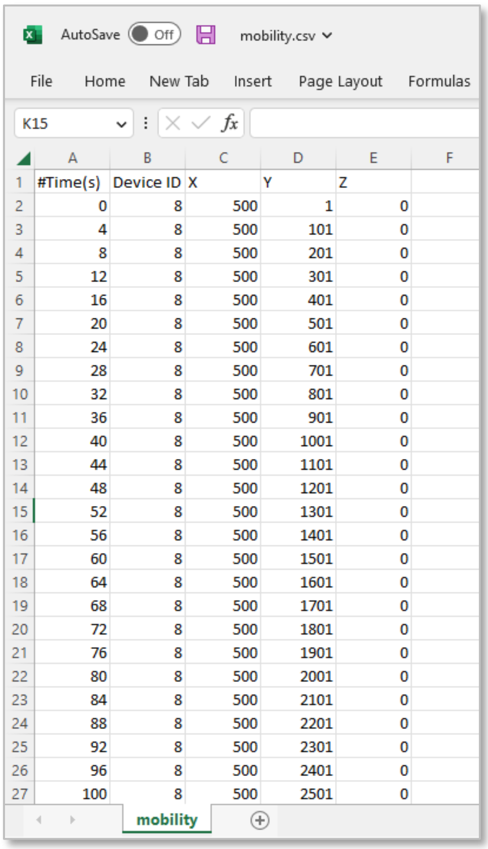

#Time(s)	Device ID	X	Y	Z
0	8	500	1	0
4	8	500	101	0
8	8	500	201	0
12	8	500	301	0
16	8	500	401	0
20	8	500	501	0
24	8	500	601	0
28	8	500	701	0
32	8	500	801	0
36	8	500	901	0
40	8	500	1001	0
44	8	500	1101	0
48	8	500	1201	0
52	8	500	1301	0
56	8	500	1401	0
60	8	500	1501	0
64	8	500	1601	0
68	8	500	1701	0
72	8	500	1801	0
76	8	500	1901	0
80	8	500	2001	0
84	8	500	2101	0
88	8	500	2201	0
92	8	500	2301	0
96	8	500	2401	0
100	8	500	2501	0

Figure 4-75: mobility.csv file

Step 11: Plots is enabled in NetSim GUI.

Step 12: Run simulation for 100s.

Results:

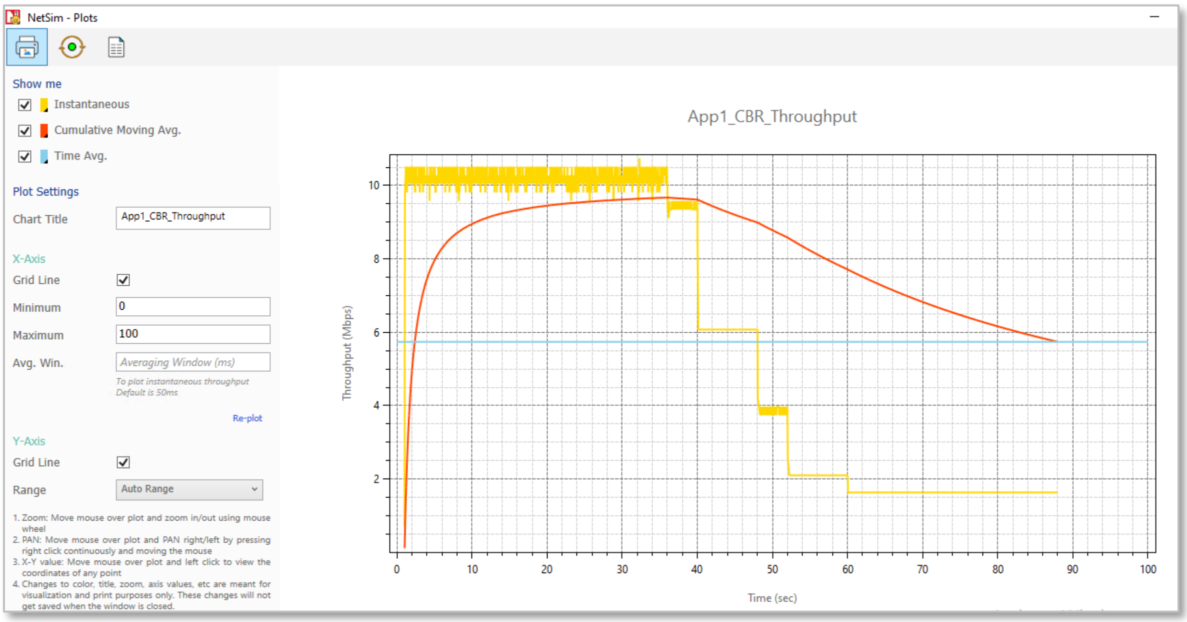

Figure 4-76: Plot of Throughput (Mbps) vs Time (sec)

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Discussion

As the UE moves away from the gNB, the Application throughput starts reducing. The maximum throughput of 10 Mbps is obtained until 36 sec. At 40s the UE is 1000m away from the gNB. Then the throughput drops to 9.5 Mbps at 40 sec and at time 48 sec (when UE is 1200m away from gNB), the throughput drops to 5.84 Mbps and at time 52 sec (when UE is 1300m away from gNB), the throughput drops to 2.10 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 3.9.1.
- Wireshark packet capture for 5G MAC
- Broadcast 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
  - 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 and Duplicate discarding.

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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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