NetSim®

Accelerate Network R & D

5G NR

A Network Simulation & Emulation Software

By



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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. The Simulation is a 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.

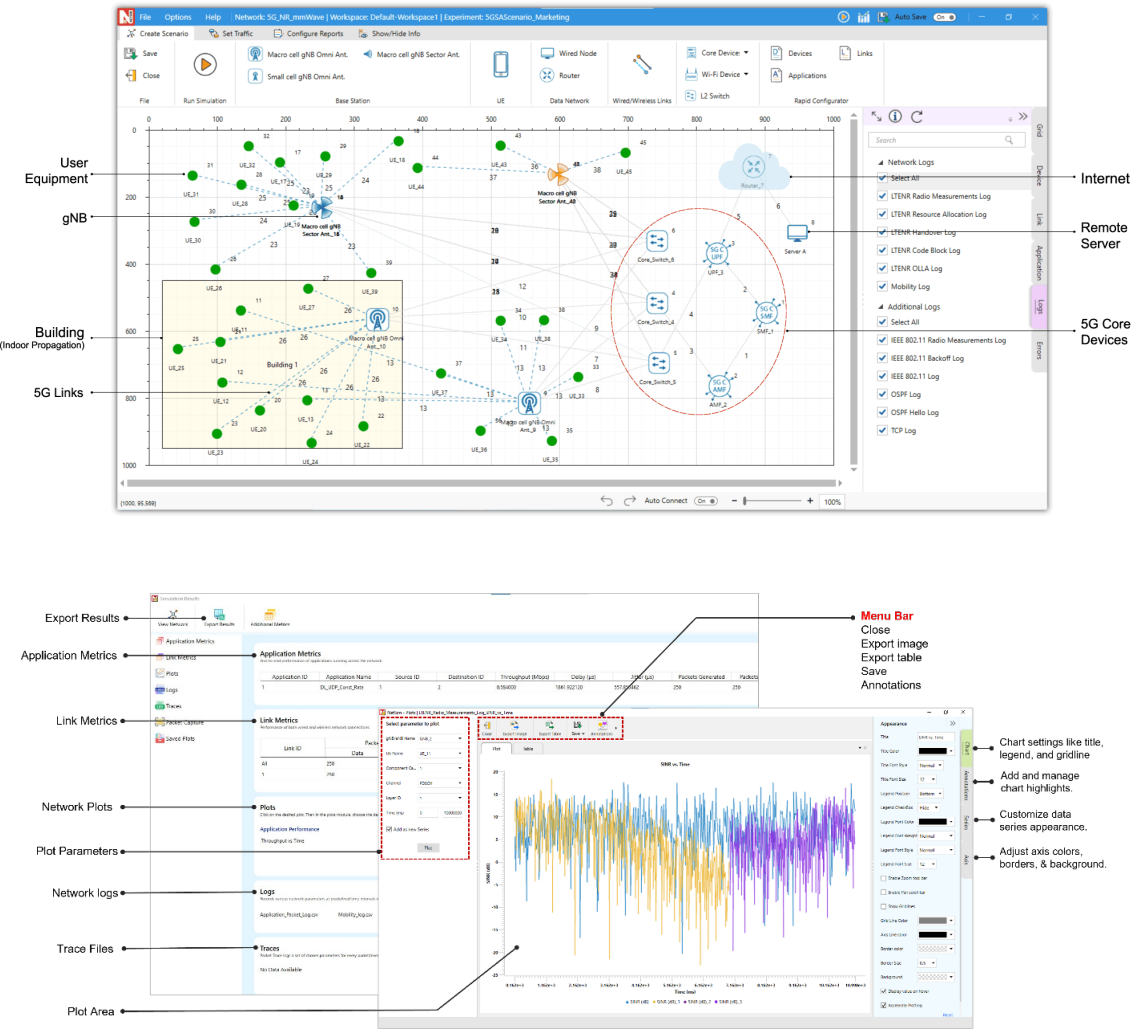


Figure 1-1: *NetSim's 5G NR design window, the results dashboard and the plots window.*

2 Simulation GUI

2.1 Create Scenario

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

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

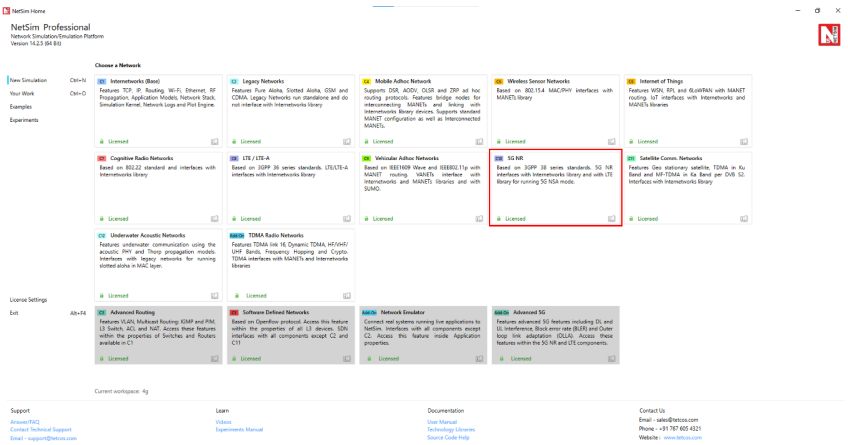


Figure 2-1: *NetSim Home Screen*

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), and UE (User Equipment). Devices are connected using 3GPP defined interfaces; O-RAN defined interfaces are not available.

2.2 NetSim 5G Network Setup

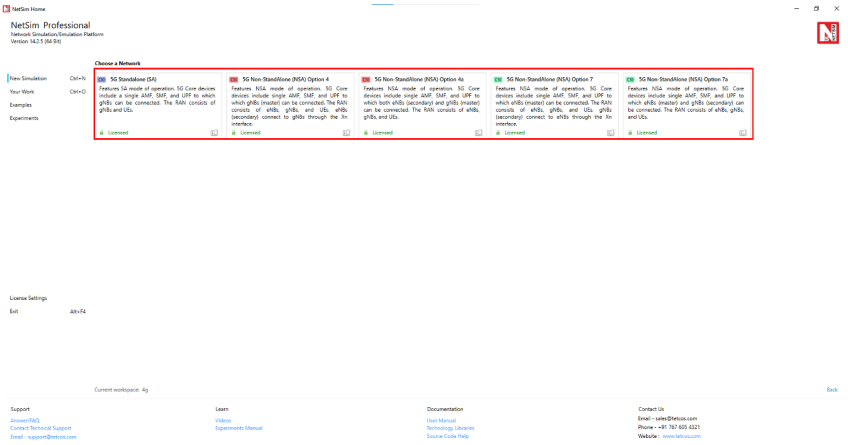


Figure 2-2: *NetSim 5G Network Setup window*

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 (5G NR) that is connected to 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 5G Core.

Standalone: In 5G Standalone 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-Standalone: In the Non-Standalone 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:

- Option 4 where only 5G Core devices are present, and EPC is not available. Option 4 is categorized into:
  - Option 4: Only gNB connects to all the 5G Core interfaces. eNB connects to the XN interface.
  - Option 4a: gNB connects to all 5G Core interfaces and eNB connects to AMF and UPF through respective interfaces.
- Option 7 where only 5G Core devices are present, and EPC is not available. Option 7 is categorized into:
  - Option 7: eNB connects to all 5G Core interfaces. gNB connects only to the XN interface.
  - 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 onto 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.
- Users 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.
- IP addressing is automatically set by NetSim. It is recommended not to change the default IP addresses.

NOTE: In NSA Mode the UEs get automatically connected to its master node. Only for secondary node UEs must be connected manually.

2.2.3 NSA Deployment Device Connectivity

The device connectivity rules are explained below. Example screenshots are available in Section 3.16.

Option 4 / 4a

- UE should mandatorily be connected to the master node (MN) first. In option 4, the MN is the gNB.

- UE should mandatorily be connected to the secondary node (SN) next. In option 4, the SN is the eNB.
- UE cannot be connected to any other device.
- The data (external) network connects to the 5G core through the UPF. This is achieved by first connecting a router (let's call it R1) to the UPF.
- Switches, nodes, APs and other routers can now be connected to R1
- Connectivity rules for the devices within the data network follow the guidelines specified in the Internetwork library document.

Option 7 / 7a

- UE should mandatorily be connected to the master node (MN) first. In option 7, the MN is the 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 follow the guidelines specified in the Internetwork library document.

2.2.4 Grid Settings

- NetSim allows users to design the network on a rectangular grid. The major and minor grid lines are displayed; major grid line values along the X and Y coordinate are displayed. Each device's X, Y coordinate is determined by its location on the grid.
- Users can choose the grid size prior to placement of the first device.
- Users can change the grid size after placing devices on the grid, but only if the new grid size is larger than the current grid size and the grid origin does not prevent the change.
- The grid length can be in the range of 10 m to 10^9 m.

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.
  - 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 n261 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 configured 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 gNBs through L2 Switch.



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

- The UE indoor/outdoor propagation state is configured through the `UE_INDOOR_OUTDOOR` parameter in the UE's Interface (5G RAN) > Physical Layer properties. Valid values are `Outdoor` (default) and `Indoor`. When set to `Indoor`, O2I building penetration loss is applied automatically under the `3GPP TR 38.901-7.4.1` pathloss model. The gNB is always treated as outdoor in the current implementation.

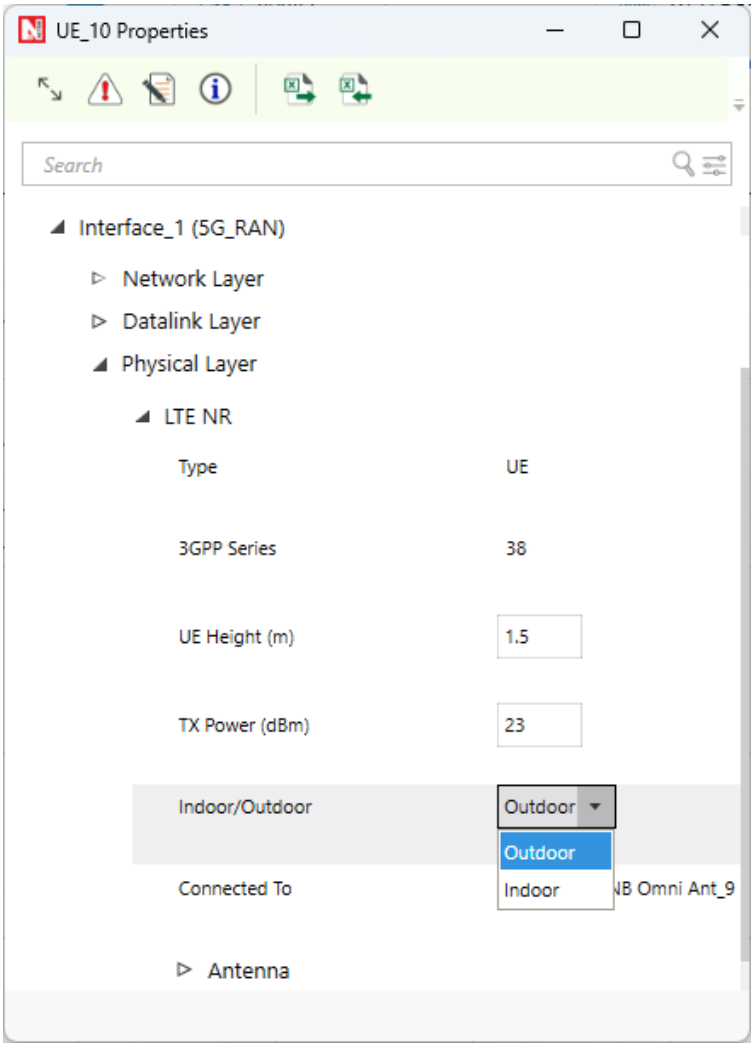


Figure 2-4: *UE properties*

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.

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

Table 2-1: *5G Config Properties — gNB Data Link Layer*

Parameter	Type	Range	Description
gNB Properties — Interface (5G RAN) – Data Link Layer			
Scheduling Type	Global	Round Robin	This is usually done to load balance and share system in circular order, handling all processes without priority
	Global	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.
	Global	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.
	Global	PFS with Rate Guarantee	NetSim uses a proportional fair scheduling (PFS) algorithm in the gNB to provide guaranteed bit rate (GBR) services for user equipment (UEs) in both downlink (DL) and uplink (UL). It enables users to configure GBR while dynamically allocating resources to maintain the minimum required bit rate.
	Local	Configuring GBR UEs	NetSim uses a proprietary PF based scheduling algorithm in the gNB to provide Guaranteed Bit Rate (GBR) services for User Equipment (UEs) in both downlink (DL) and uplink (UL). Users can configure GBR for UEs and the algorithm dynamically allocates resources to maintain the minimum required bit rate. This option allows you to configure the rate guarantee for GBR UEs.
	Local	GBR Bias Learning Rate	The GBR Bias Learning rate means the "penalty" for not meeting a user's throughput guarantee and is continuously adjusted based on the difference between achieved and guaranteed throughput. If the EWMA MAC throughput is below the guaranteed throughput, the Index Bias (Lagrange multiplier) increases, raising the user's priority and allocating more resources. If the EWMA MAC throughput exceeds the guaranteed throughput, the Index Bias decreases, lowering the user's priority and freeing resources for others.
	Local	GBR UE Index Bias Maximum	The maximum value the GBR Index Bias (Lagrange Multiplier) can range from 0 to 100.

Continued on next page

Table 2-1 continued from previous page

Parameter	Type	Range	Description
Slicing	Global	TRUE, FALSE	Network slicing is a key technology in 5G networks that enables the efficient allocation of radio access network (RAN) resources to guarantee specific service level agreements (SLAs) for different service categories. This capability allows network operators to create multiple virtual networks, or "slices," on top of a shared physical infrastructure, each tailored to meet the diverse requirements of various use cases and applications. This parameter allows users to enable/disable network slicing when simulating 5G.
Resource Sharing Technique	Global	Static, Dynamic	The two resource sharing options are defined as Static (or Hard Slicing) and Dynamic (or Soft Slicing). Static Resource Sharing: slices are allocated a fixed percentage of resources. It supports eMBB, URLLC, MIoT, V2x slice types. Dynamic Resource Sharing: the resource sharing is handled by the algorithm dynamically – it uses PFS (Proportional Fair Scheduling) with a rate guarantee, using stochastic online learning. This algorithm is derived from non-linear optimization theory.
EWMA Learning rate	Local	Default: 0.02 (Static), 0.0005 (Dynamic). Range: 0.00000001 (10^{-8}) to 0.1 (10^{-1})	EWMA Learning Rate (α) determines how important the current observation is in the calculation of the EWMA. The expression below shows how the current throughput is based on the previous throughput and the current rate. $\theta_t = (1-\alpha)\theta_{t-1} + \alpha R_t$
Lagrange multiplier learning rate	Local	Default: 0.000005. Range: 0.00000001 (10^{-8}) to 0.1 (10^{-1})	The Lagrange multiplier measures the "penalty" for not meeting a user's throughput guarantee and is continuously adjusted based on the difference between achieved and guaranteed throughput.
SSB Periodicity	Local	5, 10, 20, 40, 80, 160 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.

Continued on next page

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Table 2-1 continued from previous page

Parameter	Type	Range	Description
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 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. It can be enabled or disabled by setting the value “TRUE” or “FALSE”.
PDCP T Reordering Timer	Local	0–500 ms	This timer is used by the receiving side of an AM RLC entity in order to detect loss of RLC PDUs at lower layer. PDCP reordering is always enabled if in sequence delivery to layers above PDCP is needed.
RLC T Status Prohibit	Local	0–2400 ms	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	0–200 ms	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. Unit=ms.
RLC T Poll Retransmit	Local	5–4000 ms	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 (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.

Continued on next page

Table 2-1 continued from previous page

Parameter	Type	Range	Description
HARQ Mode	Local	TRUE, FALSE	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. 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). If the transmitter receives an ACK, it sends the next CBG. However, if the transmitter receives a NACK, it retransmits the previously transmitted CBG. Large number packet errors can be observed in packet traces 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. Max number of HARQ processes is 8 in 4G and 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 retransmission 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.

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Table 2-1 continued from previous page

Parameter	Type	Range	Description
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. 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.
Cell Individual Offset (CIO)	Local	−10 to +10 dB	CIO is added to the measured SINR of the target cell during handover evaluation. A positive CIO increases the signal value and a negative CIO decreases the signal value. CIO is used to control handovers and distribute load across cells.

Table 2-2: *5G Config Properties — gNB Physical Layer*

Parameter	Type	Range	Description
Interface (5G RAN) – Physical Layer			
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 FRAME DURATION 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 SUBFRAME DURATION 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.

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
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	−40 to 100 dBm	In NetSim the Tx power range is −40 dBm to 100 dBm. The default value for Tx power is 23 dBm for UEs and 40 dBm for gNBs. When running in MIMO mode the transmit power is split equally amongst all the MIMO layers. The number of MIMO layers is $\min(N_t, N_r)$.
Duplex Mode	Local	TDD, FDD	Time Division Duplexing: Downlink (DL) and uplink (UL) 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.
CA Type	Local	Intra-band contiguous CA, Intra-band non-contiguous CA, Single 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 dropdown shows the frequency band options for the user to choose from.

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Table 2-2 continued from previous page

Parameter	Type	Range	Description
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 on Frequency Range (FR1 & FR2), please refer to PHY Layer.			
Slot Type	Local	Mixed, Downlink, Uplink	Mixed: In Mixed slot type, there will be both downlink and uplink slots allocated. The DL:UL ratio will determine how many slots are allocated for downlink and for uplink. The default value of the DL:UL ratio is 1:1. 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 are 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. 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.

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
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	$\mu = 0, 1, 2, 3, 5, 6$	Sub carrier spacing is derived from numerology per the expression $15 \times 2^{\mu}$ kHz. 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 = 5 means subcarrier spacing 480 kHz, and 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 5 MHz 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.
Subcarrier Spacing	Local	15–960 kHz	In 5G NR, subcarrier spacing of 15, 30, 60, 120, 240, 480, and 960 KHz are supported.
Bandwidth PRB	Local	180–11520 kHz	The PRB bandwidth is dependent on numerology (μ).
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.
Slot per Subframe	Local	1, 2, 4, 8, 16, 32, 64	Number of slots in a sub-frame. Non-editable, determined by numerology.
Slot Duration (μs)	Local	1000, 500, 250, 125, 62.5, 31.25, 15.63	Slot duration is a non-editable parameter that depends on numerology selected. $\mu = 0$, Slot Duration = 1000 μs; $\mu = 1$, 500 μs; $\mu = 2$, 250 μs; $\mu = 3$, 125 μs; $\mu = 4$, 62.5 μs; $\mu = 5$, 31.25 μs; $\mu = 6$, 15.63 μs.
Cyclic Prefix	Local	Normal	If set to "normal" then symbols per slot is 14; if "extended" then 12.

NOTE: Cyclic Prefix is Extended only for a few CA types.

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
Symbol per Slot	Local	12, 14	Depends on Cyclic prefix. Normal: 14, Extended: 12.
Overhead (%) per DL slot	Local	0.01–0.99	Fraction of symbols used for control signaling. Default: 0.14 for FR1, 0.18 for FR2, 0.25 for 4G.
Overhead (%) per UL slot	Local	0.01–0.99	Fraction of symbols used for control signaling. Default: 0.08 for FR1, 0.10 for FR2, 0.25 for 4G.
Symbol Duration (μs)	Local	71.43, 35.71, 17.86, 8.93, 4.47, 2.23, 1.12	Symbol duration depends on numerology. Non-editable.
ANTENNA			
TX Antenna Count	Local	1–128 (gNB), 1–16 (UE)	The number of transmit antennas. This parameter takes effect during MIMO operation; the number of MIMO layers would be $\min(N_t, N_r)$, where N_t is the transmit antenna count at the transmitter and N_r is the receive antenna count at the receiver. The layer-wise gains depend on the fading model chosen and are explained in the 5G NR manual digital beamforming section.
RX Antenna Count	Local	1–128 (gNB), 1–16 (UE)	The number of receive antennas. This parameter takes effect during MIMO operation; the number of MIMO layers would be $\min(N_t, N_r)$, where N_t is the transmit antenna count at the transmitter and N_r is the receive antenna count at the receiver. The layer-wise gains depend on the fading model chosen and are explained in the 5G NR manual digital beamforming section.
Antenna Type	Fixed		NetSim supports Omnidirectional and Sector Antennas.
Orientation 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.
Element Gain	Local	−50 to +50	Maximum directional gain of the radiation element (in dB). Default 8 dBi.
Front to back ratio	Local	10–40	Ratio of power gain between the front and rear of a directional antenna.

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Table 2-2 continued from previous page

Parameter	Type	Range	Description
Beam width	Local	0–90	The 3 dB, or half power, beamwidth of the antenna.
PDSCH CONFIG			
MCS Table	Local	QAM64, QAM256, QAM64LOWSE	Modulation and coding scheme Table. Recommend same MCS table for PDSCH and PUSCH. For QAM64: CQI Table 1, QAM256: Table 2, QAM64LOWSE: Table 3.
X Overhead	Local	XOH0, XOH6, XOH12, XOH18	Accounts for overhead from CSI-RS, CORESET, etc.
PUSCH CONFIG			
MCS Table	Local	QAM64, QAM256, QAM64LOWSE	Same options as PDSCH.
Transform Precoding	Local	Enable/Disable	Transform Precoding is the first step to create a 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	Based on 3GPP Table 5.2.2.1-2. Must match MCS table: QAM64: Table 1, QAM256: Table 2, QAM64LOWSE: Table 3.
CHANNEL MODEL			
Pathloss Model	Local	3GPP TR 38.901-7.4.1, Log Distance, None	Signal attenuation per the mean pathloss model.
Outdoor Scenario	Local	Rural Macro (RMa), Urban Macro (UMa), Urban Micro (UMi)	Per 3GPP TR 38.900 standard.
Building Height (m)	Local	5–50m	Height of building in meters.
Street Width (m)	Local	5–50m	Width of the street in meters.
LOS/NLOS Selection	Fixed	3GPP TR 38.901-Table 7.4.2-1, User Defined	3GPP TR 38.901-Table 7.4.2-1: The LOS mode, either Line-of-sight or Non-Line-of-sight, is based on LOS probability calculated per the standard table. 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.

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
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 LOS Probability = 0, the LOS mode is set to Non-Line-of-Sight explicitly. For any value between 0 and 1, LOS mode is set per the given probability, by tossing a biased coin.
Shadow Fading Model	Local	None, 3GPP TR 38.901	Models for signal attenuation due to shadowing. 3GPP TR 38.901 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. None disables the shadow fading model.
Fading and Beamforming	Local	No Fading MIMO unit gain, No fading MIMO array gain, Rayleigh with Eigen beamforming, Rician with Eigen beamforming	Rayleigh with Eigen beamforming: NetSim uses the rich scattering in the channel to form spatial channels. The number of spatial channels is equal to the number of layers. No fading MIMO unit gain: No fading with gain equal to unity (0 dB). No fading MIMO array gain: No fading but gain equals the array gain. Rician with Eigen beamforming: the channel combines a dominant Line-of-Sight component with scattered components. See Table 3-3 for more information.
O2I Building Penetration Model	Local	Low Loss Model, High Loss Model	Shown only when Pathloss Model is `3GPP TR 38.901-7.4.1`; not available for Log-distance or None. `Rural macro`: Low Loss Model only. `Urban macro` and `Urban micro`: Low Loss Model or High Loss Model. Has no effect for `Outdoor` UEs.
Additional Loss Model	Local	None, Matlab	Additional loss models 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.
Pathloss Exponent (-)	Local	2 to 5	Pathloss exponent indicates the rate at which the pathloss increases with distance. The value depends on the specific propagation environment. Set any value between 2 to 5.
Shadowing Model	Local	None, Log Normal	Log Normal model suitable for scenarios with mobility and obstructions.
Standard Deviation (dB)	Local	5 to 12 dB	Standard deviation of log-normal shadowing distribution.
INTERFERENCE MODEL			

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
Downlink Interference Model	Global	No interference, Graded distance based Wyner model, Exact geometric model	Wyner is approximate, geometric model is exact.
Uplink Interference Model	Global	No interference, Interference over thermal	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 configured interference-over-thermal setting.
ERROR MODEL AND MCS SELECTION			
MCS selection model	Global	Ideal Shannon theorem-based rate, Shannon rate with attenuation factor	NetSim determines the modulation and coding scheme in 5G and LTE, based on received SINR, per the following models: Ideal Shannon theorem-based rate and Shannon rate with attenuation factor. Then the 3GPP standards spectral efficiency versus 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 values 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 errors in 5G and LTE. If enabled then NetSim looks up the SINR-CBS-MCS versus BLER tables to decide on the code block error rate for the chosen MCS.
Outer loop link adaptation	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.
NOTE: Refer Propagation Models (Per 3GPP TR 38.900) for technical information.			
UE Properties — Interface (5G_RAN) – Physical Layer			
UE Height (m)	Local	1–22.5	It is the height of the UE in meters.

Continued on next page

Table 2-2 continued from previous page

Parameter	Type	Range	Description
UE Indoor Outdoor	Local	Outdoor, Indoor	Sets the UE propagation state. `Indoor`: O2I building penetration loss is applied when the gNB Pathloss Model is `3GPP TR 38.901-7.4.1`. `Outdoor` (default): no O2I loss applied. The gNB is always treated as outdoor.
TX Power (dBm)	Local	−40 to 50 dBm	In NetSim the Tx power range is −40 dBm to 50 dBm. The default value for Tx power is 23 dBm for UEs and 40 dBm for gNBs. When running in MIMO mode the transmit power is split equally amongst all the MIMO layers. The number of MIMO layers is $\min(N_t, N_r)$.
UE ANTENNA			
TX Antenna Count	Local	1, 2, 4, 8, 16	The number of transmit antennas. This parameter takes effect during MIMO operation; the number of MIMO layers would be $\min(N_t, N_r)$, where N_t is the transmit antenna count at the transmitter and N_r is the receive antenna count at the receiver. The layer-wise gains depend on the fading model chosen and are explained in the 5G NR manual digital beamforming section.
RX Antenna Count	Local	1, 2, 4, 8, 16	The number of received antennas. This parameter takes effect during MIMO operation; the number of MIMO layers would be $\min(N_t, N_r)$, where N_t is the transmit antenna count at the transmitter and N_r is the receive antenna count at the receiver. The layer-wise gains depend on the fading model chosen and are explained in the 5G NR manual digital beamforming section.
5G Logs			
LTENR Radio Measurements Log	Global	Enable/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.

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Table 2-2 continued from previous page

Parameter	Type	Range	Description
LTENR Resource Allocation Log	Global	Enable/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/Disable	Records the events that occur during a handover. This contains the timestamp, 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/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/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 timestamps, gNB ID, UE ID, etc. This log can be used to understand OLLA mechanisms in 5G.
IEEE 802.11 Radio Measurement Log	Global	Enable/Disable	Records pathloss, shadowing loss, fading loss, transmitted power, received power, SNR, Interference Power, SINR, 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/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/Disable	Records events and states associated with IEEE 802.11 protocols along with time stamps. This file can be used for understanding and debugging through the protocol internals.
OSPF Log	Global	Enable/Disable	Records OSPF Protocol events: control message exchanges, interface state updates, etc.
OSPF Hello Log	Global	Enable/Disable	Logs OSPF Hello message events with timestamps.

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Table 2-2 continued from previous page

Parameter	Type	Range	Description
TCP Log	Global	Enable/Disable	Records TCP connection state transitions.
PRB Utilization log	Global	Enable/Disable	Records PRB utilization parameters over time.
TCP Congestion window log	Global	Enable/Disable	Records TCP congestion window events and states.

2.4.1 Devices: Click and drop into environment

- 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.
- Add a gNB (Macro cell gNB Omni Antenna, Small cell gNB Omni Antenna and Macro Cell 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.
  - Every gNB should be connected to at least one UE.
- Add a User Equipment (UE):
  - Click the UE icon on the toolbar and place the UE in the grid.
  - In SA & NSA mode UEs will get automatically connected to Master nodes while for the secondary nodes UEs should be connected manually.
  - Set `UE_INDOOR_OUTDOOR` in the UE's Interface (5G RAN) > Physical Layer properties to `Indoor` or `Outdoor` (default) as required. O2I penetration loss is applied automatically for `Indoor` UEs when the `3GPP TR 38.901-7.4.1` pathloss model is used.
  - A UE can never be connected to more than one gNB, and neither can it be out-of-range of all gNBs.
- Add a Router: A Router is automatically placed with the 5G Core devices and is connected with UPF/EPC.
- 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.
- 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.
- In the gNB's Interface (5G RAN) > Physical Layer > Channel Model, select the Outdoor Scenario (Rural macro, Urban macro, or Urban micro). O2I penetration loss is applied automatically for `Indoor` UEs when the `3GPP TR 38.901-7.4.1` pathloss model is used.
- Connect the devices in the 5G NR network by using Wired/Wireless Links present in the Create Scenario tab in the top ribbon.

- Configure an application as follows:
  - Click any application from the Set Traffic tab from the top ribbon.
  - Specify the source and destination devices in the network.
  - Specify other parameters as per the user requirement.
- Set the properties of UPF, AMF, SMF, gNB, UE, and other devices as follows:
  - Right-click on UPF, AMF, and SMF, then click on Open Properties as a new window and modify the interface and layer-wise properties to your requirement.
  - Right-click a gNB or UE, click on Open Properties as a new window and specify the parameters.
    * The TX Power per layer (dBm) parameter (Interface 5G RAN – Physical Layer) is local and if you change this parameter in gNB or UE, manually update the parameter for the other devices.
    * The PDCP Header Compression, PDCP Discard Delay Timer, and PDCP Out of Order Delivery parameters (Interface 5G RAN – DataLink Layer) are local and if you change any of these parameters in gNB or UE, manually update the parameter for the other devices.
  - Right-click an Access Point, L2 Switch, Wireless Node or Wired Node and specify the parameters.
    * The Interface Wireless > Physical Layer and Interface Wireless > DataLink Layer parameters are local and if you change any of these parameters in Access Point or Wireless Node, manually update the parameter for the other devices.

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 Subcarrier-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 $\mu = 0$, 1, 2 for FR1 and $\mu = 2$, 3 for FR2. The setting $\mu = 0$ corresponds to the LTE (4G) system configuration.

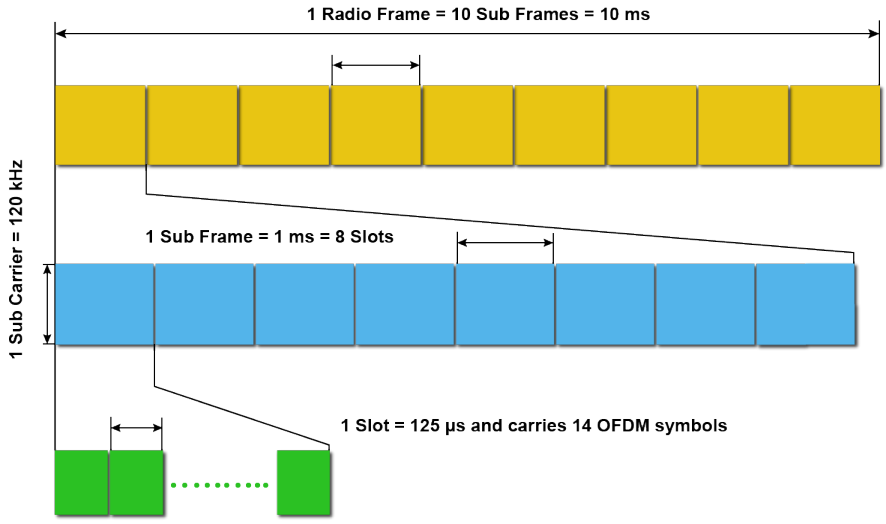


Figure 3-1: *NR Frame Structure when numerology μ is set to 3*

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 prefixes. For extended cyclic prefixes, the number of OFDM symbols per slot is 12. See Section 3.9.12.1 for more information.

In the frequency domain, the number of subcarriers per physical resource block (PRB) is fixed to 12, and the Subcarrier-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 in 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 Section 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. 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 by each associated UE-gNB pair, in DL and UL, at the start of simulation and again at every mobility event. In calculating SNR, the noise power is obtained from $N = k \times T \times B$.
- Note that the SNR/CQI is not computed/fed-back using reference signals/control channels but is computed on the data channel (PDSCH and PUSCH). Then it is assumed to be instantaneously known to the transmitter and receiver. This assumption is known as perfect 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 schemes 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 a 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 10 ms is started. Each frame in turn starts 10 subframes, each of length 1 ms. Each subframe 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.

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3.3 5G NR Stack

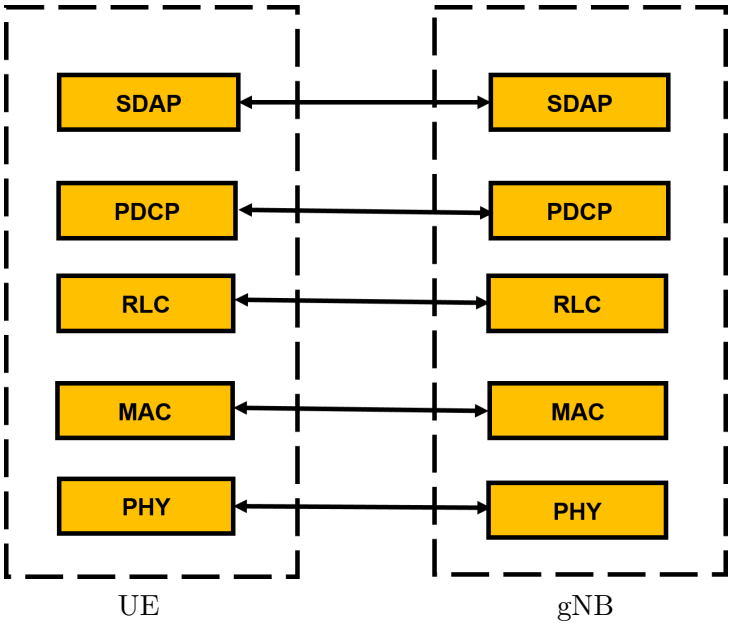


Figure 3-2: *User Plane Protocol Stack*

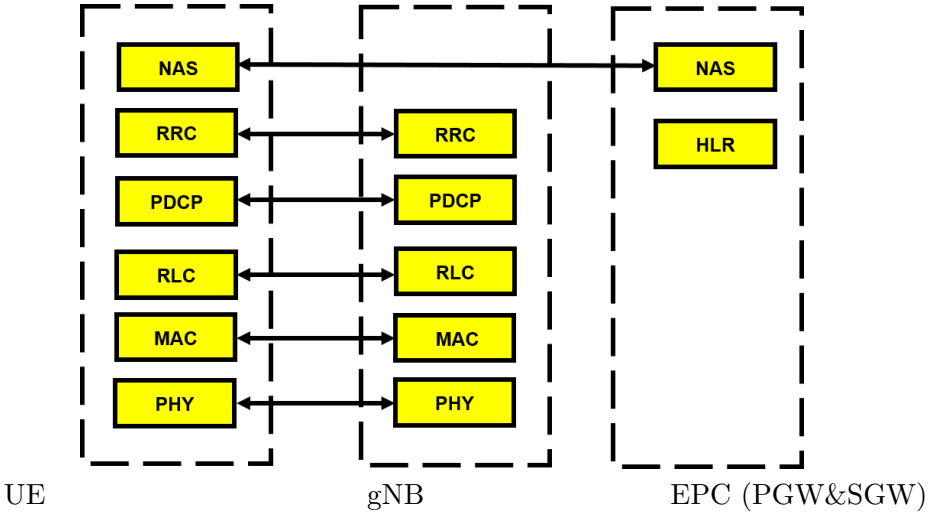


Figure 3-3: *Control Plane Protocol Stack*

3.4 SDAP (Specification: 37.324)

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.

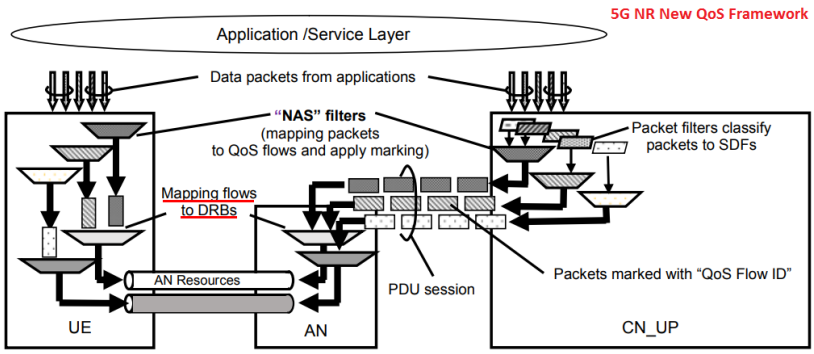


Figure 3-4: *5G Quality of Services (QoS)*

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

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

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

In the same function, the logical channel is also set to DTCH which is the dedicated traffic channel. Next comes the MAC_OUT function. This function determines what the current device is connected to i.e., if it is a UE, it finds the associated gNB, else if the current device is a gNB it finds the associated UEs. The SDAP header is then added which contains the QFI. 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 the IP layer. And finally, the HandleMacIN function decides whether the packet must be sent to another interface (if intermediate device) or sent to a 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:

- Resource type (GBR, Delay critical GBR or Non-GBR);
- Priority level.
- Packet delay budget.

- 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.

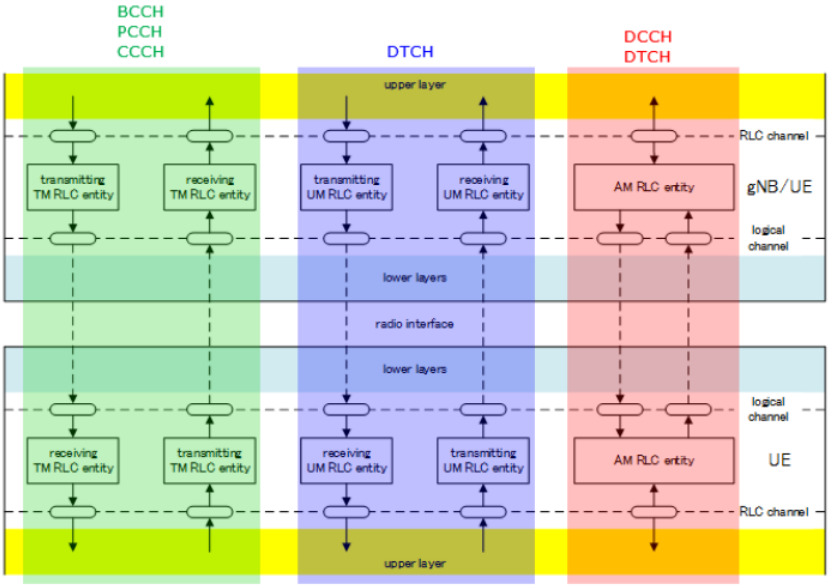


Figure 3-5: *RLC Modes of operation and RLC Entities*

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 performs both transmission and reception.

NetSim implements all the 7 entities for the RLC that are shown in Figure 3-5. Note that each of the logical channels uses a specific RLC mode:

- BCCH, PCCH, CCCH use RLC TM only.
- DCCH uses RLC AM only.
- DTCH uses 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.

UM stands for 'Unacknowledged Mode'. 'Unacknowledged Mode' means 'it does not require any reception response from the other party'. 'Reception response' simply means '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)

The RLC transmit side:

- Buffers the data and generates an RLC Header.
- Segmentation of the RLC SDU and modification of the RLC Header (Some fields in RLC header may be changed based on the segmentation status)
- Adds RLC header.

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 RLC on the receive side:

- Buffers. Here the RLC waits for all the fragments to arrive.
- Reorders, if required
- Strips the RLC header.
- Reassembles

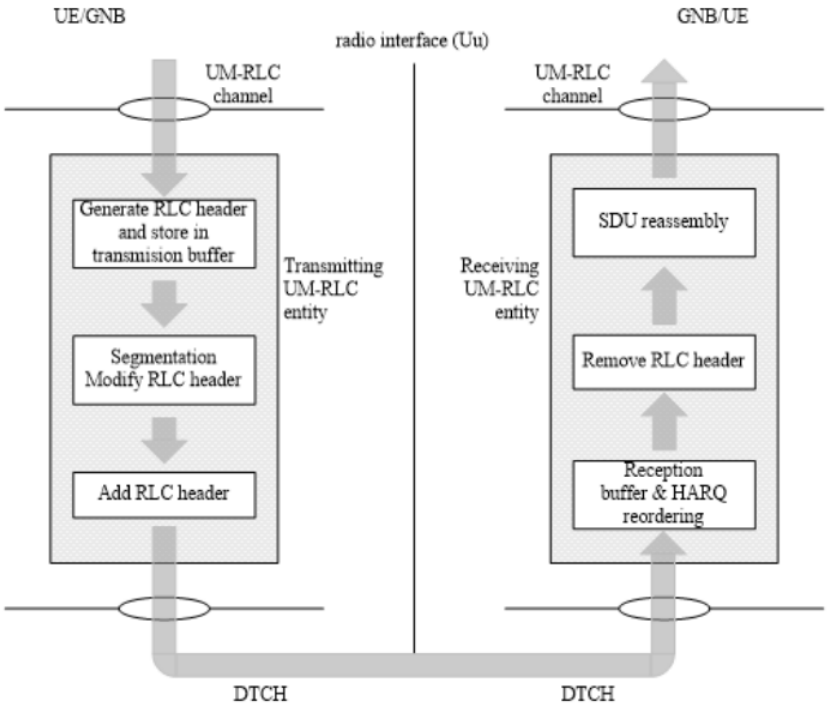


Figure 3-6: *RLC UM working.*

NetSim GUI RLC Configurable parameters

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

- t-PollRetransmit: This timer is used by the transmitting side of an AM RLC entity in order to retransmit a poll. The default value in NetSim is set to ms5 (5 milliseconds). Range is provided in the GUI dropdown menu.
- 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 the 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. The default value in NetSim is set to ms5 (5 milliseconds). Range is provided in the GUI dropdown menu.
- 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 milliseconds). Range is provided in the GUI dropdown menu. The following parameters are configured per TS 38.331 [5]:
- 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.
- 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.
- 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.

3.5.1 RLC Re-establishment

During handover, NetSim does not transfer RLC buffers from the serving cell to the target cell. This follows the RLC re-establishment behavior defined in 3GPP TS 38.322, clause 5.1.2. As per the standard, when upper layers request RLC entity re-establishment, the RLC entity discards all RLC SDUs, RLC SDU segments, and RLC PDUs, stops and resets all timers, and resets all state variables to their initial values.

In NetSim, this behavior is represented by creating fresh RLC entities for the target gNB/UE association and removing the old serving-cell RLC association. The target RLC entity starts with initial AM/UM/TM state. The old RLC entity is freed, which clears its transmission, transmitted, retransmission, AM reception, and UM reception buffers, along with AM status information and running RLC timers such as t-PollRetransmit, t-Reassembly, and t-StatusProhibit.

Therefore, RLC does not preserve or forward buffered RLC PDUs during handover. Any pending RLC data in the serving-cell RLC entity is discarded as part of re-establishment/release handling. Packet continuity across handover is maintained at the PDCP layer through PDCP context transfer and PDCP re-establishment, while RLC starts again at the target cell with initial state variables.

This maps to NetSim code as follows:

- `LTENR_RLC_ASSOCIATION(t,tin,r,rin,true)` creates the target RLC entities.

- No `fn_NetSim_LTENR_NAS_RLC_BUFFER_TRANSFER()` call is made in the handover path.
- `LTENR_RLC_ASSOCIATION(d,in,r,rin,false)` removes the serving-cell RLC entities.
- `LTENR_RLC_FreeEntity()` clears RLC buffers, stops timers, and frees the old RLC entity.

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

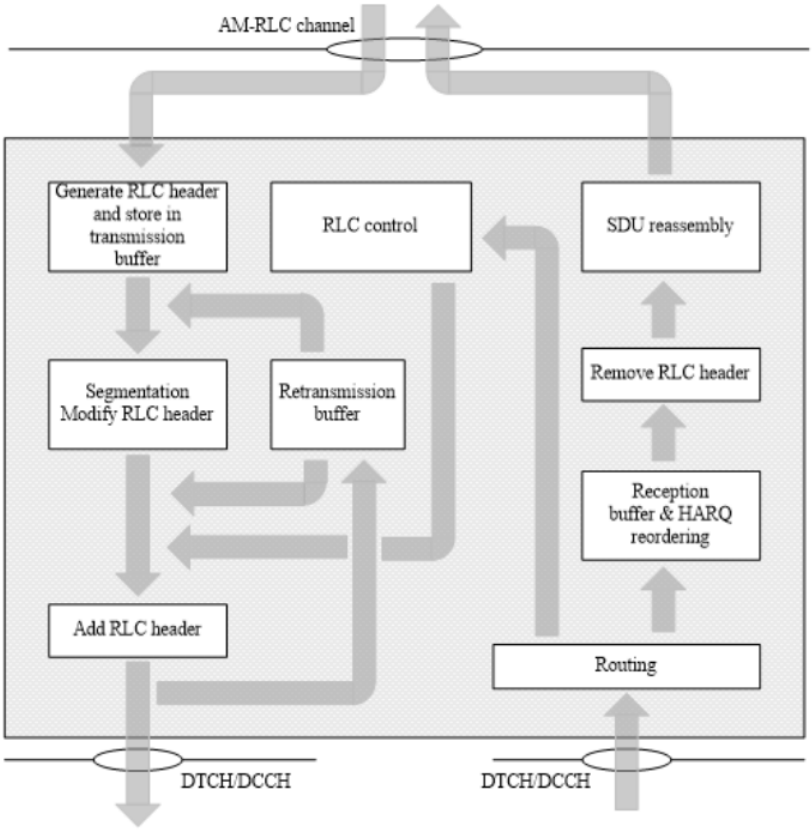


Figure 3-7: *RLC AM Working*

The functionality of RLC-AM is:

After the RLC transmitter does the segmentation/concatenation process, it adds an RLC header and then it creates two identical copies and transmits 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 gets 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:

- Transmission buffer: Queues SDUs received from higher layer (PDCP)

- Transmitted buffer: Queues SDUs that have been transmitted but for which ACK/NACK has not yet been received.
- Re-transmission Buffer: Queues RLC SDUs which are considered for retransmission. (i.e. for which NACK has been received)
- Reception Buffer: Queues fragments of SDUs (receiver side)

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

The T POLLRetransmit determines if a packet needs to be re-transmitted. If RLCAM- Ack is not received, the 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

For the normative AM transmit procedure, refer to 3GPP TS 38.322 clause 5.2.3.1 for AM data transfer and clause 5.3.3 for polling. In NetSim, these GUI-exposed RLC parameters are attached to the RLC sublayer of both gNB and UE, and they control the transmit and receive procedures of an AM RLC entity.

The transmit side operates as follows. PDCP submits SDUs to RLC, RLC segments them into AMD PDUs when needed, adds the AM header, and sends the PDUs to MAC. NetSim keeps copies in the transmission, transmitted, and retransmission buffers so that missing acknowledgements or received NACKs can trigger another transmission attempt.

The GUI parameters that control this transmit flow are:

- **RLC Poll PDU:** triggers a poll after every configured number of AMD PDUs transmitted by the AM RLC entity.
- **RLC Poll Byte:** triggers a poll after every configured amount of transmitted payload bytes.
- **RLC T Poll Retransmit:** runs at the transmitting side after a poll is sent. If the transmitter does not receive the needed STATUS feedback before this timer expires, it retransmits the poll.
- **RLC Max Retx Threshold:** limits the number of retransmissions allowed for an AMD PDU. Once the threshold is reached, NetSim stops retrying that PDU.

Although this subsection is focused on transmit operations, the same RLC property page also contains two receive-side timers because AM transmission depends on STATUS feedback from the peer receiver:

- **RLC T Status Prohibit:** runs at the receiving side and blocks repeated transmission of STATUS PDUs for the configured duration.
- **RLC T Reassembly:** runs at the receiving side to detect missing AMD PDUs or missing segments before reassembly can be finished.

Together, these six parameters define how often the transmitter requests feedback, how long it waits before polling again, how many retransmissions it allows, and how quickly the receiver reports missing data.

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3.6.2 Receive Operations

For the normative AM receive procedure, refer to 3GPP TS 38.322 clauses 5.2.3.2, 5.2.3.2.4, and 5.3.4. In NetSim, the receive-side logic is implemented in `LTENR_RLC_AM_RECEIVE_PDU()`, `LTENR_RLCAM_PLACE_AMDPDU_IN_RECEPTIONBUFFER()`, `LTENR_RLCAM_ReassembleAllBytes()`, and `LTENR_RLCAM_Handle_t_reassemblyTimer()`.

The receiving window check is done by `LTENR_RLCAM_IsSNFallsInReceivingWindow()`, which accepts an AMD PDU only when

$$\texttt{RX\_Next} \leq \texttt{SN} < \texttt{RX\_Next} + \texttt{AM\_Window\_Size}.$$

- For each accepted AMD PDU, NetSim creates or finds the per-SN entry in `AM.reception Buffer`, appends the packet, and records {`SI`, `SN`, `SO`} in `AM.recvdInfo`. The state variable `RX_Next_Highest` is updated to `SN+1` when a higher sequence number is seen.
- If the last segment for that SN is present and every byte position from `SO = 0` to the last stored segment offset has arrived, `LTENR_RLCAM_ReassembleAllBytes()` merges the segments, removes the AM header, deletes the reception-buffer entry, updates `RX_Highest _Status` and `RX_Next`, and passes the SDU to PDCP through `LTENR_CallPDCPIN()`.
- `t-Reassembly` is started when a gap is observed between `RX_Next` and `RX_Next_Highest`. On expiry, `LTENR_RLCAM_Handle_t_reassemblyTimer()` calls `LTENR_RLCAM_UpdateRece ptionBuffer()`, removes stale reception-buffer entries whose `reassembleCount` exceeds `maxRetxThreshold`, recomputes `RX_Highest_Status` and `RX_Next`, restarts the timer if the gap still exists, and then triggers STATUS reporting.

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

On receiving the AMPDU NetSim checks if

- It is within the receive window.
- The packet is not already received i.e. not a duplicate packet.

If both the conditions are true, the AMPDU is placed in the Reception Buffer and the Reassembly Timer is started. If the PDU has a Poll Request then it starts constructing the StatusPDU.

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 PDCP functionality supported in NetSim is:

- Transmit PDCP SDU
  - Sets the PDCP Sequence Number
  - Adds RLC Header.
  - Calls RLC service primitive.
- PDCP Association
  - This call back function is invoked when the UE associates/dissociates from a gNB.
- Maintenance of PDCP sequence numbers (to know more check the PDCP entity structure)
- Discard Timer:
  - When the discardTimer expires for a PDCP SDU, or the successful delivery of a PDCP SDU is confirmed by PDCP status report, the transmitting PDCP entity shall discard the PDCP SDU along with the corresponding PDCP Data PDU.
  - Discarding a PDCP SDU already associated with a PDCP SN causes a SN gap in the transmitted PDCP Data PDUs, which increases PDCP reordering delay in the receiving PDCP entity.
- Transmission Buffer (size is assumed to be infinite): This is where PDCP SDUs are stored before being sent down to a lower layer.

3.7.1 PDCP Re-Establishment

PDCP re-establishment is handled during UE mobility when the serving cell changes and the PDCP context has to be moved to the target cell. In NetSim, the serving PDCP entity transfers its transmit buffer, receive buffer, and sequence state to the target PDCP entity before re-establishment is applied.

The implementation follows 3GPP TS 38.323 PDCP state handling. Each PDCP entity maintains TX_NEXT, RX_NEXT, RX_DELIV, and RX_REORD for COUNT-based transmission, reception, duplicate detection, and in-order delivery. During re-establishment, SRB and UM DRB entities reset the PDCP COUNT state variables TX_NEXT, RX_NEXT, and RX_DELIV to their initial value after handling buffered packets. For AM DRBs, the PDCP COUNT state is maintained, while buffered packets are delivered or discarded according to the re-establishment procedure. Any running t-Reordering procedure is stopped so that old reordering context does not affect packet delivery after re-establishment.

In handover, `fn_NetSim_LTENR_NAS_PDCP_BUFFER_TRANSFER()` first moves PDCP buffers and sequence variables from the serving entity to the target entity. After this transfer, `LTENR_PDCP_REESTABLISH()` performs the bearer-specific re-establishment actions at the target gNB and UE PDCP entities. This preserves mobility-related PDCP context transfer while preventing stale buffered packets or timers from affecting post-handover packet delivery.

3.8 MAC Layer

3.8.1 Overview

NetSim 5G NR MAC implements the following features:

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

3.8.2 MAC Scheduler: 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 Section 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

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

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 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 not 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

$$R_i\left(t\right) = \frac{S\left(M_i(t), 1\right)}{\tau} \tag{2}$$

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

$$i^*\left(t\right) = \underset{j=1,\ldots,N}{\operatorname{argmax}} \left(\frac{R_j\left(t\right)}{T_j\left(t\right)} \right) \tag{3}$$

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

$$T_j\left(t\right) = \left(1 - \frac{1}{\alpha}\right) T_j\left(t-1\right) + \frac{1}{\alpha} \hat{T}_j(t) \tag{4}$$

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 user j in the subframe t. If $\hat{B}_j(t)$ is the number of PRBs allocated to user j, we finally get

$$\hat{T}_j\left(t\right) = \frac{S(M_j\left(t\right), \hat{B}_j\left(t\right))}{\tau} \tag{5}$$

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

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.

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

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 milliseconds.

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 PRB 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 is similar to what is explained in the PF scheduler.

In the code, MT scheduling uses the same scheduler status structure as the other MAC schedulers, but changes the ranking rule. In `LTENR_PRB.c`, the function `LTENR_PRB_InitRank_MaxThroughput()` sets the UE rank equal to `bitsPerPRB`. Therefore, after sorting, the UE with the largest instantaneous number of bits that can be sent per PRB is scheduled first.

The quantity `bitsPerPRB` is prepared before scheduling in `LTENR_MACScheduler_UpdateInfoForUE()` in `LTENR_MAC.c`. For each active MIMO layer, NetSim computes the transport block size for one PRB using the current AMC/MCS information and sums these values across layers. If the CQI index is zero, if RRC setup is not complete, or if the packet belongs to HARQ retransmission rather than new data, the scheduler does not use that UE for fresh MT ranking in that slot.

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

$$R_i\left(t\right) = \frac{S\left(M_i(t), 1\right)}{\tau} \tag{6}$$

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

$$i^*\left(t\right) = \underset{j=1,\ldots,N}{\operatorname{argmax}}\left(R_j\left(t\right)\right) \tag{7}$$

Once the UE list is ranked, `LTENR_PRB_SortingofRank()` orders the list in descending rank and the allocation logic computes each UE's PRB demand as

$$\left\lceil \frac{\text{bufferSize} \times 8}{\text{bitsPerPRB}} \right\rceil .$$

The available PRBs are reduced first by MAC control overhead and then by PRBs reserved for HARQ retransmissions. NetSim then gives the selected UE either its full PRB demand if enough PRBs remain, or the remaining PRBs otherwise. Thus, in a loaded cell, the scheduler tends to drain the buffers of UEs with the best instantaneous radio conditions before serving UEs with lower spectral efficiency.

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

- Carrier aggregation case: the scheduler runs on a per carrier basis.
  - PF Scheduler: $\hat{T}_j(t)$ is computed and maintained independently for each carrier.
- NSA mode: Traffic is split between 4G and 5G (eNB and gNB) above the MAC. The scheduler runs independently on the eNB and gNB.
- Association and Handover: PF Scheduler: At time of association or handover, say t_a, NetSim sets $T_j\left(t_a\right) = 1$
- Application priorities and heterogenous traffic: In 5G, the types of QoS are
  - GBR, which is transmitted in RLC UM mode. In NetSim, Applications which have a UGS priority set are transmitted in UM mode.
  - Non-GBR, which is transmitted in RLC AM mode. In NetSim, Applications which do not have a UGS priority set are transmitted in AM mode.
  - Control channel traffic, which is transmitted in RLC TM mode. NetSim assumes ideal control plane behaviour and doesn't model these transmissions.
- 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.

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3.8.7 Active Queue Management (AQM)

3.8.7.1 Overview

Active Queue Management (AQM) controls how packets are admitted to or dropped from the RLC transmission queues at the gNB before MAC scheduling takes place. Without AQM, queues can grow unchecked, leading to persistent bufferbloat and increased end-to-end latency. AQM mitigates this by proactively dropping or limiting packets before the queue overflows, providing earlier congestion feedback to the transport layer.

In NetSim, AQM is applied to user-plane traffic (Dedicated Traffic Channel, DTCH) only. Control and signalling traffic bypasses AQM and is always admitted to the queue.

3.8.7.2 Supported Algorithms

NetSim supports three queueing disciplines, selectable via the `TYPE` parameter:

1. **Drop Tail** — A simple FIFO queue with a hard buffer limit. Packets are accepted until the queue reaches the configured limit; all subsequent arrivals are dropped. Drop Tail provides no early congestion signalling and can lead to lock-out and global synchronisation effects with TCP traffic.

2. **RED (Random Early Detection)** — Maintains an exponentially weighted moving average (EWMA) of the queue size and uses it to make probabilistic drop decisions. The EWMA is updated on each packet arrival as follows:

$$\bar{q} \leftarrow \bar{q} + w_q \left(q_{\text{current}} - \bar{q}\right) \tag{8}$$

   where $\bar{q}$ is the average queue size, q_{current} is the instantaneous queue size, and w_q is a small weight (default 0.0002) that controls how quickly the average responds to queue fluctuations.

   The drop decision follows three regions:

   - If $\bar{q} <$ min_th: the packet is accepted.
   - If min_th $\leq \bar{q} <$ max_th: the packet is dropped with a probability that increases linearly from 0 to max_p as $\bar{q}$ moves from min_th to max_th.
   - If $\bar{q} \geq$ max_th: all arriving packets are dropped.

   By dropping packets before the queue is actually full, RED allows TCP senders to reduce their sending rate early, reducing average queuing delay.

3. **WRED (Weighted RED)** — Extends RED with per-priority-class thresholds. Four traffic classes are supported: *Low*, *Normal*, *Medium*, and *High*. Each class has its own min_th, max_th, and max_p. All classes share a single EWMA queue average, but the drop decision is evaluated against the thresholds of the arriving packet's priority class. This allows lower-priority traffic to be dropped more aggressively during congestion while higher-priority traffic is protected.

3.8.7.3 Configuration

AQM is configured in the gNB properties. Table 3-2 lists the available parameters.

Table 3-2: *AQM configuration parameters.*

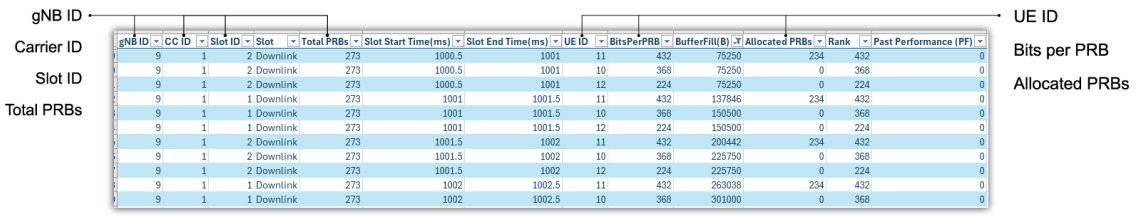
Parameter	Applies to	Default	Description
ENABLE	All	false	Enable or disable AQM
TYPE	All	DROP_TAIL	Algorithm: DROP_TAIL, RED, or WRED
QUEUE_LIMIT	All	0 (unlimited)	Hard buffer limit in MB; 0 means unlimited
WQ	RED, WRED	0.0002	EWMA weight for average queue computation
MIN_TH	RED	4.0 MB	Minimum threshold for early dropping
MAX_TH	RED	7.0 MB	Maximum threshold; all packets dropped above this
MAX_P	RED	0.05	Maximum drop probability at MAX_TH
LOW_MIN_TH	WRED	4.0 MB	Minimum threshold for Low priority class
NORMAL_MIN_TH	WRED	4.5 MB	Minimum threshold for Normal priority class
MEDIUM_MIN_TH	WRED	5.0 MB	Minimum threshold for Medium priority class
HIGH_MIN_TH	WRED	5.5 MB	Minimum threshold for High priority class
LOW_MAX_TH ... HIGH_MAX_TH	WRED	7.0 MB	Maximum thresholds (per class)
LOW_MAX_P ... HIGH_MAX_P	WRED	0.05	Maximum drop probabilities (per class)

3.8.7.4 AQM Metrics and Log

When AQM is enabled, per-interface metrics reported at the end of the simulation include the number of packets dropped by AQM, the number dropped by buffer overflow, and the average queue size. A detailed queue log file (CSV) is also written, recording per-packet enqueue and dequeue events, instantaneous and EWMA queue sizes, and drop reasons.

3.8.8 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.



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)
9	1	2	Downlink	273	1000.5	1001	11	432	75250	234	432	0
9	1	2	Downlink	273	1000.5	1001	10	368	75250	0	368	0
9	1	2	Downlink	273	1000.5	1001	12	224	75250	0	224	0
9	1	1	Downlink	273	1001	1001.5	11	432	137846	234	432	0
9	1	1	Downlink	273	1001	1001.5	10	368	150500	0	368	0
9	1	1	Downlink	273	1001	1001.5	12	224	150500	0	224	0
9	1	2	Downlink	273	1001.5	1002	11	432	200442	234	432	0
9	1	2	Downlink	273	1001.5	1002	10	368	225750	0	368	0
9	1	2	Downlink	273	1001.5	1002	12	224	225750	0	224	0
9	1	1	Downlink	273	1002	1002.5	11	432	263038	234	432	0
9	1	1	Downlink	273	1002	1002.5	10	368	301000	0	368	0

Figure 3-8: *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 that estimates end-to-end metrics such as throughput, delay, packet loss, and queue occupancy without modelling the full baseband waveform chain. In the 5G NR module, the PHY is represented at an abstraction level that captures propagation, interference, beamforming, MIMO channel effects, and packet error behaviour while avoiding symbol-level transmitter and receiver processing. This section outlines that PHY modelling scope and the main assumptions used by the simulator. The data transmission flow and the SNR, CQI, AMC, MCS, and transport block procedures are described later in Sections 3.2, 3.9.13, 3.9.14, and 3.9.15.

3.9.2 Transmit power, Total Radiated power and EIRP

According to 3GPP standard 38.901 section 7.8, and common simulation practice, the Transmit Power parameter in a NetSim gNB or eNB is the power of a single transmitter (antenna port). The default value is 40 dBm.

In contrast, vendor datasheets usually specify the total combined power of the radio unit, which may contain multiple transmitters. The relationship is

$$TRP\ (dBm) = \text{Per Transmitter Power}\ (dBm) + 10\log_{10}(NTXU) \tag{9}$$

where TRP is the Total Radiated Power and $NTXU$ is the Number of Transmitters.

Example: If a user configures the antenna counts as 32 transmit and 32 receive (32T32R), then

$$TRP = 40 + 10\log_{10}(32) = 55.05\ (dBm) \approx 320\ W \tag{10}$$

EIRP (Effective Isotropic Radiated Power) is the radiated power in the most favorable direction. It includes antenna gain.

$$EIRP\ (dBm) = \text{Total Conducted Power}\ (dBm) + \text{Antenna Gain}\ (dBi) \tag{11}$$

If 3 dB loss is assumed between conducted and radiated power,

$$\text{Total Conducted power} = 55.05 + 3 = 58.05\ dBm \tag{12}$$

And if the maximum antenna gain was 25 dBi, we have

$$EIRP = 58.05 + 25 = 83.05\ dBm \tag{13}$$

Finally, if the bandwidth was set to 100 MHz, then the EIRP density would be

$$\text{EIRP Density} = 83.05 - 10\log_{10}(100) = 63.05\ (dBm/MHz) \tag{14}$$

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3.9.3 MIMO and 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 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:

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

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

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.

$$\text{BeamFormingGain } (dB) = 10 \log_{10}(\text{EigenValue}) \tag{15}$$

- 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 Beamforming 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.

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

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	$\min(N_t, N_r)$	Eigenvalues of the Wishart Matrix. Assumes MFP and MRC
Rician with Eigen beamforming	$\min(N_t, N_r)$	Eigenvalues of HH^H (Rician channel covariance matrix). Assumes MFP and MRC.

3.9.4 Type-1 Codebook (per TS 38.214)

This section explains the implementation of TypeI CSI feedback-based precoding codebooks as defined in 3GPP LTE/NR (TS 38.214) for MIMO beamforming systems.

The implementation is generic and supports:

Different antenna geometries ($N_1 \times N_2$). Single rectangular array of antenna ports with:

N_1: Number of antenna elements in horizontal direction

N_2: Number of antenna elements in vertical direction

Multiple oversampling factors (O_1, O_2)

O_1: Horizontal oversampling factor

O_2: Vertical oversampling factor

1 to 8 transmission layers

Total antenna ports:

$$P_{CSI-RS} = 2 \times N_1 \times N_2 \tag{16}$$

The factor 2 represents dual polarization.

Algorithm:

Step 1: A random MIMO channel matrix $H \in \mathbb{C}^{N_r \times N_t}$ is generated (Rayleigh fading) between the UE and the gNB.

Step 2: Perform Singular Value Decomposition (SVD) of H to calculate Rank:

$$H = U \cdot \Sigma \cdot V^H \tag{17}$$

For each layer L:

- $W = V[:, :L]$
- $R = B \log_2 \det\left(I_{N_r} + \frac{P}{L \cdot (N_0 B + I)} HWW^H H^H\right)$
- L giving maximum rate is selected as the Rank.

Where:

- P: power of gNB multiplied by the path loss between gNB and UE
- L: number of layers (Rank)
- B: system bandwidth
- H: channel matrix
- W: precoding matrix
- N_0: noise spectral density
- I: Interference

Step 3: For the selected rank, construct all candidate precoding matrices (W) from the Type-1 codebook (as defined in 3GPP TS 38.214, Sec. 5.2.2.2.1).

Select the Precoder with maximum Frobenius norm F_i:

$$F_i = \|H \cdot W\|_F \tag{18}$$

Step 4: To reduce search time, we have adopted a new search pattern:

Coarse phase: Compute Frobenius norm for every 4th codebook entry to find a coarse best index.

Fine phase: Perform an exhaustive search within ±8 entries around this coarse index to locate the optimal precoder.

Step 5: After testing all codebook entries, the UE selects the precoder and calculates eigenvalues.

Step 6: Record the layer wise SINR and Beamforming Gains in LTENR_Radio_Measurements_Log.csv.

Codebook Generation:

Each rank corresponds to a structured precoder matrix built from $\varphi_n, \theta_p, \mu_m, v_{(l,m)}, \tilde{v}_{l,m}$ as specified in Tables 5.2.2.2.1-5 through 5.2.2.2.1-12.

φ_n, θ_p: Phase rotation terms, used to create different phase-shifted versions of the same beam.

$$\varphi_n = e^{\frac{j\pi n}{2}} \tag{19}$$

$$\theta_p = e^{\frac{j\pi p}{4}} \tag{20}$$

μ_m: It is a steering vector in the vertical direction:

$$\mu_m = \begin{bmatrix} 1 & e^{\frac{j2\pi m}{O_2 N_2}} & \dots & e^{\frac{j2\pi m(N_2-1)}{O_2 N_2}} \end{bmatrix} \tag{21}$$

$v_{(l,m)}, \tilde{v}_{l,m}$: Combines horizontal and vertical (from μ_m) steering into a 2D beam.

$$v_{(l,m)} = \begin{bmatrix} \mu_m & e^{\frac{j2\pi l}{O_1 N_1}} \cdot \mu_m & \dots & e^{\frac{j2\pi l(N_1-1)}{O_1 N_1}} \cdot \mu_m \end{bmatrix}^T \tag{22}$$

$$\tilde{v}_{l,m} = \begin{bmatrix} \mu_m & e^{\frac{j4\pi l}{O_1 N_1}} \cdot \mu_m & \dots & e^{\frac{j4\pi l(N_1/2-1)}{O_1 N_1}} \cdot \mu_m \end{bmatrix}^T \tag{23}$$

Each precoder is identified by indices $i_{11}, i_{12}, i_{13}, i_2$. The ranges of these indices depend on N_1, N_2, O_1, O_2 and Rank L.

N_1, N_2: Number of antennas in the horizontal and vertical direction of the panel.

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O_1, O_2: Oversampling factor in horizontal and vertical direction. They increase the resolution of the beam grid in the horizontal (O_1) and vertical (O_2) directions.

Example: If the horizontal dimension has $N_1 = 4$ antenna elements, we will normally get 4 discrete beams. With $O_1 = 2$ oversampling, the grid is refined, and we now get $4 \times 2 = 8$ candidate beams in the horizontal direction, allowing better coverage of possible beam angles.

The code loops over all valid index combinations, generating all possible candidate precoders.

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

$$y_j = \sqrt{\lambda_j} x_j + w_j \tag{24}$$

- 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.
- 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 (eigenvalue) 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.
- 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. Modelling frequency selective fading within each user has been avoided to reduce computation time; NetSim already chooses a different fading gain every coherence time. Hence further averaging over frequency is not modelled. Note that the scheduler does not allot RBs based on CQI feedback and hence modelling frequency selectivity is not necessary.

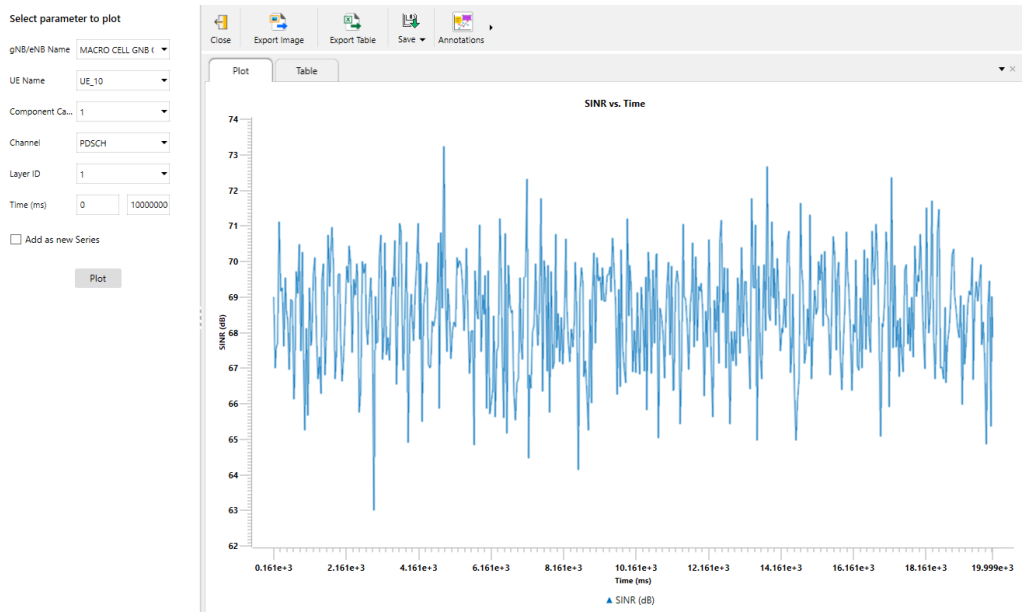


Figure 3-9: *An example NetSim output showing SINR vs. time for each MIMO layer, as the UE moves away from the gNB. The beamforming gain is recalculated every coherence time.*

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. 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.

3.9.5.1 SSB-Specific Assumptions for Analog Beamforming

- 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 is used in signal-strength calculations for initial access and handovers.
- The analog beamforming gain computed is a wideband estimate.
- 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 overheads (OH),

and the fractions are different for DL, UL, FR1, and FR2 as explained in Section 3.9. Analog beamforming measurements are assumed to be part of this overhead.

- Initial access and handover decisions are based on the received SSB SNR, defined as

$$SNR = \frac{\text{RxSignalLevel } (dB) + \text{AnalogBFGain } (dB)}{N_0 \times W} \tag{25}$$

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, NetSim assumes that SSB interference from other gNBs is 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 is negligible. Hence SNR is used.

$$\text{RxSignalLevel} = \text{gNBTxPower} + \text{PathGain} + \text{ShadowFading} \tag{26}$$

- 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).
- NetSim does not implement analog beamforming in the PDSCH or in the PUSCH. Digital beamforming can be enabled in the PDSCH/PUSCH as explained earlier in this section.
- Analog beamforming is supported both in 5G (gNBs) and in 4G (eNBs).
- The UE's optimal receive beam is assumed to be perfectly aligned to the gNB's optimal transmit beam. As shown in the figure below, the UE measures RSRP based on the selected best SSB from serving and neighbouring cells.

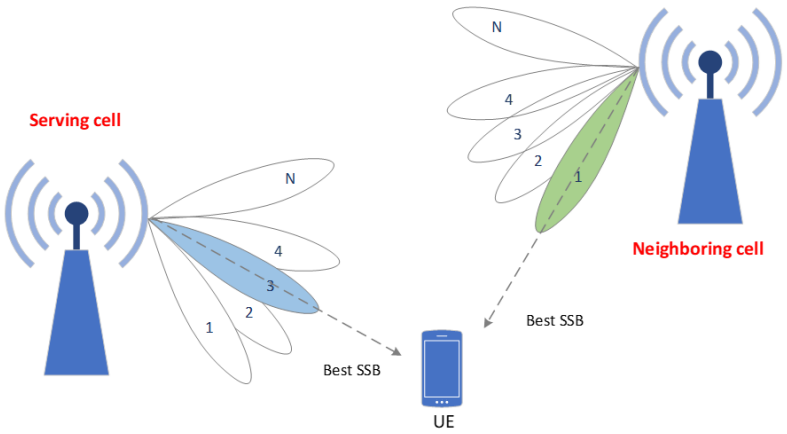


Figure 3-10: *UE Measuring RSRP using Beamforming*

- Based on the above, NetSim computes an upper bound on the average analog beamforming gain (dB) as $10\log_{10}(N_t \times N_r)$. Here N_t is the transmit antenna count at the gNB and N_r is the receive antenna count at the UE.

- Beam selection and alignment are assumed to occur instantaneously. There is no time delay for beam selection, SSB burst periodicity, and related processing. Users requiring such time delays can attempt to model them using the handover interruption time variable available in the gNB properties.

3.9.6 Analog beamforming in the SSB

In analog beamforming, multiple antennas concentrate radiated power toward a selected direction, improving SSB detection at the UE. NetSim uses analog beamforming only for the SS/PBCH control-plane measurements described in Section 3.9.5. Table 3-4 summarizes the difference between analog and digital beamforming.

Table 3-4: *Difference between Analog and digital beamforming*

	Analog Beamforming	Digital Beamforming
Benefit	Array gain	Spatial Multiplexing/Diversity
Principle	Steers the main lobe toward a direction using phased-array weights. Directional and channel-independent.	Uses channel-dependent precoding and combining to create parallel data streams.
Typical use	mmWave, short range, LOS	Low/mid band, medium/long range, NLOS

3.9.6.1 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.

3.9.7 Rank Estimation

The channel rank determines the number of parallel data streams (layers) that can be transmitted between the base station (BS) and user equipment (UE) in a MIMO system. This value is influenced by the propagation environment, channel model and the beamforming technique used.

The table below shows the rank algorithms supported when different fading and beamforming models are used.

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Table 3-5: *Rank algorithms with respect to Fading models.*

Fading Model	Beamforming	Rank Algorithm(s) Supported
No Fading	Unit Gain	Max Rank, Min (N_t, N_r)
No Fading	Array Gain	Max Rank, Min (N_t, N_r)
Rayleigh	Eigen	Max Rank, Min (N_t, N_r), Max Rate
Rician	Eigen	Max Rank, Min (N_t, N_r), Max Rate
Rayleigh	Type-1 BF	Max Rate
Rician	Type-1 BF	Max Rate

The Max Rate Algorithm

In this case, each UE sees a channel matrix H of dimensions $N_r \times N_t$ representing the channel from the BS to the UE. The optimal number of layers is selected by solving:

$$\max_{1 \le m \le \min\{N_r, N_t\}} \left(\sum_{i=1}^{m} \log \left(1 + \frac{SINR}{m} \right) \right) \tag{27}$$

where the SINR for the i-th layer is computed as:

$$SINR = \frac{P \cdot \beta \cdot \sigma^2}{N_o \cdot B + I} \tag{28}$$

Where:

- P: Tx power of BS (gNB)
- β: path loss between BS and UE_k
- σ: i-th largest singular value of H_k
- N_o: noise spectral density
- B: system bandwidth
- I: Out-of-cell Interference

In NetSim, the Max Rate algorithm is a process that finds the best number of spatial layers (the channel rank) and computes their beamforming gains. The process starts by generating the channel matrix (H) using the chosen fading model, typically by calling the Rician or Rayleigh channel generator.

Instead of guessing the number of layers, NetSim tests every possible layer count (L), from 1 up to the hardware antenna limit. For each test, it calculates the potential beamforming gains depending on the selected mode:

- **Eigen Beamforming** (`LTENR_Fading.c`): NetSim finds the mathematically ideal beamforming gains. It uses SVD (Singular Value Decomposition) directly on the channel matrix to calculate the top L values, representing unconstrained spatial multiplexing.
- **Type-1 Codebook** (`LTENR_Codebook.c`): NetSim searches through a standard library of 3GPP codebooks. It starts with a coarse search to find a good match, followed by a finer search to pick the best codeword for that rank. Once the best codeword is found, NetSim applies it to the channel and extracts the resulting layer-wise gains.

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Once the gains are known for a candidate rank, NetSim computes the received power for each layer, includes path loss, antenna gain, noise, and interference, and then evaluates the link quality using the per-layer SINR.

The Max Rate algorithm in NetSim is more than a simple rule for picking a number. It is a joint procedure that selects the best layer count, finds the precoder (using ideal SVD or 3GPP codebooks), and provides the beamforming gains that the PHY layer uses for link adaptation and throughput.

3.9.7.1 Logging of the Channel Rank

The channel rank selected by the system is logged for each transmission instance in the file LTENR_Radio_Measurements_Log.csv, under the column titled "Rank".

3.9.8 Fast fading

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 uses 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.

3.9.8.1 Rician Fading for MIMO Systems

We denote N_t: Number of transmit antennas, N_r: Number of receive antennas, and K: Rician K-factor. The range of K in NetSim is 0 to 10,000 with support for two decimals. When $K = 0$ we get Rayleigh fading and when $K \to \infty$ we get a deterministic LOS channel i.e., a constant gain channel.

NetSim applies Eigen beamforming and precoding with the number of MIMO-layers (also called channel-rank) $m = \min(N_t, N_r)$.

NetSim creates a H matrix of size $N_r \times N_t$ with each element

$$h_{ij} = x + iy \tag{29}$$

where $x, y \sim N\left(\mu, \sigma^2\right)$ with $\mu = \sqrt{\frac{K}{2(K+1)}}$, and $\sigma = \sqrt{\frac{1}{2(K+1)}}$

Let λ_i be the eigen values of HH^H. Then the layer wise gains (in linear scale) are given by

$$\text{Gains} = \{\lambda_1, \lambda_2, \ldots, \lambda_{\min(N_t, N_r)}\} \tag{30}$$

These gains are recorded in the columns "Beamforming Gain" in the Radio Measurements log file.

3.9.9 Antenna: Omni and Sector

NetSim implements both Omni and sector antennas. With Omni directional antennas the gain in all directions is 0 dB.

The sector antennas are modeled per the 2D parabolic antenna pattern given in 3GPP TR 37.840. To accurately simulate a tri-sector gNB, it is necessary to deploy three "Macro Cell Sector Antennas," each configured with the appropriate boresight angles to represent the three 120-degree sectors effectively. For example, the boresight angles could be set to 60°, 180°, and 300°. This configuration ensures that the antennas collectively cover a full 360° area, with each sector providing a 120-degree field of coverage. By adjusting the boresight angles in this manner, the configuration can accurately reflect the directional characteristics of a tri-sector gNB.

The horizontal radiation pattern of a sector antenna is given by

$$A_{E,H}(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right] \tag{31}$$

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). This is a user input with a default setting of 30 dB.

φ is the angle formed between the direction of interest (i.e., the line connecting the UE to the gNB) and the antenna's boresight direction (azimuth angle).

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

The sector antenna gain is given by the expression

$$A_E(\varphi, \theta) = G_{E,max} - \min\{-[A_{E,H}(\varphi) + A_{E,V}(\theta)], A_m\} \tag{32}$$

where, $A_{E,V}(\theta)$ is currently 0 dB, and is a parameter reserved for future use to include the vertical radiation pattern of the antenna, and

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

The boresight angle denotes the azimuthal direction of maximum gain, or the highest radiated power, and is a user input. This can vary from 0 to 360 degrees. 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 angle increases in an anti-clockwise direction from the positive X-axis. The unit for angle is degrees.

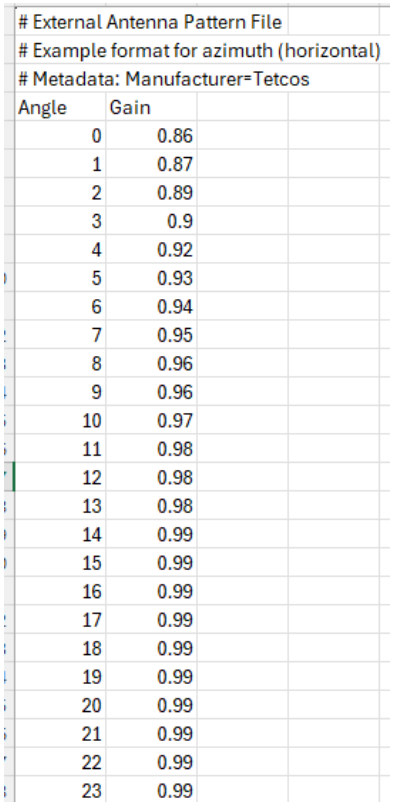
3.9.9.1 External Antenna Pattern

External Antenna Pattern allows the user define antenna gain values in a CSV file. In LTENR, this antenna model is used for sector antennas when Antenna Type is set to Sector Antenna and Antenna Model is set to External Antenna. NetSim reads the gain table from the External Antenna Pattern File and applies the gain value corresponding to the relative antenna angle.

Here, ϕ is the azimuth angle between the line joining the gNB and the UE and the antenna boresight direction. In the implementation, this angle is computed from the node coordinates using `atan2(dy, dx)` and then adjusted by subtracting the configured boresight angle.

The CSV file must contain angle-gain pairs in degrees and dB. During simulation, NetSim selects the gain associated with the highest angle in the table that is less than or equal to the

computed ϕ value. If no matching entry is found, the gain is taken as 0 dB.



External Antenna Pattern File
Example format for azimuth (horizontal)
Metadata: Manufacturer=Tetcos

Angle	Gain
0	0.86
1	0.87
2	0.89
3	0.9
4	0.92
5	0.93
6	0.94
7	0.95
8	0.96
9	0.96
10	0.97
11	0.98
12	0.98
13	0.98
14	0.99
15	0.99
16	0.99
17	0.99
18	0.99
19	0.99
20	0.99
21	0.99
22	0.99
23	0.99

Figure 3-11: *External antenna pattern file*

3.9.10 NR Frequency Bands

The NR frequency ranges are specified in the following standard references:

- 3GPP TS 38.101-1: FR1 frequency range definition.
- 3GPP TS 38.101-2: FR2 frequency range definition.

3.9.10.1 NR Band – FR 1

The FR1 bands implemented in NetSim are selected from 3GPP TS 38.101-1 V17.8.0 (`ts_138 10101v170800p`), Table 5.2-1.

- TDD Single Band in Duplex mode, namely n34, n38, n39, n40, n41, n50, n51, n77, n78, n79, n259, n260, n261 and n262.
- FDD Single Band in Duplex mode, namely n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n66, n70, n71 and n74.

Maximum transmission bandwidth configuration Refer to 3GPP TS 38.101-1 V17.8.0 (`ts_13810101v170800p`), Table 5.3.2-1 for the maximum transmission bandwidth configuration N_{RB} values used for FR1.

Minimum guard band and transmission bandwidth configuration Refer to 3GPP TS 38.101-1 V17.8.0 (`ts_13810101v170800p`), Table 5.3.3-1 for the FR1 minimum guard-band values.

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

$$\frac{(BW_{channel} \times 1000\ (\text{kHz}) - N_{RB} \times SCS \times 12) - SCS}{2} \tag{33}$$

where the N_{RB} values are from 3GPP TS 38.101-1 V17.8.0 (`ts_13810101v170800p`), Table 5.3.2-1.

For receiving BS SCS 240 kHz, refer to 3GPP TS 38.101-2 V17.8.0 (`ts_13810102v170800`), Table 5.3.3-2 for the minimum guard-band values.

3.9.10.2 NR Band – FR 2

The FR2 bands implemented in NetSim are selected from 3GPP TS 38.101-2 V17.8.0 (`ts_13810102v170800`), Table 5.2-1.

Maximum transmission bandwidth configuration Refer to 3GPP TS 38.101-2 V17.8.0 (`ts_13810102v170800`), Table 5.3.2-1 for the maximum transmission bandwidth configuration N_{RB} values used for FR2.

Minimum guard band and transmission bandwidth configuration Refer to 3GPP TS 38.101-2 V17.8.0 (`ts_13810102v170800`), Table 5.3.3-1 for the FR2 minimum guard-band values.

3.9.11 UE channel bandwidth

3.9.11.1 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.

3.9.12 Frame structure and physical resources

3.9.12.1 Numerologies

Multiple OFDM numerologies are supported as specified in the following standard reference:

- 3GPP TS 38.211, Table 4.2-1: Supported transmission numerologies, subcarrier spacing, and cyclic prefix combinations.

The numerology μ and the cyclic prefix for a bandwidth part are obtained from the higher-layer parameters `subcarrierSpacing` and `cyclicPrefix`, respectively.

3.9.12.2 Frames and subframes

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

3.9.12.3 Slots

For subcarrier spacing configuration μ, slots are numbered $n_s^\mu \in \{0, \ldots, N_{slot}^{subframe,\mu} - 1\}$ in increasing order within a subframe and $n_{s,f}^\mu \in \{0, \ldots, N_{slot}^{frame,\mu} - 1\}$ in increasing order within a frame. There are N_{symb}^{slot} consecutive OFDM symbols in a slot, as specified in 3GPP TS 38.211 Tables 4.3.2-1 and 4.3.2-2. The start of slot n_s^μ in a subframe is aligned in time with the start of OFDM symbol $n_s^\mu \cdot N_{symb}^{slot}$ 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 $N_{Rx-Tx} \cdot T_c$ after the end of the last received downlink symbol in the same or different cell within the group of cells, where N_{Rx-Tx} is specified in 3GPP TS 38.211 Table 4.3.2-3.

A UE not capable of full-duplex communication among a group of cells is not expected to receive in the downlink in one cell within the group of cells earlier than $N_{Tx-Rx} \cdot T_c$ after the end of the last transmitted uplink symbol in the same or different cell within the group of cells, where N_{Tx-Rx} is specified in 3GPP TS 38.211 Table 4.3.2-3.

The OFDM slot structure for normal cyclic prefix is specified in the following standard reference:

- 3GPP TS 38.211, Table 4.3.2-1: Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix.

Table 3-5: *Number of OFDM symbols per slot, slots per frame, and slots per subframe for extended cyclic prefix from Standards Table 4.3.2-2*

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

The uplink and downlink transition times are specified in the following standard reference:

- 3GPP TS 38.211, Table 4.3.2-3: Transition time values for N_{Rx-Tx} and N_{Tx-Rx} in FR1 and FR2.

3.9.12.4 Slot structure in NetSim

In NetSim, the slot structure follows the configured DL:UL ratio. The following points summarize the examples used here.

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.

- For $\mu = 0$, there is 1 slot per subframe and 10 slots per frame.
- For DL:UL ratios such as 1:1, 1:4, and 4:1, NetSim derives the slot sequence from the configured ratio instead of using a separate lookup table.

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.

- For $\mu = 1$, there are 2 slots per subframe and 20 slots per frame.
- For DL:UL ratios such as 1:1, 1:4, and 4:1, NetSim derives the slot sequence from the configured ratio instead of using a separate lookup table.

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

3.9.13 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).

3.9.13.1 Channel quality indicator (CQI)

A wideband CQI is computed based on the spectral efficiency obtained from the SINR calculated on the PDSCH and PUSCH. The SINR 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 modulation order and code rate are based on the table chosen by the user. In the NetSim GUI users can select “table1” (3GPP TS 38.214, Table 5.2.2.1-2), “table2” (3GPP TS 38.214, Table 5.2.2.1-3) or “table3” (3GPP TS 38.214, Table 5.2.2.1-4, or the URLLC table).

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

The first 4-bit CQI mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.2.2.1-2: 4-bit CQI Table 1.

The second 4-bit CQI mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.2.2.1-3: 4-bit CQI Table 2.

The third 4-bit CQI mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.2.2.1-4: 4-bit CQI Table 3.

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3.9.14 Modulation order, 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 (ν), the total number of allocated PRBs to determine the transport block size.

3.9.14.1 MCS tables

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

- QAM64 Table: 3GPP TS 38.214, Table 5.1.3.1-1.
- QAM256 Table: 3GPP TS 38.214, Table 5.1.3.1-2.
- QAM64LowSE Table: 3GPP TS 38.214, Table 5.1.3.1-3.

The UE and gNB then use 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 Section 3.9.18. 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 summarized below.

- If transform precoding is enabled, NetSim uses 3GPP TS 38.214 Table 6.1.4.1-1 for QAM64, Table 6.1.4.1-2 for QAM64LowSE, and Table 5.1.3.1-2 for QAM256.
- If transform precoding is disabled, NetSim uses 3GPP TS 38.214 Table 5.1.3.1-1 for QAM64, Table 5.1.3.1-3 for QAM64LowSE, and Table 5.1.3.1-2 for QAM256.

The first PDSCH MCS mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.1.3.1-1: MCS index table 1 for PDSCH.

The second PDSCH MCS mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.1.3.1-2: MCS index table 2 for PDSCH.

The third PDSCH MCS mapping is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.1.3.1-3: MCS index table 3 for PDSCH.

The PUSCH MCS mapping for transform precoding with 64QAM is specified in the following standard reference:

- 3GPP TS 38.214, Table 6.1.4.1-1: MCS index table for PUSCH with transform precoding and 64QAM.

The PUSCH MCS mapping for transform precoding with 64QAM Low SE is specified in the following standard reference:

- 3GPP TS 38.214, Table 6.1.4.1-2: MCS index table 2 for PUSCH with transform precoding and 64QAM Low SE.

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3.9.15 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 of which are implemented in NetSim.

NetSim first determines the TBS as specified below:

- The UE shall first determine the number of REs (N_{RE}) within the slot.
  - A UE first determines the number of REs allocated for PDSCH within a PRB (N'_{RE}) by $N'_{RE} = N_{sc}^{RB} \times N_{symb}^{PRB} - N_{DMRS}^{PRB} - N_{oh}^{PRB}$, where $N_{sc}^{RB} = 12$ is the number of subcarriers in a physical resource block, N_{symb}^{slot} is the number of symbols of the PDSCH allocation within the slot, N_{DMRS}^{PRB} is the number of REs for DM-RS per PRB, and N_{oh}^{PRB} is set to 0.
  - A UE determines the total number of REs allocated for PDSCH (N_{RE}) by $N_{RE} = \min(156, N'_{RE}) \times n_{PRB}$, where n_{PRB} is the total number of allocated PRBs for the UE.
- Intermediate number of information bits (N_{info}) is obtained by

$$N_{info} = N_{RE} \times R \times Q_m \times \nu$$

$$TBS_{temp} = N_{RE} \times R \times Q_m \times \nu$$

- 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 to find the closest TBS that is not less than N'_{info}.

The TBS lookup for $N_{info} \leq 3824$ is specified in the following standard reference:

- 3GPP TS 38.214, Table 5.1.3.2-1: TBS values for $N_{info} \leq 3824$.

- When $N_{info} > 3824$, TBS is determined as follows:
  - Quantized $N'_{info} = \max\left(3840, 2^n \times \text{round}\left(\frac{N_{info}-24}{2^n}\right)\right)$, where $n = \lfloor \log_2(N_{info} - 24) \rfloor - 5$.
  - if $R \leq \frac{1}{4}$: $TBS = 8C \left\lceil \frac{N'_{info}+24}{8C} \right\rceil - 24$, where $C = \left\lceil \frac{N'_{info}+24}{3816} \right\rceil$
  - else if $N'_{info} > 8424$: $TBS = 8C \left\lceil \frac{N'_{info}+24}{8C} \right\rceil - 24$, where $C = \left\lceil \frac{N'_{info}+24}{8424} \right\rceil$
  - else: $TBS = 8 \left\lceil \frac{N'_{info}+24}{8} \right\rceil - 24$

3.9.16 HARQ

3.9.16.1 Introduction

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

- 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.
- 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).
- If the transmitter receives an ACK, it sends the next CBG. However, if the transmitter receives a NACK, it retransmits the previously transmitted CBG.
- 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).

3.9.16.2 Implementation in NetSim

- HARQ is implemented in 4G (eNB) and in 5G (gNB) in both downlink and uplink.
- 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
- Each HARQ process transmits one Transport Block (TB) at any time.
- When operating in MIMO, each layer handles a different TB. This means that one TB is not transmitted across multiple layers.
- Each TB is split into Code blocks (CBs) and CBs are grouped into Code Block Groups (CBGs).
- At the receiver the CBGs are given to a multiplexer which combines the CBGs into a TB.
- 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.

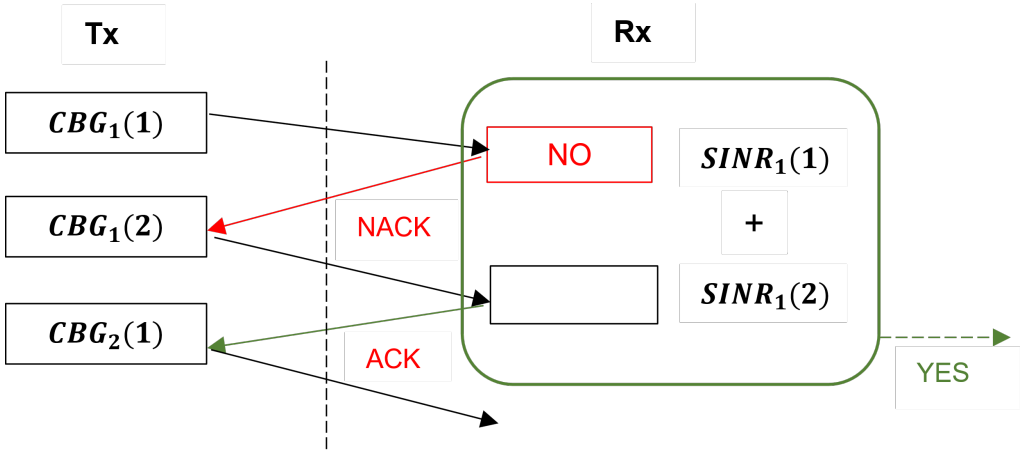


Figure 3-12: *We see the HARQ transmission process. The transmitter sends CBG1 which is errored. Therefore, the receiver sends a NACK. CBG1 is then retransmitted (transmission attempt 2). The receiver then soft combines the first and second transmissions, which is successful and hence sends back an ACK.*

- 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.
- 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.
- 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

3.9.16.3 Assumptions and limitations

- 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.
- 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.

3.9.16.4 Transmission flow

- 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.
  - 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.
  - 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 discussed in Section 3.25.
- TBs are then split to Code blocks (CBs). The code block size calculation and TB segmentation is explained in Section 3.9.17.
- CBs are grouped into code block groups (CBGs).
  - 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).
- TBs are transmitted by transmitting CBGs, which in turn comprise CBs.
- BLER is applied upon CBG reception at the receiver.

- If any CB is in error, the transmitter retransmits the entire CBG of which that CB is a part.
- The receiver then soft combines the first transmission and all subsequent retransmissions.
  - 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

$$\text{CombinedSINR}_3^{Tx} = \text{SINR}_3^{Tx} + \text{SINR}_2^{Tx} + \text{SINR}_1^{Tx} \tag{34}$$

- BLER is applied on the improved (combined) SINR by tossing a biased coin.
- If any CB is in error, go to step 6, subject to transmit limit of 4 (retransmit limit of 3).
- If all CBGs (in a TB) are successful, then at the receiver, the TB is sent up to the RLC.
- Else, the entire TB is dropped.

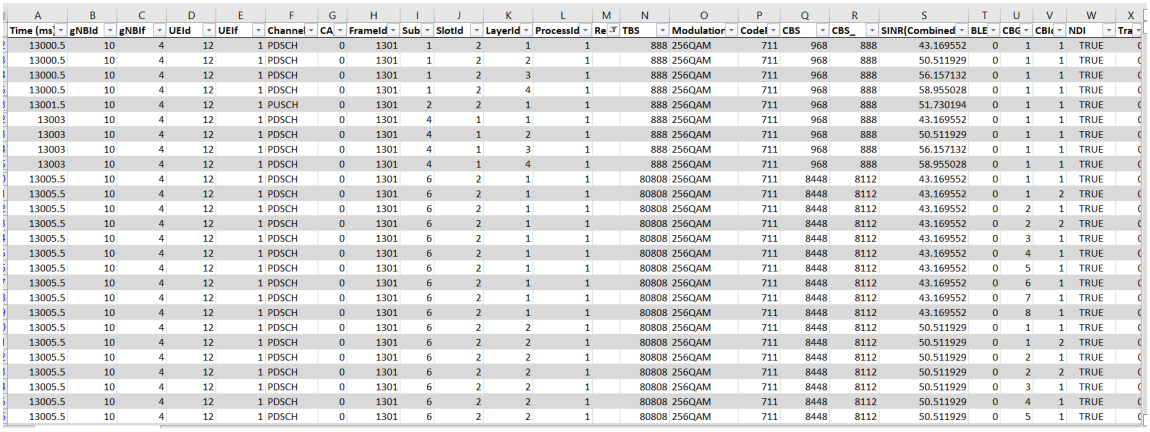
3.9.16.5 Special cases

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 retransmitted. Hence remaining PRBs left — after retransmitting the errored CBG — must be allocated to a non-Max-SINR UE. Also note that, the non-Max-SINR UE's CBGs may also be errored in which case those CBGs need to be retransmitted. This complicating factor leads to a breakdown in the general belief that Max-throughput scheduler leads to Max-SINR UE getting all throughput with other UEs getting NIL throughput.

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.

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3.9.16.6 Logging



Time (ms)	gNBId	gNBIf	UEId	UEIf	Channe	CA	FrameId	Sub	SlotId	LayerId	ProcessId	Re	TBS	Modulation	Codel	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	
13000.5	10	4	12	1	PDSCH	0	1301	1	2	2	1		888	256QAM	711	968	888	50.511929	0	1	1	TRUE	
13000.5	10	4	12	1	PDSCH	0	1301	1	2	3	1		888	256QAM	711	968	888	56.157132	0	1	1	TRUE	
13000.5	10	4	12	1	PDSCH	0	1301	1	2	4	1		888	256QAM	711	968	888	58.955028	0	1	1	TRUE	
13001.5	10	4	12	1	PUSCH	0	1301	2	2	1	1		888	256QAM	711	968	888	51.730194	0	1	1	TRUE	
13003	10	4	12	1	PDSCH	0	1301	4	1	1	1		888	256QAM	711	968	888	43.169552	0	1	1	TRUE	
13003	10	4	12	1	PDSCH	0	1301	4	1	2	1		888	256QAM	711	968	888	50.511929	0	1	1	TRUE	
13003	10	4	12	1	PDSCH	0	1301	4	1	3	1		888	256QAM	711	968	888	56.157132	0	1	1	TRUE	
13003	10	4	12	1	PDSCH	0	1301	4	1	4	1		888	256QAM	711	968	888	58.955028	0	1	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	1	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	1	2	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	2	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	2	2	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	3	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	4	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	5	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	6	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	7	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	1	1		80808	256QAM	711	8448	8112	43.169552	0	8	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	1	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	1	2	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	2	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	2	2	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	3	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	4	1	TRUE	
13005.5	10	4	12	1	PDSCH	0	1301	6	2	2	1		80808	256QAM	711	8448	8112	50.511929	0	5	1	TRUE	

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

- Transmission attempts 1, 2, 3 and 4 are indexed as 0, 1, 2, 3. If the 4th attempt is errored, the CBG is dropped.
- 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.
- Note that if a TB is in error then all the packets that were part of the TB will be marked as error.
- The transmission/re-transmission of CBs is logged in the Code Block logfile.
- The remarks column would have messages for HARQ preparation and would be blank for actual transmissions.
- TBS is always logged on a per layer basis.
- CBGID is also on a per layer basis.
- SINR reported in the CBG log is the post-soft combining SINR.

Time (ms)	gNBId	gNBIf	UEId	UEIf	Channe	CA	FrameId	Sub	SlotId	LayerId	ProcessId	Re	TBS	Modulation	Codel	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*

3.9.16.7 HARQ turn off

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

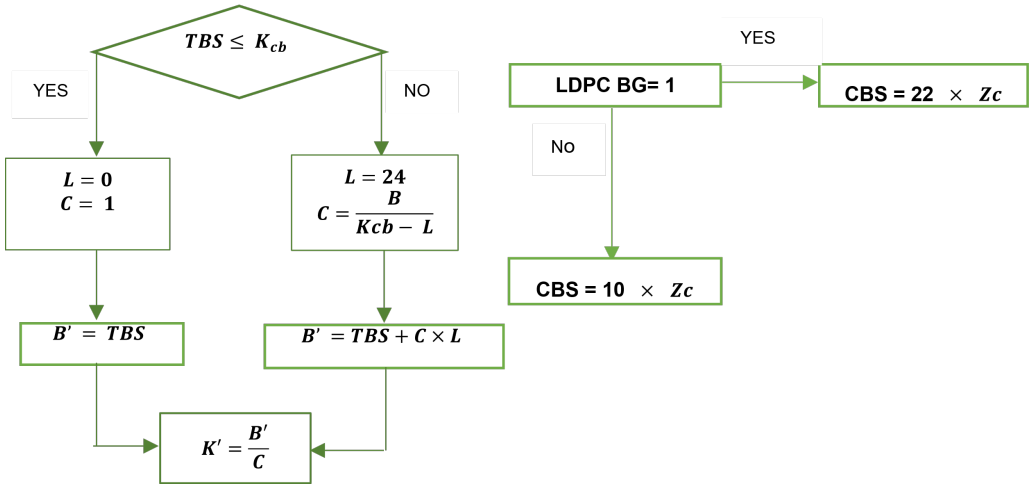
NetSim allows users to turn HARQ OFF via the GUI. Note that the code block log will continue to be written. Users will notice that errored CBGs are not retransmitted if HARQ is turned OFF. Since the CB/CBG is in error, that entire TB to which it belongs will be in error.

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

3.9.17 Segmentation of transport block into code blocks

- If the transport block size is larger than 3824, a 16-bit CRC is added at the end of the transport block or a 24-bit CRC is added.
- The transport block is divided into multiple equal size code blocks when the transport block size exceeds a threshold.
- For quasi-cyclic low-density parity-check code (QC-LDPC) base graph 1, the threshold is equal to 8448.
- For QC-LDPC base graph 2, the threshold is equal to 3840. In 5G NR, the maximum code block size number is 8448.
- An additional 24-bit CRC is added at the end of each code block when there is a segmentation.
- A CBG can have up to 2/4/6/8 CBs.
- 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 Z_c is calculated by selecting minimum Z_c in all sets of lifting size tables, such that: $K_b \times Z_c \geq K$. K_b denotes the number of information bit columns for the lifting size Z_c.

3.9.18 BLER and CQI/MCS selection

NetSim GUI allows users to 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.

- Zero BLER
  - MCS Selection: Ideal Shannon theorem-based rate
    - The spectral efficiency (SE) is computed as

$$\text{SpectralEfficiency} = \log_2(1 + SINR) \tag{35}$$

- This Spectral efficiency (SE) is matched with the Channel Quality Indicator (CQI) table, selecting the highest SE that does not exceed this calculated value. This SE (determined from the CQI table) then guides the selection of modulation and coding from the MCS table. For example if the SINR is -1.4 dB, then $\log_2(1 + 10^{-1.4/10}) = 0.782$. The highest SE ≤ 0.782 from the CQI table-2 is 0.3770. This value is then looked up in the MCS table-2; the modulation order is 2 and the code rate is 193.
- Data is transmitted at this MCS with zero BLER.
- The spectral efficiency to MCS table is explained in Section 3.9.14 (Modulation order, code rate, and TBS determination).
- MCS Selection: Shannon rate with attenuation factor — MCS is chosen as in the case of Ideal Shannon Theorem-based rate, but with the spectral efficiency calculated as:

$$\text{SpectralEfficiency} = \alpha \times \log_2(1 + SINR) \tag{36}$$

Where 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 Spectral Efficiency $= \alpha \times \log_2(1 + \beta \times SINR)$ 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.

- 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 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. See Section 3.9.20 for working of OLLA.

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3.9.19 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.

3.9.20 Outer Loop Link Adaptation (OLLA)

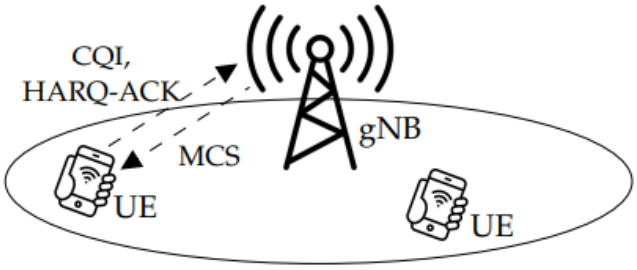


Figure 3-15: *UE reports CQI based on SINR and the gNB transmits data at an MCS based on CQI*

During the downlink AMC process, a user equipment (UE) reports the channel quality indicator (CQI) of the link to the gNB. This CQI is based on the received instantaneous 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 (ACK or NACK). The offset is updated continuously based on the HARQ feedback, such that the average Block Error Rate ($BLER_A$) converges to a predefined target ($BLER_T$).

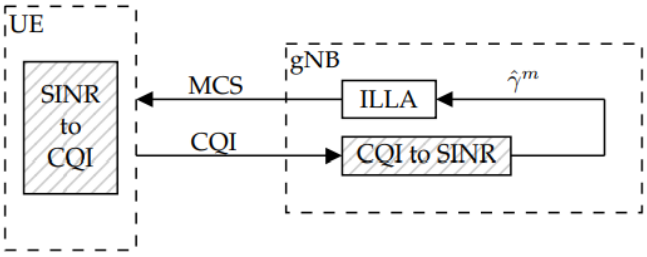


Figure 3-16: *MCS selection per inner loop link adaptation (without OLLA)*

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.

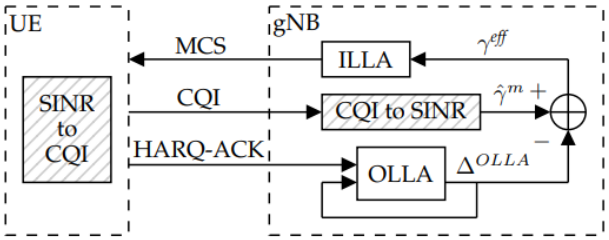


Figure 3-17: *MCS selection with OLLA*

The OLLA compensation is as follows:

$$\Delta_{OLLA}(k) = \Delta_{OLLA}(k-1) + \Delta_{up} \times e(k) - \Delta_{down} \times (1 - e(k)) \tag{37}$$

Where $e(k) = 0$ for ACK and $e(k) = 1$ for NACK. This can be written as:

$$\Delta_{OLLA}(k) = \begin{cases} \Delta_{OLLA}(k-1) - \Delta_{down} & \text{ACK}, e(k) = 0 \\ \Delta_{OLLA}(k-1) + \Delta_{up} & \text{NACK}, e(k) = 1 \end{cases} \tag{38}$$

We see that when ACK is received, Δ_{OLLA} is decreased by Δ_{down}, and when NACK is received, Δ_{OLLA} is increased by Δ_{up}.

The estimated SINR compensated by the OLLA mechanism is given by the following relationship in the log scale (units of dB):

$$\gamma_{eff}(k,n) = \hat{\gamma}_m(k,a) - \Delta_{olla}(k,n) \tag{39}$$

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.

The ratio $\frac{\Delta_{down}}{\Delta_{up}}$ controls the target BLER:

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

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 gNB. For these connections, OLLA reaches steady state and Δ_{OLLA} fluctuates around the proper value due to random system errors. In contrast, for small activity connections, convergence is not guaranteed, unless Δ_{OLLA} is properly initialized.

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When Δ_{ini} is too large, γ_{eff} is initially far below the actual channel 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 $\Delta_{down} = 0.1$ 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 re-transmissions, 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.

3.9.21 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 3GPP TR 38.900 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 $\alpha \times \log_2(1 + \frac{E_b}{N_0})$. 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 the threshold, then a handover procedure is initiated.

3.9.22 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 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.

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- Go to <NetSim-Install-directory>/docs/xml (for example C:\ProgramFiles\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 supports 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 options takes a long time in the NetSim GUI.

3.9.23 CA Configuration Table (based on 3GPP TR 38.716 Release 16)

Carrier aggregation can be configured in the gNB's Physical Layer properties. The NetSim CA options in this section follow the Release 16 3GPP carrier aggregation combinations listed in 3GPP TR 38.716. The CA rows listed below are taken from the following standards tables:

- 3GPP TR 38.716-01-01, Table 5.3.1-1: bandwidth combination sets for CA_2DL_n41C_1UL_n41A.
- 3GPP TR 38.716-01-01, Table 7.1.1-1 and Table 7.2.2-1: FR2 intra-band contiguous CA combinations for the n257 and n258 rows.
- 3GPP TR 38.716-01-01, Table 6.1.1-1, Table 6.2.2-1, Table 6.3.1-1, Table 6.5.2-1, and Table 6.6.2-1: FR1 intra-band non-contiguous CA combinations for n66, n41, n25, n3, and n7.
- 3GPP TR 38.716-01-01, Table 8.1-1 through Table 8.1-8, Table 8.3-1, Table 8.3-2, and the Table 8.4 family: FR2 intra-band non-contiguous CA combinations for the n260 and n261 rows.
- 3GPP TR 38.716-02-00, Table 6.8.1.2-1, Table 6.10.1.2-1, Table 6.13.1.2-1, Table 6.15.1.2-1, Table 6.17.1.2-1, Table 6.23.1.2-1, Table 6.24.1.2-1, Table 6.25.1.2-1, Table 8.5.2-1, Table 8.6.2-1, Table 8.7.2-1, Table 8.9.1.2-1, and Table 8.10.1.2-1: 2-band inter-band CA combinations with 2 DL and 1 or 2 UL carriers.
- 3GPP TR 38.716-02-00, Table 6.38.1.2-1, Table 6.28.1.2-1, Table 6.19.1.2-1, Table 6.29.1.2-1, Table 6.30.1.2-1, Table 6.34.1.2-1, Table 6.31.1.2-1, Table 6.22.1.2-1, Table 6.3.1.2-1, Table 6.4.1.2-1, and Table 6.14.1.2-1: FDD inter-band CA combinations with 2 DL and 1 or 2 UL carriers.
- 3GPP TR 38.716-03-01, Table 6.8.2-1: 3 DL and 1 UL CA combinations for CA_n66A_n70A_n71A, CA_n66B_n70A_n71A, and CA_n66(2A)_n70A_n71A.
- The SINGLE_BAND rows are operating band entries from 3GPP TS 38.101-1 and 3GPP TS 38.101-2, not carrier aggregation combinations from TR 38.716.

3.9.24 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.

$$\text{data rate (in Mbps)} = 10^{-6} \sum_{j=1}^{J} \left(v_{\text{Layers}}^{(j)} \right) \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R \frac{N_{\text{PRB}}^{\text{BW}(j),\mu} \cdot 12}{T_s^{\mu}} \left(1 - OH^{(j)} \right) \quad (40)$$

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, $v_{\text{Layers}}^{(j)}$ is the maximum number of supported layers given by higher layer parameter maxNumberMIMO-LayersPDSCH for downlink and maximum of higher layer parameters maxNumberMIMO-LayersCB-PUSCH and maxNumberMIMO-LayersNonCB-PUSCH for uplink.
- $Q_m^{(j)}$ is the maximum supported modulation order given by higher layer parameter supportedModulationOrderDL for downlink and higher layer parameter supportedModulationOrderUL for uplink.
- f^j is the scaling factor given by higher layer parameter scalingFactor and can take the values 1, 0.8, 0.75, and 0.4.
- μ is the numerology (as defined in TS 38.211 [6]).
- T_s^{μ} is the average OFDM symbol duration in a subframe for numerology μ, i.e., $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$.
- Note that normal cyclic prefix is assumed, which has 14 OFDM symbols per slot or $14 \times 2^{\mu}$ symbols per millisecond.
- $N_{\text{PRB}}^{\text{BW}(j),\mu}$ is the maximum Resource Block allocation in bandwidth $\text{BW}^{(j)}$ with numerology μ as defined in 5.3 TS 38.101-1 [2] and 5.3 TS 38.101-2 [3], where $\text{BW}^{(j)}$ 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

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

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

$$\text{data rate (in Mbps)} = 10^{-3} \sum_{j=1}^{J} \text{TBS}_j \tag{41}$$

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.

3.11 Propagation Models (Per 3GPP TR 38.900)

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 a 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 3.9.3 and 3.9.4 for a detailed explanation. In essence, the eigenvalue 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 10 ms. The coherence time is common to all UEs attached to a gNB.

The pathloss for each UE–gNB link also depends on the UE indoor/outdoor setting. NetSim reads the per-UE parameter `UE_INDOOR_OUTDOOR` to determine whether O2I penetration loss is applied. The gNB is always treated as outdoor. The outdoor propagation scenario (`currentScenario`) is taken from the gNB parameter `OUTDOOR_SCENARIO` (Rural macro, Urban macro, or Urban micro).

For an `Indoor` UE:

- `dist2Dindoor` is sampled once from the 3GPP O2I uniform distribution and stored in the propagation info structure.
- `dist2Doutdoor = dist2D - dist2Dindoor`; `dist3Doutdoor` is derived from `dist2Doutdoor`.
- LOS/NLOS determination uses `dist2Doutdoor`.
- Base pathloss uses `dist2Doutdoor/dist3Doutdoor`.
- O2I building penetration loss (computed from `dist2Dindoor`) is added on top.

For an `Outdoor` UE, `dist2D/dist3D` are used directly and no O2I loss is added.

3.11.2 Pathloss Formulas

The pathloss models are summarized in the table below and the distance definitions are indicated in the accompanying figures. Note that the distribution of the shadow fading is log-normal, and its standard deviation for each scenario is given in the table.

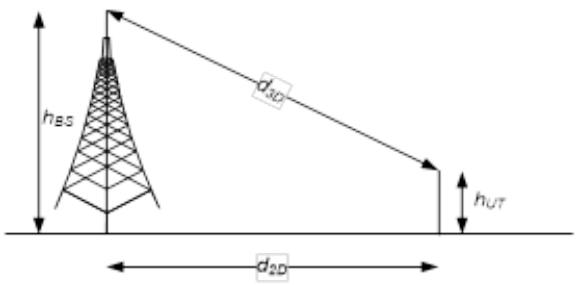


Figure 3-17: Definition of d_{2D} and d_{3D} from Standards Figure 7.4.1-1

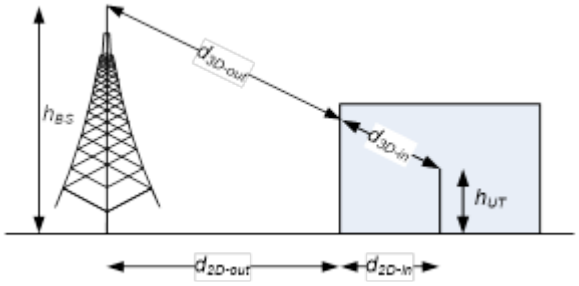


Figure 3-18: Definition of $d_{2D\text{-}out}$, $d_{2D\text{-}in}$, and $d_{2C\text{-}out}$ and $d_{3D\text{-}out}$, $d_{3D\text{-}out}$ for indoor UTs from Standards Figure 7.4.1-2

Note that,

$$d_{\text{3D-out}} + d_{\text{3D-in}} = \sqrt{(d_{\text{2D-out}} + d_{\text{2D-in}})^2 + (h_{\text{BS}} - h_{\text{UT}})^2} \qquad (7.4.1\text{-}2) \qquad (42)$$

PathlossModel: Refer to Standards Table 7.4.1-1.

Note 1: Breakpoint distance $d'_{\mathrm{BP}} = \dfrac{4 \times h'_{\mathrm{BS}} \times h'_{\mathrm{UT}} \times f_c}{c}$, 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: $h'_{\mathrm{BS}} = h_{\mathrm{BS}} - h_E$, $h'_{\mathrm{UT}} = h_{\mathrm{UT}} - h_E$, where h_{BS} and h_{UT} are the actual antenna heights, and h_E is the effective environment height. For UMi $h_E = 1.0$ m. For UMa $h_E = 1$ m with a probability equal to $\dfrac{1}{1 + C(d_{2D}, h_{\mathrm{UT}})}$ and chosen from a discrete uniform distribution uniform $(12, 15, \ldots, (h_{\mathrm{UT}} - 1.5))$ otherwise. With $C(d_{2D}, h_{\mathrm{UT}})$ given by

$$C\left(d_{2D}, h_{\mathrm{UT}}\right) = \begin{cases} 0 & , h_{\mathrm{UT}} < 13 \text{ m} \\ \left(\dfrac{h_{\mathrm{UT}} - 13}{10}\right)^{1.5} g\left(d_{2D}\right) & , 13 \text{ m} \le h_{\mathrm{UT}} \le 23 \text{ m} \end{cases} \tag{43}$$

Where,

$$g\left(d_{2D}\right) = \begin{cases} 0 & , d_{2D} \le 18 \text{ m} \\ \dfrac{5}{4}\left(\dfrac{d_{2D}}{100}\right)^3 \exp\left(\dfrac{-d_{2D}}{150}\right) & , 18 \text{ m} < d_{2D} \end{cases} \tag{44}$$

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 TR 36.873 with simplified format and

$PL_{\text{UMa-LOS}}$ = Pathloss of UMa LOS outdoor scenario.

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

Note 5: Break point distance $d_{\mathrm{BP}} = \dfrac{2\pi \times h_{\mathrm{BS}} \times h_{\mathrm{UT}} \times f_c}{c}$, 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 1 GHz, all distance related values are normalized by 1 m, unless it is stated otherwise.

NetSim enforces the following:

RMa, UMa, UMi: If $d_{2D} < 10$ m then $d_{2D} = 10$ m

InH: If $d_{2D} < 1$ m then $d_{2D} = 1$ m

3.11.3 LOS Probability

The Line-Of-Sight (LOS) probabilities are given in the table below.

Table 3-6: *LOS probability from Standards Table 7.4.2-1.*

Scenario	LOS probability (distance is in meters)
RMa	$P_{LOS} = 1, \quad d_{2D} \le 10$ $P_{LOS} = \exp\left(-\frac{d_{2D}-10}{1000}\right), \quad d_{2D} > 10$
UMi – Street canyon	$P_{LOS} = 1, \quad d_{2D} \le 18$ $P_{LOS} = \frac{18}{d_{2D}} + \exp\left(-\frac{d_{2D}}{36}\right)\left(1 - \frac{18}{d_{2D}}\right), \quad d_{2D} > 18$
UMa	$P_{LOS} = 1, \quad d_{2D} \le 18$ $P_{LOS} = \left(\frac{18}{d_{2D}} + \exp\left(-\frac{d_{2D}}{63}\right)\left(1 - \frac{18}{d_{2D}}\right)\right) \times \left(1 + C'(h_{UT})\frac{5}{4}\left(\frac{d_{2D}}{100}\right)^3 \exp\left(-\frac{d_{2D}}{150}\right)\right),$ $d_{2D} > 18$
Indoor – Mixed office	$P_{LOS} = 1, \quad d_{2D} \le 1.2$ $P_{LOS} = \exp\left(-\frac{d_{2D}-1.2}{4.7}\right), \quad 1.2 < d_{2D} < 6.5$ $P_{LOS} = 0.32\exp\left(-\frac{d_{2D}-6.5}{32.6}\right), \quad d_{2D} \ge 6.5$
Indoor – Open office	$P_{LOS} = 1, \quad d_{2D} \le 5$ $P_{LOS} = \exp\left(-\frac{d_{2D}-5}{70.8}\right), \quad 5 < d_{2D} \le 49$ $P_{LOS} = 0.54\exp\left(-\frac{d_{2D}-49}{211.7}\right), \quad d_{2D} > 49$

NOTE: The LOS probability is derived with assuming antenna heights of 3 m for indoor, 10 m for UMi, and 25 m for UMa. For UMa, $C'(h_{UT}) = 0$ when $h_{UT} \le 13$ m and $C'(h_{UT}) = \left(\frac{h_{UT}-13}{10}\right)^{1.5}$ when $13\,\text{m} < h_{UT} \le 23\,\text{m}$.

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:

$$PL = PL_b + PL_{tw} + PL_{in} + N\left(0, \sigma_P^2\right) \qquad \text{(7.4-2)} \tag{45}$$

where PL_b is the basic outdoor pathloss given in Sub Clause 7.4.1, where d_{3D} is replaced by $d_{\text{3D-out}} + d_{\text{3D-in}}$. 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:

$$PL_{tw} = PL_{npi} - 10\log_{10}\left(\sum_{i=1}^{N}\left(p_i \times 10^{\frac{L_{\text{material\_i}}}{-10}}\right)\right) \qquad \text{(7.4-3)} \tag{46}$$

PL_{npi} is an additional loss added to the external wall loss to account for non-perpendicular

incidence; $L_{\text{material\_i}} = a_{\text{material\_i}} + b_{\text{material\_i}}$, f is the penetration loss of material i example values of which can be found in the table below, p_i is proportion of i-th materials, where $\sum_{i=1}^{N} p_i = 1$; and N is the number of materials.

Table 3-7: *Material penetration losses from Standards Table 7.4.3-1.*

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

The following table 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.

Table 3-8: *O2I building penetration loss model from Standards Table 7.4.3-2.*

Model	Pathloss through external wall: PL_{tw} [dB]	Indoor loss: PL_{in} [dB]	Standard deviation: σ_P [dB]
Low-loss model	$5 - 10\log_{10}\left(0.3 \times 10^{-L_{\text{glass}}/10} + 0.7 \times 10^{-L_{\text{concrete}}/10}\right)$	$0.5\, d_{\text{2D-in}}$	4.4
High-loss model	$5 - 10\log_{10}\left(0.7 \times 10^{-L_{\text{IRRglass}}/10} + 0.3 \times 10^{-L_{\text{concrete}}/10}\right)$	$0.5\, d_{\text{2D-in}}$	6.5

$d_{\text{2D-in}}$ 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. $d_{\text{2D-in}}$ shall be UT-specifically generated.

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

Only the low-loss model is applicable to RMa.

3.11.4.2 O2I Model Usage

The O2I models (Low Loss and High Loss, defined in Table 3-8) are applied when the UE is configured as `Indoor` via the `UE_INDOOR_OUTDOOR` parameter. O2I loss is computed only when the gNB pathloss model is set to `3GPP TR 38.901-7.4.1`; it is not applied for the Log-distance or None models. For UEs configured as `Outdoor`, no O2I loss is added. An `Indoor` UE can still experience LOS or NLOS propagation conditions; LOS/NLOS is evaluated using the outdoor portion of the link (`dist2Doutdoor`). The building contribution is captured entirely by the O2I penetration loss term, which is added on top of the outdoor-distance-based pathloss. Scenario restrictions: `Rural macro` supports Low Loss Model only. `Urban macro` and `Urban micro` support both Low Loss Model and High Loss Model.

3.12 Additional Loss Model

Apart from the channel losses per the 3GPP TR 38.900 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/matlab/matlab_external/register-matlab-as-automation-server.html

3.12.1 Configuration

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

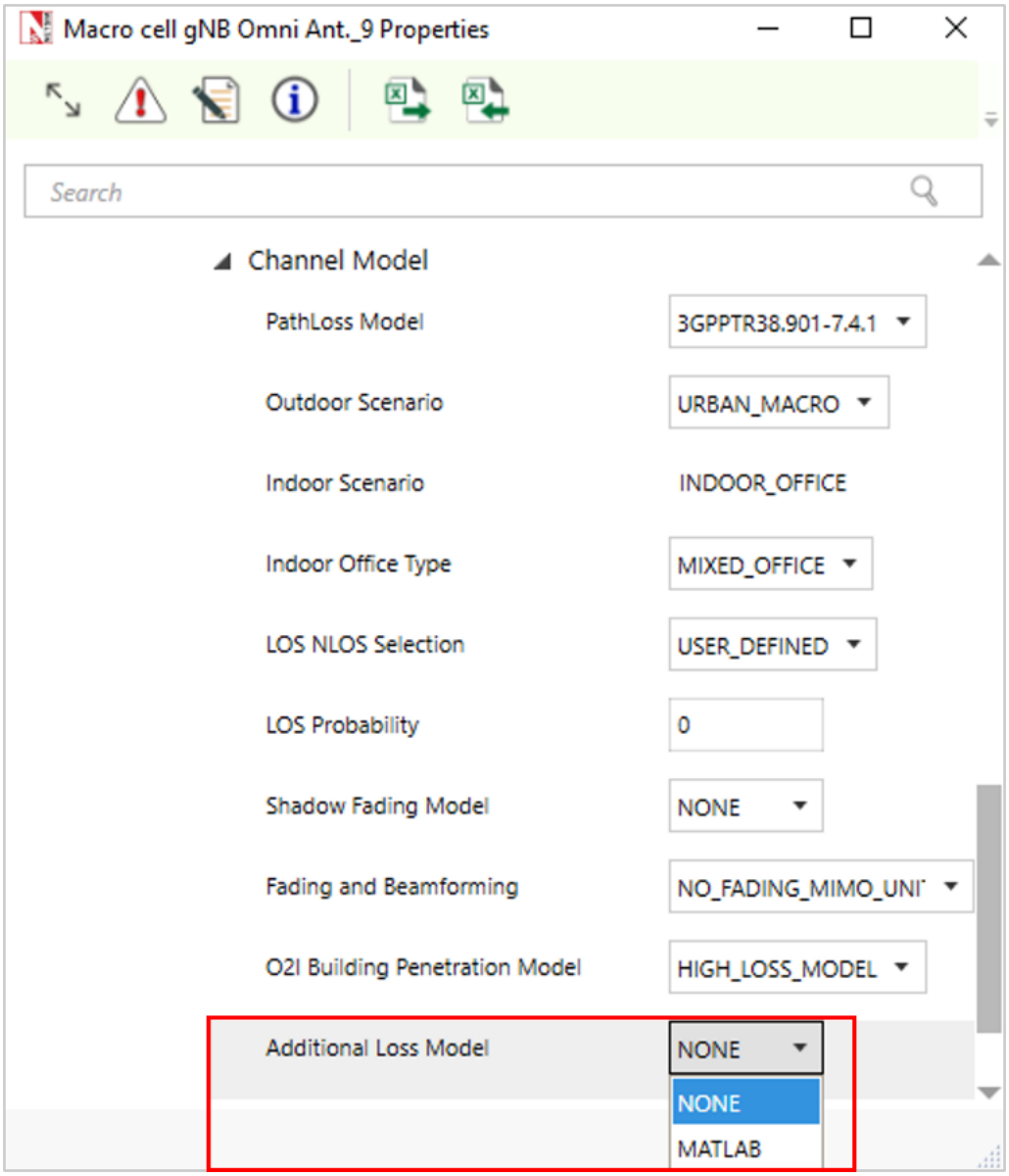


Figure 3-18: *gNB > Interface (5G_RAN) > Physical layer properties.*

The same configuration can be applied in the eNB's LTE interface properties under the channel models section of the Physical Layer.

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

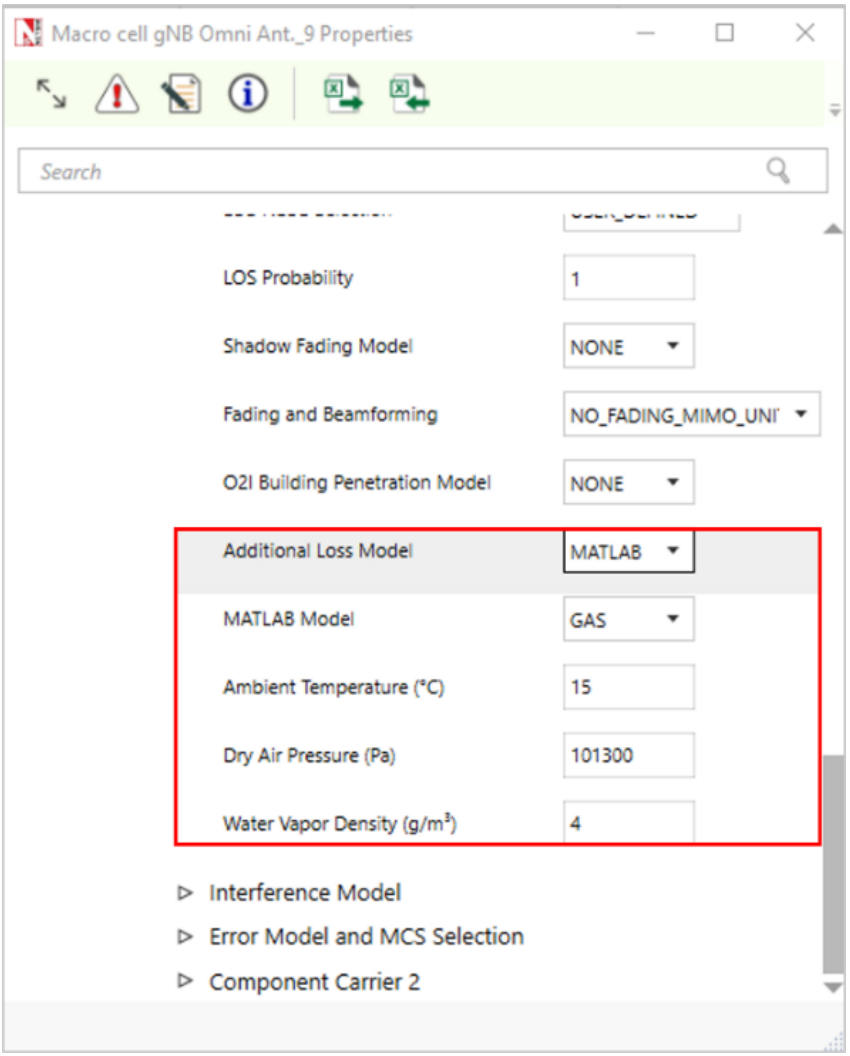


Figure 3-19: *Additional Loss Model set to MATLAB in gNB > Interface (5G RAN) > Physical layer properties.*

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

Table 3-9: *Parameters in the various MATLAB additional loss models.*

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

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

3.12.2 Running Simulation

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

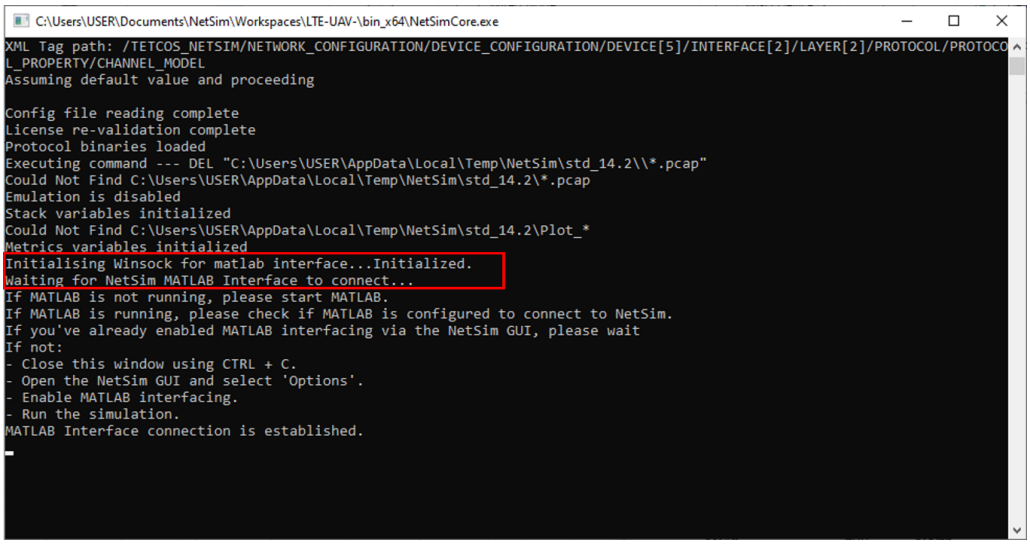


Figure 3-20: *NetSim Simulation console waits for MATLAB Interface process to connect.*

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:

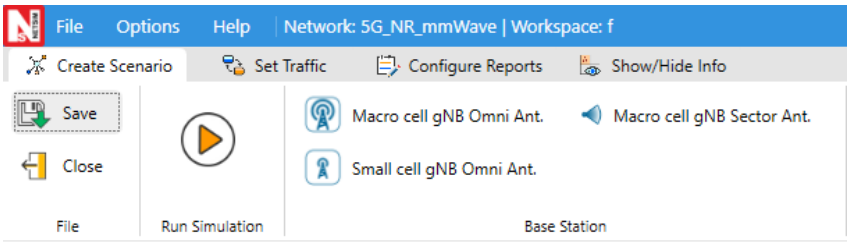


Figure 3-21: *Open MATLAB Window Options.*

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

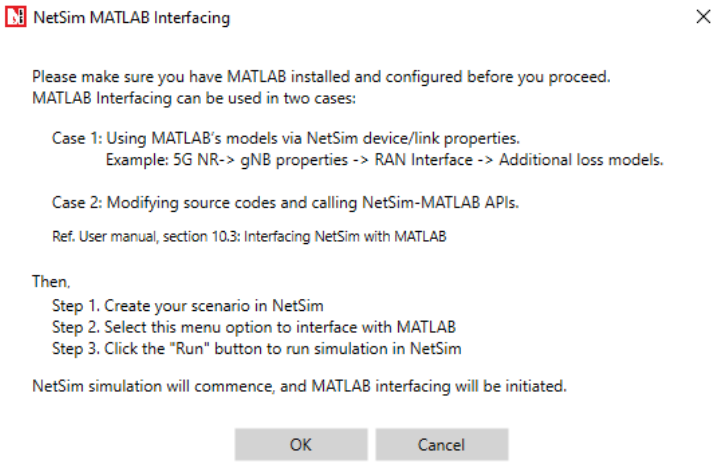


Figure 3-22: *MATLAB Interface warning message.*

- 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:

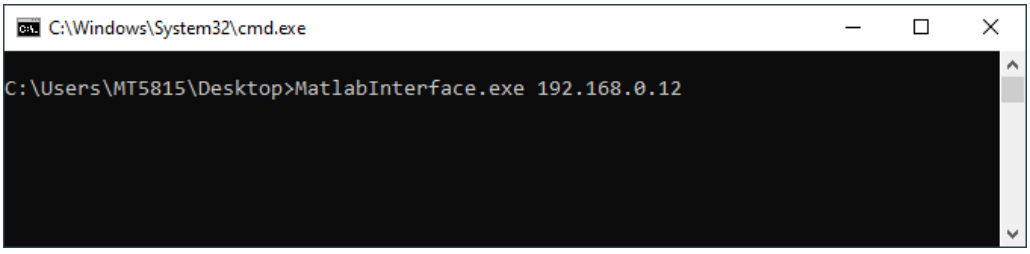


Figure 3-23: *MATLAB interface over an IP address.*

In both above cases, the MATLAB Interface process starts MATLAB process (MATLAB command window will open in minimized state) after which simulation in NetSim will start. During the simulation communication between NetSim and MATLAB is established to send inputs from

NetSim to MATLAB pathloss models and to receive pathloss from MATLAB to NetSim happens via the MATLAB Interface process as shown below:

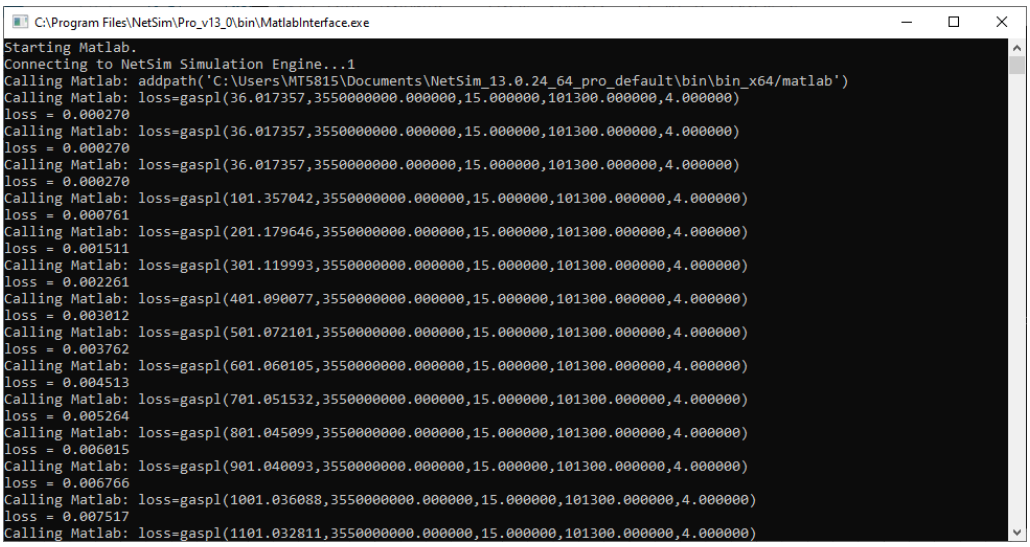


Figure 3-24: *Runtime MATLAB interfacing window.*

The pathloss value obtained from MATLAB is added to the total loss calculated as per the 3GPP TR 38.900 specifications. At simulation end the MATLAB Interface process closes the MATLAB process that it started.

3.13 Downlink Interference Model

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 below.

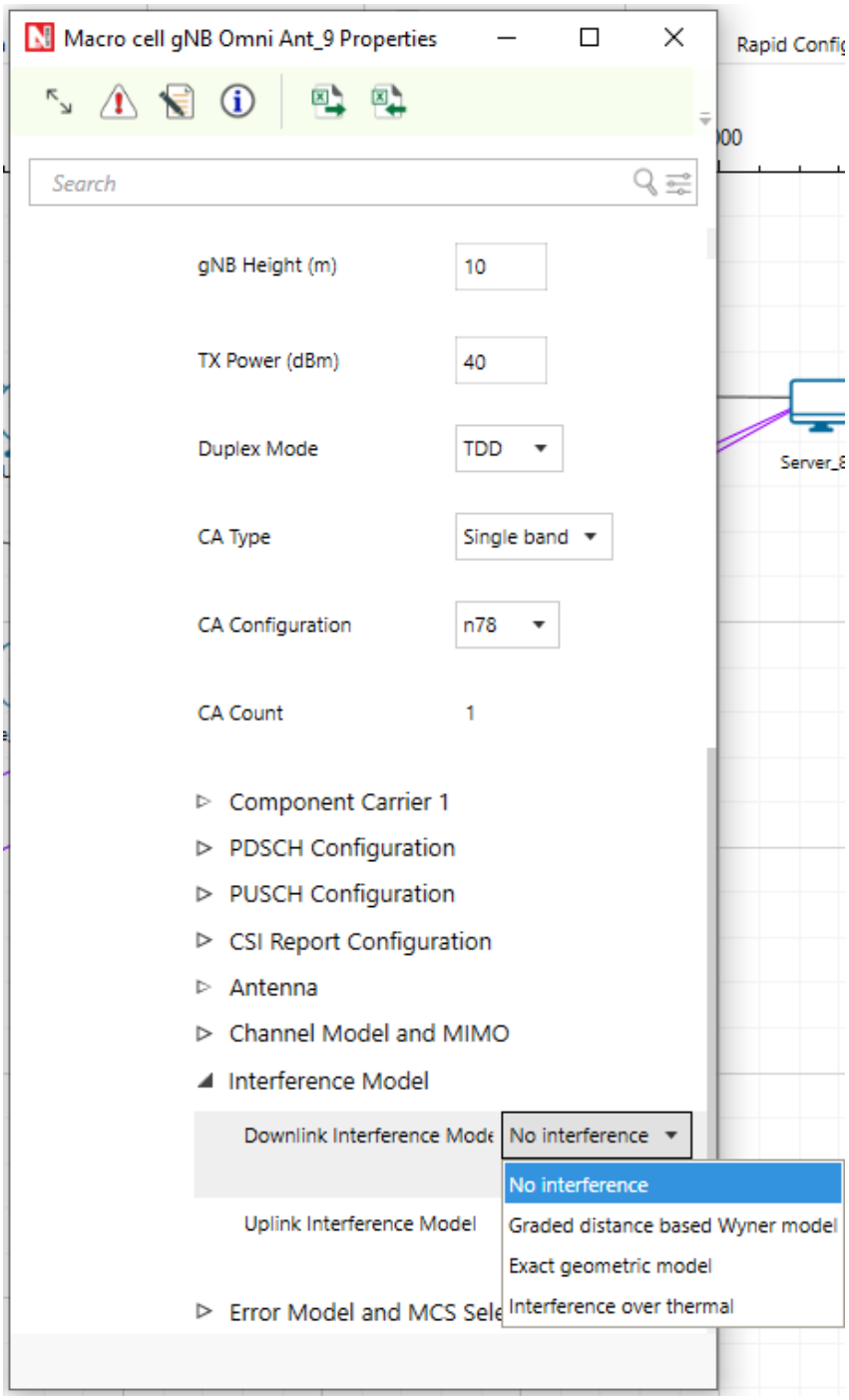


Figure 3-25: *gNB > Interface (5G RAN) > Physical layer properties.*

Downlink Interference Model is set to NO INTERFERENCE by default.

3.13.2 Graded Distance-Based Wyner Model

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

- Only interference from (two) adjacent cells is considered.
- Random user locations and pathloss 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 pathloss 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.
- 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:

$$0 \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times 1 \tag{47}$$

$$\left(\frac{DDR_{th}}{K}\right) \times 1 \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times 2 \tag{48}$$

$$\ldots \tag{49}$$

$$\ldots \left(\frac{DDR_{th}}{K}\right) \times (K-1) \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} < \left(\frac{DDR_{th}}{K}\right) \times K \tag{50}$$

$$\left(\frac{DDR_{th}}{K}\right) \times K \leq \frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} \tag{51}$$

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 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

$$\text{InterferencePower from } BS_j \text{ (dB)} = \text{ReceivedPower from } BS_i \text{ (dBm)} - I_n^j \text{ (dB)} \tag{52}$$

Therefore, we have I_n^i (dB) $= P_{\text{serving}}^{BS}$ (dBm) $- P_{\text{Interfering}}^{BS}$ (dBm). This is equivalent to the Wyner model with $\alpha = \dfrac{P_{\text{Interfering}}^{BS}}{P_{\text{serving}}^{BS}}$ 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

$$SINR = \frac{\text{Received power from } BS_i + \text{BeamFormingGain}}{\text{NoisePower} + \sum \text{InterferencePower}} \tag{53}$$

- 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 $20 \geq I_{K-1} \geq \ldots \geq I_0 \geq 0$. 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 $SINR_{\text{CellEdge}}$ 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.

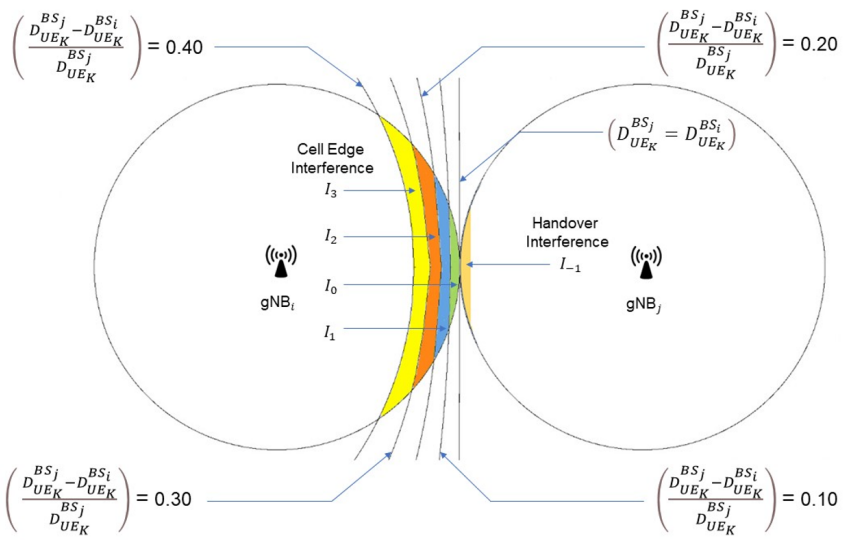


Figure 3-26: *Interference zones are the regions within the four curves and the cell boundary of gNB_i. This example is for a case involving just 2 BSs with $DDR = 0.4$ and $K = 4$. The four curves are therefore the equations where $\frac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}}$ is equal to $\frac{k}{4} = 0.1$, $\frac{2k}{4} = 0.2$, $\frac{3k}{4} = 0.3$, and $\frac{4k}{4} = 0.4$. The handover interference region is also shown.*

- In case $\dfrac{\left(D_{UE_K}^{BS_j} - D_{UE_K}^{BS_i}\right)}{D_{UE_K}^{BS_j}} > DDR_{th}$, 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 (3 dB 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 $-3 \text{ dB} \leq I_{-1} \leq 0 \text{ dB}$.
- 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`

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.

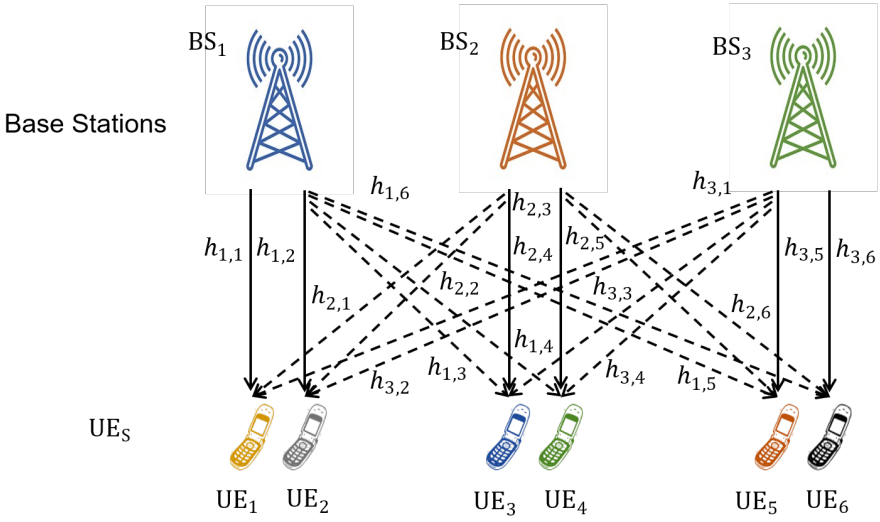


Figure 3-27: *A simple scenario with 3 BSs and 6 UEs. The bold lines represent direct signals while the dashed lines represent interfering signals.*

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

$$I_{UE_k}^{BS_j} = P^{BS_j} - PL_{UE_k}^{BS_j} \tag{54}$$

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

$$SINR_{UE_k} = \frac{\text{Received power from } BS_i + \text{(Eigen)BeamFormingGain}}{\text{NoisePower} + \sum_j I_{UE_k}^{BS_j}} \tag{55}$$

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

$$P_{UE_k}^{BS_i} = \left(\frac{P_i}{PL_{UE_k}^{BS_i}} \right) \tag{56}$$

- 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

$$I_{ik} = \Sigma_j \, I_{ik}^{j} \times \left(\frac{RB_{UE_k}^{\text{slot}}}{RB_{\text{total}}^{\text{slot}}} \right) \tag{57}$$

- Assumptions:

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

  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

$$k \times T \times RB_{UE_k}^{\text{slot}} \tag{58}$$

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

Therefore,

$$SINR = \frac{P_{UE_k}^{BS_i} \times \left(\frac{RB_{UE_k}^{\text{slot}}}{RB_{\text{total}}^{\text{slot}}} \right)}{k \times T \times RB_{UE_k}^{\text{slot}} + \Sigma_j \, I_{ik}^{j} \times \left(\frac{RB_{UE_k}^{\text{slot}}}{RB_{\text{total}}^{\text{slot}}} \right)} = \frac{P_{UE_k}^{BS_i}}{k \times T \times RB_{\text{total}}^{\text{slot}} + \Sigma_j \, I_{ik}^{j}} \tag{59}$$

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.

$$SINR_L = \frac{P_{UE_k}^{BS_i} \times \lambda_L}{k \times T \times RB_{\text{total}}^{\text{slot}} + \Sigma_j \, I_{ik}^{j}} \tag{60}$$

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 pathloss between BS1 and UE2. This is because the long-term statistical average of the square of the magnitude of the 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.

3.14 Uplink Interference Model

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 it available in the eNB/gNB properties. The expression for the signal to interference noise ratio is given by

$$SINR\ (\text{dB}) = SNR\ (\text{dB}) - \text{IoT}\ (\text{dB}) \tag{61}$$

$$\text{IoT}\ (\text{dB}) = SNR\ (\text{dB}) - SINR\ (\text{dB}) \tag{62}$$

Converting to linear

$$10 \times \log_{10}(\text{IoT}\ (\text{linear})) = 10 \times \log_{10}\left(\frac{SNR}{SINR}\right) = 10 \times \log_{10}\left(\frac{\frac{S}{N}}{\frac{S}{N+I}}\right) \tag{63}$$

$$\text{IoT}\ (\text{linear}) = \frac{I+N}{N} \tag{64}$$

Therefore, with N being the thermal noise, the interference power in linear scale is

$$I = N \times (\text{IoT (linear)} - 1) \tag{65}$$

We thus get the Interference power in dBm as

$$I\ (\text{dBm}) = 10 \times \log_{10}\left(N \times \left(10^{\text{IOT(dB)}} - 1\right)\right) \tag{66}$$

This value of I in dBm units is logged in the Radio Measurements csv file (if turned on). Example outputs are provided in the table below for various values of IoT and Bandwidth.

Table 3-10: *Example table showing interference in dBm that will be logged in radio measurements file for different IoT (dB) and Bandwidth (MHz) settings.*

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	1	−87.29
10	−103.82	1	−94.28

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 a single AMF, SMF and UPF.

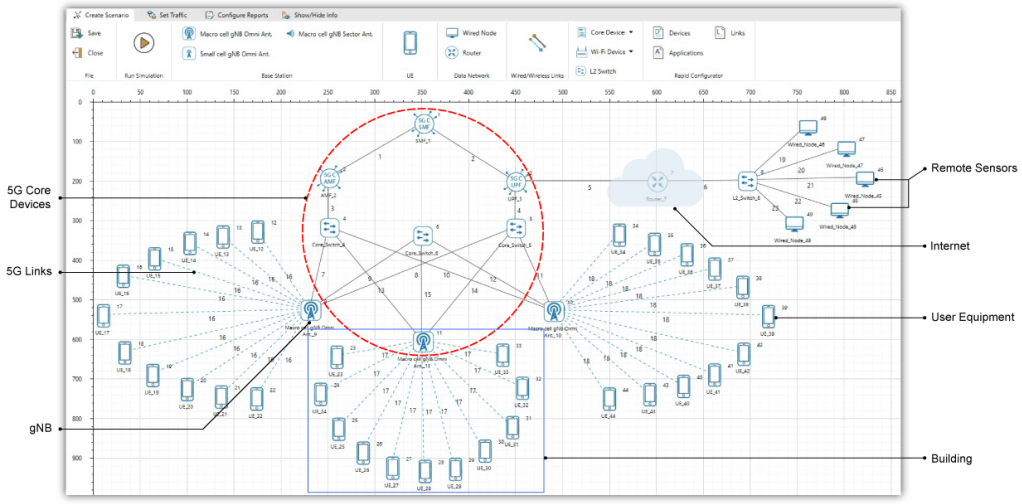


Figure 3-28: *5G Network scenario consisting of multiple UEs and gNBs connected to 5G Core — AMF, SMF and UPF. The UPF is connected to the Data Network/Internet.*

NetSim 5G Core model has been designed as follows:

- The Packet type supported in NetSim 5G Core is IPv4.
- A single set of SMF/UPF/AMF entities are only available. Scenarios with inter SMF mobility / inter AMF mobility are not supported in NetSim.
- 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.
- 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.

- A UE has the following interactions:
  - The random-access procedure to initiate communication with the gNB.
  - Setup the RRC connection with the gNB.
  - Perform NAS level authentication.
  - Handle the RRC Reconfiguration from the gNB and this message sets up the default PDU session.
  - The UE concludes the registration procedure.
  - Data flow takes place in both the downlink and uplink directions.
- The gNB acts as a bridge between the UE and the 5G Core. The gNB:
  - Handles the random-access request from the UE and assigns resources for initiating the RRC connection.
  - Set 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.
  - Transports the Registration Request from the UE to the AMF.
  - Carries the NAS signalling between the UE and the gNB.
  - The 5G Core initiates the default PDU session setup. A Registration Accept is also received from the UE.
  - Activates the default PDU session via the RRC Reconfiguration message. It also transports the Registration Complete message to the AMF.
  - The downlink and uplink data flow takes place between the UE and the Internet.
- The AMF or Access Mobility Function coordinates the 5G Standalone registration procedure.
  - Handles the Initial UE Message from the gNB. This message carries the Registration Request from the UE.
  - On receiving the Registration Request, the AMF obtains the UE context.
  - 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.
  - When the gNB signals that the Initial Context setup has been completed, the AMF updates the SMF context.

  - The AMF also notifies the SMF when the session is ready for uplink and downlink data transfer.
  - All messages related to session management are forwarded over the N11 reference interface to the Session Management Function (SMF).

- The SMF or Session Management Function serves as a control plane entity and it is responsible for the session management.
  - The SMF assigns an IP address to be used for sending uplink data.
  - The SMF selects the UPF to be used for the session.
  - The SMF updates the UPF using PFCP messages via the N4 control-data plane interface.

- The UPF or User Plane function is a data plane component that handles user data.
  - 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.
  - 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.
  - 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).
  - 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:

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

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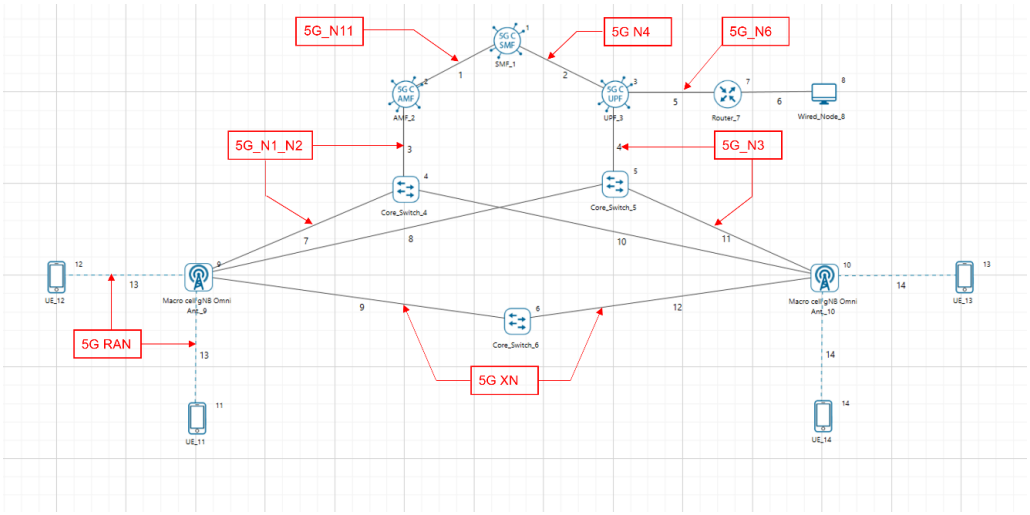


Figure 3-29: *5G Network scenario depicting the 5G Interfaces in NetSim.*

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:

- INITIAL UE MESSAGE AND REGISTRATION REQUEST
- INITIAL CONTEXT SETUP REQUEST
- INITIAL CONTEXT SETUP RESPONSE AND REGISTRATION COMPLETE
- PATH SWITCH REQUEST
- 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:

- CREATE SESSION REQUEST
- CREATE SESSION RESPONSE
- MODIFY BEARER REQUEST
- 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.

3.15.2 Cell Selection and UE Attach Procedure

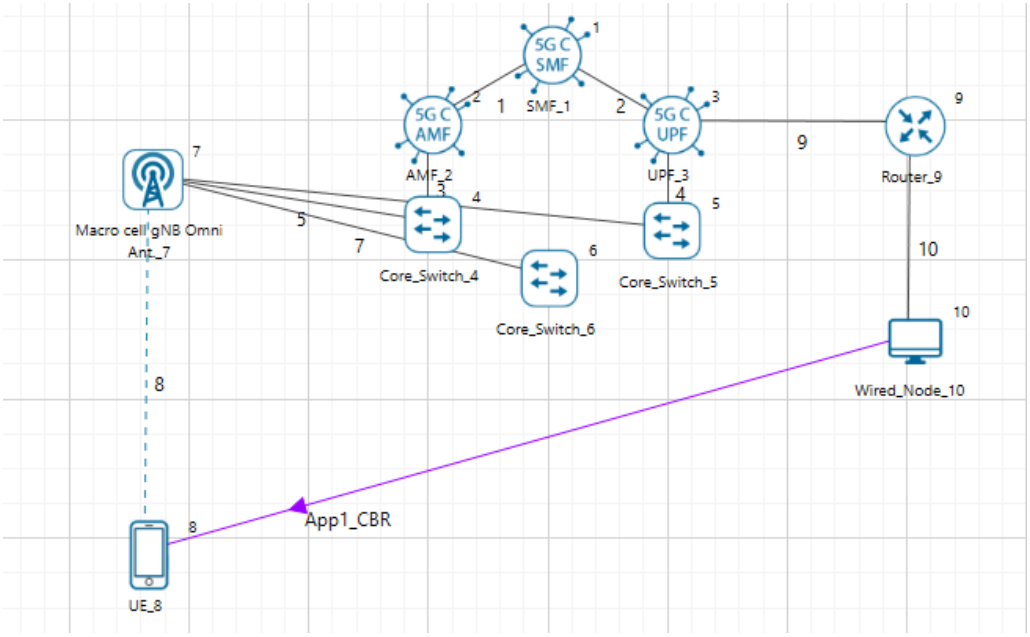


Figure 3-30: *A 5G network scenario with a Single UE connected to a gNB which is connected to the 5G Core and the UE downloads data from the Server (Wired Node).*

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.

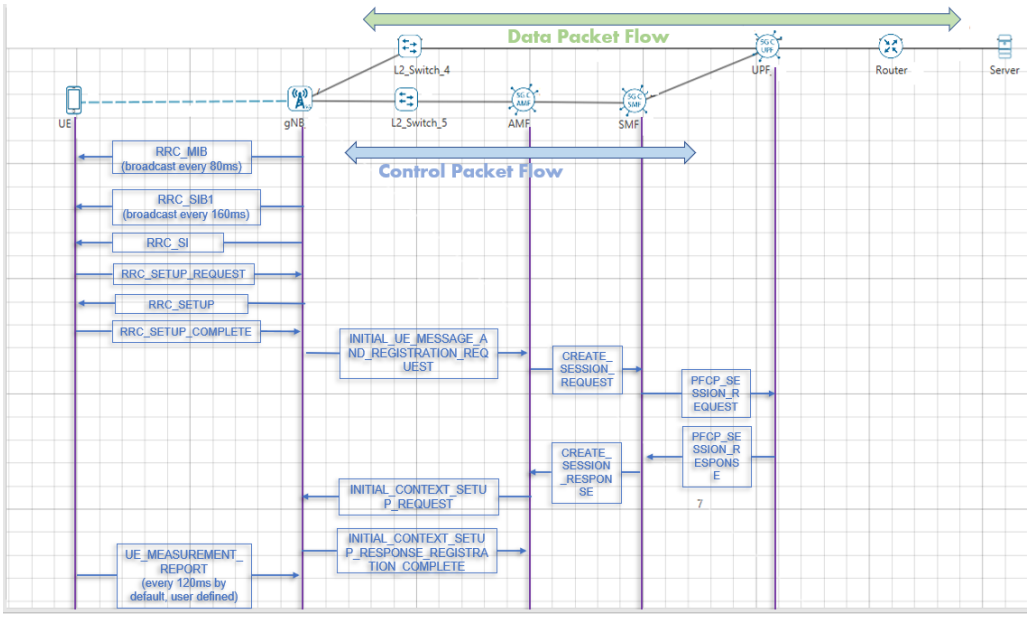


Figure 3-31: *UE Attach Procedure.*

The attachment process is as follows:

- 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 × n'.
  - The transmission of MIB packets 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.

- RRC System Information Block 1 packets are broadcast by the gNBs to all the UEs. These packets are transmitted periodically every 160 ms.
  - 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 × n'.
  - The size of each SIB1 packet is 8 Bytes. This can be observed in the Phy Layer Payload field in the packet trace.

- 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 to which gNB the UE will eventually be attached.

- RRC System Information is 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 160.9 ms.
  - 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.

- The RRC Setup Request will be sent by the UE to the connected gNB within 2.5 ms 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.

- 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.

- 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.

- 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	

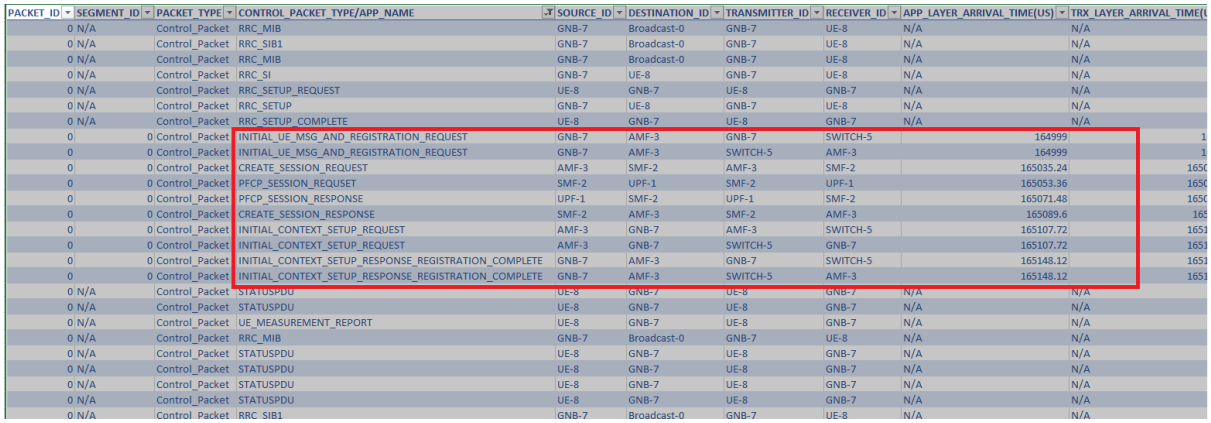
Figure 3-32: *RRC connection establishment in Packet Trace.*

3.15.3 5G Core Connection Management Process

This functionality is based on 3GPP 38.413.

- The gNB will introduce the UE to the 5G Core after the initial gNB-UE attachment process.
- 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.
- 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.
- 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.
- Further, AMF will send the Initial Context Setup Request to the gNB to confirm the setup of a UE context.
- The gNB will send Initial Context Setup and Registration Complete messages 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	165
0	0	Control_Packet	PFCP_SESSION_REQUSET	SMF-2	UPF-1	SMF-2	UPF-1	165053.36	165
0	0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-1	SMF-2	UPF-1	SMF-2	165071.48	165
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	165
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-3	GNB-7	SWITCH-5	GNB-7	165107.72	165
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE	GNB-7	AMF-3	GNB-7	SWITCH-5	165148.12	165
0	0	Control_Packet	INITIAL_CONTEXT_SETUP_RESPONSE_REGISTRATION_COMPLETE	GNB-7	AMF-3	SWITCH-5	AMF-3	165148.12	165
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 3-33: *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 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:

- 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:
  - Option 4: Only gNB connects to all the 5G Core interfaces. eNB connects to the XN interface.
  - Option 4a: gNB connects to all 5G Core interfaces and eNB connects to AMF and UPF through respective interfaces.
- 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:
  - Option 7: eNB connects to all 5G Core interfaces. gNB connects only to the XN interface.
  - Option 7a: gNB connects to all the 5G Core interfaces. eNB connects to AMF and UPF through the respective interfaces.

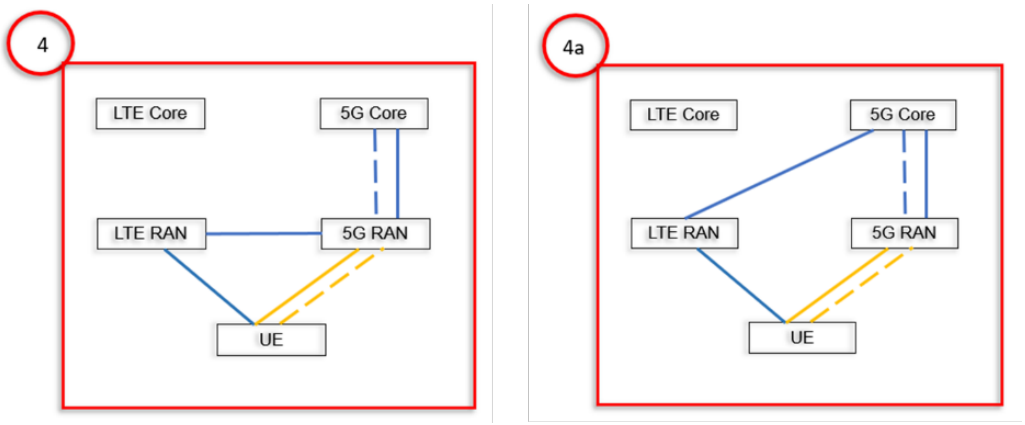


Figure 3-34: *NSA deployment — Option 4, Option 4a Networking modes.*

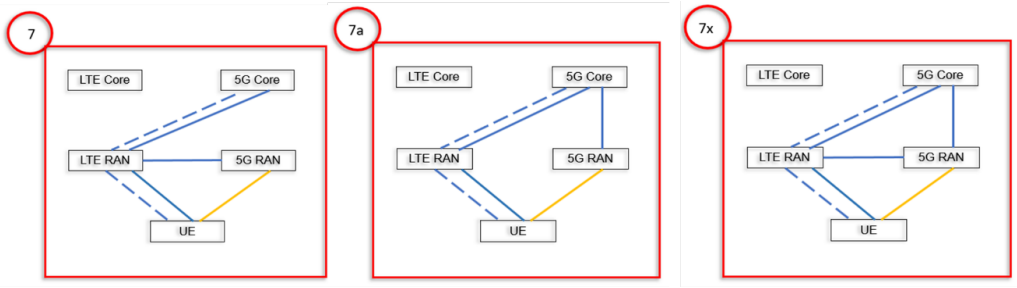


Figure 3-35: *NSA deployment — Option 7, Option 7a Networking modes.*

In Options 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 connect 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.

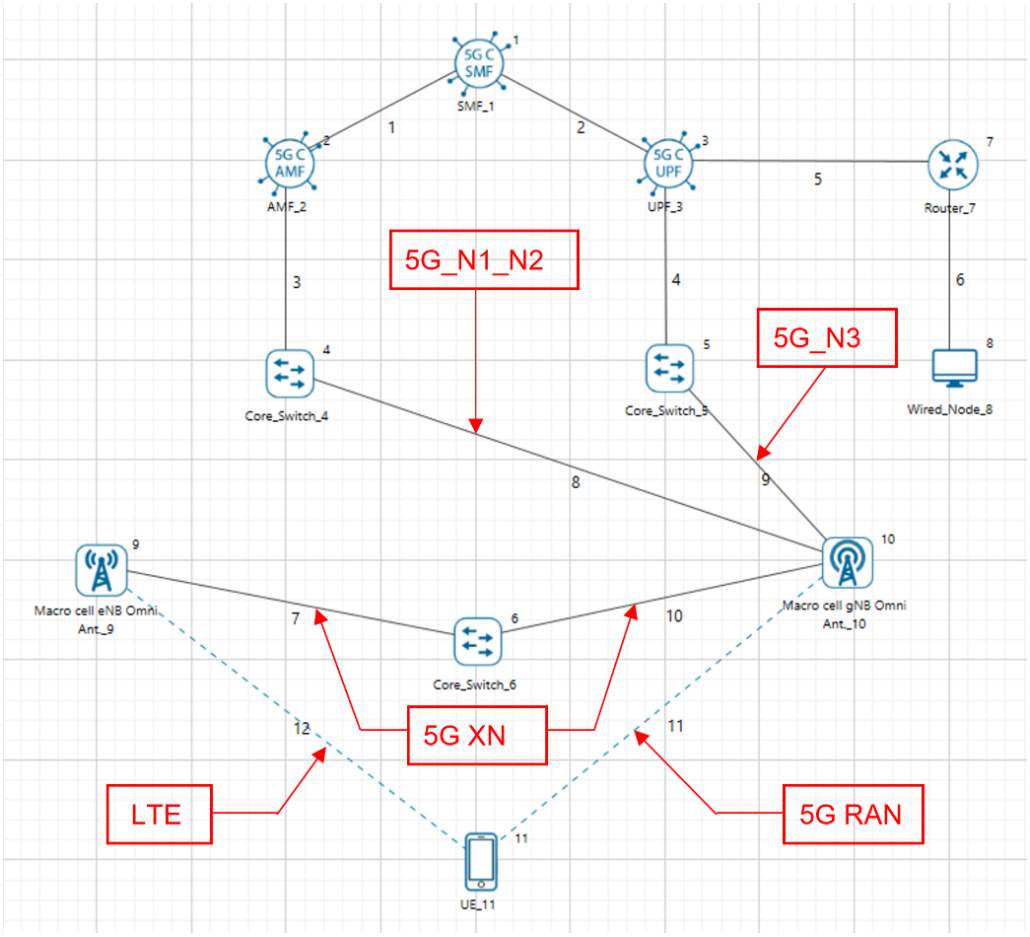


Figure 3-36: *NSA deployment — Option 4 networking mode in NetSim.*

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 interfaces. 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 5 using the 5G N3 interface and to the AMF via Switch 4 using the 5G N1 N2 interface. The gNBs can be inter-connected using the XN interface and does not have XN interface for eNBs. Hence direct communication between eNB and gNB is not possible. The UEs present in the network consists of two interfaces, an LTE interface and a 5G RAN interface.

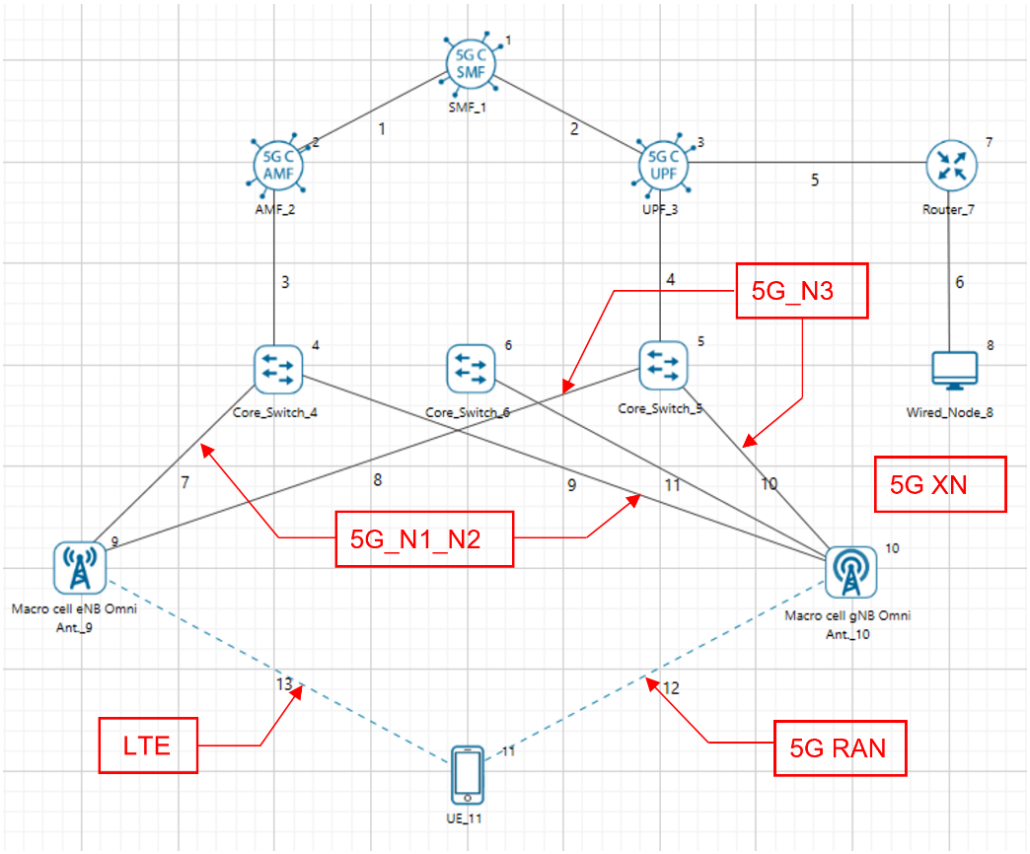


Figure 3-37: *NSA deployment — Option 4a networking mode in NetSim.*

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_5 using the 5G_N3 interface and to the AMF via Switch 4 using the 5G N1-N2 interface. The gNBs and eNBs are inter-connected using the XN interface and hence direct communication between eNB and gNB is possible. The UEs present in the network consists of two interfaces, an LTE interface and a 5G RAN interface. The data is delivered to the UE when it comes to the 5G NR through the LTE-RAN.

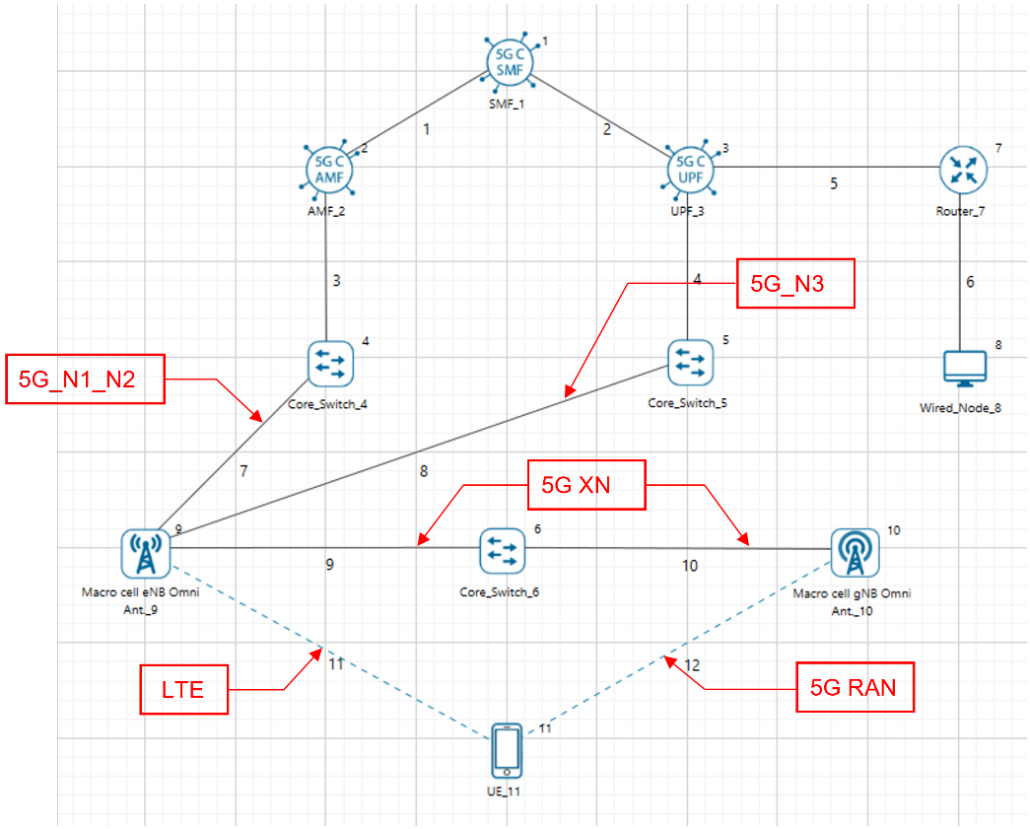


Figure 3-38: *NSA deployment — Option 7 networking mode in NetSim.*

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 5 using the 5G N3 interface and to the AMF via Switch 4 using the 5G N1-N2 interface. The gNBs do not have an XN Interface and eNBs are 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.

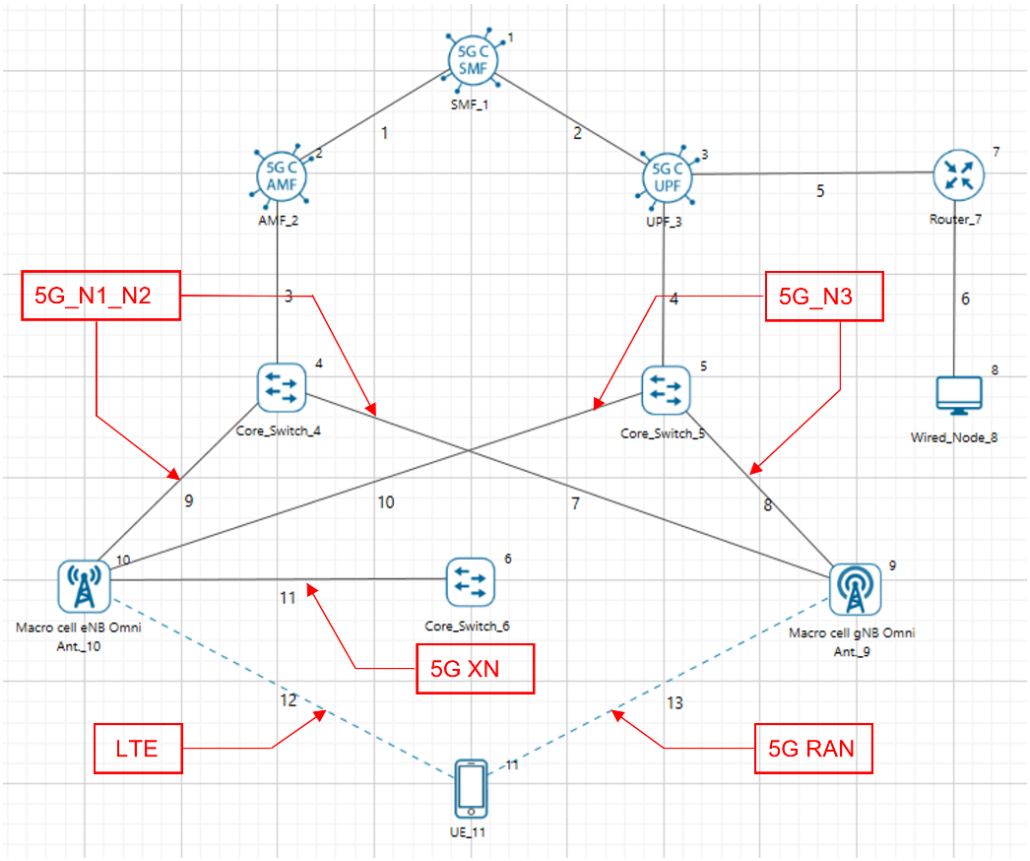


Figure 3-39: *NSA deployment — Option 7a networking mode in NetSim.*

3.17 NSA Packet Flow

3.17.1 Option 4

Consider the following network scenario:

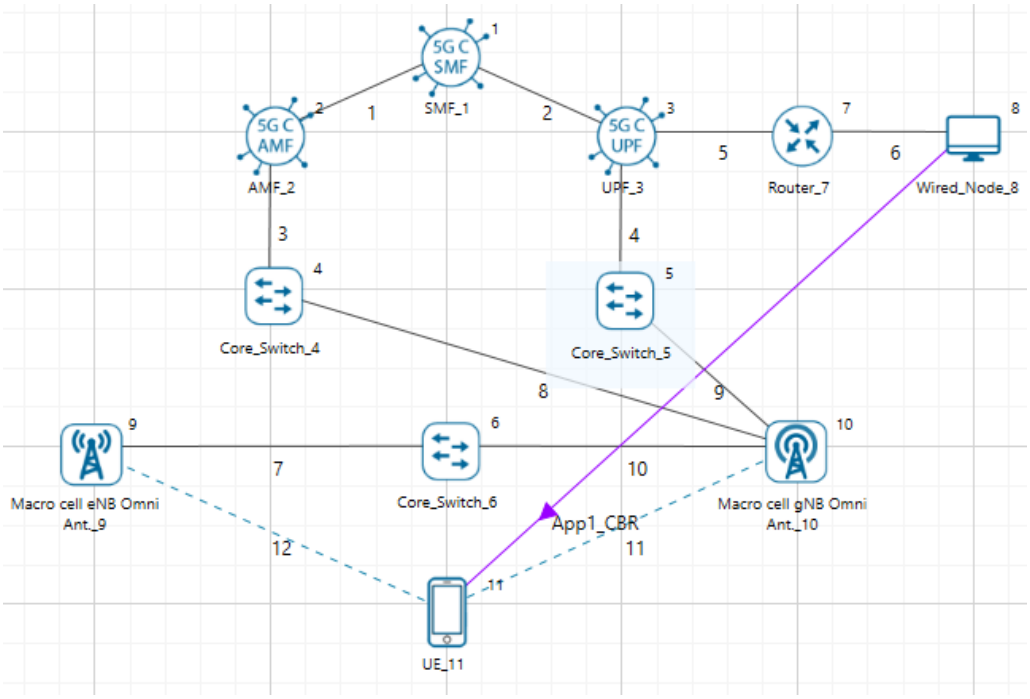


Figure 3-40: *NSA deployment — Option 4 networking mode in NetSim.*

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

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:

- The MN, gNB will broadcast the RRC MIB packets to the UE every 80 ms and RRC SIB1 every 160 ms.
- After the transmission of the RRC MIB and RRC SIB1 packets, the gNB will send RRC SI packet to the UE.
- After reception of RRC SI packet, UE will send RRC Setup Request to the gNB.
- On receiving the RRC Setup Request packet, the gNB will acknowledge the request by transmitting RRC Setup packet to the UE.
- The UE will send back the RRC Setup Complete packet on the receipt of RRC Setup message.
- The gNB will send INITIAL UE MSG AND REGISTRATION REQUEST to the AMF via Core Switch 4 through the N1 N3 interface.
- AMF will send a CREATE SESSION REQUEST to SMF through N8 interface.
- SMF will send PFCP SESSION REQUEST to UPF through N5 interface.
- UPF will send back the response packet to SMF, i.e., PFCP SESSION RESPONSE.
- SMF will send back the response packet to AMF, i.e., CREATE SESSION RESPONSE.
- AMF will send the INITIAL CONTEXT SETUP REQUEST to the gNB via Core Switch 4.

- On the receipt of Context setup request, gNB will send INITIAL CONTEXT SETUP RESPONSE REGISTRATION COMPLETE packet to the AMF via Core Switch 4 through the N1-N3 interface.
- This marks the completion of UE registration process.
- 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 → Data Link Layer.
- After the UE registration, the MN node will send DC SEC CELL ADDITION REQUEST to the SN via the Core Switch 6.
- On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC SEC CELL ADDITION RESPONSE.
- After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
- As per the current splitting algorithm in NetSim, when application QoS is set to BE, RTPS, ERTPS, or NRTPS, the data packet will be transmitted to the UPF through the N6 interface. From the UPF, it goes to the gNB (MN) via Core Switch 5 through the N2 interface, and from the gNB, it will be transmitted to the UE through the RAN interface.
- When the application QoS is set to UGS, the data packet will flow from the UPF to the gNB via Core Switch 5. From the gNB, the packet gets transmitted to the eNB via Core Switch 6 through the XN interface, and then to the UE.

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

A	C	D	E	F	G	H
PACKET_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	GNB-10	SWITCH-4
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	SWITCH-4	AMF-2
0	Control_Packet	CREATE_SESSION_REQUEST	AMF-2	SMF-1	AMF-2	SMF-1
0	Control_Packet	PFCP_SESSION_REQUSET	SMF-1	UPF-3	SMF-1	UPF-3
0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-3	SMF-1	UPF-3	SMF-1
0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-1	AMF-2	SMF-1	AMF-2
0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-2	GNB-10	AMF-2	SWITCH-4

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

3.17.2 Option 4a

Consider the following network scenario:

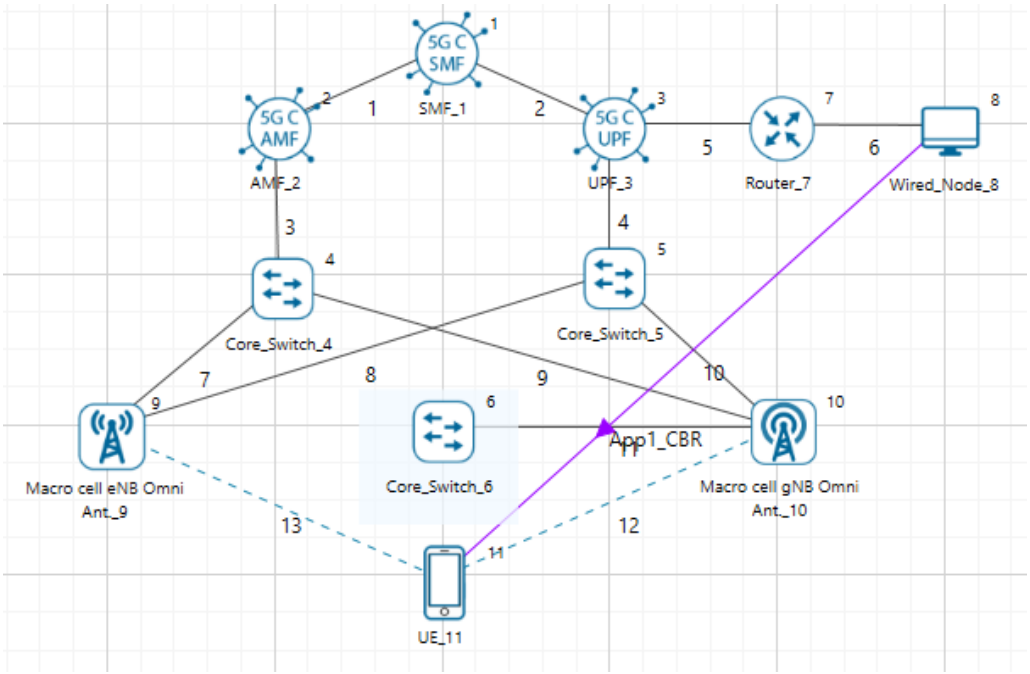


Figure 3-42: *NSA deployment — Option 4a networking mode in NetSim.*

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

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

- The MN, gNB will broadcast the RRC MIB packets to the UE every 80 ms and RRC SIB1 every 160 ms.
- After the transmission of the RRC MIB and RRC SIB1 packets, the gNB will send RRC SI packet to the UE.
- After reception of RRC SI packet, UE will send RRC Setup Request to the gNB.
- On receiving the RRC Setup Request packet, the gNB will acknowledge the request by transmitting RRC Setup packet to the UE.
- The UE will send back the RRC Setup Complete packet on the receipt of RRC Setup message.
- The gNB will send INITIAL UE MSG AND REGISTRATION REQUEST to the AMF via Core Switch 4 through the N1 N3 interface.
- AMF will send CREATE SESSION REQUEST to SMF through N8 interface.
- SMF will send PFCP SESSION REQUEST to UPF through N5 interface.
- UPF will send back the response packet to SMF, i.e., PFCP SESSION RESPONSE.
- SMF will send back the response packet to AMF, i.e., CREATE SESSION RESPONSE.
- AMF will send the INITIAL CONTEXT SETUP REQUEST to the gNB via Core Switch 4.

- On the receipt of Context setup request, gNB will send INITIAL CONTEXT SETUP RESPONSE REGISTRATION COMPLETE packet to the AMF via Core Switch 4 through the N1-N3 interface.
- This marks the completion of UE registration process.
- 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 → Data Link Layer.
- After the UE registration, the MN node will send DC SEC CELL ADDITION REQUEST to the SN via the Core Switch 6.
- On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC SEC CELL ADDITION RESPONSE.
- After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
- 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 Core Switch 5 through the N2 interface, and from the gNB it will be transmitted to the UE through the RAN interface.
- The second data packet will flow from UPF to the gNB via Core Switch 5 and from the gNB, the packet gets transmitted to the eNB via Core Switch 6 through the XN interface and then to the UE.
- 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:

A	C	D	E	F	G	H
PACKET_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	GNB-10	SWITCH-4
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	SWITCH-4	AMF-2
0	Control_Packet	CREATE_SESSION_REQUEST	AMF-2	SMF-1	AMF-2	SMF-1
0	Control_Packet	PFCP_SESSION_REQUSET	SMF-1	UPF-3	SMF-1	UPF-3
0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-3	SMF-1	UPF-3	SMF-1
0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-1	AMF-2	SMF-1	AMF-2
0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-2	GNB-10	AMF-2	SWITCH-4

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

3.17.3 Option 7

Consider the following network scenario:

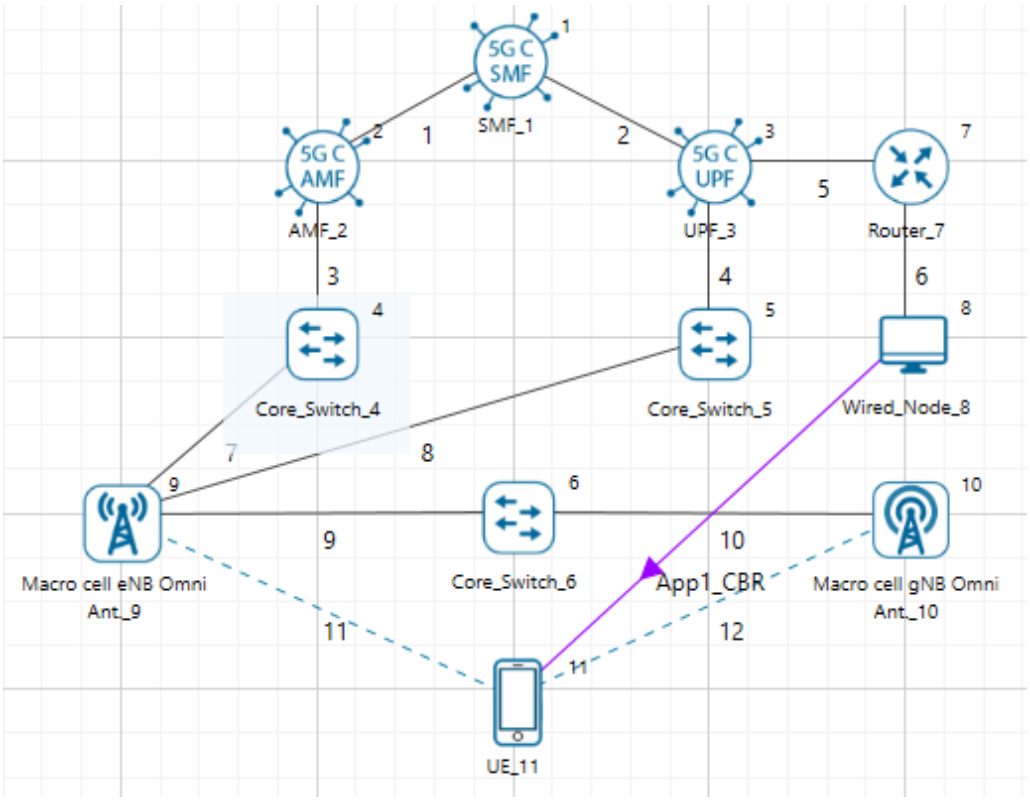


Figure 3-44: *NSA deployment — Option 7 networking mode in NetSim.*

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

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:

- The MN, eNB will broadcast the RRC MIB packets to the UE every 40 ms and RRC SIB1 every 80 ms.
- After the transmission of the RRC MIB and RRC SIB1 packets, the eNB will send RRC SI packet to the UE.
- After reception of RRC SI packet, UE will send RRC Setup Request to the eNB.
- On receiving the RRC Setup Request packet, the eNB will acknowledge the request by transmitting RRC Setup packet to the UE.
- The UE will send back the RRC Setup Complete packet on the receipt of RRC Setup message.
- The eNB will send INITIAL UE message AND REGISTRATION REQUEST to the AMF via Core Switch 4 through the N1-N3 interface.
- AMF will send CREATE SESSION REQUEST to SMF through N8 interface.

- SMF will send PFCP SESSION REQUEST to UPF through N5 interface.
- UPF will send back the response packet to SMF, i.e., PFCP SESSION RESPONSE.
- SMF will send back the response packet to AMF, i.e., CREATE SESSION RESPONSE.
- AMF will send the INITIAL CONTEXT SETUP REQUEST to the eNB via Core Switch 4.
- On the receipt of Context setup request, eNB will send INITIAL CONTEXT SETUP RESPONSE REGISTRATION COMPLETE packet to the AMF via Core Switch 4 through the N1-N3 interface.
- This marks the completion of UE registration process.
- 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 → Data Link Layer.
- After the UE registration, the MN node will send DC SEC CELL ADDITION REQUEST to the SN via the Core Switch 6.
- On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e., DC SEC CELL ADDITION RESPONSE.
- After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
- As per the current splitting algorithm in NetSim, when application QoS is set to BE, RTPS, ERTPS, or NRTPS, the data packet will flow from UPF to the eNB via Core Switch 5 and then from eNB to the gNB via Core Switch 6 through XN interface and then to the UE.
- When the application QoS is set to UGS, the data packet will be transmitted to the UPF through the N6 interface and from the UPF it goes to the MN, eNB via Core Switch 5 through the N2 interface, and from the eNB it will be transmitted to the UE through the LTE interface.

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

A	C	D	E	F	G	H
PACKET_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	GNB-10	SWITCH-4
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	SWITCH-4	AMF-2
0	Control_Packet	CREATE_SESSION_REQUEST	AMF-2	SMF-1	AMF-2	SMF-1
0	Control_Packet	PFCP_SESSION_REQUSET	SMF-1	UPF-3	SMF-1	UPF-3
0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-3	SMF-1	UPF-3	SMF-1
0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-1	AMF-2	SMF-1	AMF-2
0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-2	GNB-10	AMF-2	SWITCH-4

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

3.17.4 Option 7a

Consider the following network scenario:

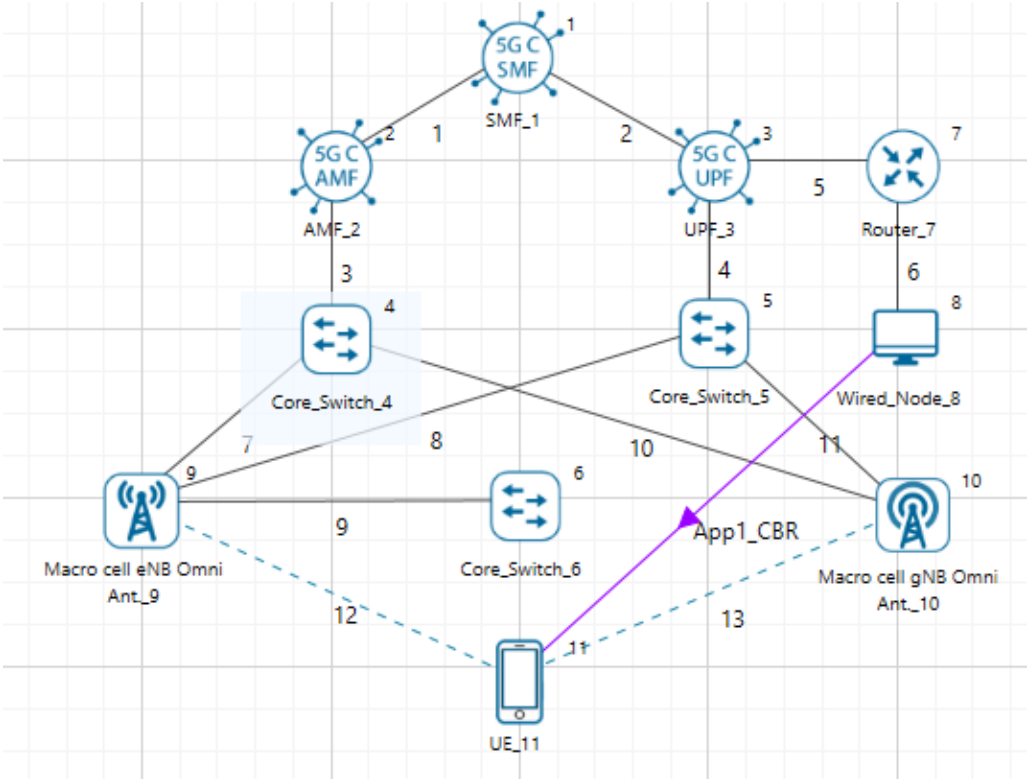


Figure 3-46: *NSA deployment — Option 7a networking mode in NetSim.*

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

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

- The MN, eNB will broadcast the RRC MIB packets to the UE every 40 ms and RRC SIB1 every 80 ms.
- After the transmission of the RRC MIB and RRC SIB1 packets, the eNB will send RRC SI packet to the UE.
- After reception of RRC SI packet, UE will send RRC Setup Request to the eNB.
- On receiving the RRC Setup Request packet, the eNB will acknowledge the request by transmitting RRC Setup packet to the UE.
- The UE will send back the RRC Setup Complete packet on the receipt of RRC Setup message.
- The eNB will send INITIAL UE MSG AND REGISTRATION REQUEST to the AMF via Core Switch 4 through the N1-N3 interface.
- AMF will send CREATE SESSION REQUEST to SMF through N8 interface.
- SMF will send PFCP SESSION REQUEST to UPF through N5 interface.
- UPF will send back the response packet to SMF, i.e., PFCP SESSION RESPONSE.
- SMF will send back the response packet to AMF, i.e., CREATE SESSION RESPONSE.
- AMF will send the INITIAL CONTEXT SETUP REQUEST to the eNB via Core Switch 4.
- On the receipt of Context setup request, eNB will send INITIAL CONTEXT SETUP RESPONSE REGISTRATION COMPLETE packet to the AMF via Core Switch 4 through the N1 N3 interface.
- This marks the completion of UE registration process.
- 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 → Data Link Layer.
- DC SEC CELL ADDITION REQUEST to the SN via the Core Switch 5.
- On the receipt of this secondary cell addition request, the SN sends back the response packet, i.e. DC SEC CELL ADDITION RESPONSE.
- After the UE attachment procedure, the data packets will be transmitted from the server to the UE based on the splitting algorithm.
- 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 Core Switch 5 through the N2 interface, and from the eNB it will be transmitted to the UE through the LTE interface.
- The second data packet will flow from UPF to the gNB via Core Switch 5 and then from gNB to the UE.
- Similarly, the third packet will flow through the MN, fourth through the SN and so on.

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

A	C	D	E	F	G	H
PACKET_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SIB1	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_MIB	GNB-10	Broadcast-0	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SI	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_REQUEST	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP	GNB-10	UE-11	GNB-10	UE-11
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	RRC_SETUP_COMPLETE	UE-11	GNB-10	UE-11	GNB-10
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	GNB-10	SWITCH-4
0	Control_Packet	INITIAL_UE_MSG_AND_REGISTRATION_F	GNB-10	AMF-2	SWITCH-4	AMF-2
0	Control_Packet	CREATE_SESSION_REQUEST	AMF-2	SMF-1	AMF-2	SMF-1
0	Control_Packet	PFCP_SESSION_REQUSET	SMF-1	UPF-3	SMF-1	UPF-3
0	Control_Packet	PFCP_SESSION_RESPONSE	UPF-3	SMF-1	UPF-3	SMF-1
0	Control_Packet	CREATE_SESSION_RESPONSE	SMF-1	AMF-2	SMF-1	AMF-2
0	Control_Packet	INITIAL_CONTEXT_SETUP_REQUEST	AMF-2	GNB-10	AMF-2	SWITCH-4

Figure 3-47: *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.

In keeping with the above, in NetSim's 5G model, 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. The only difference between the SSB and PDSCH is the beamforming gain calculations. The hand-over decision is based on the SSB-SNR measured at UE from the serving-gNB and the target-gNB. Since the noise power would typically be the same for the s-gNB and t-gNB signals, in effect the handover is based on received signal level on the SSB.

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. Ericsson 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.

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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 eventTriggered 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 hysteresis which adds a time threshold.

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

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).

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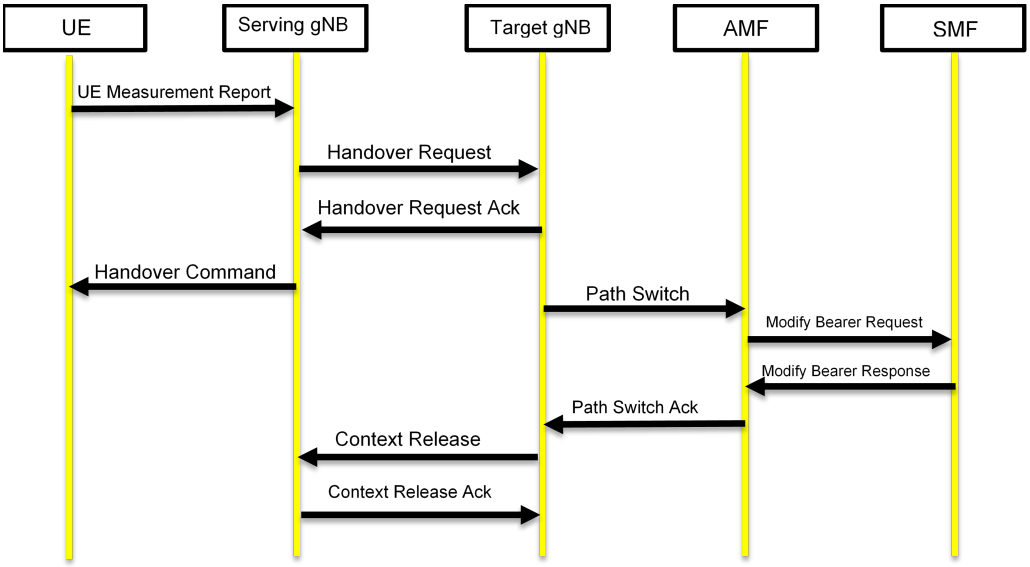


Figure 3-48: *Control packet flow in the 5G handover process.*

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

- 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 5 ms in NetSim and is a user configurable parameter.
- At some time, neighbor cell RSRP (measured as SNR in NetSim) becomes offset higher than serving cell RSRP.
- 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.
- 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.
- After receiving HANDOVER REQUEST ACK the serving gNB sends the HANDOVER COMMAND to UE.
- Then the HANDOVER COMMAND packet is sent by source gNB to the UE.
- The target gNB then sends RRC Reconfiguration message to UE. If UE is in RRC Connected mode then the target gNB is assigned as new source gNB for the UE.
- The target gNB will send the PATH SWITCH packet to the AMF through the N1-N2 interface (via a core switch).
- When the AMF receives the PATH SWITCH packet, it sends MODIFY BEARER REQUEST to the SMF. This is over the N11 interface.

- The SMF on receiving the MODIFY BEARER REQUEST sends back the MODIFY BEARER RESPONSE to the AMF.
- 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.
- The target gNB then 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.
- Then RRC Reconfiguration takes place between target gNB and UE.
- UE starts sending the UE MEASUREMENT REPORT to the new source gNB.

PACKET_ID	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	NW_LAYER_ARRIVAL_TIME(US)	MAC_LAYER_ARRIVAL_TIME(US)	PHY_LAYER_ARR
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 3-49: *Screenshot 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 or receive user data. Handover Interruption time can be configured in the Data Link layer properties of the gNB as shown below.

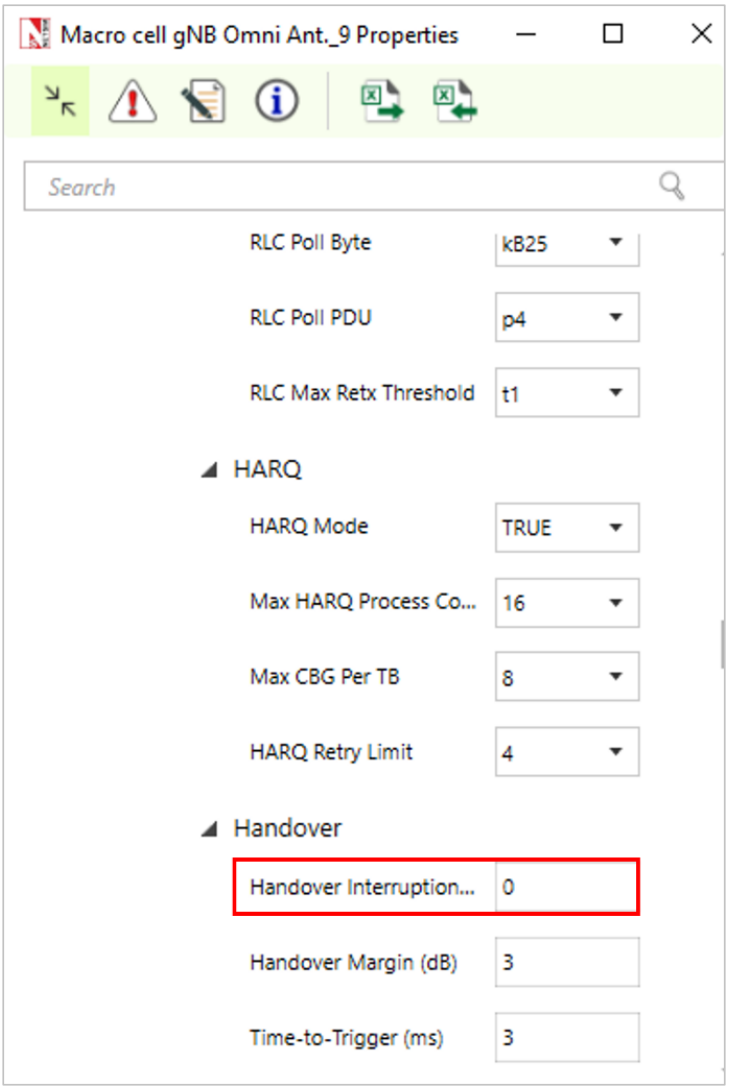


Figure 3-50: *Screenshot showing handover interruption time in gNB properties.*

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 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, 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 T_{RH}, one could argue 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, $SNR_{UE(SSB)}^{t\text{-gNB}}$ is offset, Δ, higher than received signal strength (on the downlink in the SSB) from serving gNB $SNR_{UE(SSB)}^{s\text{-gNB}}$. This offset, Δ,

is also known as the Hand Over Margin (HOM). Thus, A3 event is triggered when, in dB scale,

$$SNR^{t\text{-gNB}}_{UE(SSB)}(t) - SNR^{s\text{-gNB}}_{UE(SSB)}(t) \geq \Delta \qquad (1) \tag{67}$$

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

$$SNR^{t\text{-gNB}}_{UE(SSB)}(t) - SNR^{s\text{-gNB}}_{UE(SSB)}(t) = RSRP^{t\text{-gNB}}_{UE(SSB)}(t) - RSRP^{s\text{-gNB}}_{UE(SSB)}(t) \tag{68}$$

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

- when a measurement report is sent, which is every measurement interval T_{MI} (default 5 ms), and
- 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 satisfies (67). 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 (67) holds true for a duration equal to T_{TTT}.

Since NetSim is a discrete event simulator its internal virtual clock progresses (virtual) time at events. Therefore, NetSim cannot check for (67) continuously over time. The test of whether (67) 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 (67) at all mobility and measurement events within the TTT period. If condition (67) 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, $SNR^{t\text{-gNB}}_{UE(SSB)}$, or $SNR^{s\text{-gNB}}_{UE(SSB)}$ within the T_{TTT} window and (67) is evaluated on instantaneous powers at all events.

NetSim Time-to-trigger variable

- is global scope; it remains the constant across the network, and
- can be set by the user in the range [0 ms, 5120 ms] as defined in the standards.

Algorithm

- When A3 condition is met AddTrigger event is added.
- Check (67) at all measurement report events and mobility events.
- If at any event (67) doesn't hold remove the AddTrigger event.

- Else, if (67) holds at all events within the TTT, initiate H/O trigger upon expiry of TTT interval.

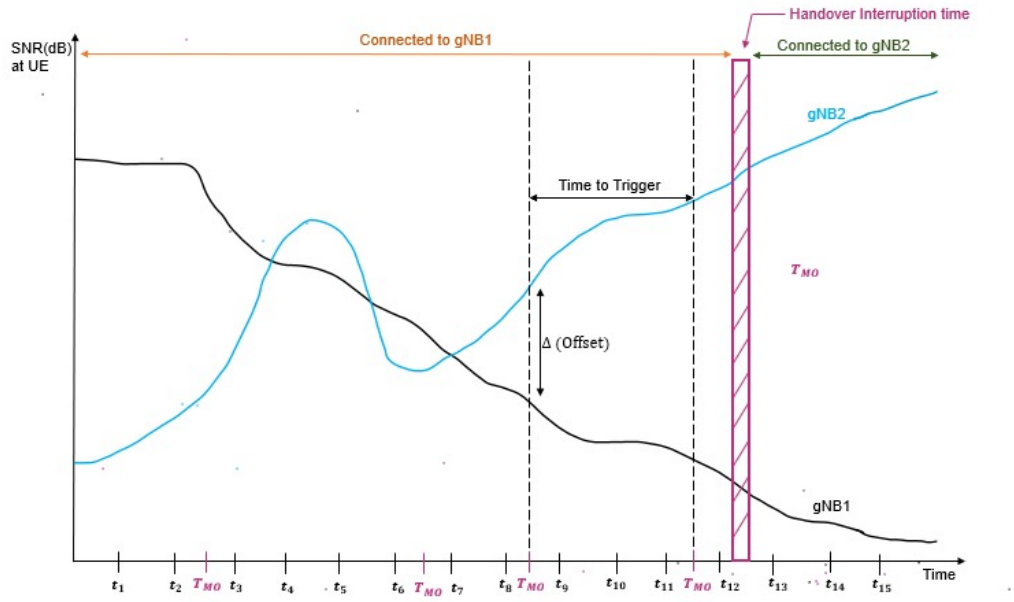


Figure 3-51: *We see the SNR variation with time measured by UE from gNB1 (black) and gNB2 (blue). Time to trigger starts the instant $SNR_{UE}^{gNB2} - SNR_{UE}^{gNB1} > \Delta$. Once this condition holds for a duration equal to time-to-trigger, handover is initiated. Users can also configure a handover interruption time during which the UE is not connected to either gNB. Post this the UE gets associated with gNB2.*

3.18.6.1 Assumptions and Limitations

- Time to trigger (T_{TTT}) will be implemented for 5G Standalone (SA) mode. NetSim assumes non failure of:
  - Measurement reports
  - Handover messages
- Handovers are always successful. There are no handover failures on account of admission control at t-gNB.
- In NetSim, UEs can be handed over to gNBs of different frequencies as long as (67) 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).
- 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 $(SNR^{gNB}_{UE(SSB)} - SNR^{\text{s-gNB}}_{UE(SSB)} > \Delta)$ is met:
    * If matrix entry T^{j}_{trigger} is currently -1, then update $T^{j}_{\text{trigger}} = T_{\text{current}}$, where T_{current} is current simulation time.
    * Else (matrix entry is not -1): If $T_{\text{current}} - T^{j}_{\text{trigger}} \geq TTT$, initiate handover procedure.
  - Else: If the matrix entry T^{j}_{trigger} 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 Data Link layer properties of the gNB as shown below.

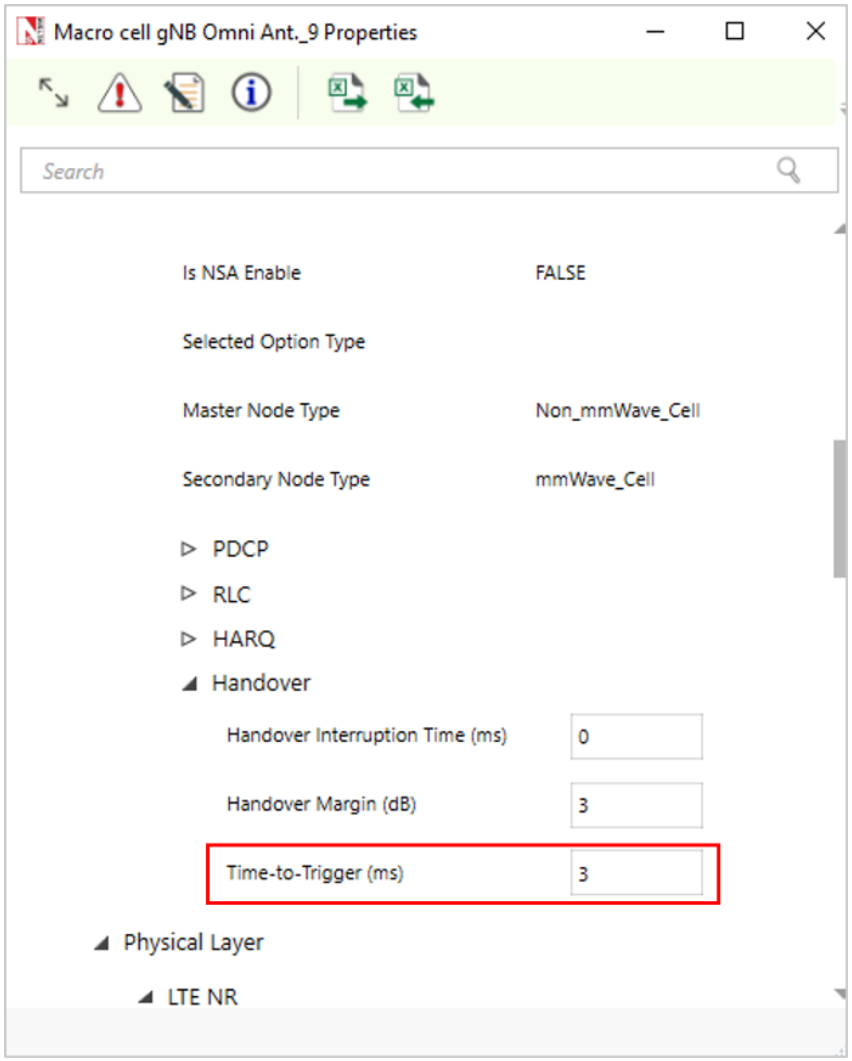


Figure 3-52: *Time-to-Trigger configuration in gNB/eNB Data Link layer properties.*

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

3.18.6.4 Enabling the LTENR Handover Log

The LTENR Handover log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR Handover log under Network Logs as shown below.

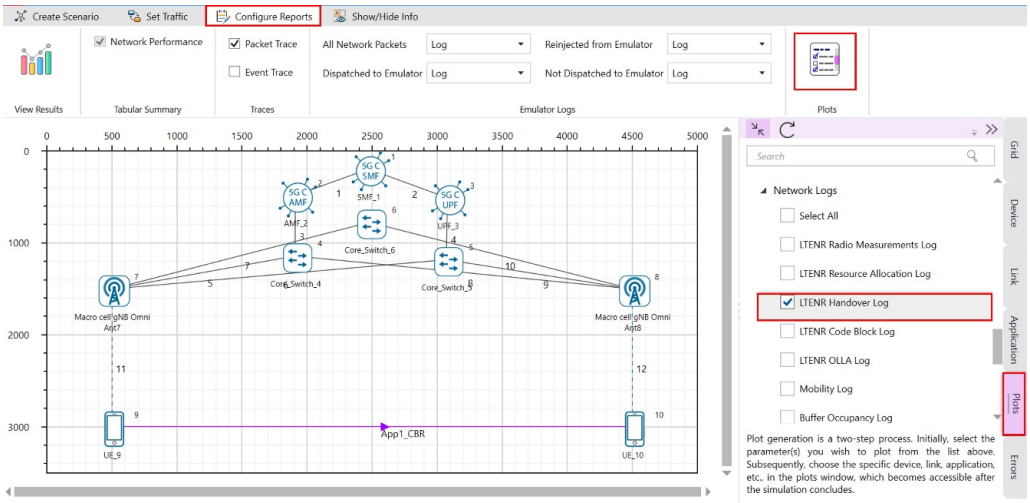


Figure 3-53: *Enabling the LTENR Handover log.*

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

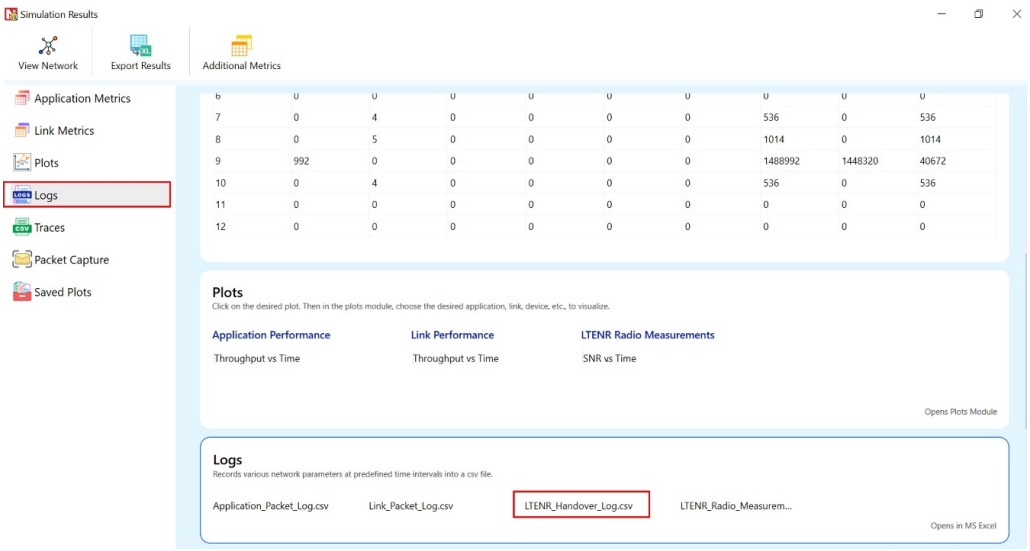
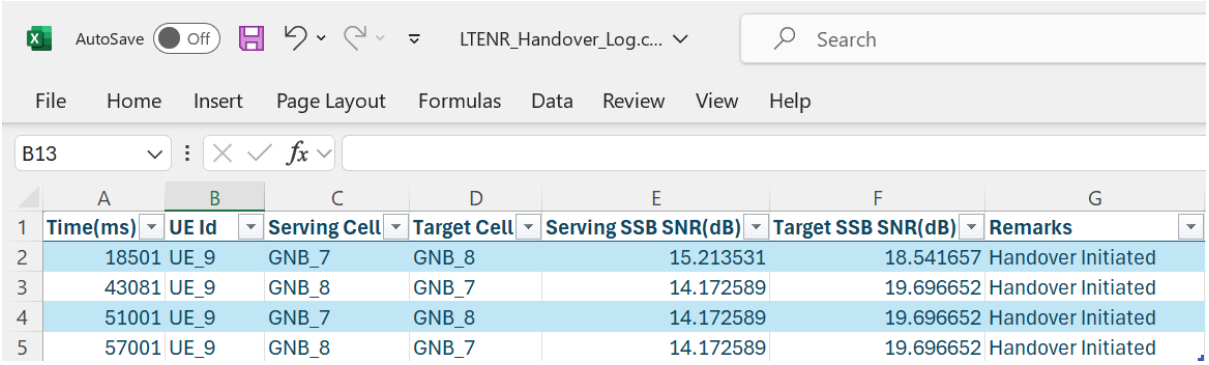


Figure 3-54: *Accessing Handover log from NetSim results dashboard.*

The log file consists of timestamps in Milliseconds, associated UE name, the serving cell name, target cell name, serving SSB SNR, Target SSB SNR and the Remarks.

Entries are written to the file when a handover condition is met. For example, when running the 5G-Handover scenario with the Time-To-Trigger (TTT) set to 2560 milliseconds (or 2.56 seconds) and mobility configured such that the User Equipment (UE) moves toward the target gNB and then returns to the serving gNB, handovers typically occur in a ping-pong manner.

The following entries are logged in the Handover log:



AutoSave Off LTENR_Handover_Log.c... Search

File Home Insert Page Layout Formulas Data Review View Help

B13

	A	B	C	D	E	F	G
1	Time(ms)	UE Id	Serving Cell	Target Cell	Serving SSB SNR(dB)	Target SSB SNR(dB)	Remarks
2	18501	UE_9	GNB_7	GNB_8	15.213531	18.541657	Handover Initiated
3	43081	UE_9	GNB_8	GNB_7	14.172589	19.696652	Handover Initiated
4	51001	UE_9	GNB_7	GNB_8	14.172589	19.696652	Handover Initiated
5	57001	UE_9	GNB_8	GNB_7	14.172589	19.696652	Handover Initiated

Figure 3-55: *TTT log showing entries with handover conditions met at different time intervals.*

- From the log file we can see that initially the UE is associated with gNB7. Around 18.5 seconds, the handover is initiated when $SNR^{gNB}_{UE(SSB)} - SNR^{\text{s-gNB}}_{UE(SSB)} > \Delta$ (3 dB).
- Since UE 9 is configured with mobility, it moves back to gNB 7 from gNB 8.
- Again, at 43.8 seconds, the handover condition is met when the SNR from gNB 7 is greater than from gNB 8 as UE 9 moves towards gNB 7.
- Similarly, you can observe that the handover conditions are met again at 51 and 57 seconds.

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 Radio Link Failure and Handover Failure

NetSim models two connection failure mechanisms in the 5G NR library. Radio Link Failure (RLF) detects a prolonged loss of the radio link while the UE is in normal connected operation. Too-Late Handover Failure detects a handover whose target cell can no longer support the UE at the instant the cell switch executes. Both mechanisms share a common out-of-sync threshold, buffer flush procedure, and recovery path, which are described once below and then referenced by each feature.

3.19.1 Out-of-Sync Threshold (Qout)

Both mechanisms are driven by the SSB downlink SNR, that is, the same measurement used for the handover decision (Section 3.18.1), and not by the OLLA-adjusted PDSCH CQI. The SSB SNR is converted to a spectral efficiency, $\alpha \times \log_2(1 + \text{SNR})$, and mapped to a CQI index through the CQI table configured in the CSI report configuration (Section 3.9.18). The link is then classified as:

- Out-of-sync (Qout) when the resulting CQI is 0, that is, the link cannot carry even the lowest modulation and coding scheme.
- In-sync (Qin) when the resulting CQI is 1 or higher.

The SSB is used rather than the PDSCH because RLF monitors the radio link, not the data service. The PDSCH CQI includes interference and the OLLA offset (Section 3.9.20) and therefore reaches zero at a shorter range. As a result there is a region in which user throughput has already stopped while the link is still in-sync, so no RLF is declared. This is expected behaviour and mirrors real networks, in which data service can be lost before a radio link failure is declared. The out-of-coverage condition described in Section 3.9.21 refers to this data-channel condition and is distinct from the Qout condition used here.

3.19.2 Radio Link Failure

RLF follows the radio link monitoring procedure of 3GPP TS 38.331 and TS 38.133. The serving cell's SSB-SNR CQI is evaluated once per slot for each connected UE, and drives the following counters and timers:

- When the link is out-of-sync (CQI = 0), the out-of-sync counter N310 is incremented and the in-sync counter N311 is reset. Once N310 reaches its threshold, the failure timer T310 is started.
- When the link returns in-sync (CQI $\geq$ 1) while T310 is running, N311 is incremented. Once N311 reaches its threshold, T310 is stopped and the counters are reset. No RLF is declared and the UE remains connected. This is what prevents a brief fade from causing a spurious failure.
- If T310 expires without such a recovery, RLF is declared.

On RLF declaration NetSim logs the event, and then releases the failed serving cell: buffered PDCP and RLC packets are discarded, the PHY, PDCP, RLC and SDAP associations are removed, the UE is removed from the radio link, the core network mapping is cleaned up, and the OLLA offset is reset so that the first MCS after reconnection is not biased by the pre-failure link adaptation state. Stale measurement reports and the stale selected-cell information are cleared, and the re-establishment timer T311 is started.

Figure 3-56 shows this state machine as implemented in NetSim: the SSB-SNR CQI drives the N310/T310/N311/T311 counters and timers, with the recovery branch (N311 stops T310 before it expires) and the failure branch (T310 expiry declares RLF and starts T311).

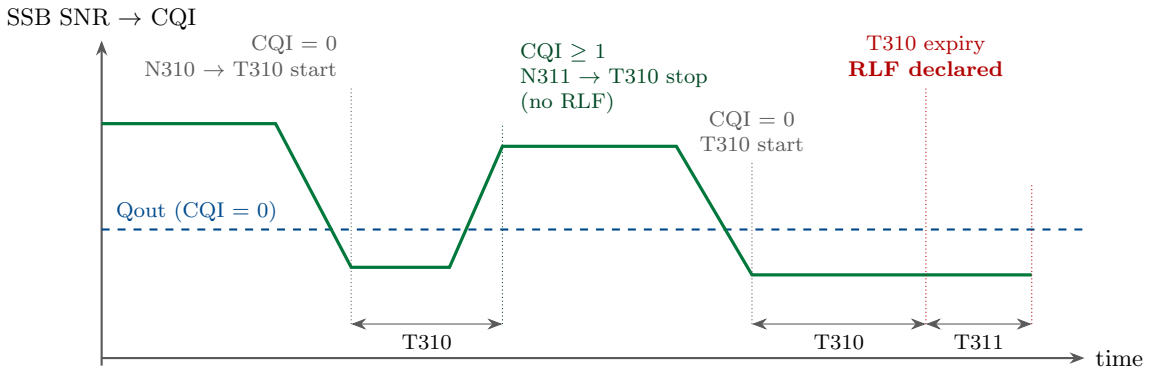


Figure 3-56: *RLF radio link monitoring in NetSim. Redrawn from 3GPP TS 38.331 (clause 5.3.10) and TS 38.133 (clause 8.1).*

3.19.3 Too-Late Handover Failure

A too-late handover is one of the mobility robustness failures described in 3GPP TS 38.300. The handover decision is taken when the A3 condition and time-to-trigger are met, but the cell switch is executed only after the handover interruption (Section 3.18.5). Because the UE continues to move during the interruption, the measurement report on which the decision was based can be stale by the time the switch executes.

NetSim therefore evaluates the target cell at the instant of the cell switch:

- The target cell's current SSB SNR is read and mapped to a CQI using the same Qout mapping described above.
- If the CQI is 1 or higher, the target is still usable and the handover proceeds exactly as before. A successful handover is unaffected by this check.
- If the CQI is 0, the target can no longer support the UE and the handover is declared too late. The switch is aborted, the failure is logged, and the UE is recovered through the path described below.

When the handover is aborted, only the source cell context is released, because the UE never joined the target. The cleanup performed is the same as for RLF, that is, the buffers are flushed rather than transferred, the source associations are removed, and the core network mapping and OLLA offset are cleaned up. No path switch is performed.

No randomness is injected. A too-late handover arises from the existing simulation physics, and becomes more likely with a larger handover interruption time, a higher UE speed, thin cell-edge margins, or a sharp fall in signal level with distance.

Figure 3-57 shows the same failure as SSB SNR over time. At the decision instant (T0) the target is above Qout, so the handover is triggered; but the UE keeps moving, and the network continues to work from that T0 reading. By the execution instant (T2) the target has fallen below Qout, and because the decision was based on the now-stale T0 value the handover is aborted at T2 and the UE re-establishes through the RLF path.

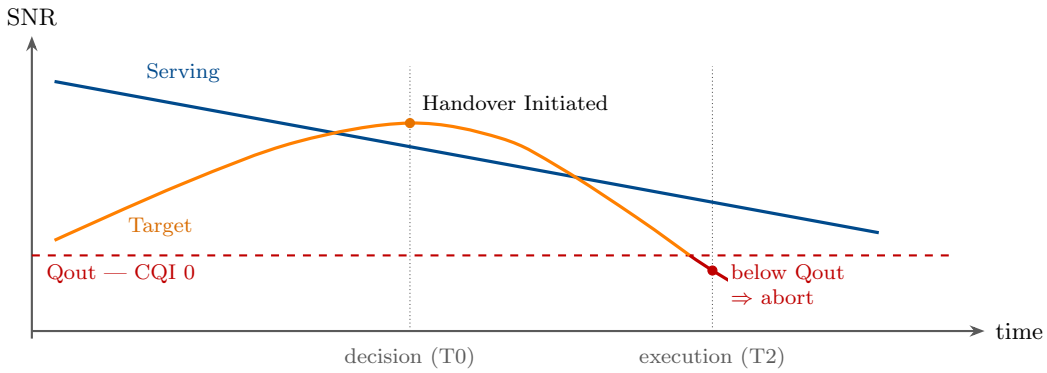


Figure 3-57: *Too-late handover as SSB SNR over time. The target is above Qout at the decision (T0) but below it by execution (T2); the handover is aborted rather than completed.*

Figure 3-58 places the same check within the standard handover message sequence. Steps 1 to 5 are the ordinary intra-NR handover of TS 38.300; the addition is the target re-evaluation at the cell switch (T2), which either lets the handover complete or aborts it.

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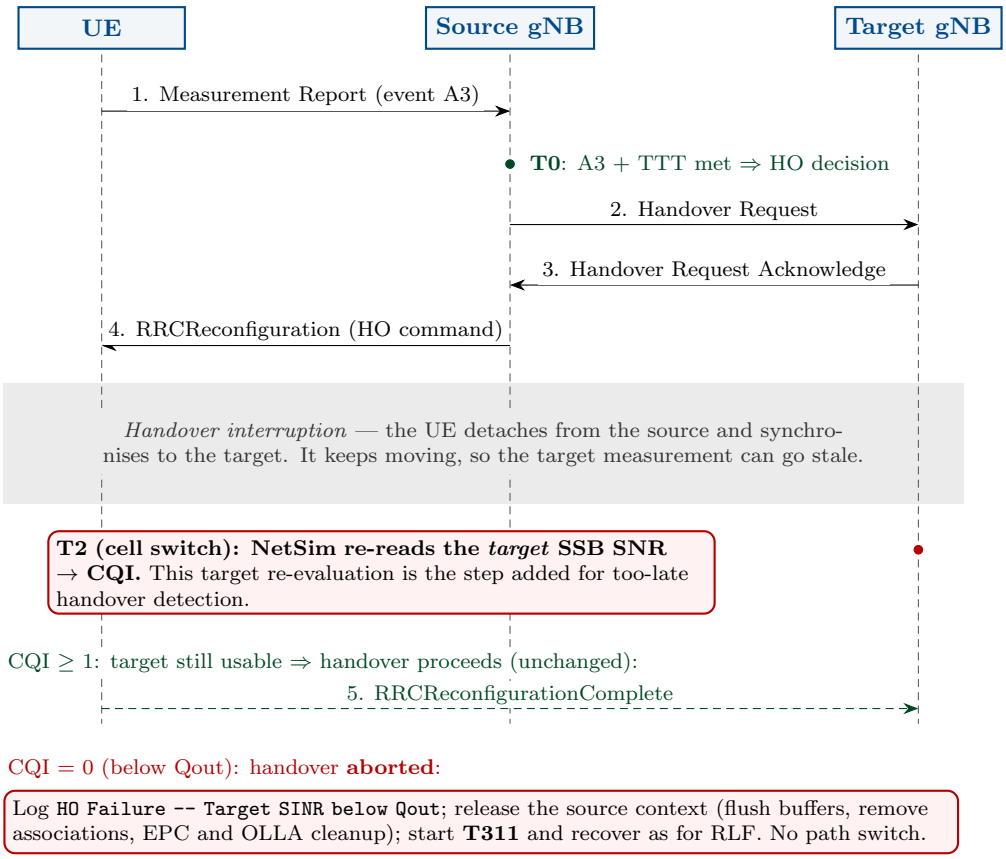


Figure 3-58: *Too-late handover detection within the intra-NR handover procedure. Steps 1–5 follow 3GPP TS 38.300 (clause 9.2.3); the T2 target re-evaluation is added by NetSim.*

3.19.4 Recovery

Both failures end in the same recovery path. The UE leaves the connected state with T311 running. On T311 expiry the UE moves to idle and performs cell selection (Section 3.15.2). A candidate cell is accepted only once its SSB SNR maps to a CQI of 1 or higher, so the UE does not reconnect to a cell that cannot sustain the link. Depending on the scenario the UE may re-establish on the original cell once it returns to coverage, on a different cell, or remain idle for the rest of the simulation if no cell qualifies.

3.19.5 Configuration and Logging

The timers and counters are taken from the ueTimersAndConstants information element broadcast in SIB1, and use the 3GPP default values, namely T310, T311, N310 and N311. No new GUI parameter is introduced. The behaviour is driven by the existing handover parameters, that is, the handover interruption time, the time-to-trigger, and the handover margin.

The Handover Log file (Section 3.24) records the following remarks in addition to the handover entries:

- RLF Declared T310 expired, written when T310 expires and RLF is declared. The serving cell and its SSB SNR at that instant are reported.
- T311 expired UE transitions to IDLE, written when the re-establishment timer expires.

- HO Failure – Target SINR below Qout, written when a handover is aborted because the target cell is below Qout at the cell switch. The source and target cells and both SSB SNR values are reported.

3.19.6 Simplifications

In a real UE the out-of-sync and in-sync conditions are evaluated on the hypothetical PDCCH block error rate, using thresholds of 10% and 2% respectively, with layer 1 filtering of the resulting indications (TS 38.133, Section 8.1.1). NetSim uses the per-slot CQI derived from the SSB SNR as the proxy for these indications, with CQI $= 0$ taken as out-of-sync and CQI ≥ 1 as in-sync, and without layer 1 filtering. The N310, N311, T310 and T311 counters and timers still model the standard radio link monitoring state machine on top of this proxy, which is consistent with the level of physical layer abstraction used elsewhere in the NetSim 5G model (Section 3.18.1).

3.20 Network Slicing

NetSim supports network slicing in 5G from v14.1 onwards.

3.20.1 RAN Slicing

RAN slicing in 5G involves dividing the Radio Access Network into multiple virtual slices, each tailored to serve specific service requirements. The RAN slicing implementation in NetSim is explained below:

- **Scope:** Network slicing in NetSim focuses solely on RAN slicing and does not cover Core and Transport slicing.
- **Identification:** Each network slice is identified by a single Network Slice Selection Assistance Information (S-NSSAI) or a Slice ID, consisting of a Slice Service Type (SST) and a Slice Differentiator (SD).
- **Slice Type and Differentiator:** The Slice Type (SST) signifies the expected behaviour of the network slice in terms of features and services. The Slice Differentiator (SD) distinguishes multiple instances of the same slice type.
- **Resource Sharing Options:** Two resource sharing options are defined: (a) Static slicing (or hard slicing) and (b) Dynamic slicing (or soft slicing).
- **Static Slicing:** Supported Slice Types are eMBB, URLLC, MIoT, and V2X. Slices are allocated a fixed percentage of resources.
- **Dynamic Slicing:** The supported Slice Type is eMBB. A proprietary algorithm uses PFS (Proportional Fair Scheduling) with Rate Guarantee employing stochastic online learning. The dynamic slicing algorithm is derived from Non-linear Optimization Theory.

3.20.2 Slice Configuration

Network Slicing can be configured in the gNB RAN interface, Datalink layer properties. Depending on the Scheduling Type selection the available Resource Allocation Techniques to choose from will vary.

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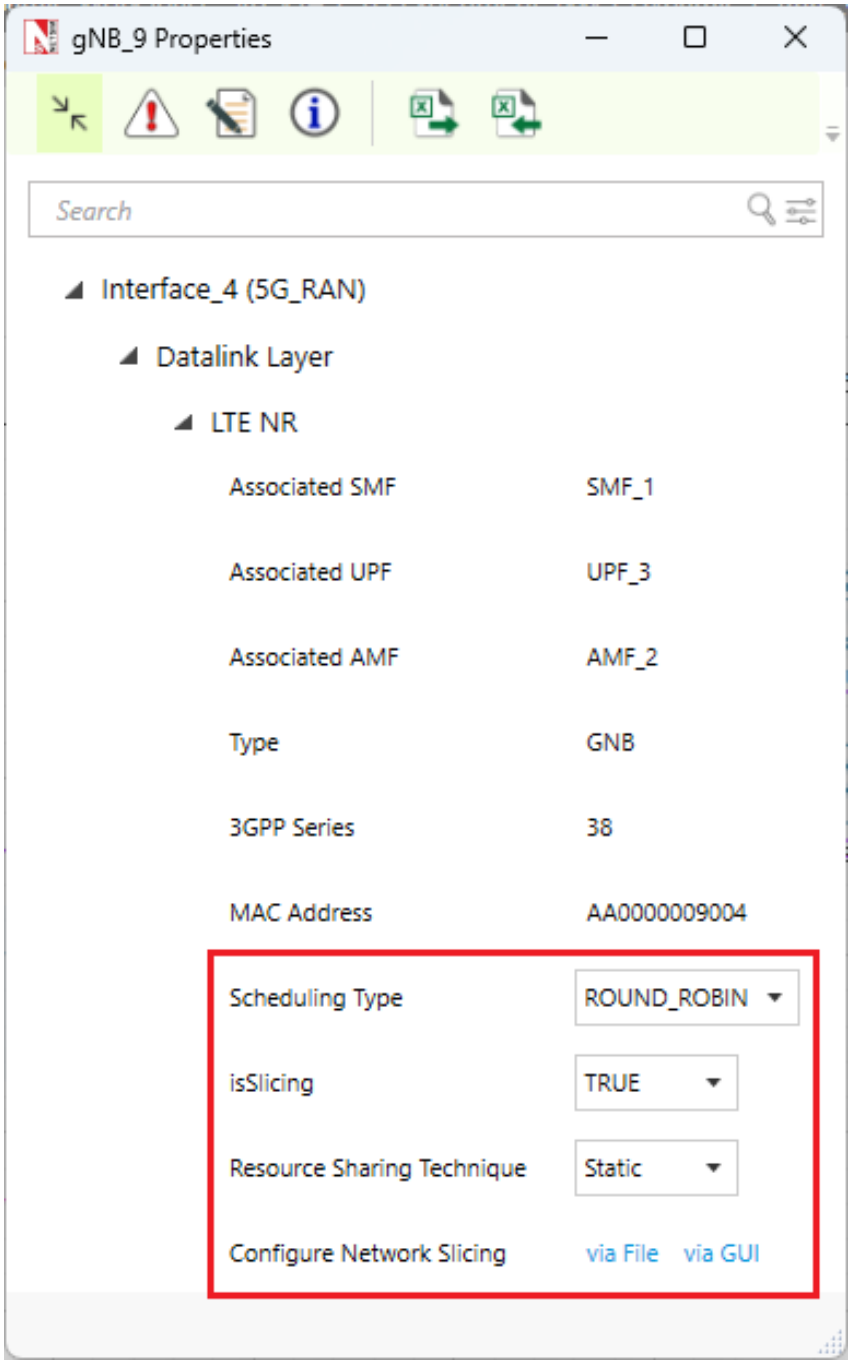


Figure 3-59: *gNB RAN Interface Datalink Layer properties with slice configuration options.*

The following table contains a list of scheduling types supported in the gNBs and the corresponding resource allocation techniques that can be selected.

Table 3-11: *Resource Allocation Techniques based on the Scheduling type selection.*

Scheduling Type	Network Slicing – Resource Allocation Technique
Round Robin	Static
Max Throughput	Static
Proportional Fair	Static
PFS with rate guarantee	Dynamic

Network Slicing can be configured in NetSim using the Slice Configurator GUI or via a CSV input file. When the configuration is done via the GUI, a CSV file will be automatically generated. Network Slicing is global to all the gNBs in a 5G network and hence if enabled and configured in a gNB, will be applicable to all the gNBs.

3.20.2.1 Slice Configurator GUI

The slice configurator allows users to select the Number of slices initially, and based on the Resource Sharing Technique selected, the slice table gets populated automatically, where users can configure the properties and map UEs to different slices.

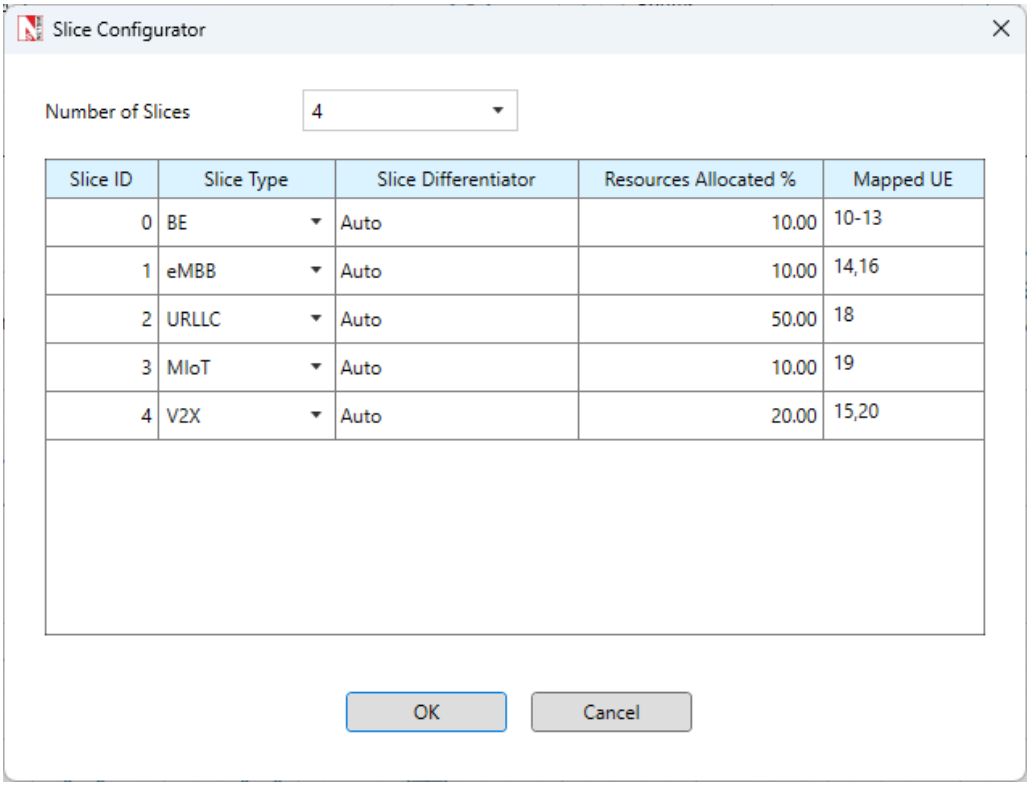


Figure 3-60: *Static Network Slicing Configurator GUI.*

Static Slice Configurator:

- Slice ID 0 is the default slice with Slice Type BE.
- For all rows, the parameters, Slice ID and Slice Differentiator are non-editable.
- Slice Type can be modified and set to one of the following values:

- BE
- eMBB
- URLLC
- MIoT
- V2X
- The resource allocation column should be configured such that the sum of resource allocation percentage is exactly equal to 100.

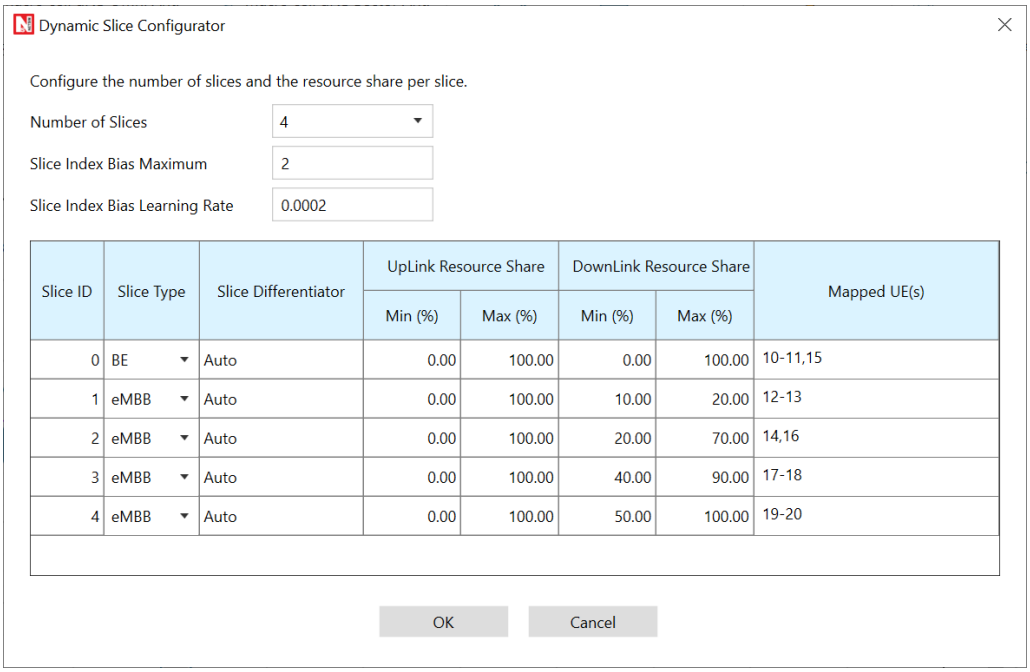


Figure 3-61: *Dynamic Network Slicing Configurator GUI.*

Dynamic Slice Configurator:

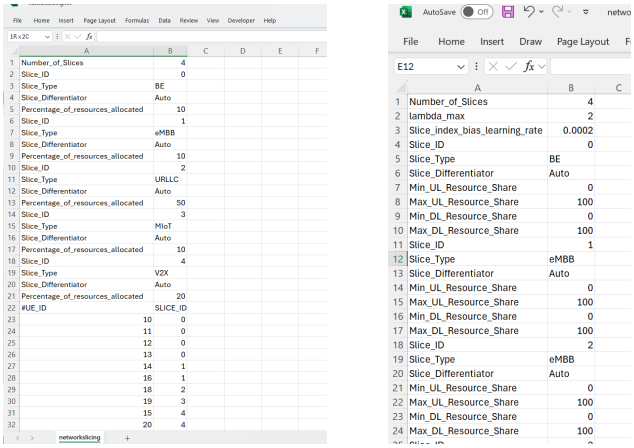
- Slice ID 0 is the default slice with Slice Type BE. All the other slices are eMBB.
- For all rows, the parameters, Slice ID and Slice Differentiator are non-editable.
- Min and Max percentage of resource share can be specified individually for DL and UL in Mbps, for each slice.

Slice – UE Mapping:

- Mapped UE column accepts UE IDs as input which can be:
  - Comma separated (‘,‘)
  - Range: specified by starting ID and ending ID separated by ‘-‘. For e.g.: 10-20 includes all UEs starting from ID 10 to 20.
  - This column can also be left blank without any UE assigned.

Network Slicing CSV input file:

- Based on the configuration done in the slicing configurator GUI, a networkslicing.csv file is automatically generated as shown below:



	A	B
1	Number_of_Slices	4
2	Slice_ID	0
3	Slice_Type	BE
4	Slice_Differentiator	Auto
5	Percentage_of_resources_allocated	10
6	Slice_ID	1
7	Slice_Type	eMBB
8	Slice_Differentiator	Auto
9	Percentage_of_resources_allocated	10
10	Slice_ID	2
11	Slice_Type	URLLC
12	Slice_Differentiator	Auto
13	Percentage_of_resources_allocated	50
14	Slice_ID	3
15	Slice_Type	MIoT
16	Slice_Differentiator	Auto
17	Percentage_of_resources_allocated	10
18	Slice_ID	4
19	Slice_Type	V2X
20	Slice_Differentiator	Auto
21	Percentage_of_resources_allocated	20
22	#UE_ID	SLICE_ID
23	10	0
24	11	0
25	12	0
26	13	0
27	14	1
28	16	1
29	18	2
30	19	3
31	15	4
32	20	4

	A	B	C
1	Number_of_Slices	4	
2	lambda_max	2	
3	Slice_index_bias_learning_rate	0.0002	
4	Slice_ID	0	
5	Slice_Type	BE	
6	Slice_Differentiator	Auto	
7	Min_UL_Resource_Share	0	
8	Max_UL_Resource_Share	100	
9	Min_DL_Resource_Share	0	
10	Max_DL_Resource_Share	100	
11	Slice_ID	1	
12	Slice_Type	eMBB	
13	Slice_Differentiator	Auto	
14	Min_UL_Resource_Share	0	
15	Max_UL_Resource_Share	100	
16	Min_DL_Resource_Share	0	
17	Max_DL_Resource_Share	100	
18	Slice_ID	2	
19	Slice_Type	eMBB	
20	Slice_Differentiator	Auto	
21	Min_UL_Resource_Share	0	
22	Max_UL_Resource_Share	100	
23	Min_DL_Resource_Share	0	
24	Max_DL_Resource_Share	100	

Figure 3-62: *Left: Network Slicing CSV log showing the Static slice configuration. Right: Network Slicing CSV log showing the Dynamic slice configuration.*

- The UE to Slice ID mapping is written individually for each UE in the CSV file which is read and used for simulations.

The GUI configuration is stored in an external CSV file and the same file can also be edited outside NetSim. In the gNB properties, this file is selected using *Configure Network Slicing* under *5G_RAN > Datalink Layer*. For Round Robin, Max Throughput, and Proportional Fair scheduling, the configurator uses the static template `networkslicing.csv`. For PFS with rate guarantee, the configurator exposes static and dynamic slicing, and the dynamic template is `Dynamicnetworkslicing.csv`.

At run time, the LTE-NR slicing module loads the CSV from the simulation `IOPath` under `ConfigSupport`. The installed parser in `LTENR_NetworkSlicing.c` reads the slice count, per-slice parameters, and UE-to-slice mapping from this file.

Static slicing uses the following keys:

- `Number_of_Slices`
- `Slice_ID`
- `Slice_Type`
- `Slice_Differentiator`
- `Percentage_of_resources_allocated`
- `#UE_ID,SLICE_ID`, followed by one mapping row for each UE

A static file created from the template has the following form:

```
Number_of_Slices,2
Slice_ID,0
```

```
Slice_Type,BE
Slice_Differentiator,Auto
Percentage_of_resources_allocated,55
Slice_ID,1
Slice_Type,eMBB
Slice_Differentiator,Auto
Percentage_of_resources_allocated,45
#UE_ID,SLICE_ID
10,0
11,1
```

Dynamic slicing adds the learning and UL/DL share parameters listed below:

- `lambda_max`
- `Slice_index_bias_learning_rate`
- `Min_UL_Resource_Share`
- `Max_UL_Resource_Share`
- `Min_DL_Resource_Share`
- `Max_DL_Resource_Share`

If a UE ID in the CSV does not exist in the scenario, NetSim reports the invalid device ID during configuration loading.

3.20.3 Recording Slice-Based Resource Allocation

The LTENR Resource Allocation log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR Resource Allocation log as shown below. Refer to section 3.23 for further information.

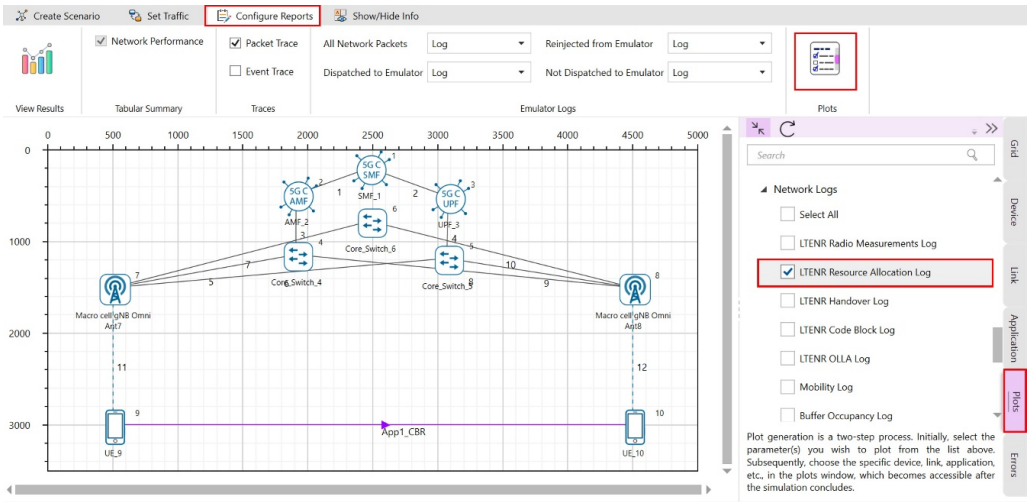
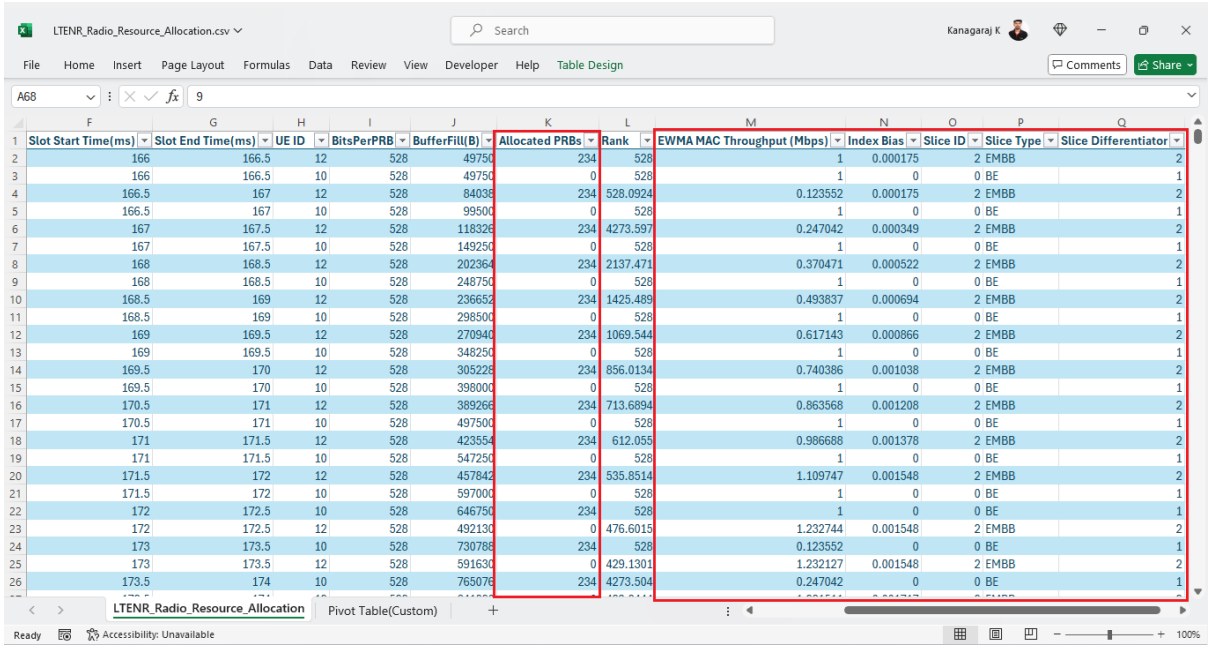


Figure 3-63: *Enabling LTENR Resource Allocation log.*

When network slicing is enabled, the log will include additional columns such as the Slice ID, Slice Type and Slice Differentiator.



LTENR_Radio_Resource_Allocation.csv

Slot Start Time(ms)	Slot End Time(ms)	UE ID	BitsPerPRB	BufferFill(B)	Allocated PRBs	Rank	EWMA MAC Throughput (Mbps)	Index Bias	Slice ID	Slice Type	Slice Differentiator
166	166.5	12	528	49750	234	528	1	0.000175	2	EMBB	2
166	166.5	10	528	49750	0	528	1	0	0	BE	1
166.5	167	12	528	84038	234	528.0924	0.123552	0.000175	2	EMBB	2
166.5	167	10	528	99500	0	528	1	0	0	BE	1
167	167.5	12	528	118326	234	4273.597	0.247042	0.000349	2	EMBB	2
167	167.5	10	528	149250	0	528	1	0	0	BE	1
168	168.5	12	528	202364	234	2137.471	0.370471	0.000522	2	EMBB	2
168	168.5	10	528	248750	0	528	1	0	0	BE	1
168.5	169	12	528	236652	234	1425.489	0.493837	0.000694	2	EMBB	2
168.5	169	10	528	298500	0	528	1	0	0	BE	1
169	169.5	12	528	270940	234	1069.544	0.617143	0.000866	2	EMBB	2
169	169.5	10	528	348250	0	528	1	0	0	BE	1
169.5	170	12	528	305228	234	856.0134	0.740386	0.001038	2	EMBB	2
169.5	170	10	528	398000	0	528	1	0	0	BE	1
170.5	171	12	528	389266	234	713.6894	0.863568	0.001208	2	EMBB	2
170.5	171	10	528	497500	0	528	1	0	0	BE	1
171	171.5	12	528	423554	234	612.055	0.986688	0.001378	2	EMBB	2
171	171.5	10	528	547250	0	528	1	0	0	BE	1
171.5	172	12	528	457842	234	535.8514	1.109747	0.001548	2	EMBB	2
171.5	172	10	528	597000	0	528	1	0	0	BE	1
172	172.5	10	528	646750	234	528	1	0	0	BE	1
172	172.5	12	528	492130	0	476.6015	1.232744	0.001548	2	EMBB	2
173	173.5	10	528	730788	234	528	0.123552	0	0	BE	1
173	173.5	12	528	591630	0	429.1301	1.232127	0.001548	2	EMBB	2
173.5	174	10	528	765076	234	4273.504	0.247042	0	0	BE	1

Figure 3-64: *LTE NR Radio Resource Allocation log with entries associated with Network Slicing.*

This log can be used to identify the resource allocation on a per slice basis based on the network configuration. Based on the resource allocation percentage of a slice, a fraction of PRBs will be available to be allocated to the UEs belonging to that slice. The PRBs allocated to the UEs can be found in the Allocated PRBs column.

Consider the following network with 1 gNB and 2 UEs downloading data from a server.

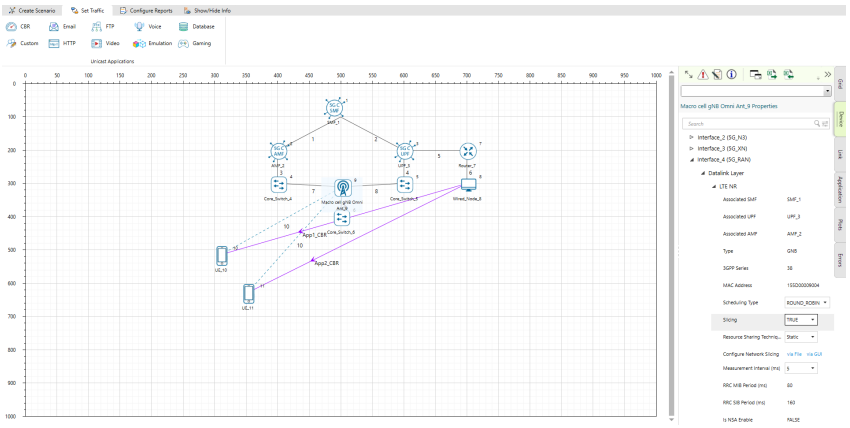


Figure 3-65: *5G network configuration with a gNB and 2 UEs performing download from a server.*

Network Slicing is enabled and configured such that UE 10 gets 55% of the resources and UE 11 gets 45% of the resources as shown below:

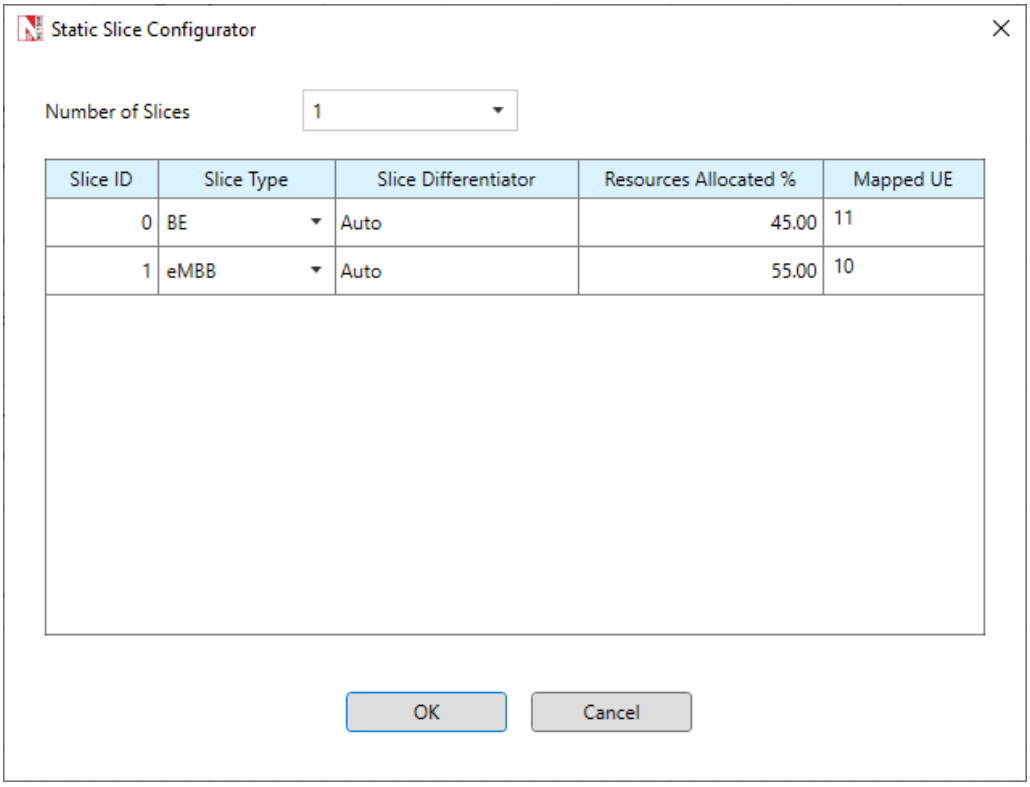


Figure 3-66: *Slice Configurator showing BE and eMBB slices configured with 45% and 55% of resources.*

For example, in the Pivot table (Custom) sheet, by adding Slice Type to Rows and Allocated PRBs to Values, and setting the Allocated PRBs property to show value as % of grand total, we can obtain the percentage of resources allocated on a per slice type basis as shown below:

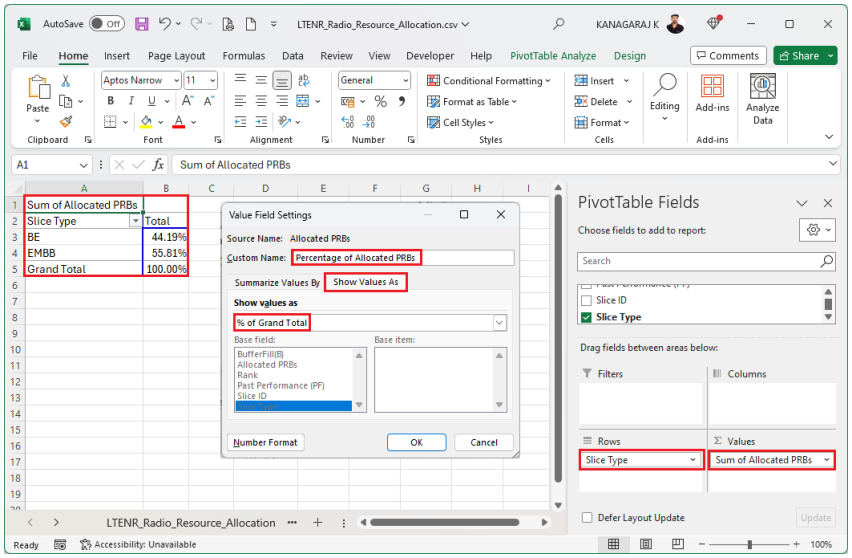


Figure 3-67: *Pivot table showing the percentage of resources allocated to each Slice Type.*

The pivot table shows the resource allocation to slice types as per the configuration done in the slice configurator.

3.20.4 Plotting Slicing Parameters

NetSim allows users to generate time series plots for EWMA MAC throughput and the Dynamic slicing Index Bias parameters. These plots can be enabled prior to running the simulation.

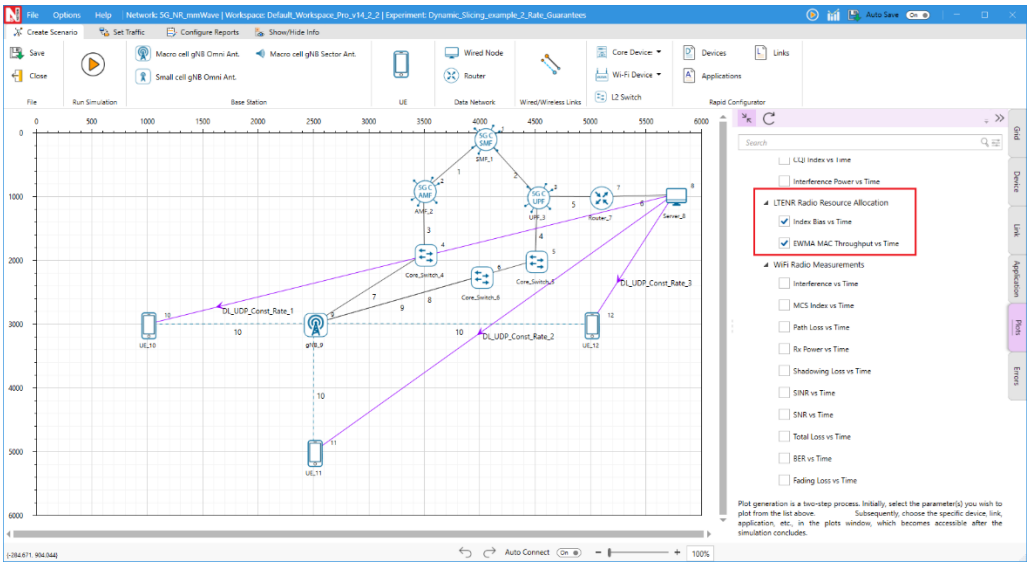


Figure 3-68: *Enabling Index Bias and EWMA MAC throughput plots.*

After the Simulation the plots can be accessed from the results dashboard under the plots section.

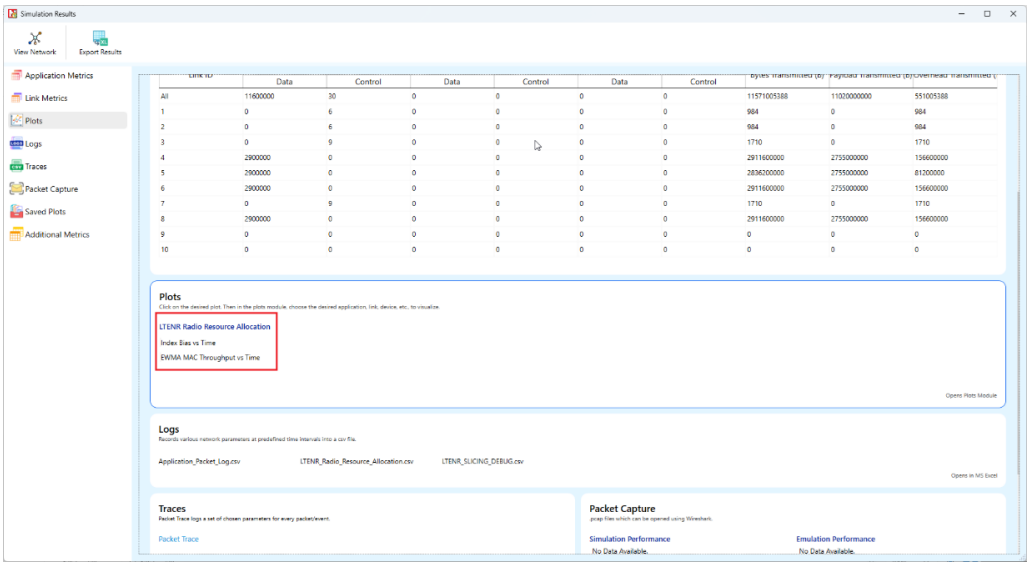


Figure 3-69: *Accessing Index Bias and EWMA MAC throughput plots from results dashboard.*

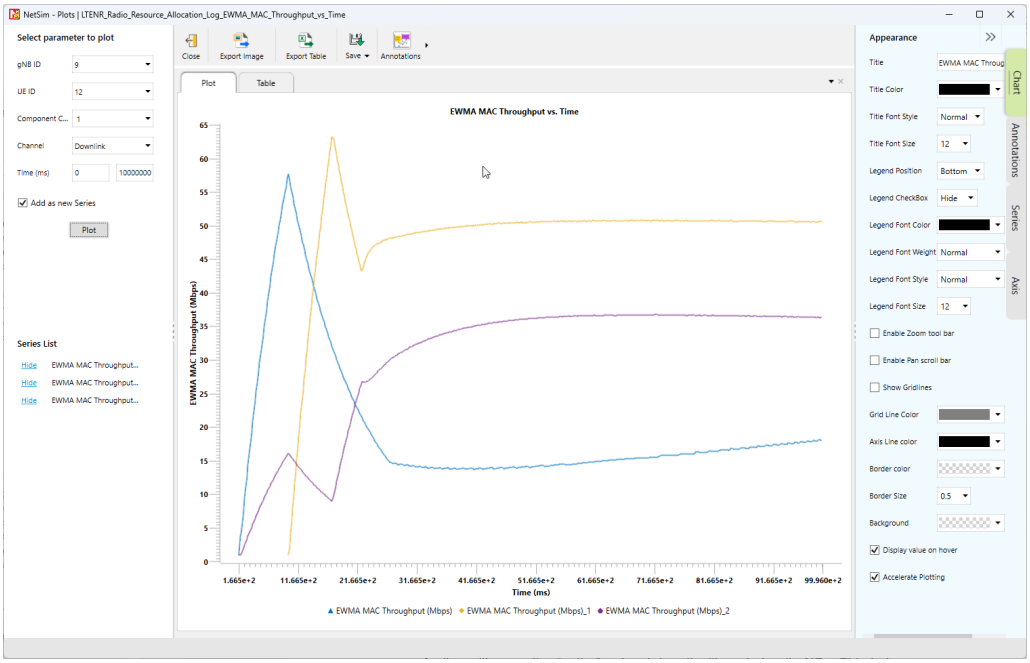


Figure 3-70: *EWMA MAC Throughput vs Time.*

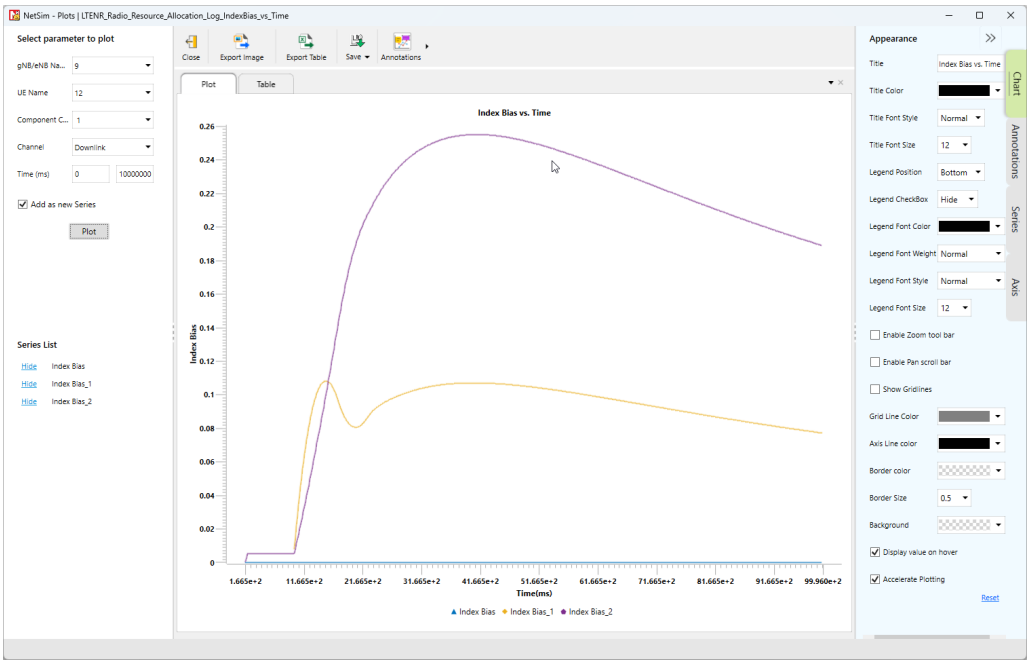


Figure 3-71: *Index Bias vs Time.*

Detailed information about Network Slicing is provided in the link below:

https://support.tetcos.com/en/support/solutions/articles/14000159642-network-slicing-in-5g

3.20.5 Limitations

- Core slicing and transport slicing are not supported.
- A slice will cover the "entire" network i.e., it will apply to all gNBs. This is known as

horizontal slicing. "Vertical slicing" by which only a certain subset of gNBs (also called area) implement network slicing is not supported.

- Assumptions in the working of 5G Core:
- Any UE can connect to any slice. No frequency restriction.
- Currently, there is no RAN-core signaling; hence NSSF, PCF functions are not part of the 5G core.
- Single SMF, AMF and UPF. Multiple SMFs and UPFs will be made available when implementing core slicing.
- NetSim's focus is network performance; hence NSI, NSMF, NSSMF, CSMF are abstracted.
- NetSim assumes that the control packet flow between the UE, AMF and NSSF for slice selection is instantaneous and successful.
- All traffic from the UE uses the same slice type.
- Users must take care to map the UE to the right slice type. For example: if a voice application is set at some UE, then that UE must be mapped to a URLLC slice.
- Slicing is supported only in 5G SA mode.

3.21 LTENR Results, Packet Trace and Plots

Table 3-12: *LTENR results Packet trace parameter descriptions.*

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 Destination 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

3.21.1 LTE NR Log

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 3-72: *LTE NR Packet Trace. Depending on Excel settings in some cases the entire header may not be displayed. Users can do Ctrl + A (Select All) → Right Click → Format Cells → Alignment → Wrap Text to view the complete header.*

3.21.2 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 is 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 3-13: *RLC header fields.*

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

- SN: The SN field indicates the sequence number of the corresponding RLC SDU. For RLC AM, the sequence number is incremented by one for every RLC SDU. For RLC UM, the sequence number is incremented by one for every segmented RLC SDU. RLC service data units (SDUs) coming from the upper layer are segmented or concatenated to RLC protocol data units (PDUs) which have 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.

3.21.3 LTENR Event Trace

3.21.3.1 Sub Event Types

- **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 10 ms, the event gets triggered every 10 ms.
  - `(LTENR->LTENR Phy.c-> LTENR addStartFrameEvent())`
- **LTENR Start Subframe**
  - Each frame consists of 10 subframes.
  - Event gets triggered every 1 ms.
  - `(LTENR->LTENR Phy.c-> LTENR addStartSubFrameEvent())`
- **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())`
- **LTENR Generate RRC MIB**
  - The timer event triggered every 80 ms to generate and broadcast MIB packets from gNBs to all UEs.
  - `(LTE-NR->LTENR GNBRRC.c->fn_NetSim_LTENR_GNBRRC_GenerateMIB())`
- **LTENR Generate RRC SIB1**
  - The timer event triggered every 160 ms to generate and broadcast SIB1 packets from gNB to all UEs.
  - `(LTE-NR-> LTENR GNBRRC.c-> fn_NetSim_LTENR_GNBRRC_GenerateSIB1())`
- **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 160.9 ms, during the initial attachment process.
  - `(LTE-NR->LTENR GNBRRC.c->fn_NETSIM_LTENR_SUBEVENT_GENERATE_SI())`

- **LTENR Generate RRC Setup Request**
  - Triggered when RRC setup request gets transmitted by UE to connected gNB.
- **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))`
- **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())`
- **LTENR Generate RRC Setup Complete**
  - Timer event triggered during the successful establishment of RRC connection.
- **LTENR Generate RRC UE Measurement Report Request**
  - Timer event triggered every 120 ms, when the gNB sends a measurement report request to UE.
- **LTENR Generate RRC UE Measurement Report**
  - Timer event triggered when UE sends measurement report to the serving gNB which contains SINR information from all the gNBs.
  - Triggered at 240 ms after RRC connection establishment and then triggered every 120 ms.
- **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 DISCARDTIMER())`
- **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 3 dB.
- **Handover Request Ack**
  - Timer event triggered when the target gNB receives a handover request from the serving gNB and sends back an acknowledgement for the handover request.
- **Handover Request Command**

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

- **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())`

- **Path Switch**
  - Triggered when the target gNB sends the path switch packet to the EPC in order to transfer the data path from serving gNB to target gNB.

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

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

- **UE Context Release Ack**
  - Triggered when acknowledgement is provided by serving gNB to the target gNB on receipt of context release packet.

3.22 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 Measurements log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR Radio Measurements log under Network Logs as shown below.

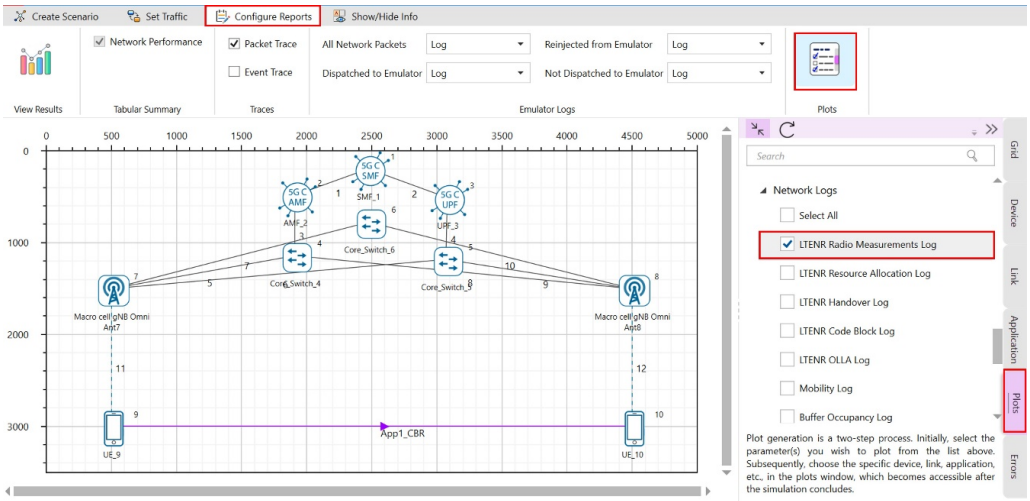


Figure 3-73: *Enabling LTENR Radio Measurement log.*

The LTENR Radio Measurement Log.csv file will contain the following information:

- Time in Milliseconds
- 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.

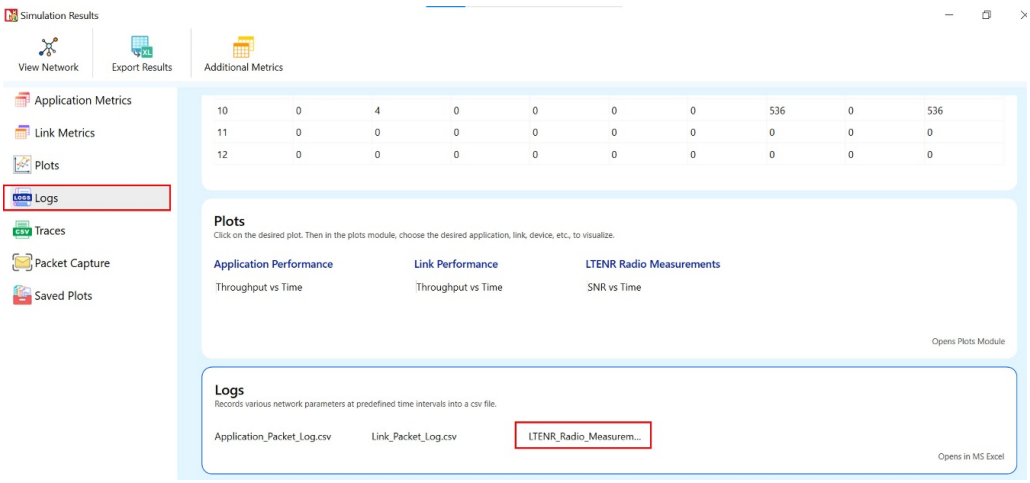
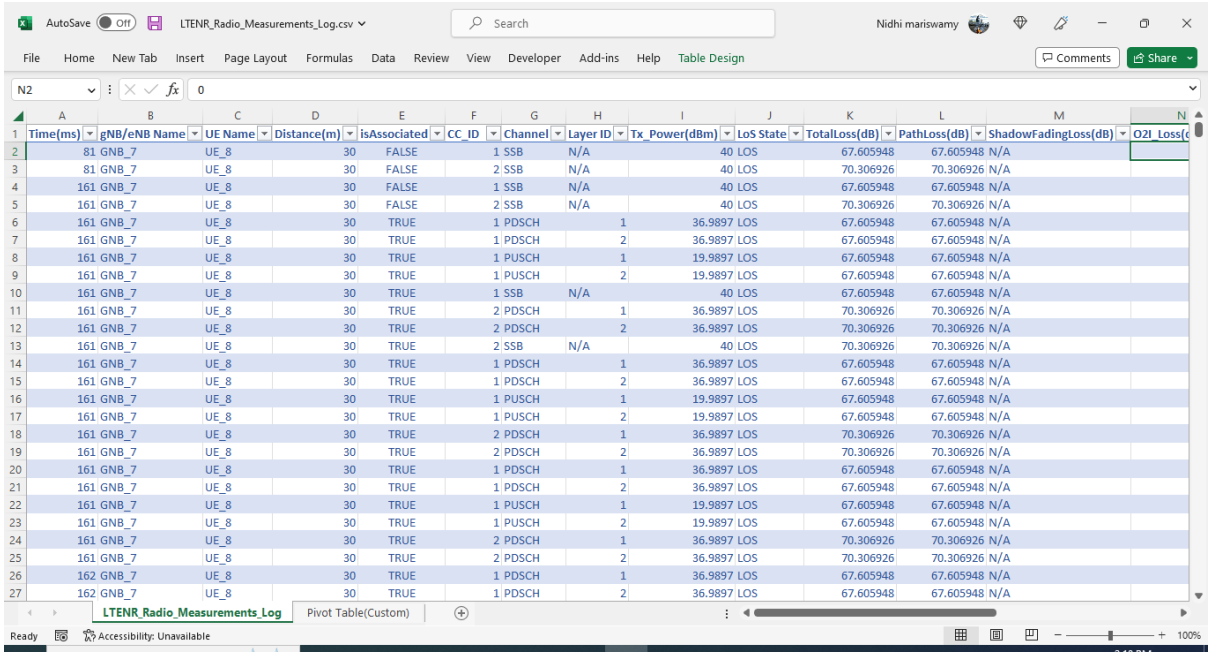


Figure 3-74: *LTENR Radio Measurement Log file highlighted in the Results window.*



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(c
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 3-75: *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.
- 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.

- 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.

3.23 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 Resource Allocation log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR Resource Allocation as shown below.

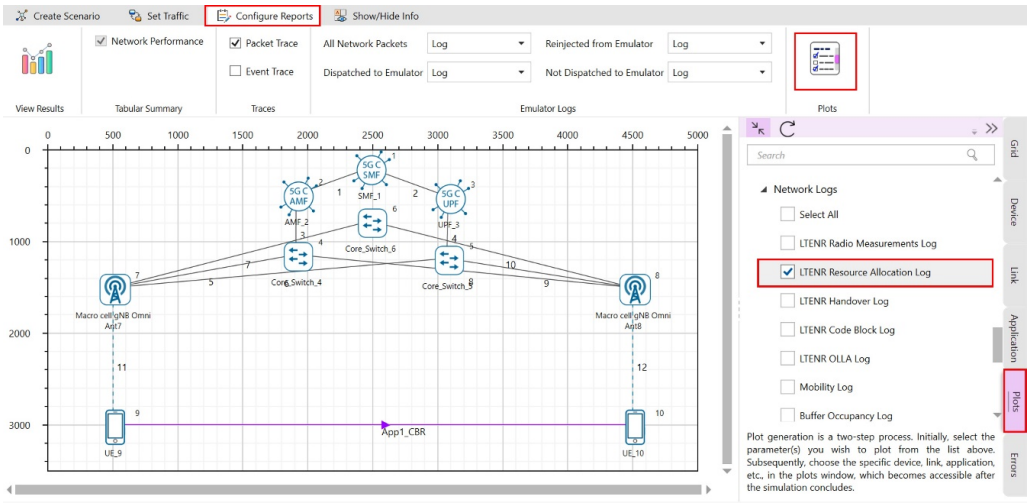


Figure 3-76: *Enabling LTENR Resource Allocation log.*

The LTE Radio Resource Allocation.csv file will contain the following information:

- gNB ID
- Component Carrier ID
- Slot ID
- Slot
- Total PRBs
- Slot Start Time(ms)
- Slot End Time(ms)
- UE ID
- BitsPerPRB

- BufferFill(B)
- Rank
- Allocated PRBs

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

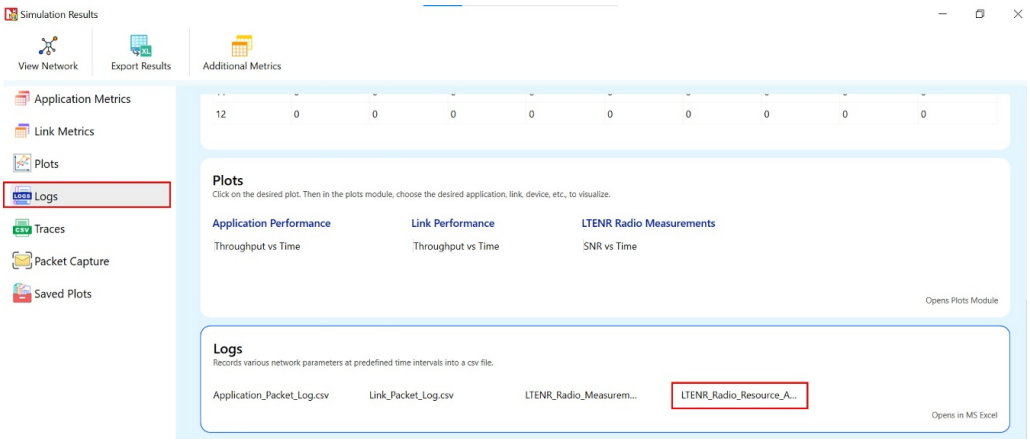


Figure 3-77: *LTENR_Radio Resource Allocation Log file highlighted in the Results window.*

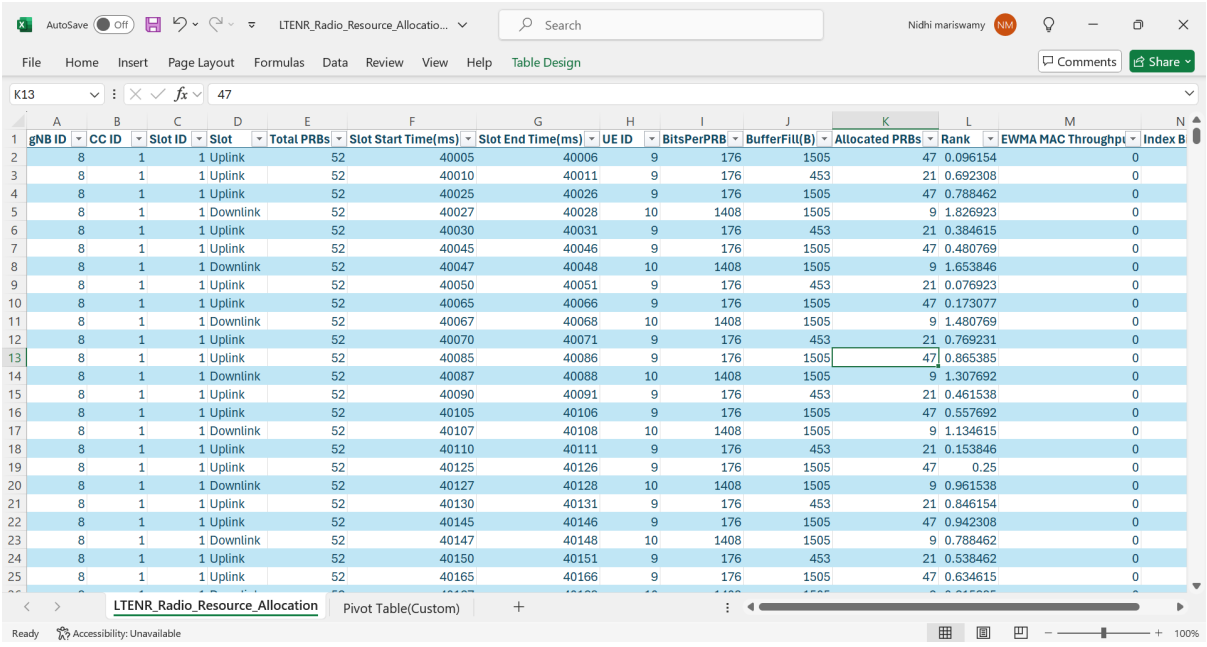


Figure 3-78: *LTENR Radio Resource Allocation Log.csv file.*

Implementation details and assumptions:

- In the case of scheduling algorithms such as Max Throughput when all PRBs 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.

3.24 Handover Log File

NetSim Handover Log records the events that occur during a handover. This contains the timestamp, UE ID, serving cell ID, target cell ID, Serving SSB SNR(dB), Target SSB SNR(dB) and Remarks (time at which the handover initiation and handover offset 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 log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR Handover log under Network Logs as shown below.

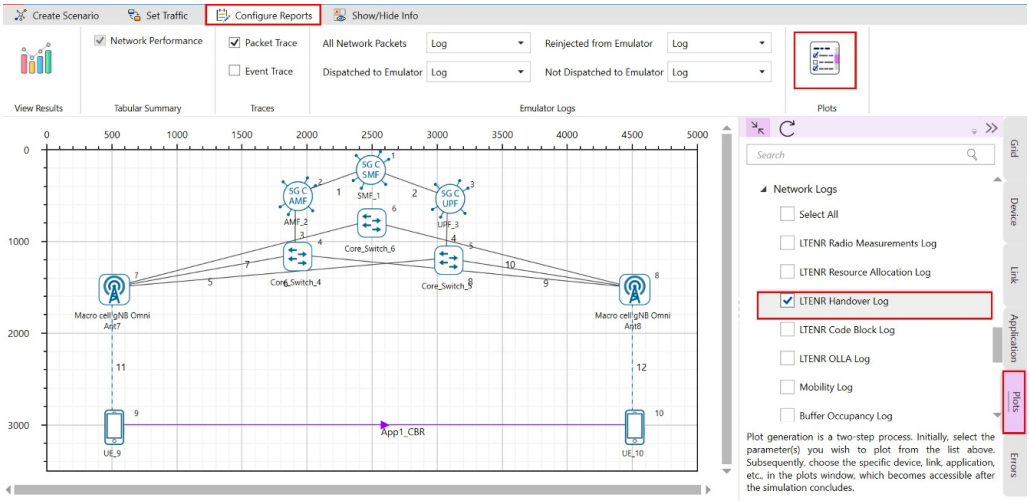


Figure 3-79: *Enabling LTENR Handover Log.*

The LTE Handover Log.csv file will contain the following information:

- Time in microseconds
- UE ID
- Serving cell
- Target cell
- Serving SSB SNR (dB)
- Target SSB SNR (dB)
- Remarks
- The log file can be accessed from the Simulations Results Window under the log file drop down in the left pane.

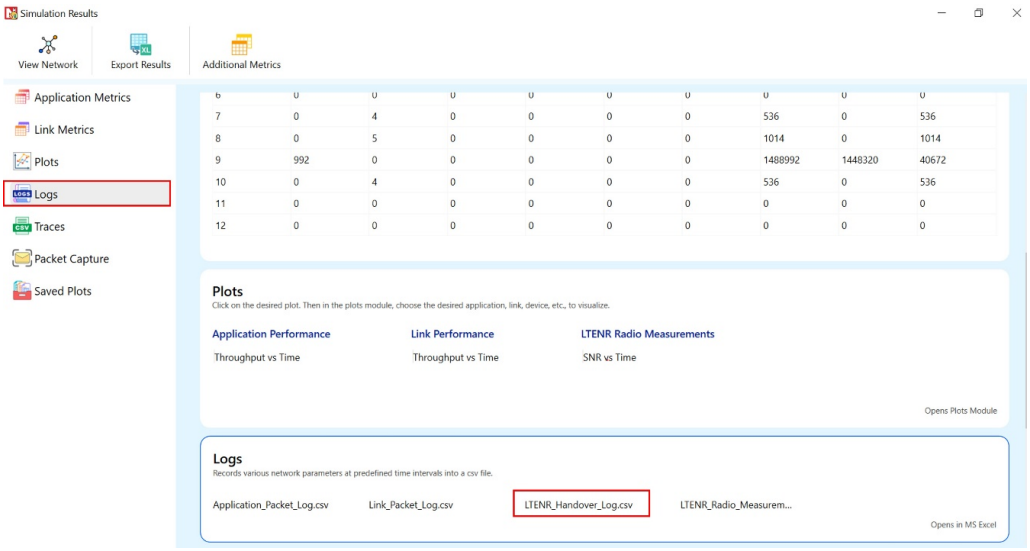
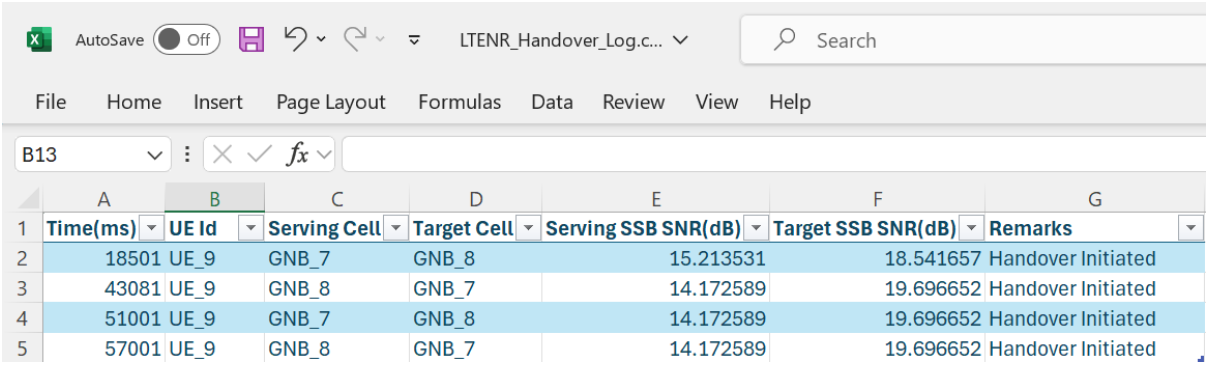


Figure 3-80: *LTENR_Handover_Log.csv file highlighted in the Results window.*



	A	B	C	D	E	F	G
1	Time(ms)	UE Id	Serving Cell	Target Cell	Serving SSB SNR(dB)	Target SSB SNR(dB)	Remarks
2	18501	UE_9	GNB_7	GNB_8	15.213531	18.541657	Handover Initiated
3	43081	UE_9	GNB_8	GNB_7	14.172589	19.696652	Handover Initiated
4	51001	UE_9	GNB_7	GNB_8	14.172589	19.696652	Handover Initiated
5	57001	UE_9	GNB_8	GNB_7	14.172589	19.696652	Handover Initiated

Figure 3-81: *LTENR Handover Log.csv file.*

3.25 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 configure reports in top ribbon > Plots > Select Code Block log under Network Logs as shown below.

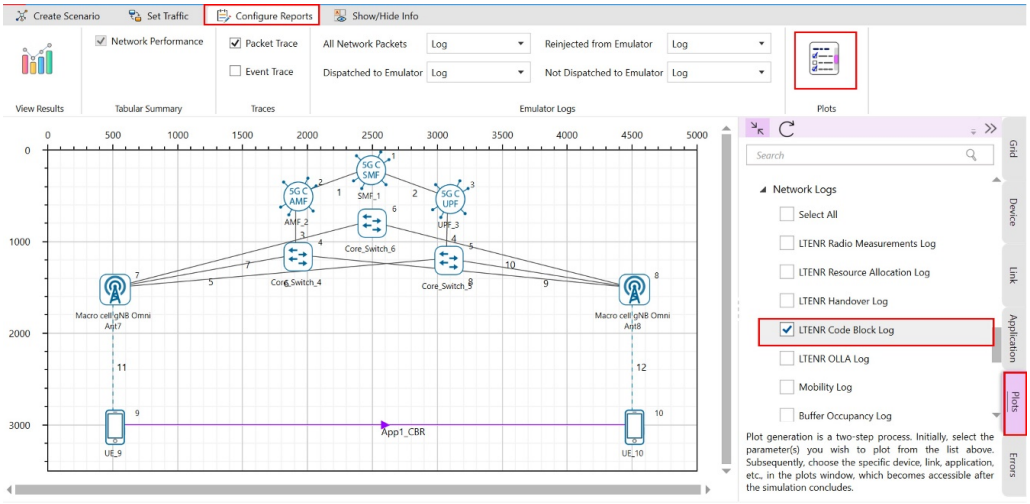


Figure 3-82: *Enabling LTENR Code Block Log.*

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

- 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.

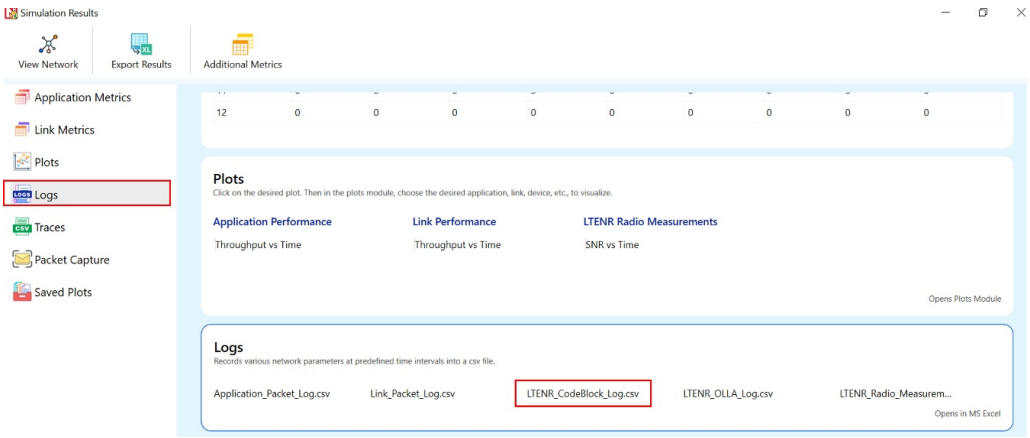


Figure 3-83: *LTENR_CodeBlock_Log.csv file highlighted in the Results window.*

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 3-84: *LTENR_CodeBlock_Log.csv file.*

3.26 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 OLLA log can be enabled by clicking on configure reports in top ribbon > Plots > Select OLLA log under Network Logs as shown below.

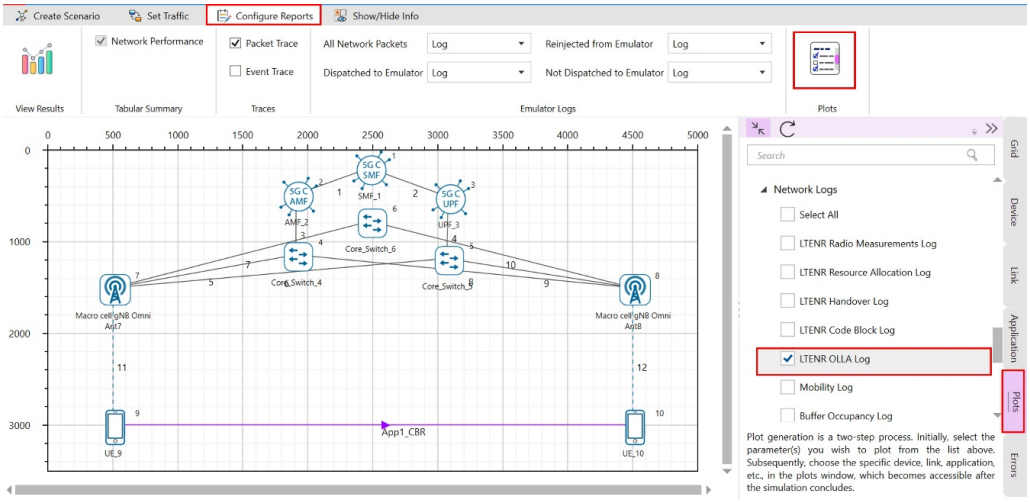


Figure 3-85: *Enabling LTENR OLLA Log.*

The LTENR OLLA Log.csv file will contain the following information:

- Time in ms
- eNB/gNB Name
- 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.

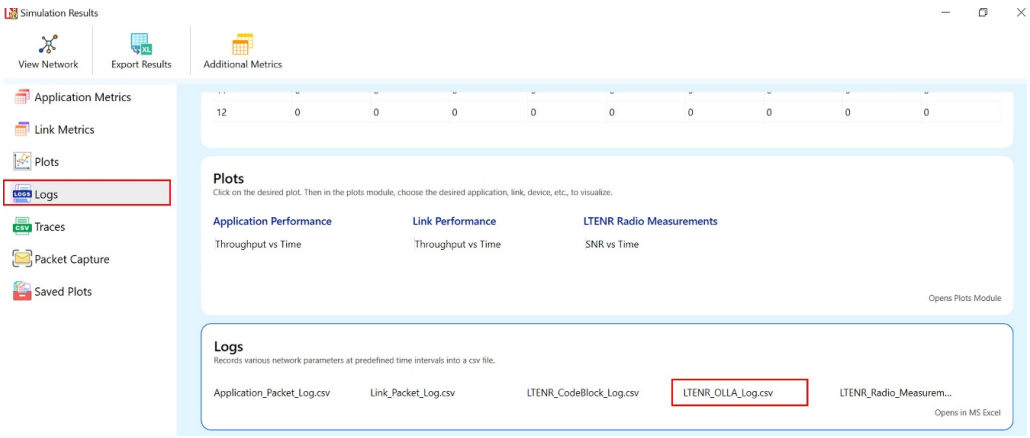


Figure 3-86: *LTENR OLLA Log.csv file highlighted in the Results window.*

Time(ms)	eNB/gNB Name	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
80.5	MACRO CELL ENB C	UE_5	1	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	1	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	1	1	9	1	1	PUSCH	123.817656	0	123.817656	15	15
80.5	MACRO CELL ENB C	UE_5	2	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	2	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	2	1	9	1	1	PUSCH	123.817656	0	123.817656	15	15
80.5	MACRO CELL ENB C	UE_5	3	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	3	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	3	1	9	1	1	PUSCH	123.817656	0	123.817656	15	15
80.5	MACRO CELL ENB C	UE_5	4	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	4	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_5	4	1	9	1	1	PUSCH	123.817656	0	123.817656	15	15
80.5	MACRO CELL ENB C	UE_6	1	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_6	1	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_6	1	1	9	1	1	PUSCH	123.817656	0	123.817656	15	15
80.5	MACRO CELL ENB C	UE_6	2	1	9	1	1	PDSCH	137.807356	0	137.807356	15	15
80.5	MACRO CELL ENB C	UE_6	2	2	9	1	1	PDSCH	137.807356	0	137.807356	15	15

Figure 3-87: *LTENR OLLA Log.csv file.*

3.27 LTENR PRB Utilization Log File

NetSim LTENR PRB Utilization Log records the parameters associated with PRB Utilization, including the proportion of PRBs used out of the total PRBs available, along with timestamps. This log tracks changes in PRB utilization over time, providing data on network load. It can identify patterns such as usage times, congestion or periods of under-utilization, helping to understand PRB allocation mechanisms in 5G.

The LTENR PRB utilization log can be enabled by clicking on configure reports in top ribbon > Plots > Select LTENR PRB Utilization log under Network Logs as shown below.

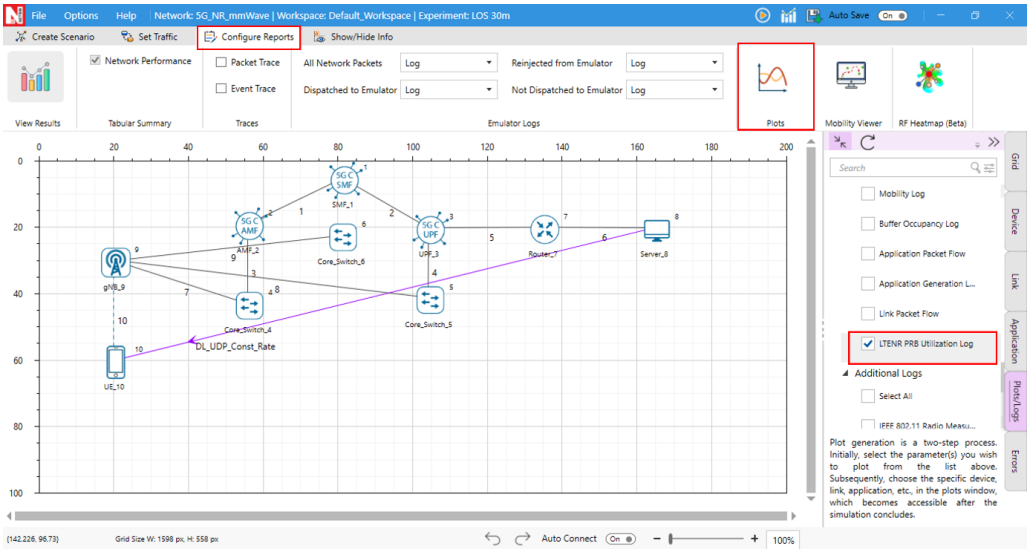


Figure 3-88: *Enabling LTENR PRB utilization log.*

The LTENR PRB utilization Log.csv file will contain the following information:

- Slot Time(ms)
- gNB ID
- Slot
- CC ID
- Slice ID
- Total PRBs
- Control PRBs
- Available PRBs
- Total Allocated PRBs
- PRB Utilization (%)
- EWMA PRB Utilization (%)

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

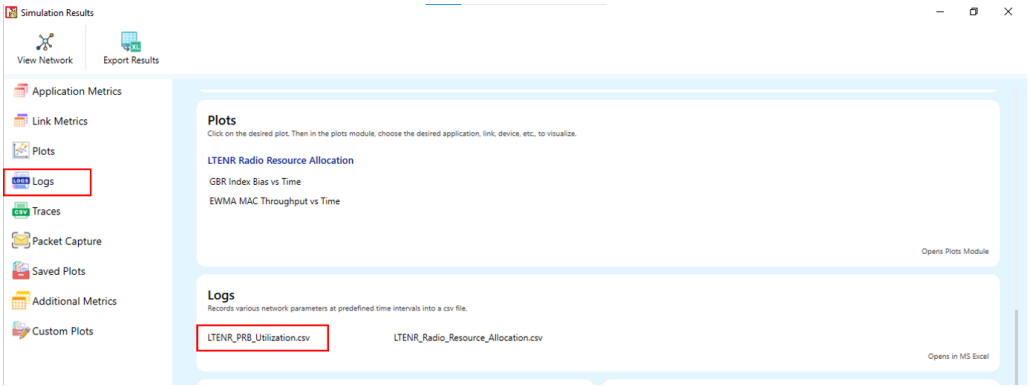
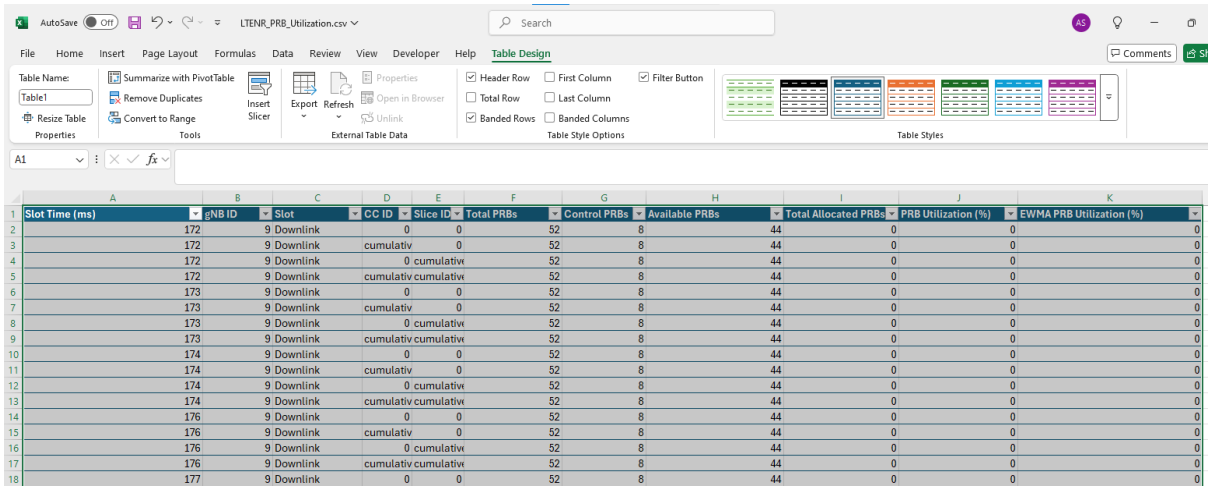


Figure 3-89: *LTENR PRB Utilization Log.csv file highlighted in the Results window.*

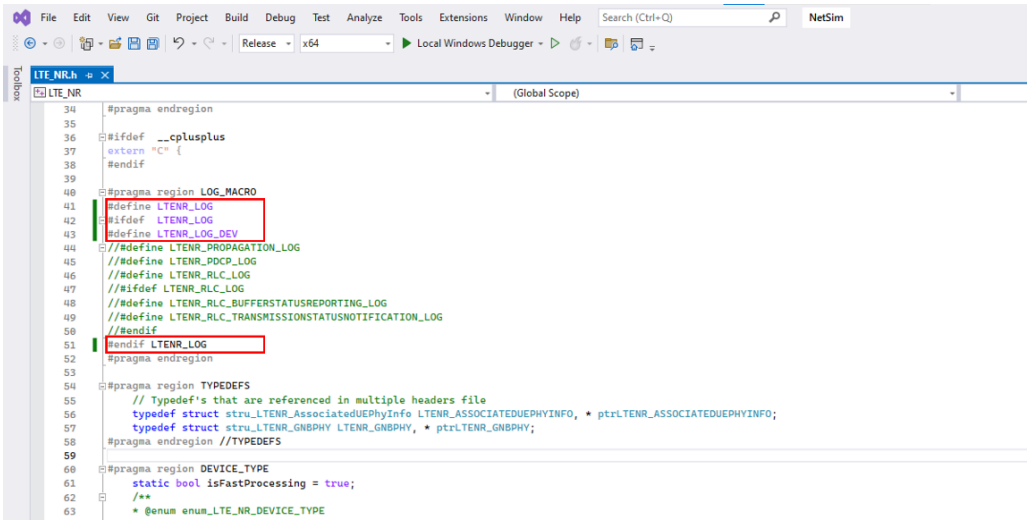


Slot Time (ms)	gNB ID	Slot	CC ID	Slice ID	Total PRBs	Control PRBs	Available PRBs	Total Allocated PRBs	PRB Utilization (%)	EWMA PRB Utilization (%)
172	9	Downlink	0	0	52	8	44	0	0	0
172	9	Downlink	cumulativ	0	52	8	44	0	0	0
172	9	Downlink	0	cumulativ	52	8	44	0	0	0
172	9	Downlink	cumulativ	cumulativ	52	8	44	0	0	0
173	9	Downlink	0	0	52	8	44	0	0	0
173	9	Downlink	cumulativ	0	52	8	44	0	0	0
173	9	Downlink	0	cumulativ	52	8	44	0	0	0
173	9	Downlink	cumulativ	cumulativ	52	8	44	0	0	0
174	9	Downlink	0	0	52	8	44	0	0	0
174	9	Downlink	cumulativ	0	52	8	44	0	0	0
174	9	Downlink	0	cumulativ	52	8	44	0	0	0
174	9	Downlink	cumulativ	cumulativ	52	8	44	0	0	0
176	9	Downlink	0	0	52	8	44	0	0	0
176	9	Downlink	cumulativ	0	52	8	44	0	0	0
176	9	Downlink	0	cumulativ	52	8	44	0	0	0
176	9	Downlink	cumulativ	cumulativ	52	8	44	0	0	0
177	9	Downlink	0	0	52	8	44	0	0	0

Figure 3-90: *LTENR PRB Utilization csv file.*

3.28 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`, `#ifdef LTENR_LOG`, `#define LTENR_LOG_DEV` and `#endif LTENR_LOG`.



```
#pragma endregion

#ifdef __cplusplus
extern "C" {
#endif

#pragma region LOG_MACRO
#define LTENR_LOG
#ifdef LTENR_LOG
#define LTENR_LOG_DEV
//#define LTENR_PROPAGATION_LOG
//#define LTENR_PDCP_LOG
//#define LTENR_RLC_LOG
//#ifdef LTENR_RLC_LOG
//#define LTENR_RLC_BUFFERSTATUSREPORTING_LOG
//#define LTENR_RLC_TRANSMISSIONSTATUSNOTIFICATION_LOG
//#endif
#endif LTENR_LOG
#pragma endregion

#pragma region TYPEDEFS
    // Typedef's that are referenced in multiple headers file
    typedef struct stru_LTENR_AssociatedUEPhyInfo LTENR_ASSOCIATEDUEPHYINFO, * ptrLTENR_ASSOCIATEDUEPHYINFO;
    typedef struct stru_LTENR_GNBPHY LTENR_GNBPHY, * ptrLTENR_GNBPHY;
#pragma endregion //TYPEDEFS

#pragma region DEVICE_TYPE
    static bool isFastProcessing = true;
    /**
    * @enum enum_LTE_NR_DEVICE_TYPE
```

Figure 3-91: *Enable LTE NR log file in visual studio.*

Then rebuild the code and run the simulation.

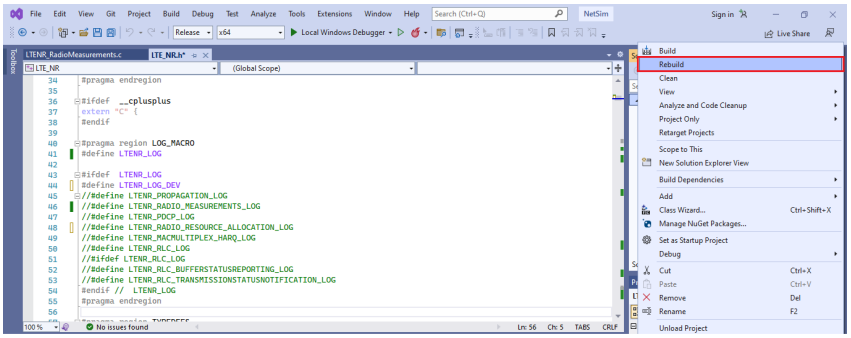


Figure 3-92: *Rebuild 5G Project.*

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

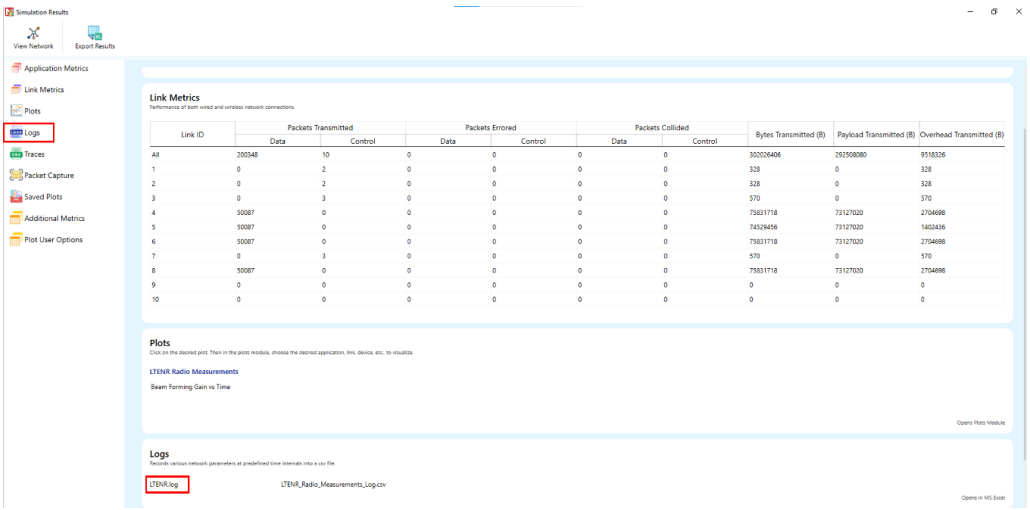


Figure 3-93: *Results Window.*

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 × [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 × [1024]: 948.000000
- Spectral efficiency: 7.406300

4 Featured Examples

4.1 Derive from 3GPP standards the theoretical data rate and throughput for a 1gNB - 2UE scenario, and compare with simulation

4.1.1 Introduction

NetSim calculates the PHY rate per the 3GPP formula, which is explained in the infographic below.

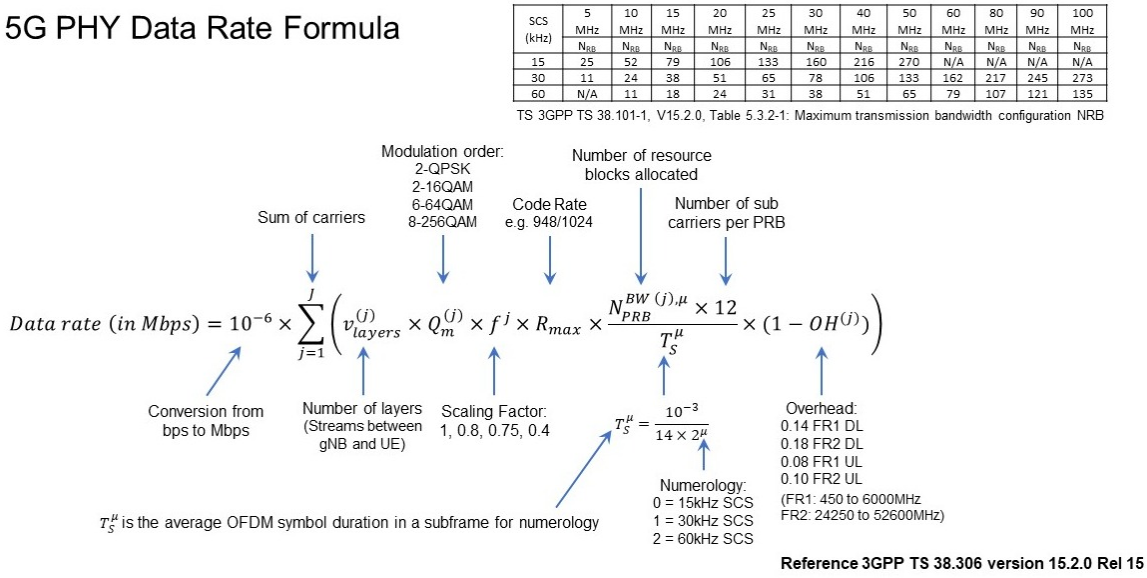


Figure 4-1: *5G PHY Rate Formula in NetSim*

A simple, approximate way to think of the above formula is

$$Data\ Rate = BW \times Q \times R \times N \times (1 - OH) \quad \ldots(1) \tag{69}$$

where Data rate is the per carrier PHY rate, BW is the allocated bandwidth to the particular UE, Q is the modulation order, R is the code rate, N is the number of MIMO layers, and OH is the Overhead. In NetSim, OH is usually taken as 2/14 since we have 2 control symbols in a slot spanning 14 symbols.

How is the formula in (1) equivalent to the 3GPP formula? Let's examine the variables.

Q, R, N, and (1-OH) are common to both

The scaling factor in NetSim is assumed as 1

The data rate in (1) per carrier and needed to be summed up for multiple carriers

What remains to be shown is that BW is the same as $N_{prb} \times 12/T_s$. In this 12 is the number of subcarriers and T_s represents the symbol duration which varies with numerology. 10^{-3} represents 1 ms, 14 is the number of OFDM symbols and 2^{μ} adjusts the slot duration based on the numerology. When we calculate $N_{prb} \times 12/T_s$, we are essentially calculating the total number of subcarriers allocated within the given symbol duration, which is nothing, but the bandwidth allocated to that device. The simplified formula we provided would yield a slightly higher estimate compared to the 3GPP formula because of the way N_{prb} is calculated in the standards.

When operating in TDD mode, the above computation would give the two-way (downlink + uplink) data rate. Therefore, the downlink data rate would be

$$DL\text{-}rate = Data\ Rate \times DL\text{-}Fraction \qquad \ldots(2) \tag{70}$$

While BW, OH, and N are based on user inputs in NetSim, Q and R are dependent on the modulation and coding scheme (MCS). The MCS i.e., Q and R, is chosen by looking up the 3GPP spectral efficiency to MCS table assuming ideal Shannon rate whereby

$$Spectral\text{-}Efficiency = \log_2(1 + SINR[linear]) \qquad \ldots(3) \tag{71}$$

The expression thus becomes

$$\frac{DL}{UL} Data\ Rate\ [Mbps] = BW\ [MHz] \times Q\ \left[\frac{bits}{symbol}\right] \times R \times N \times (1-OH) \times \left(\frac{DL}{UL} fraction\right) \qquad \ldots(4) \tag{72}$$

Bandwidth is the cycles per second which translates to the number of signal changes (or symbol transmissions) per second. Hence multiplying BW and Q gives Mbits/sec when BW is in MHz. The other terms are dimensionless.

Now, in 5G, the transmitter adapts its PHY layer MCS depending on the receiver's SINR. The SINR in turn depends on the received power, which is transmit-power less pathloss. In NetSim users can record the radio measurements to obtain the SINR and MCS (for each UE) over time if the channel is time varying.

4.1.2 Network Setup

Open NetSim, Select Examples → 5G NR → 5G data rate and throughput computation then click on the tile in the middle panel to load the example as shown in below screenshot.

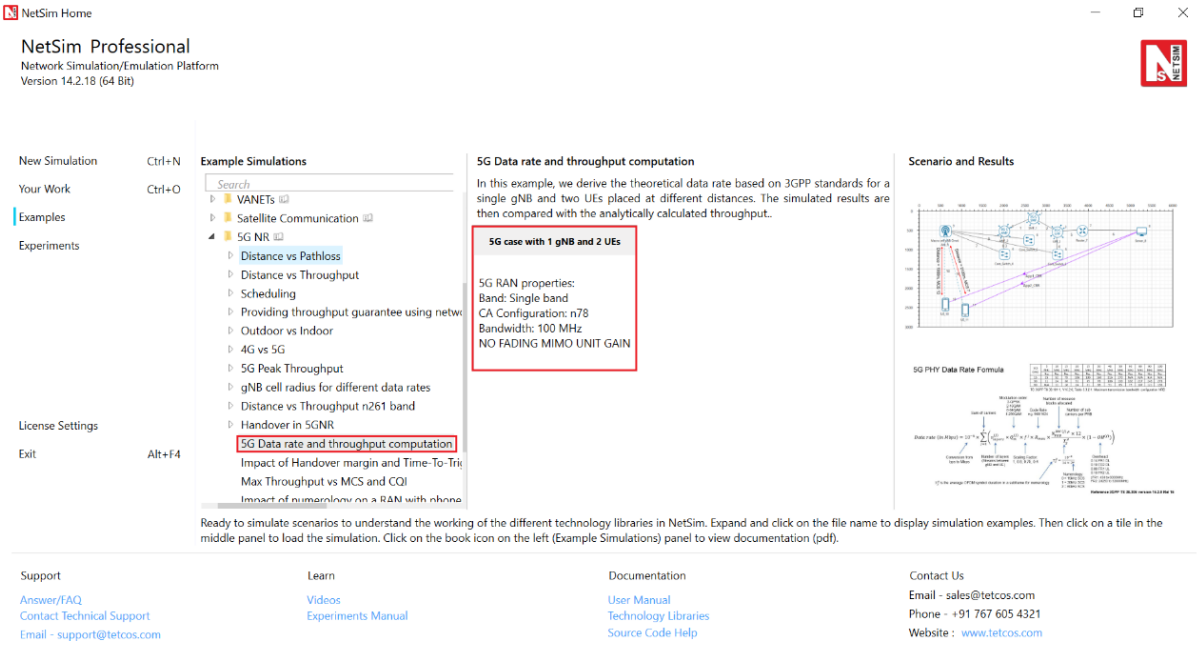


Figure 4-2: *List of 5G examples showing 5G data rate and throughput computation*

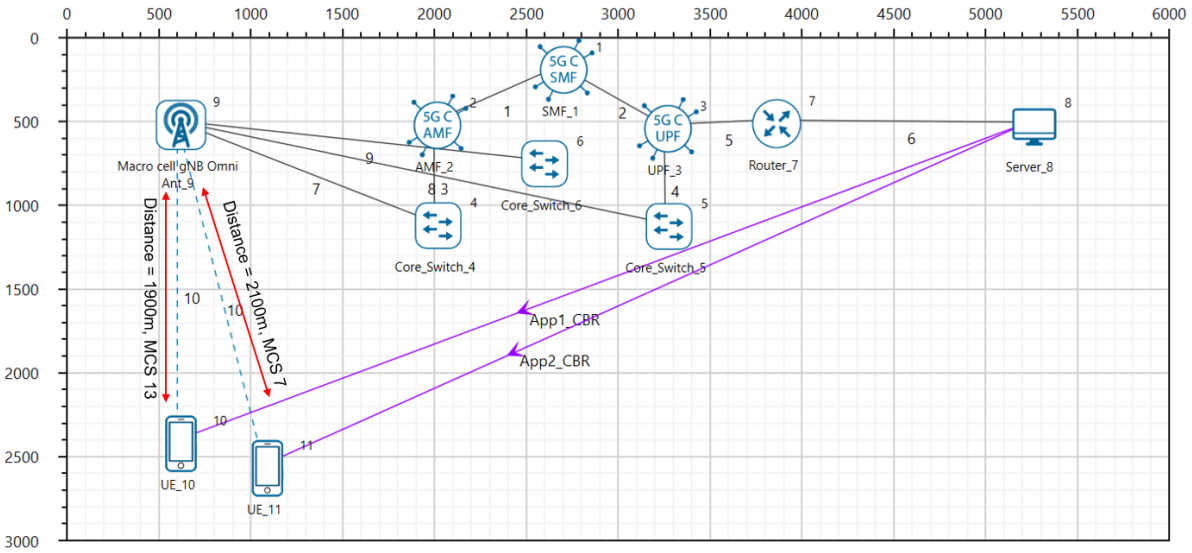


Figure 4-3: *Network setup for studying the 5G data rate and throughput computation.*

4.1.3 Network Settings

- Grid length is set to 6000m × 3000m by clicking on the grid panel on right.
- Consider a single Macro cell gNB and two UEs. The distance from the gNB to the first UE should be 1900m, and the distance to the second UE should be 2100m.
- Click on the gNB and expand property panel on right and set the properties in 5G RAN layer as mentioned in the below table.

Table 4-1: *5G RAN Datalink and Physical layer properties.*

Properties	
Datalink Layer Properties	
Scheduling type	Round Robin
Physical Layer Properties	
CA type	Single band
CA Configuration	n78
CA1	
Numerology	1
Channel Bandwidth	100 MHz
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Rural macro
LOS NLOS Selection	User defined
LOS Probability	1
Shadow Fading Model	3GPP TR 38.901-7.4.1
Fast Fading Model	No Fading

- Set Transmitter and Receiver antenna count as shown in the below table.

Table 4-2: *Tx and Rx Antenna counts for gNB and UE*

Device	Tx Antenna Count	Rx Antenna Count
gNB	2	2
UE 1	1	1
UE 2	2	2

- Create a CBR application for both UEs from the servers by clicking on the Set Traffic tab in the ribbon at the top. Keep the packet size at the default (1460 B) and change the inter-arrival time to 97.33 μs, thereby generating 120 Mbps of data for each UE.
- Enable the LTE NR Radio Measurement log by clicking on Configure reports tab and plots.

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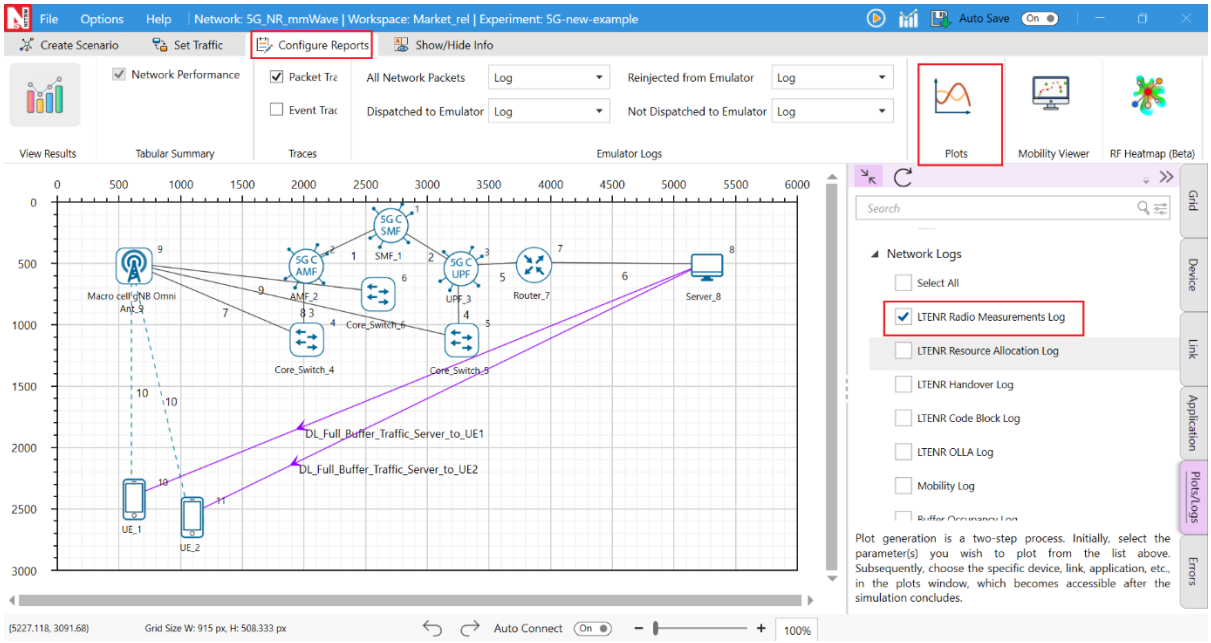


Figure 4-4: *Enabling the LTENR Radio Measurement log*

- Run the simulation for 10 seconds.

4.1.4 Results

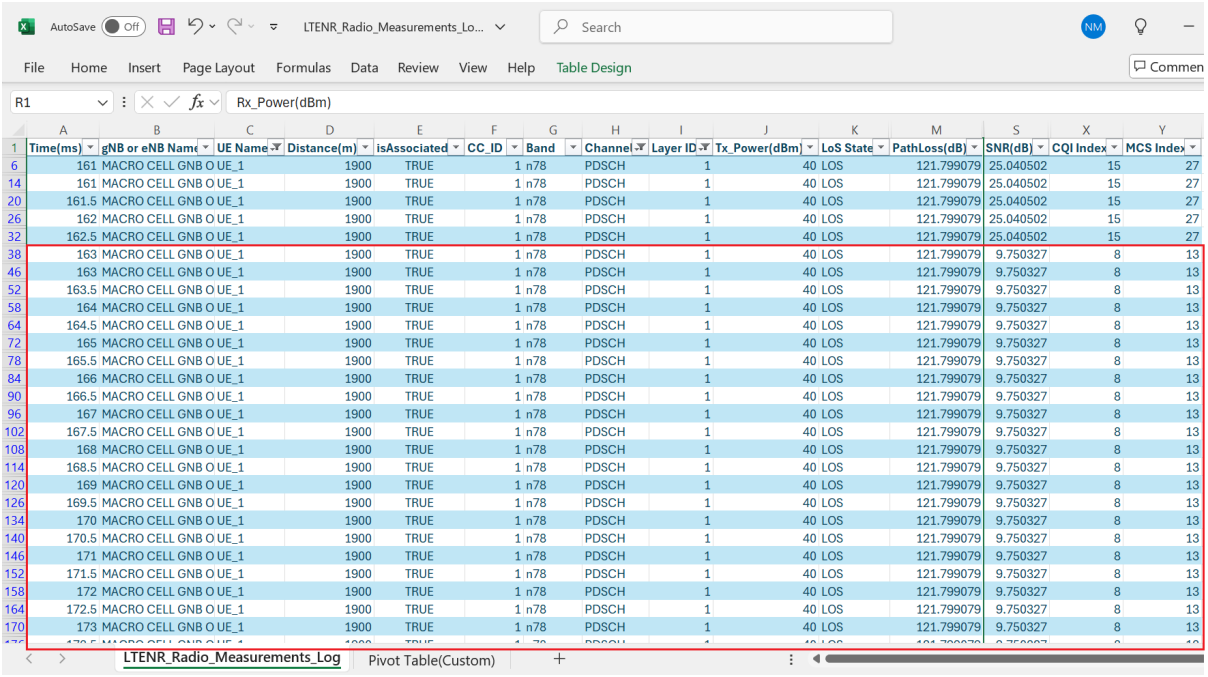
Application Metrics

End-to-end performance of applications running across the network.

App. ID	App. Name	Src. ID	Dest. ID	Gen. Rate (M	Thput. (Mbp	Delay (µs)	Jitter (µs)	Pkts. Gen.	Pkts. Recd.	Payload Gen.	Payload Recc
1	App1_CBR	8	10	120.000000	95.368368	1100836.81155	1228.837723	102744	81651	150006240	119210460
2	App2_CBR	8	11	120.000000	109.818864	498028.30558	1095.813449	102744	94023	150006240	137273580

Figure 4-5: *Application metrics showing throughput results.*

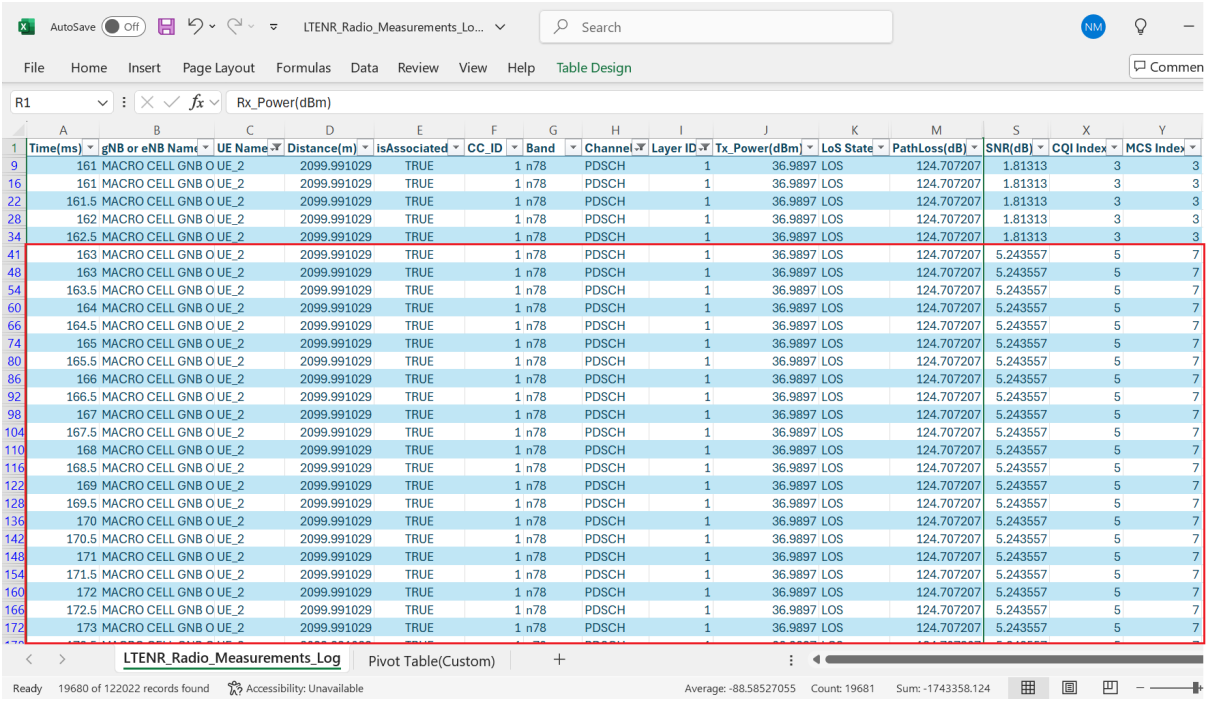
Open LTENR Radio measurement log from simulation results window and filter the channel to PDSCH, Layer ID to 1, To observe the MCS, CQI, Pathloss and SNR values for UE 1, filter the UE ID to UE 1



Time(ms)	gNB or eNB Name	UE Name	Distance(m)	isAssociated	CC_ID	Band	Channel	Layer ID	Tx_Power(dBm)	LoS State	PathLoss(dB)	SNR(dB)	CQI Index	MCS Index
161	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	25.040502	15	27
161	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	25.040502	15	27
161.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	25.040502	15	27
162	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	25.040502	15	27
162.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	25.040502	15	27
163	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
163	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
163.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
164	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
164.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
165	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
165.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
166	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
166.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
167	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
167.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
168	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
168.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
169	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
169.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
170	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
170.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
171	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
171.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
172	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
172.5	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13
173	MACRO CELL GNB O	UE_1	1900	TRUE	1	n78	PDSCH	1	40	LOS	121.799079	9.750327	8	13

Figure 4-6: *LTENR Radio Measurement log showing the MCS value for UE 1*

Filter the UE ID to UE 2, to observe the MCS, CQI, Pathloss and SNR values for UE 2 alone.



Time(ms)	gNB or eNB Name	UE Name	Distance(m)	isAssociated	CC_ID	Band	Channel	Layer ID	Tx_Power(dBm)	LoS State	PathLoss(dB)	SNR(dB)	CQI Index	MCS Index
161	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	1.81313	3	3
161	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	1.81313	3	3
161.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	1.81313	3	3
162	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	1.81313	3	3
162.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	1.81313	3	3
163	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
163	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
163.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
164	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
164.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
165	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
165.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
166	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
166.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
167	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
167.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
168	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
168.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
169	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
169.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
170	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
170.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
171	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
171.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
172	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
172.5	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7
173	MACRO CELL GNB O	UE_2	2099.991029	TRUE	1	n78	PDSCH	1	36.9897	LOS	124.707207	5.243557	5	7

Figure 4-7: *LTENR Radio Measurement log showing the MCS value for UE 2*

NOTE: The values obtained till 163 ms are during RRC association time, hence consider the values after 163 ms.

The PHY Data Rate Calculations for UE 1

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

where $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$

For UE 1,

The number of layers $v = 1$, since the Tx and Rx antenna of UE count is 1×1, Obtained MCS is 13 which means the Q_m (Modulation order) is 6, $f = 1$, $N_{PRB} = 273$, OH in downlink for FR1 is 0.14.

$$Data\ Rate\ [Mbps] = 10^{-6}\left(1 \times 6 \times 1 \times \frac{567}{1024} \times \frac{273 \times 12}{\left(\frac{10^{-3}}{14 \cdot 2^{1}}\right)} \times (1 - 0.14)\right) = 262.08 \text{ Mbps} \quad (73)$$

This is total Data Rate which includes DL and UL. The DL data rate would be

$DL\ Data\ rate = Data\ Rate\ (Mbps) \times \frac{DL}{DL+UL} = 262.08 \times \frac{4}{5} = 209.66$ Mbps

Since, we have 2 UE, with round robin resource allocation, alternate slots are allocated to each UE, therefore the PHY throughput for UE1 would be

$$PDSCH\ PHY\ Throughput\ [Mbps] = \frac{DL\ Data\ rate\ [Mbps]}{2} = \frac{209.66}{2} = 104.83 \text{ Mbps} \quad (74)$$

This is PHY layer throughput, and hence Application layer throughput would be

$$DL\ App\ throughput\ [Mbps] = PDSCH\ PHY\ Throughput \times \frac{App\ layer\ Pkt\ Size}{Phy\ layer\ Pkt\ Size} \quad (75)$$

The PHY Data Rate Calculations for UE 2

For UE 2,

The number of layers $v = 2$, since the Tx and Rx antenna of UE count is 2×2, Obtained MCS is 7 which means the Q_m (Modulation order) is 4, $f = 1$, $N_{PRB} = 273$, OH in downlink for FR1 is 0.14.

$$Data\ Rate\ [Mbps] = 10^{-6}\left(2 \times 4 \times 1 \times \frac{490}{1024} \times \frac{273 \times 12}{\left(\frac{10^{-3}}{14 \cdot 2^{1}}\right)} \times (1 - 0.14)\right) = 301.98 \text{ Mbps} \quad (76)$$

This is total Data Rate which includes DL and UL. The DL data rate would be

$DL\ Data\ rate = Data\ Rate\ (Mbps) \times \frac{DL}{DL+UL} = 301.98 \times \frac{4}{5} = 241.58$ Mbps

Since, we have 2 UE, with round robin resource allocation, alternate slots are allocated to each UE, therefore the PHY throughput for UE1 would be

$$PDSCH\ PHY\ Throughput\ [Mbps] = \frac{DL\ Data\ rate\ [Mbps]}{2} = \frac{241.58}{2} = 120.79 \text{ Mbps} \quad (77)$$

This is PHY layer throughput, and hence Application layer throughput would be

$$DL\ App\ throughput\ [Mbps] = PDSCH\ PHY\ Throughput \times \frac{App\ layer\ Pkt\ Size}{Phy\ layer\ Pkt\ Size} \quad (78)$$

4.1.5 Results and discussion

We run a simulation in NetSim per the above scenario and obtain the throughput values tabulated below.

Table 4-3: *Table showing Analytical and simulated throughput results.*

	PHY Data Rate (Analytical throughput) in Mbps	Application throughput (Simulation) in Mbps
UE 1	101.69	95.36
UE 2	116.48	109.81

UE 2 achieves higher throughput despite being further from the gNB due to 2×2 MIMO vs 1×1 MIMO UE 1.

The application layer throughput would be

$$DL\ App\ Throughput = DL\ DataRate \times (App\ Layer\ Packet\ Size) \tag{79}$$

$$DL\ App\ throughput = DL\ Data\ Rate \times \frac{App\ layer\ packet\ size}{Phy\ layer\ packet\ size} \quad \ldots(4)$$

The computation of the PHY layer packet size is complex. It involves various layers adding overheads: the Transport layer (UDP) contributes 8 B, and the Network Layer (IP) adds 20 B. The MAC layer introduces additional overhead, with the SDAP header contributing 1B and the PDCP header adding 16B. At this point, the packet size is the size of the application layer packet plus 45 B. The MAC layer in 5G further processes these packets, fitting them into transport blocks (TBs). These TBs are then divided into code blocks (CBs), which are grouped into code block groups (CBGs) for transmission over the air. The sizes of the TB and CB depend on various parameters, and additional overheads are incurred during this process. As a result, it's challenging to provide a simple analytical formula for PHY layer packet size. A reasonable estimate would be about 5–10% reduction between the PHY rate and the application throughput. This is what we observe when we compare the simulation results with the theoretical predictions in the above table.

The above discussion assumes a conservative MCS is selected, ensuring a Block Error Rate (BLER) of zero. However, if a more aggressive MCS is chosen, which typically has a higher throughput but also a higher t-BLER (e.g., 5% or 10%), the computation must account for this increased BLER.

4.1.6 Exercises

- Explain how changing the DL:UL ratio would affect the results? Redo the theoretical calculations for DL:UL ratio of 1:1 and compare against simulation.
- Change the gNB UE distances such that the MCSs seen by the UEs are different for e.g., MCS 17 and MCS 23. Compute the theoretical throughput and compare against simulation.

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4.2 Effect of distance on pathloss, SINR and MCS (7-Cell Hexagonal Layout, Urban Macro Propagation, NLOS)

The experiment aims to analyze how the performance of a UE changes as it moves away from its serving gNB. In real-world scenarios, users are mobile, and their distance from the base station affects signal strength. By simulating a linear movement of the UE away from the gNB, we can observe how parameters such as pathloss, SINR, and MCS change with distance. This helps determine the coverage limit of the gNB, identify when the signal is no longer sufficient for communication, and plan for handover decisions.

Network Layout for UE Coverage Analysis in Multi-Cell Scenario:

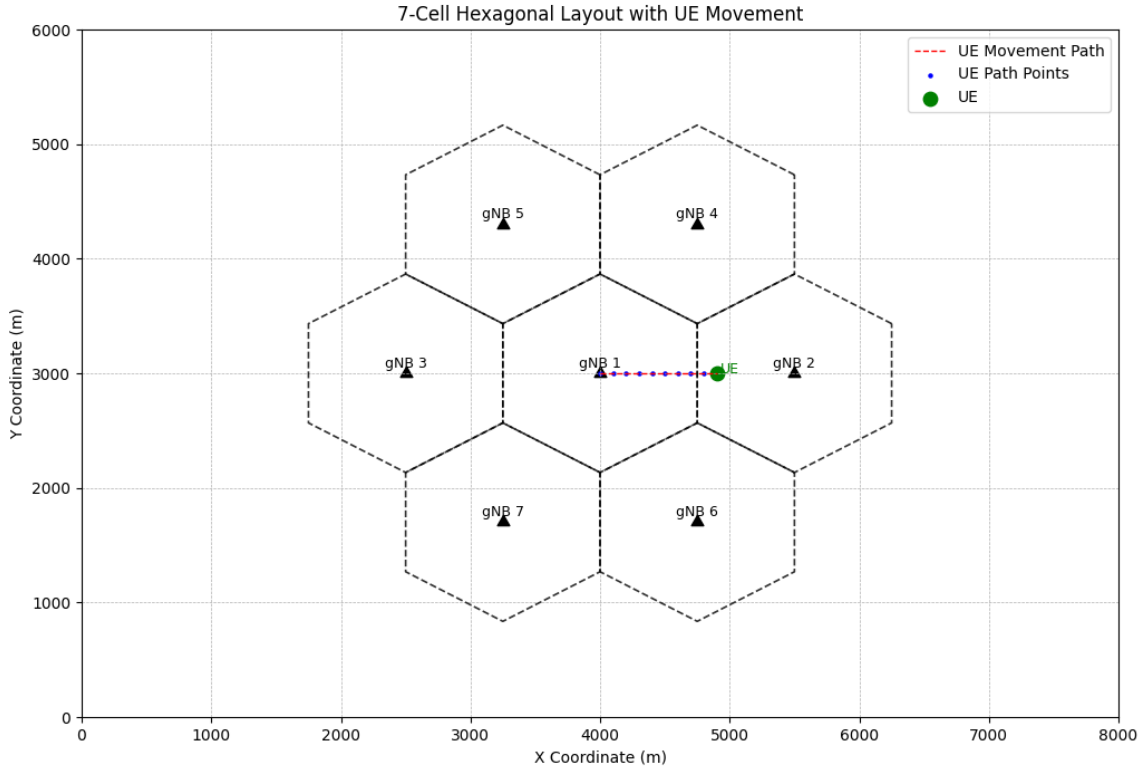


Figure 4-8: *A logical diagram with the 7-cell hexagonal network topology; the UE is initially close to gNB1 and moves east towards gNB2.*

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

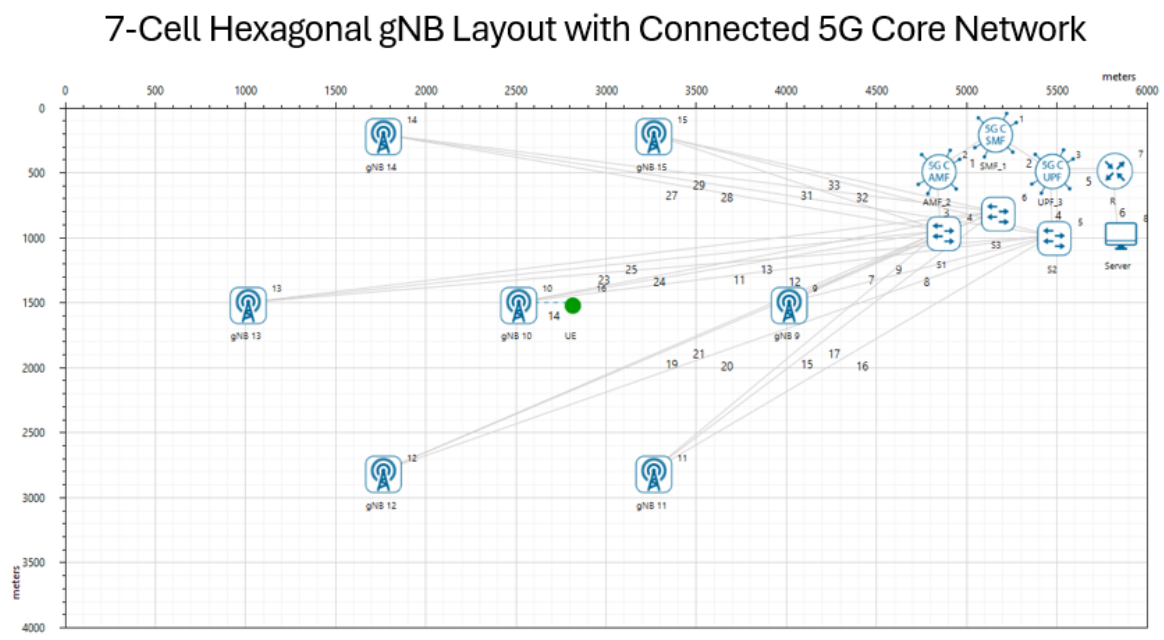


Figure 4-9: *Equivalent scenario in NetSim. In this network setup to study how Pathloss, SINR, and MCS vary with distance*

Settings done in example config file

- Set distance between all gNB as 1500m
- Set the gNB properties as follows. To configure it, click on gNB. On the right side, expand the property panel, go to the physical layer of the Interface (RAN) layer, and set the properties below

Table 4-4: *gNB > Interface (5G RAN) > Physical layer properties*

Properties	
CA Configuration	n78
Antenna	
TX Antenna Count	1
RX Antenna Count	1
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban macro
LOS NLOS Selection	User defined
LOS Probability	0
Shadow Fading Model	None
Interference Model	
Downlink Interference Model	Exact geometric model

- Set TX Antenna and RX Antenna as 1 in UE properties > Interface (5G RAN) > Physical Layer.

- In the Device Position Properties of UE, set Mobility Model as File Based Mobility

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

Table 4-5: *The values set in the Mobility.csv file. The Y value remains constant while the X value is increased to configure movement towards the east.*

#Time(s)	Device ID	X	Y	Z
2	16	2600	1500	0
4	16	2700	1500	0
6	16	2800	1500	0
8	16	2900	1500	0
10	16	3000	1500	0
12	16	3100	1500	0
14	16	3200	1500	0
16	16	3300	1500	0
18	16	3400	1500	0
20	16	3500	1500	0

- Create a CBR application between Wired Node 8 and UE 16 from the set traffic tab in the ribbon on top. Click on the created application, and in the right-side property panel, set the transport protocol to UDP, keeping the other application properties as default.
- The LTENR Radio measurement log file must be enabled from the design window.
- LTENR Radio measurement Log can be enabled by clicking on the icon in Configure Reports > Plots > Network Logs option as shown below

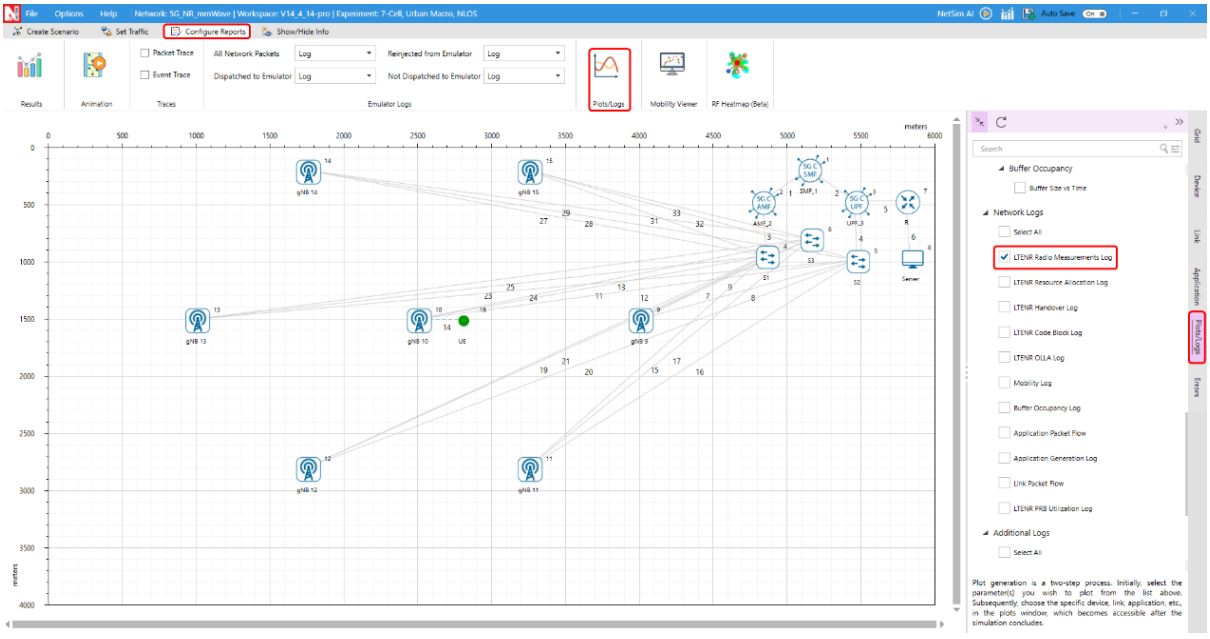


Figure 4-10: *Enabling LTENR Radio Measurements Log.*

- Run simulation for 20s, after the simulation completes Go to results window click on logs options and open LTENR Radio Measurement Log.csv and note down the Pathloss, SINR and MCS.

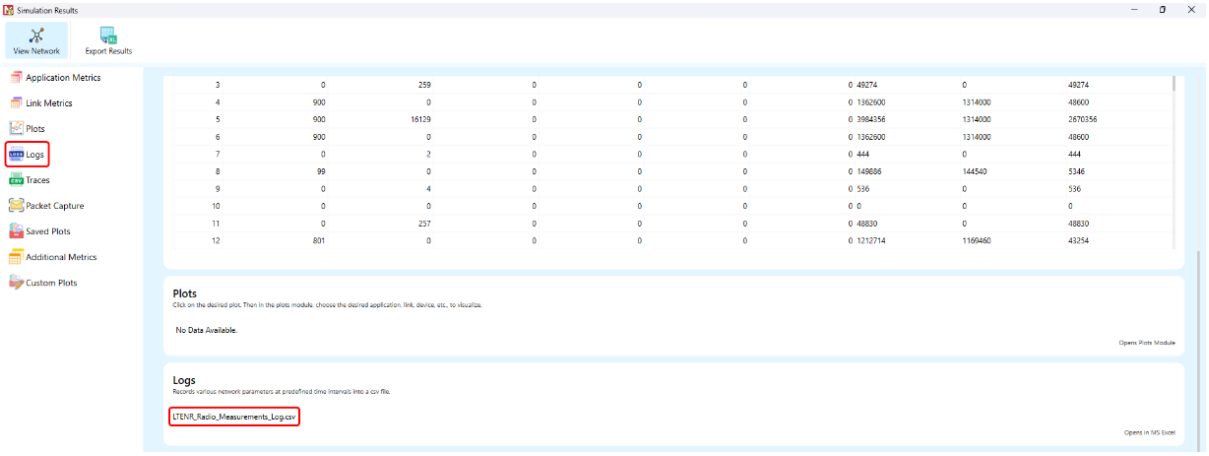


Figure 4-11: *Results window*

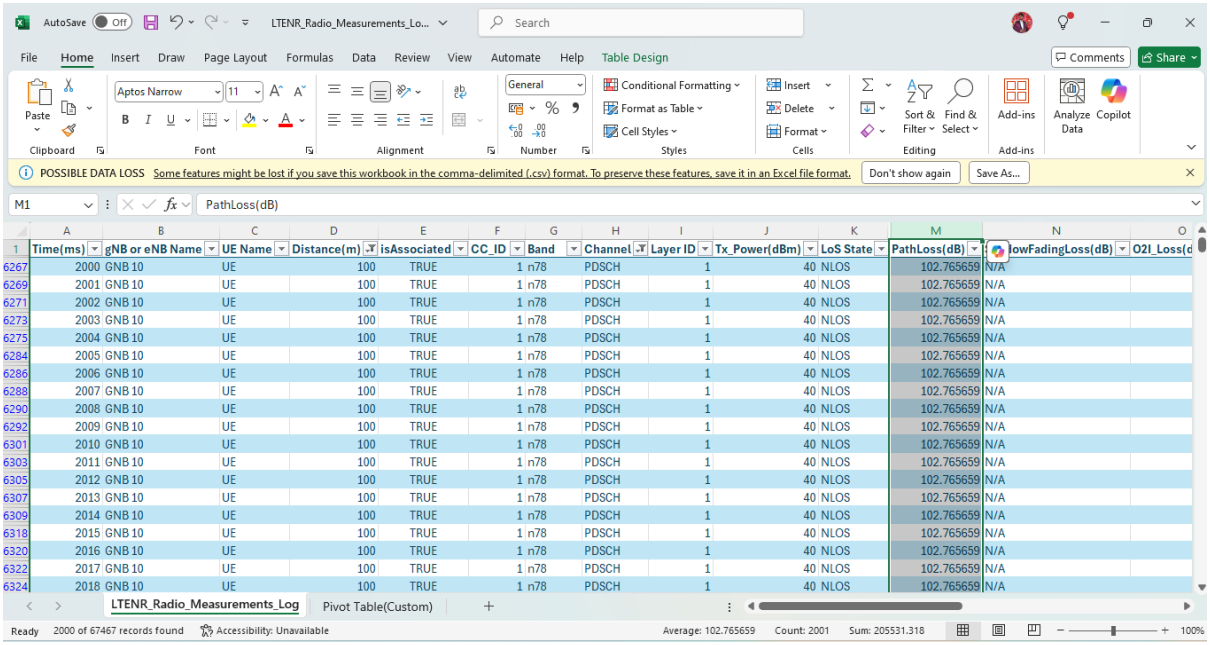


Figure 4-12: *LTENR Radio Measurement log.csv file*

Filter channel to PDSCH, and vary the distance by filtering to 100, 200, 300, 400, 500, 600, 700, 800 and 900. Record the Pathloss, SINR, and MCS values from the log file.

Results

Table 4-6: *Results for Pathloss vs Distance, SINR vs Distance, MCS vs Distance*

Distance (m)	Pathloss (dB)	SINR (dB)	MCS
100	102.7656	36.2866	27
200	114.4841	24.4183	27
300	121.3573	17.2854	21
400	126.2369	12.0169	15
500	130.0228	7.6774	11
600	133.1164	3.86867	6
700	135.7322	0.1114	3
800	137.9982	−3.6469	1
900	139.9971	−7.6709	0

As the UE moves away from gNB 10 along the defined mobility path, the signal quality gradually decreases due to increasing pathloss. Initially, at close proximity (100–200 meters), the SINR remains high, supporting a high Modulation and Coding Scheme (MCS) index of 27, which enables maximum throughput. However, as the distance increases, the signal experiences significant attenuation. By the time the UE reaches 500 meters, the SINR drops to 7.68 dB and the MCS reduces to 11, indicating reduced spectral efficiency. Beyond this point, the SINR continues to decline rapidly, becoming negative past 700 meters. At 900 meters, the SINR falls to −7.67 dB and the MCS drops to 0, meaning the UE can no longer sustain a viable communication link with gNB 10. This point effectively marks the edge of the gNB's coverage area, beyond which the UE must perform a handover to a neighboring cell or face radio link failure.

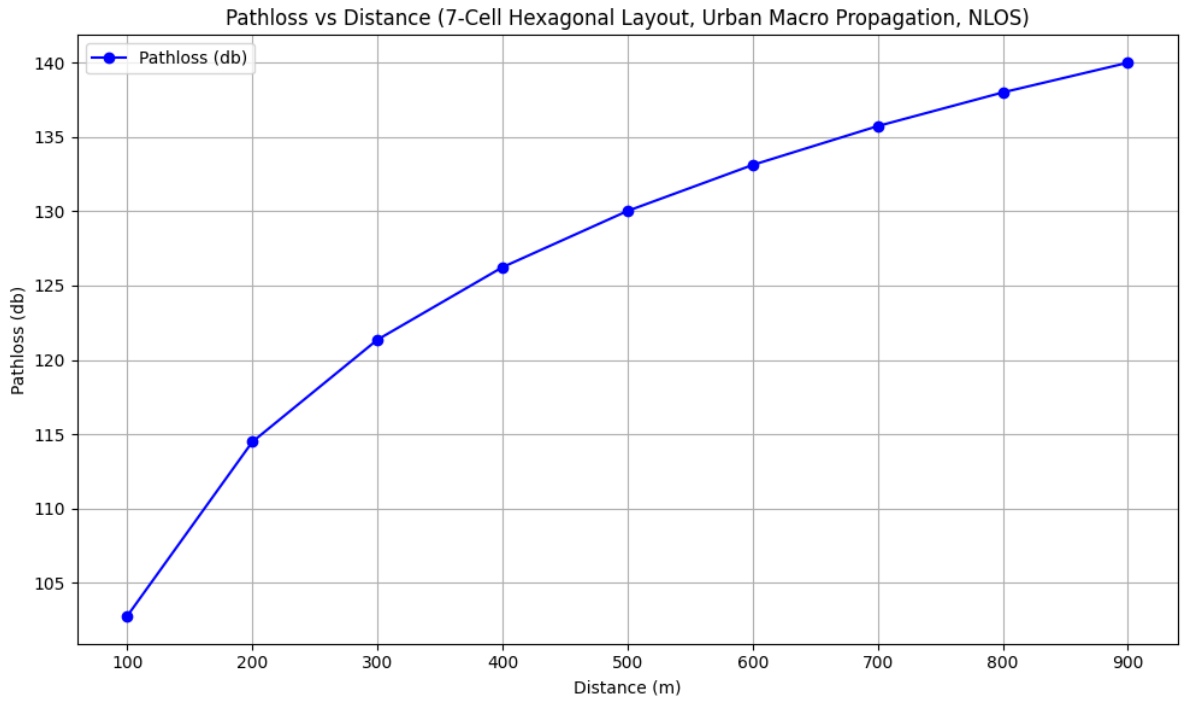


Figure 4-13: *Pathloss vs Distance – As the UE moves farther from the gNB, signal attenuation increases, leading to higher pathloss values.*

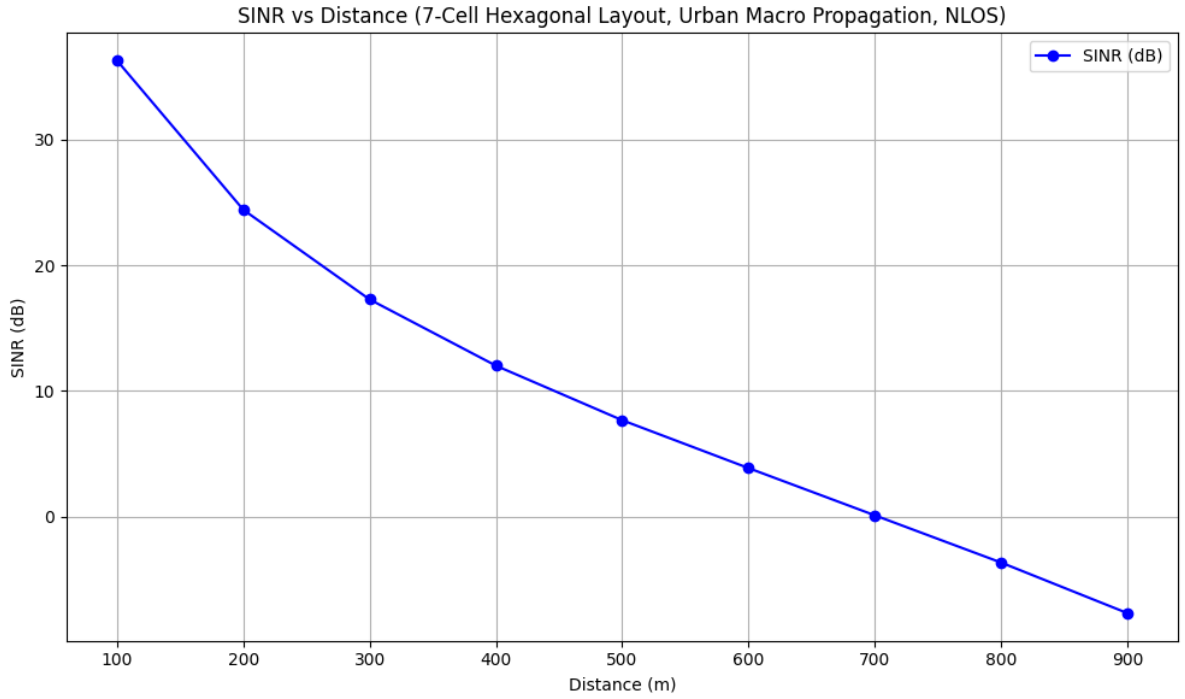


Figure 4-14: *SINR vs Distance – The SINR is highest when the UE is near the gNB and progressively decreases with increasing distance, reflecting the impact of signal degradation and rising interference from neighboring cell.*

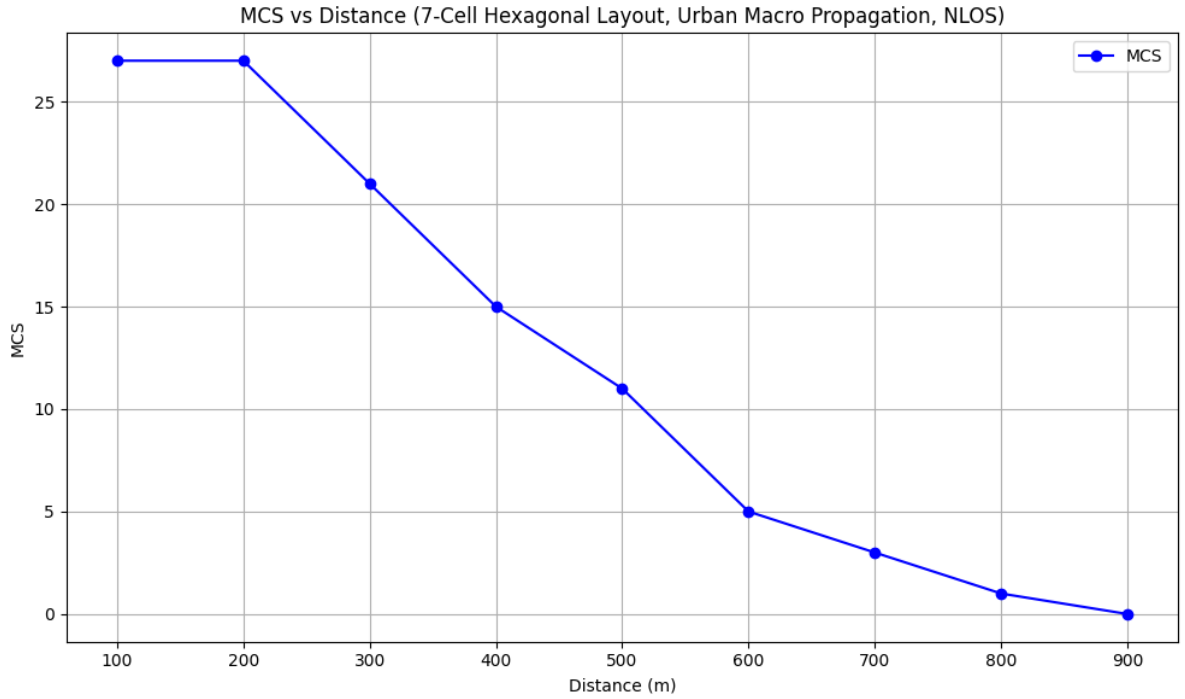


Figure 4-15: *MCS vs Distance – As the UE moves farther from the gNB and signal quality declines, the MCS value decreases. This reflects the network's adaptive modulation strategy to maintain reliable communication at lower data rates.*

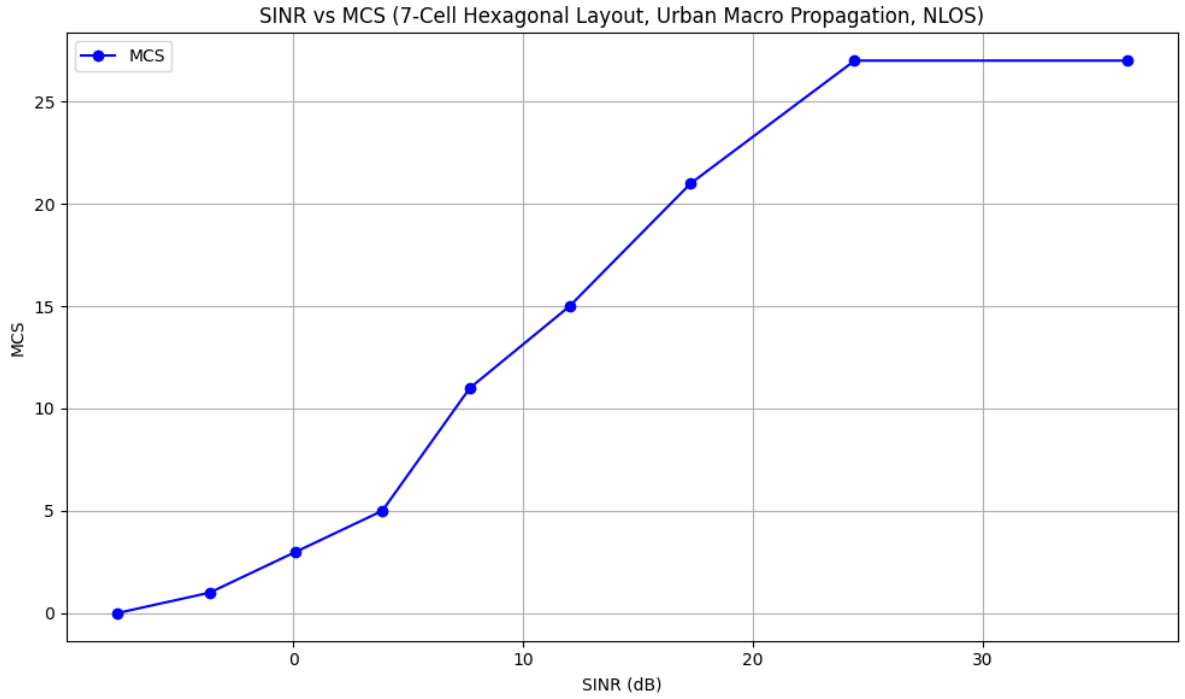


Figure 4-16: *MCS vs SINR – The graph illustrates the relationship between SINR and MCS. At higher SINR the link adapts to a higher MCS and at a lower SINR the link adapts to a lower MCS. The highest MCS per 3GPP standards is MCS 28.*

CQI Interpretation and MCS Selection Using 3GPP 38.214

The 3GPP standards Spectral Efficiency vs. MCS table is used to select the appropriate MCS (Modulation and Coding Scheme). This selection can be based on the 64QAM, 256QAM, or 64QAMLOWSE table, depending on the configuration chosen by the user. In this example, we have used the 256QAM table.

The CQI (Channel Quality Indicator) indices and their corresponding interpretations are taken from 3GPP 38.214 Table 5.2.2.1-3, which defines CQI reporting for QPSK, 16QAM, 64QAM, and 256QAM.

It is recommended that users configure the same MCS table for both PDSCH (Physical Downlink Shared Channel) and PUSCH (Physical Uplink Shared Channel)

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Table 4-7: *Spectral efficiency to MCS table defined in 3GPP Standards for 256 QAM.*

MCS	Modulation	SINR (dB)	Spectral Efficiency	CQI
27	256QAM	36.28	7.4063	15
25	256QAM	21.98	6.9141	14
23	256QAM	20.52	6.2266	13
21	256QAM	17.28	5.5547	12
19	64QAM	15.56	5.1152	11
17	64QAM	14.49	4.5234	10
15	64QAM	12.01	3.9023	9
13	64QAM	10.64	3.3223	8
11	64QAM	7.67	2.7305	7
9	16QAM	7.09	2.4063	6
7	16QAM	5.88	1.9141	5
5	16QAM	3.80	1.4766	4
3	QPSK	0.11	0.8770	3
1	QPSK	−3.64	0.3770	2
0	QPSK	−7.67	0.1523	1

In 5G networks, Modulation and Coding Scheme (MCS) plays a critical role in determining the spectral efficiency, which is a measure of how efficiently the available bandwidth is used to transmit data. The 3GPP specifications, particularly 38.214, define a mapping between MCS indices and their corresponding modulation orders and coding rates. Each MCS index corresponds to a specific spectral efficiency value, calculated based on the number of bits per symbol and the applied coding rate. For example, a low MCS index such as 0 uses QPSK with a low coding rate, resulting in low spectral efficiency but high robustness, while a high MCS index like 27 or 28 uses 256-QAM with a high coding rate, achieving high spectral efficiency suitable for strong channel conditions. This standardized mapping ensures that 5G systems can dynamically adapt transmission parameters to channel quality, maximizing throughput while maintaining reliability.

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. 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.

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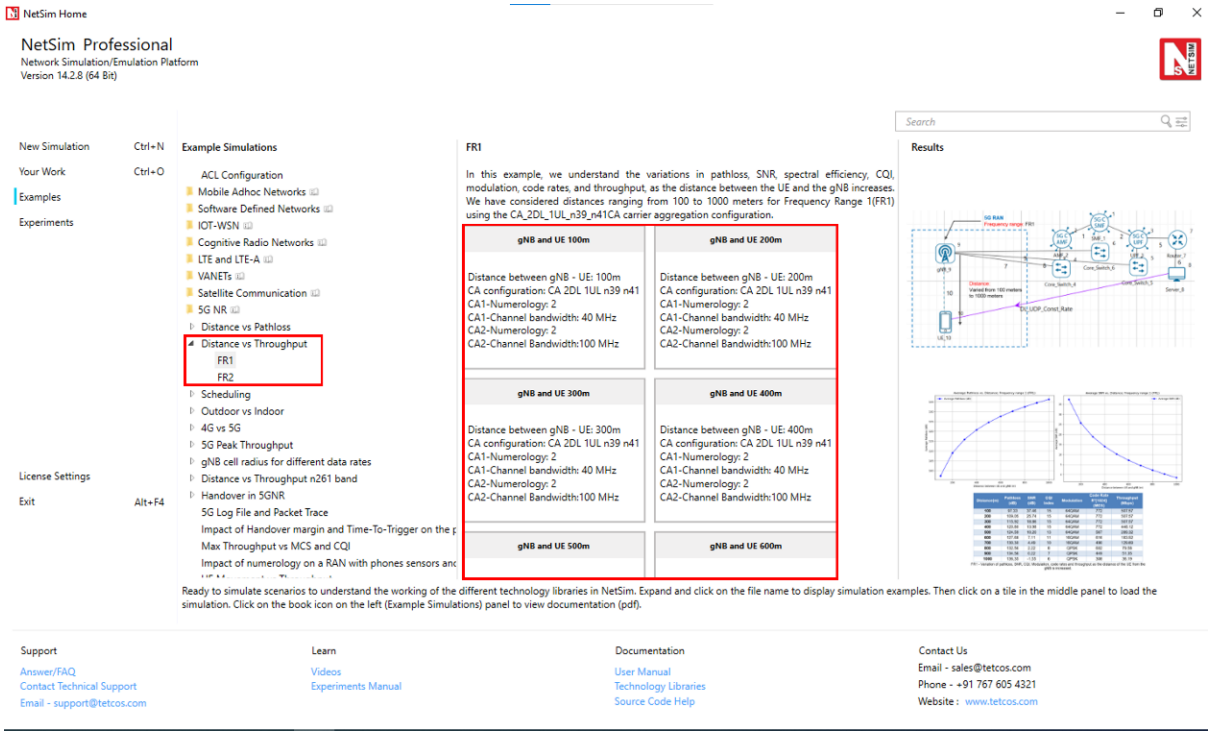


Figure 4-17: *List of scenarios for the example of Distance vs Throughput*

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

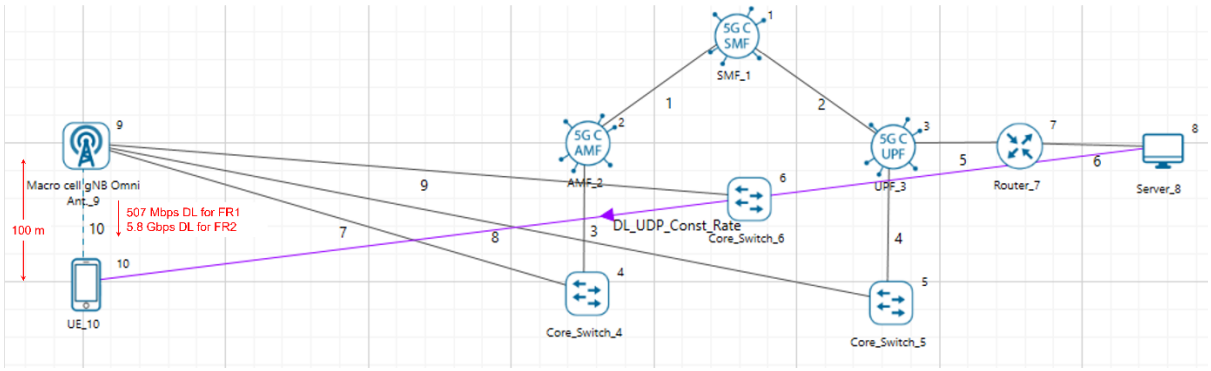


Figure 4-18: *Network setup for studying the Distance vs Throughput*

4.3.1 Frequency Range - FR1

Settings done in example config file.

- Set grid length as 2000m × 1000m from grid setting property panel on the right. This needs to be done before any device is placed on the grid.
- Set distance between gNB 9 and UE 10 as 100m.
- Click on gNB and expand the property panel on right side go to Interface (5G RAN) PHYSICAL LAYER, set the following properties as shown below.

Table 4-8: *gNB > Interface (5G RAN) > Physical layer properties*

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
PDSCH and PUSCH Configuration	
MCS Table	QAM64LOWSE
CSI Report Configuration	
CQI Table	TABLE3
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS NLOS Selection	User Defined
LOS Probability	0
Shadow Fading Model	None
Fast Fading Model	No Fading

- Set Tx Antenna Count and Rx Antenna Count in gNB as 2 and 2.
- Set Tx Antenna Count and Rx Antenna Count in UE as 2 and 2.
- Go to Application properties and set the following properties as shown below.

Table 4-9: *Application properties*

Application Properties	
Source Id	8
Destination Id	10
QoS	UGS
Transport Protocol	UDP
Packet Size	1460 Bytes
Inter Arrival time	23 μs
Start Time	1 s

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

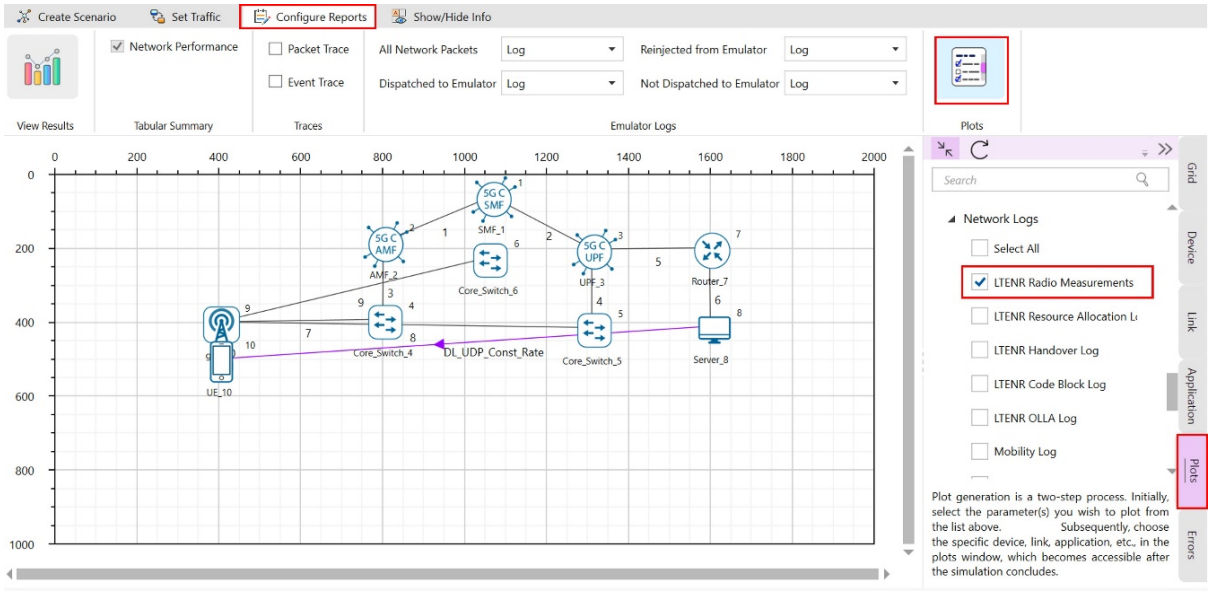


Figure 4-19: *Enabling log files in NetSim GUI.*

- 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

- Set grid length as 1000m × 500m from grid setting property panel.
- Set distance between gNB 9 and UE 10 as 50m.
- Click on gNB and expand the property panel on right side go to Interface (5G RAN) PHYSICAL LAYER, set the following properties as shown below.

Table 4-10: *gNB > Interface (5G RAN) > Physical layer properties*

Properties			
Physical Layer Properties			
CA Type	Intra Band Contiguous CA		
CA Configuration	CA_n258G		
	Numerology	Channel Bandwidth (MHz) per carrier	Frequency Range
CA1,CA2	3	400	FR2
Channel Model			
Pathloss Model	3GPP TR 38.901-7.4.1		
Shadow Fading Model	None		
Fast Fading Model	No Fading		
Outdoor Scenario	Urban macro		
LOS NLOS Selection	User defined		
LOS Probability	0		
MCS Table	QAM256		
CQI Table	TABLE2		

- Set Tx Antenna Count and Rx Antenna Count in gNB as 2 and 2.
- Set Tx Antenna Count and Rx Antenna Count in UE as 2 and 2.
- Go to Application properties and set the following properties as shown below.

Table 4-11: *Application properties*

Application Properties	
Source Id	8
Destination Id	10
QoS	UGS
Transport Protocol	UDP
Packet Size	1460 Bytes
Inter Arrival time	2μs
Start Time	1s

- The LTENR Radio measurement log file can be enabled as per the information provided above in Step 7.
- Run Simulation for 1.05s, after simulation completes go to results 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

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).

Table 4-12: *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)	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	490.03
500	124.59	10.20	13	64QAM	567	336.59
600	127.68	7.11	11	16QAM	616	214.43
700	130.30	4.49	10	16QAM	490	131.36
800	132.56	2.22	8	QPSK	602	86.04
900	134.56	0.22	7	QPSK	449	56.09
1000	136.35	−1.55	6	QPSK	308	40.72

Table 4-13: *FR 2 - Variation of pathloss, SNR, MCS, 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	20	256QAM	682.5	2860.89
100	120.01	4.77	7	16QAM	490	1025.50
150	126.86	−2.06	2	QPSK	193	296.90
200	131.73	−6.94	0	QPSK	120	107.92

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 obtained from the Transport Block Size Determination calculations given in Section 3.9.15. 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



Figure 4-20: *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.

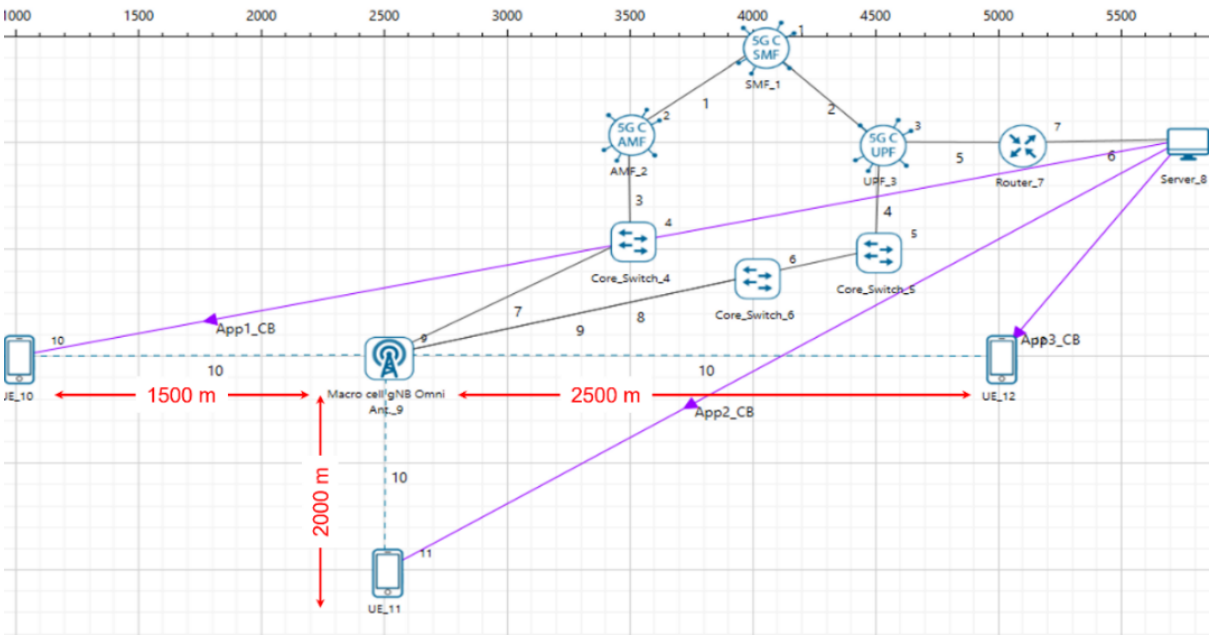


Figure 4-21: *Network set up for studying the Scheduling example.*

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

- Set grid length as 12000m × 6000m from grid property panel on the right.
- Set distance as follows.

  - gNB 9 to UE 10 = 1500m
  - gNB 9 to UE 11 = 2000m, and
  - gNB 9 to UE 12 = 2500m

- Go to gNB properties → 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.

Table 4-14: *gNB > Interface (5G RAN) > Datalink and Physical layer properties*

Properties	
Datalink Layer Properties	
Scheduling Type	Varies: Proportional Fair, Max throughput, Round Robin
Physical Layer Properties	
CA type	Single Band
CA Configuration	n78
CA1	
Numerology	1
Channel Bandwidth	100 MHz
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban macro
LOS NLOS Selection	User defined
LOS Probability	1
Shadow Fading Model	None
Fast Fading Model	No Fading

- Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in gNB properties.
- Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in all the UEs.
- Go to the Set Traffic tab in the top ribbon and create a CBR application as shown in the table below. To change the transport protocol, QoS, and IAT, click on the application and change the properties in the right-side property panel.

Table 4-15: *Application properties*

Application Properties	Application 1	Application 2	Application 3
Application Type	CBR	CBR	CBR
Source ID	8	8	8
Destination ID	10	11	12
QoS	UGS	UGS	UGS
Transport Protocol	UDP	UDP	UDP
Packet Size	1460 Bytes	1460 Bytes	1460 Bytes
Inter-arrival time	58.4 μs	58.4 μs	58.4 μs
Start Time	1s	1s	1s

- Run Simulation for 10 s 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.

Table 4-16: *UDP download throughputs for different scheduling algorithms when all three 3 UEs simultaneously downloading data*

Scheduling	Application 1	Application 2	Application 3	Aggregate
Round Robin	64.65	37.22	19.59	121.46
Proportional Fair	64.65	37.23	19.59	121.46
Max Throughput	193.94	0.00	0.00	193.94

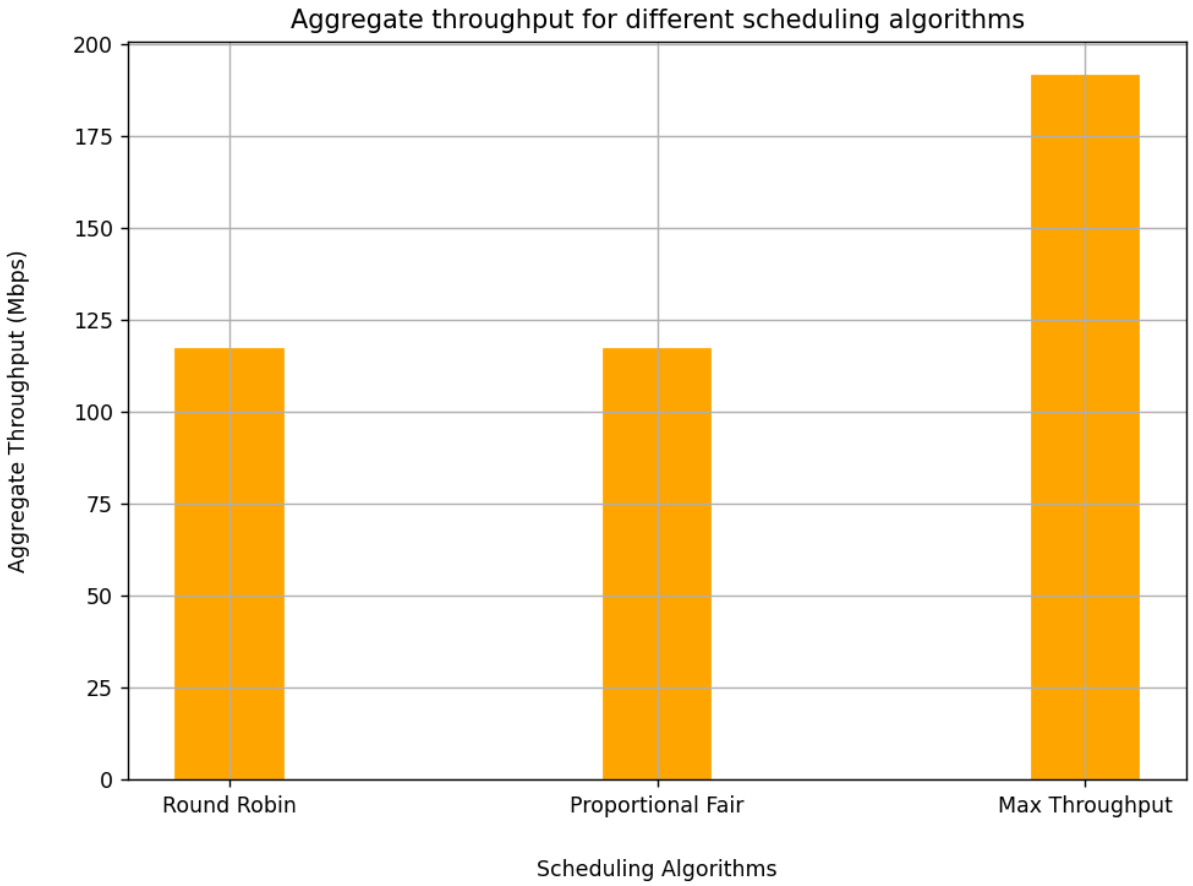


Figure 4-22: *Aggregate throughput for different scheduling algorithms*

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.

Table 4-17: *UE throughputs if they were run standalone (without the other UEs downloading data)*

Distance from gNB (m)	Application ID	Throughput (Mbps)	Remarks
1500	1	193.94	UE 1 alone has full buffer DL traffic
2000	2	111.66	UE 2 alone has full buffer DL traffic
2500	3	49.95	UE 3 alone has full buffer DL traffic

The PHY rate is decided per the received SNR. Therefore, a UE closer to the gNB will get a higher data rate than a UE further away. In this example the distances from the gNB are such that UE12 Distance > UE11 Distance > UE10 Distance.

In Round Robin PRBs are allocated equally among all three nodes. However, throughputs are in the order UE10 Distance > UE11 Distance > UE12 Distance 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 4-17. 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 throughput 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.

- Click on gNB and go to 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.

Table 4-18: *gNB > Interface (5G RAN) > Physical and Datalink layer properties.*

Properties	
Datalink Layer Properties	
Scheduling Type	Varies: Proportional Fair, Max throughput, Round Robin
Physical Layer Properties	
CA Type	Single Band
CA Configuration	n78
CA1	
Numerology	1
Channel Bandwidth	100 MHz
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS NLOS Selection	User Defined
LOS Probability	1
Fast Fading Model	Rayleigh
MIMO Beamforming Model	Eigen

- Run Simulation for 10s and note down throughput value in the results window in each sample.
- Enable EWMA MAC throughput plot

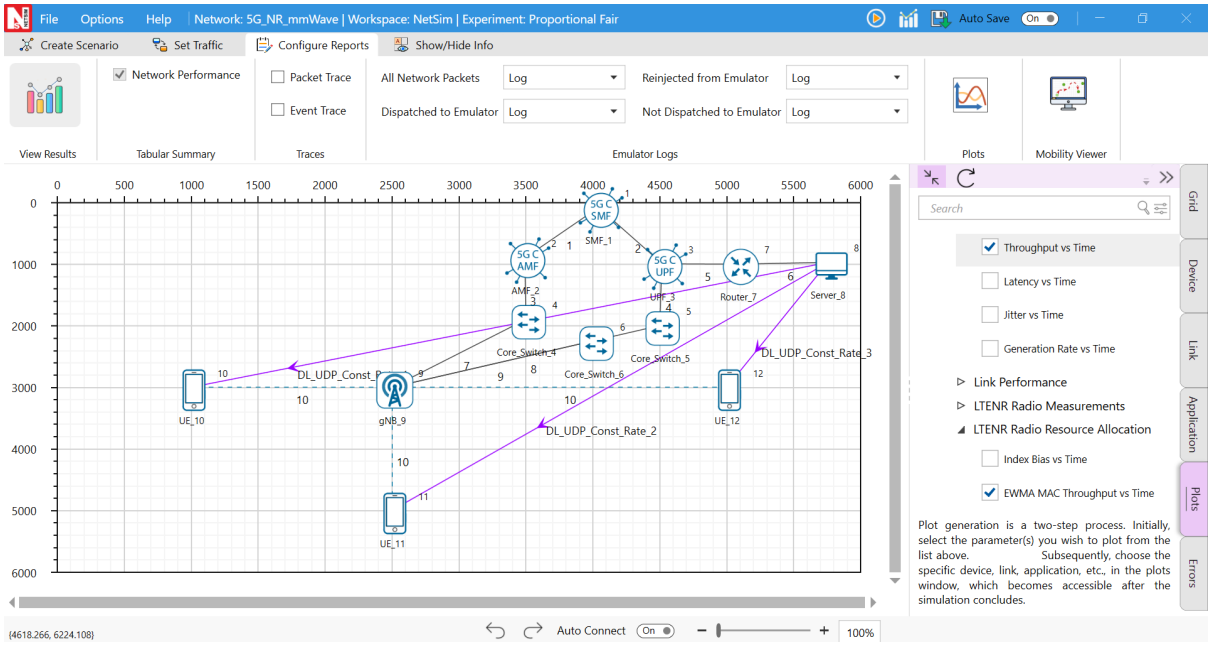


Figure 4-23: *Enabling the EWMA MAC Throughput log*

Results and discussions

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

Table 4-19: *UDP download throughputs for different scheduling algorithms when all three 3 UEs simultaneously download data with time varying channel.*

Scheduling	Application 1	Application 2	Application 3	Aggregate
Round Robin	51.58	30.06	18.34	100.00
Proportional Fair	69.82	41.95	24.73	136.5
Max Throughput	139.84	28.19	5.32	173.35

While running the Proportional fair sample enable Application throughput vs time and EWMA MAC throughput plot to observe the throughput differences.

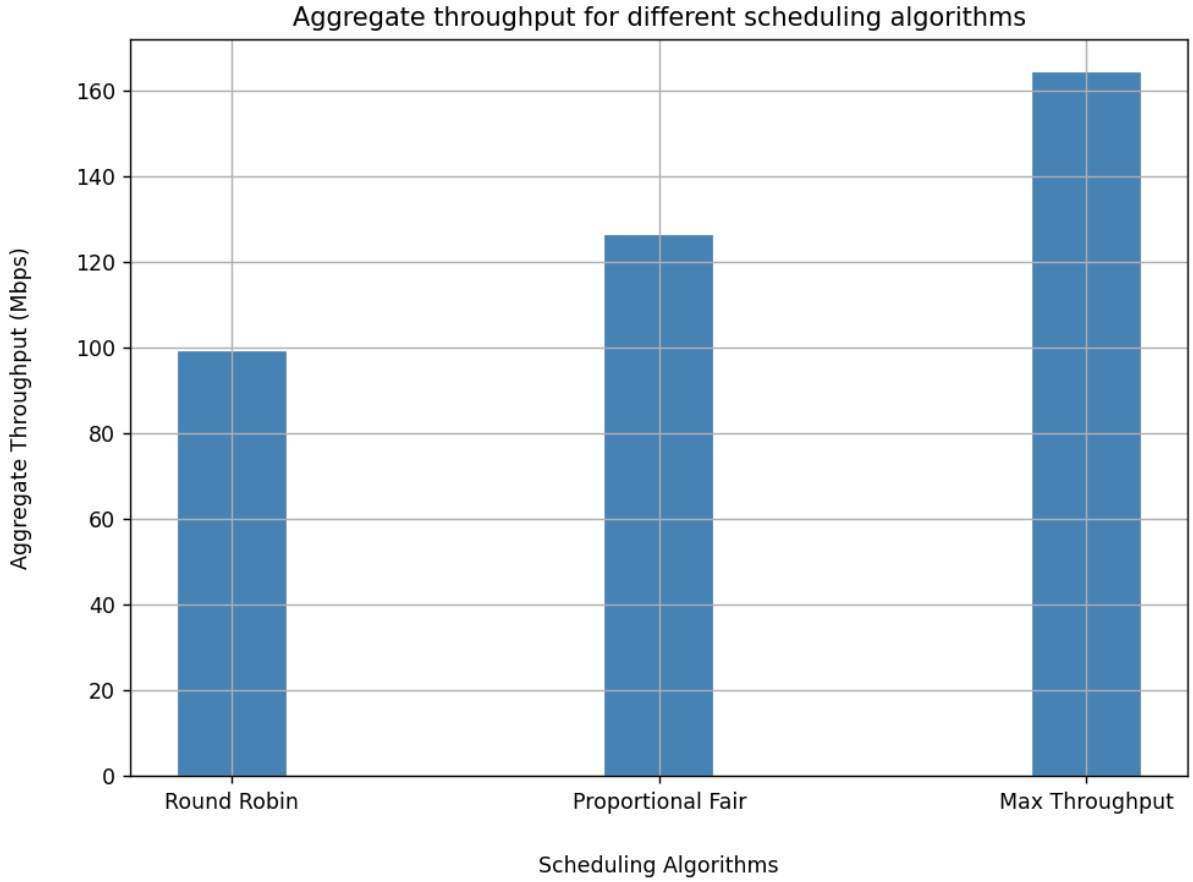


Figure 4-24: *Aggregate throughput for different scheduling algorithms*

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 4-19; observe how this is different from Table 4-17 where the channel is not time varying.

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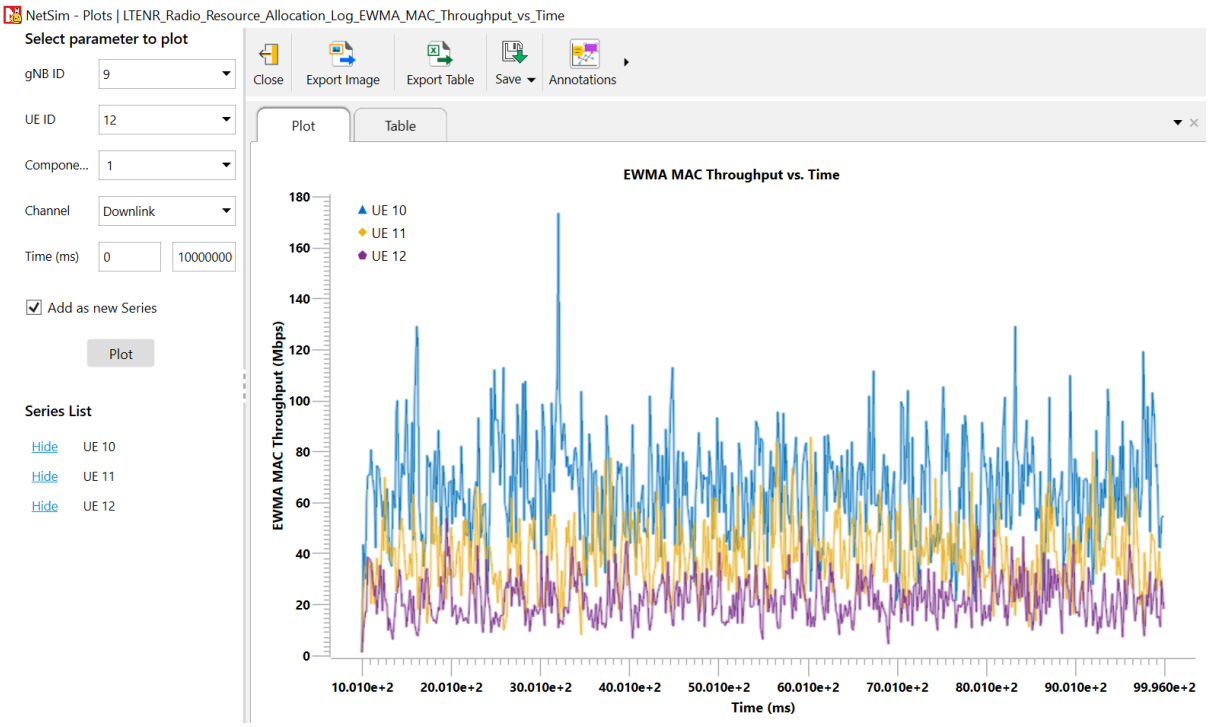


Figure 4-25: *EWMA MAC throughput stacked for UE 10, UE 11, and UE 12*

In the earlier results we observed the average (overtime) throughput while in Figure 4-25 we observed the MAC throughput vs Time for all 3 UEs. Key points are:

- Channel Coherence Time: The wireless channel fading gain changes at this time scale, causing fluctuations in the signal quality and, consequently, the achievable throughput.
- Proportional Fair Scheduler Behavior: The Proportional Fair (PF) scheduling algorithm aims to balance fairness and throughput by allocating resources to users based on their current channel quality relative to their average throughput

This dynamic allocation process leads to throughput variations as the scheduler continuously adjusts resource assignments to maintain fairness while exploiting favorable channel conditions. Thus, when a user experiences good channel conditions relative to their average, they receive more resources, leading to increased throughput. Conversely, when channel conditions degrade or other users are prioritized, a user's throughput will decrease. The MAC throughput would be higher than the application throughput because of the overheads of the various layers.

4.5 Load balancing in 5G using Cell Individual Offset (CIO)

4.5.1 Introduction

Overview

Mobility load balancing is a 3GPP Release 17 AI/ML for NG RAN Use Case. It involves transferring load from overloaded cells to under-loaded neighboring cells, for optimizing network performance and user experience. This study describes the network setup, presents the simulation results before and after applying CIO-based load balancing, and discusses the observed outcomes.

Concept

Default Association: The default user equipment (UE) association with a base station is based on Maximum signal strength.

Load Balancing Goal: Modify the association/handover criteria to distribute network load efficiently across available cells.

Role of Cell Individual Offset (CIO)

Cell Individual Offset (CIO) is a configurable parameter used to artificially modify the signal quality measurement of a target cell during the handover evaluation process. In NetSim, the CIO value is added to the measured SINR of the candidate cell.

$$SINR_{eff} = SINR_{actual} + CIO \tag{80}$$

- A positive CIO increases the effective signal value.
- A negative CIO decreases the effective signal value.

CIO is typically applied to control handovers and implement load balancing across cells.

4.5.2 Network Setup

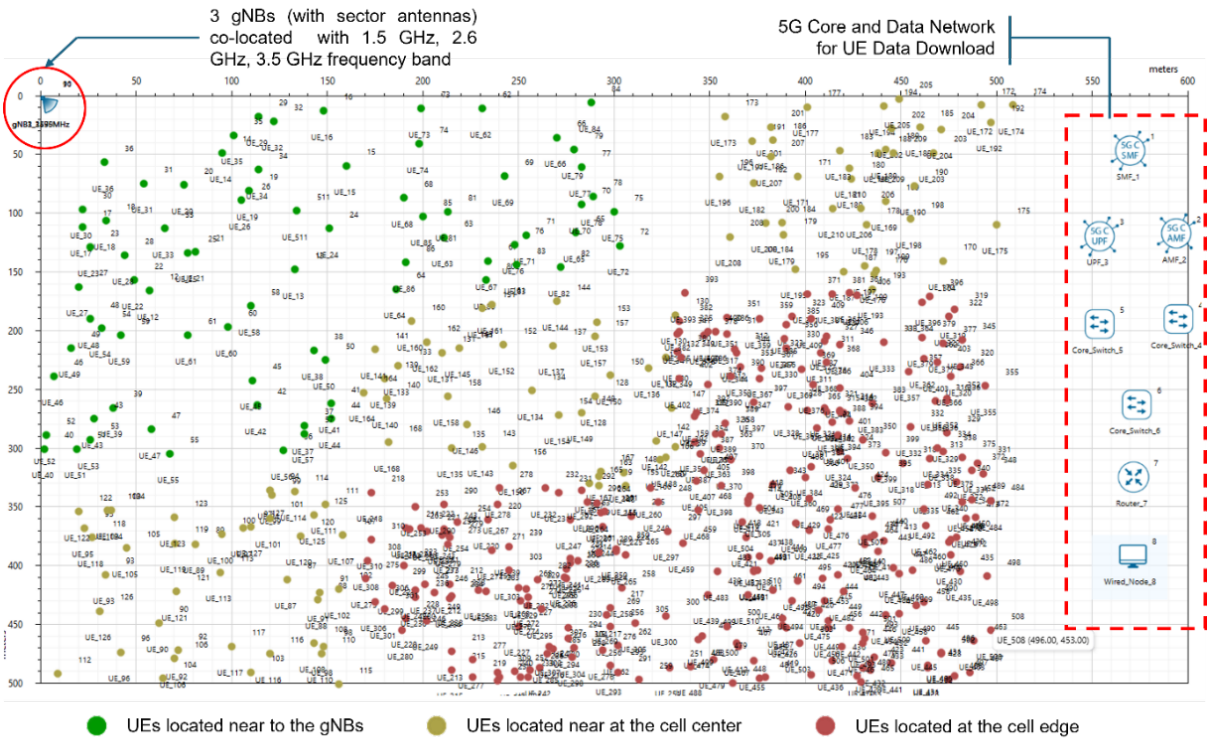


Figure 4-26: *Network setup for load balancing. There is a total of 500 UEs, 75 near cell, 125 mid cell and 300 cell edge UEs. Without load balancing most of the UEs would associate with the low band (1.5 GHz) gNB given the lower path loss. We use CIO for load balancing.*

4.5.3 Network Settings

- Environment size is set to 600m × 500m

- Consider three Macro cell gNB sector antennas and 500 UEs spread across the network grid such that
- 75 UEs are located near the gNBs (represented in green)
- 125 UEs are located near at the cell center (represented in yellow)
- 300 UEs are located at the cell edge. (represented in red)
- The 3 gNBs (with sector antennas) are co-located at the top left with 120°.
- gNB 1 operates in the n50 (1.5 GHz band)
- gNB 2 operates in the n38 (2.6 GHz band)
- gNB 3 operates in the n78 (3.5 GHz band)
- The gNB properties and the Traffic model properties are set as follows:

Table 4-20: *Device and Application properties*

System Model and Parameters	
No of gNBs	3 (3 sector carriers)
No of UEs	500
Band	n78, n50, n38
gNB Properties	
Numerology	1
Channel Bandwidth (MHz)	40
Antenna	4T4R
Pathloss model	Log Distance
Pathloss Exponent (η)	3.8
Shadowing Model	Log Normal
Standard Deviation (dB)	5
Simulation Time (s)	10
Traffic Model	
Traffic Type	Custom
Traffic generation rate	467.2 Kbps
Packet size	1460B
Inter packet arrival time	25000 μs (Exponential)

- Set the Cell Individual Offset present under Interface (RAN) > Datalink Layer > Handover > Cell Individual Offset as follows:
- gNB1 1475 MHz: −4.77 dB
- gNB2 2595 MHz: 0 dB
- gNB3 3550 MHz: 4.77 dB.
- These negative CIO value shifts the load away from gNB1; the positive CIO value shifts the load towards gNB3.

- Enable PRB Utilization vs time Plots and Radio resource allocation log
- Run the simulation for 10 seconds.

4.5.4 Results

After simulation, plot the PRB Utilization for the three gNBs i.e., gNB1 1475MHz, gNB2 2595MHz, gNB3 3550MHz with CIO and without CIO.

- PRB Utilization vs time plot without CIO (default configuration)

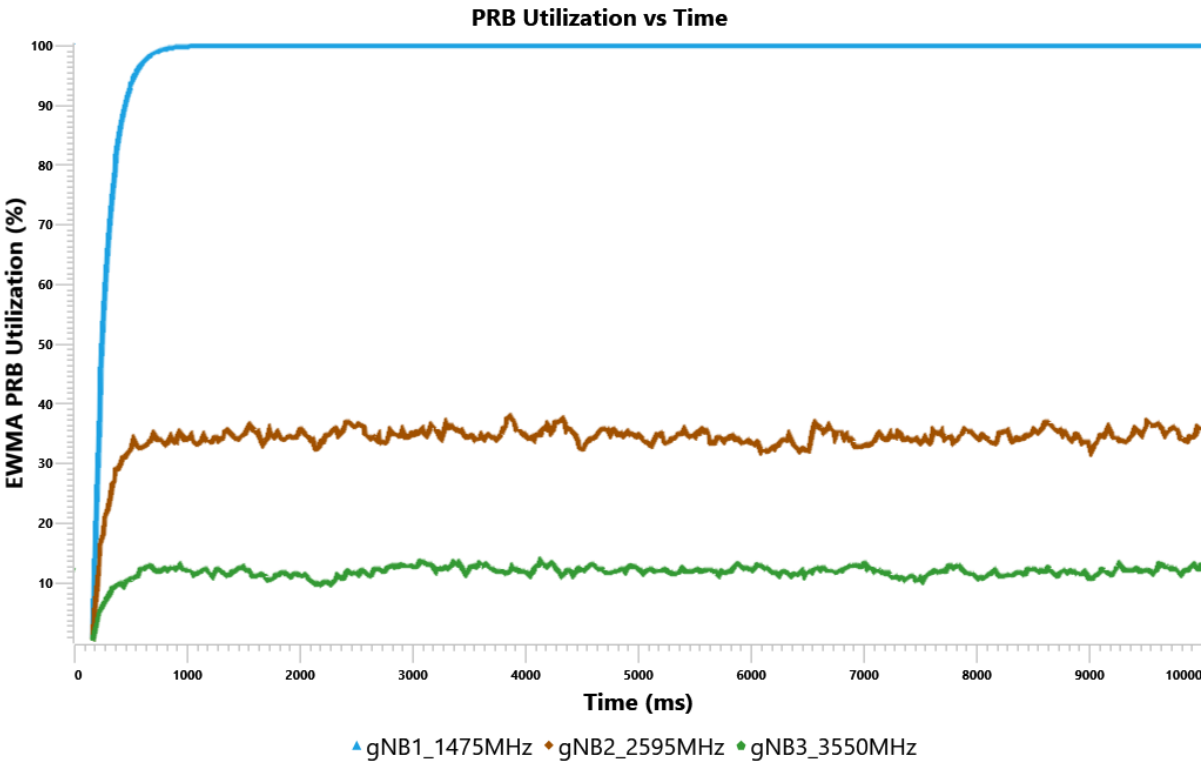


Figure 4-27: *(Exponentially weighted moving) Average PRB Utilization of the 3 gNBs without load balancing*

PRB Utilization vs time plot with CIO enabled

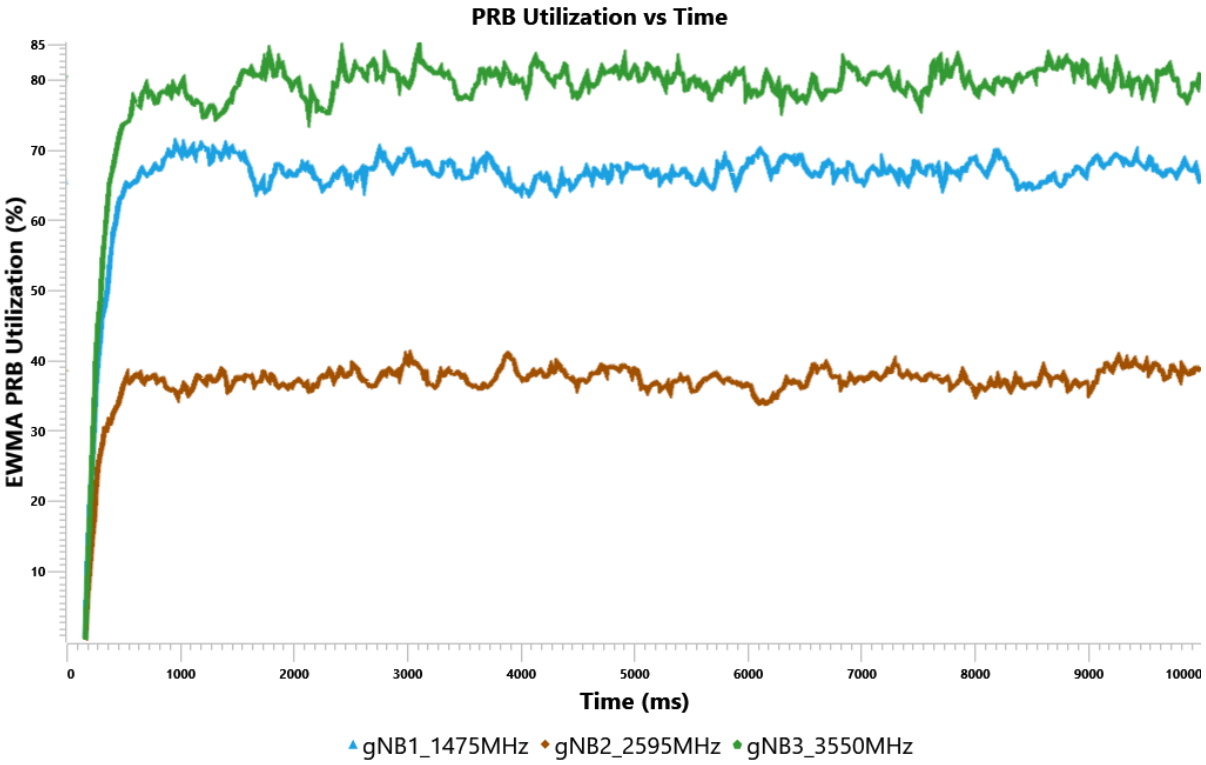


Figure 4-28: *(Exponentially weighted moving) Average PRB Utilization of the 3 gNBs with load balancing*

4.5.5 Discussion

These graphs show resource (PRB) usage of different 5G base stations over time, comparing scenarios with and without load balancing.

Without load balancing (Figure 4-27): Base station 1 (gNB1_1475MHz) is overloaded at ∼100% while gNB2 (2575 MHz) and gNB3 (3550 MHz) are underused and operating around 30% and 25% PRB utilization respectively.

With load balancing (Figure 4-28): Resource usage is more evenly distributed across all base stations, with gNB1 around 60–70% and other gNBs operating at 30–40%.

We can observe the association of UEs with gNBs before and after load balancing.

To analyze this, we use the LTENRRadioMeasurementsLog.csv and DeviceList.xlsx files.

A Python script reads the UE association entries at two time points—initial and post-load balancing—and generates corresponding plots.

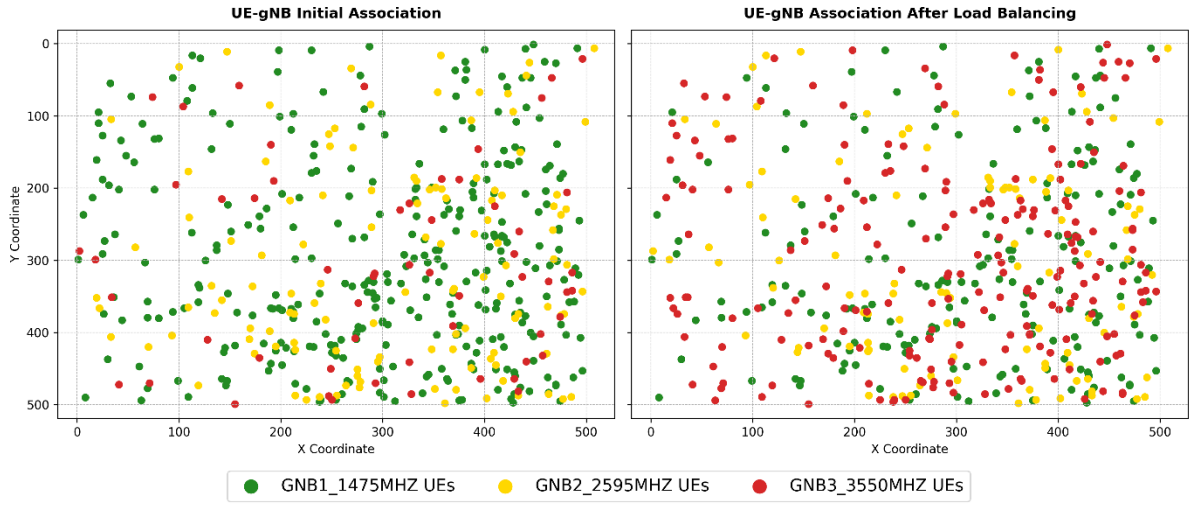


Figure 4-29: *Initial UE association (left) and association after load balancing (right). The left clearly shows a higher concentration of UEs (green dots) associated with gNB1_1475MHz, which operates on the lower frequency band. The right panel shows a more uniform distribution of UEs across the three gNBs due to the CIO application*

Table 4-21: *Initial association count of UEs*

gNB	Count of Associated UEs
gNB1 1475 MHz	321
gNB2 2595 MHz	122
gNB3 3550 MHz	57
Total	500

Table 4-22: *Association count of UEs after load balancing*

gNB	Count of Associated UEs
gNB1 1475 MHz	192
gNB2 2595 MHz	105
gNB3 3550 MHz	203
Total	500

Python code for data analysis and visualization

```
import pandas as pd
import matplotlib.pyplot as plt
import numpy as np
import sys
import os

def get_color_map():
    return {
        'GNB1_1475MHZ': '#228B22',  # Green
        'GNB2_2595MHZ': '#FFD700',  # Yellow
```

```
        'GNB3_3550MHZ': '#d62728'   # Red
    }

def plot_combined_association(log_df, device_list_df, output_dir):
    snapshots = {
        161.5: 'UE-gNB Initial Association',
        220: 'UE-gNB Association After Load Balancing'
    }
    fig, axs = plt.subplots(1, 2, figsize=(14, 6), sharex=True, sharey=True)
    color_map = get_color_map()
    gnb_names = list(color_map.keys())

    all_x = device_list_df['X Pos/LON']
    all_y = device_list_df['Y Pos/LAT']
    x_min, x_max = all_x.min() - 20, all_x.max() + 20
    y_min, y_max = all_y.min() - 20, all_y.max() + 20

    for ax, (time_snapshot, title) in zip(axs, snapshots.items()):
        filtered_df = log_df[(log_df['Time(ms)'] == time_snapshot) &
                             (log_df['Channel'] == 'PDSCH') &
                             (log_df['isAssociated'] == True)]

        merged_df = pd.merge(filtered_df, device_list_df, how='left',
                             left_on='UE Name', right_on='Device Name')

        for gnb in gnb_names:
            ue_group = merged_df[merged_df['gNB or eNB Name'] == gnb]
            ax.scatter(ue_group['X Pos/LON'], ue_group['Y Pos/LAT'],
                       label=f'{gnb} UEs', s=30, marker='o',
                       color=color_map[gnb])

        gnb_data = device_list_df[
            device_list_df['Device Type'].str.contains('gNB')]
        for _, gnb in gnb_data.iterrows():
            ax.scatter(gnb['X Pos/LON'], gnb['Y Pos/LAT'],
                       label=gnb['Device Name'], s=70, marker='^',
                       color='black')

        ax.set_title(title, fontweight='bold', fontsize=12, pad=10)
        ax.set_xlabel('X Coordinate', fontsize=10)
        ax.set_xlim(x_min, x_max)
        ax.set_ylim(y_max, y_min)
        ax.grid(True, linestyle='--', linewidth=0.5)

    axs[0].set_ylabel('Y Coordinate', fontsize=10)
    handles, labels = axs[1].get_legend_handles_labels()
    fig.legend(handles, labels, loc='lower center',
               fontsize=14, ncol=3, markerscale=2)
    plt.tight_layout(rect=[0, 0.08, 1, 1])
    output_path = os.path.join(output_dir,
                               'combined_association_plot.png')
```

```
    plt.savefig(output_path, dpi=300)
    plt.close()
    print(f"Combined plot saved: {output_path}")

if __name__ == '__main__':
    if len(sys.argv) != 4:
        print("Usage: python combined_association.py "
              "<log_csv_path> <device_list_excel_path> "
              "<output_directory>")
        sys.exit(1)

    log_path = sys.argv[1]
    device_path = sys.argv[2]
    output_dir = sys.argv[3]

    log_df = pd.read_csv(log_path)
    device_df = pd.read_excel(device_path)
    plot_combined_association(log_df, device_df, output_dir)
```

4.6 4G vs. 5G: Capacity analysis for video downloads

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

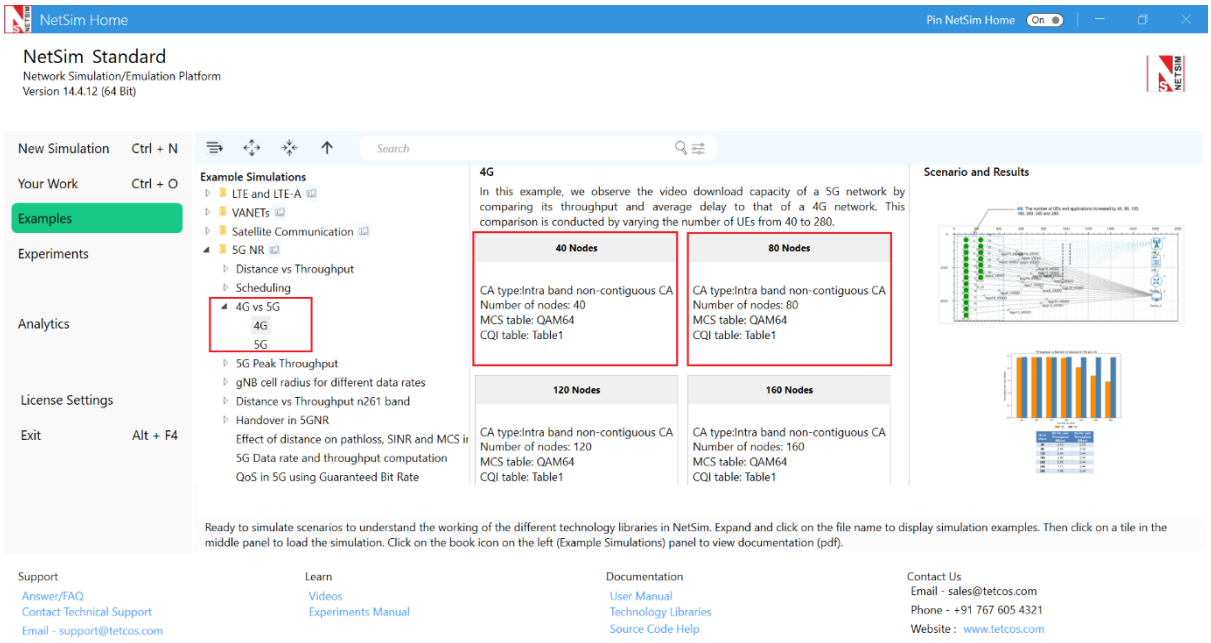


Figure 4-30: *List of scenarios for the example of 4G vs 5G*

4.6.1 4G

Under 4G click on 40 Nodes Sample, the following network diagram illustrates what the NetSim UI displays when you open the example configuration file.

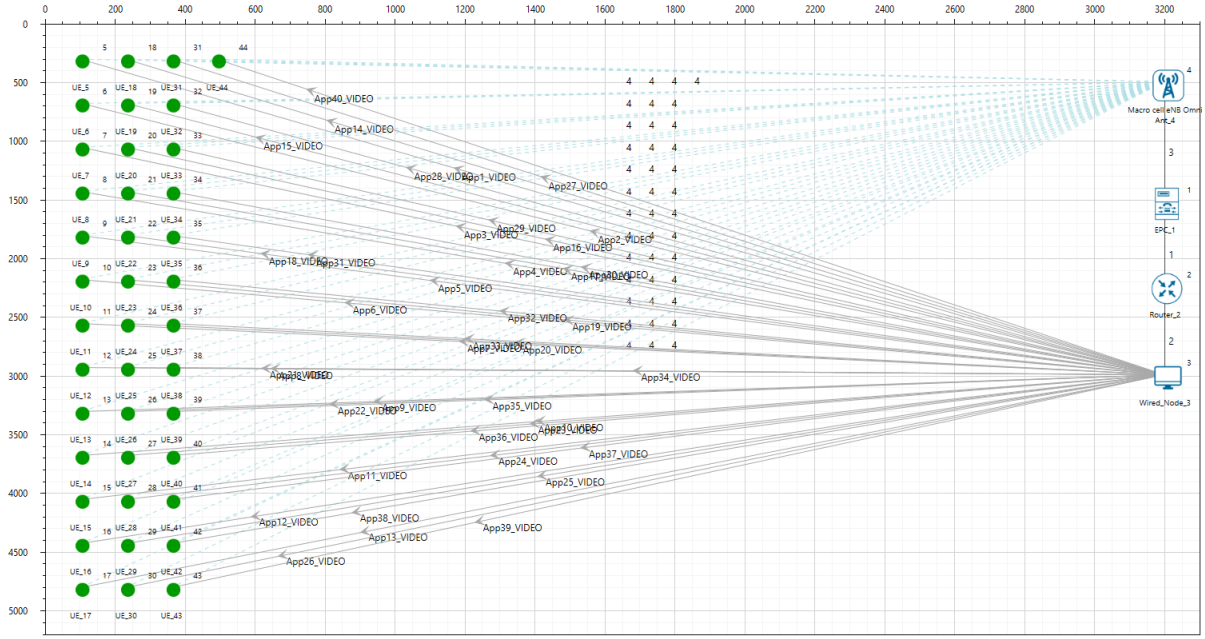


Figure 4-31: *Network setup for studying the 4G*

Settings done in example config file:

- Set grid length as 3300×5200m from grid property panel on the right.
- Set the following property as shown in below given Table.

Table 4-23: *eNB > Interface (LTE) > Physical layer properties*

eNB Properties → Interface (LTE)				
CA Type	Intra Band Non-Contiguous CA			
CA Configuration	CA_4DL_42C_42C_2UL_42C_BCS1			
	Freq. Range	DL UL Ratio	Numerology	Channel BW
CA1	FR1	1:1	0	20 MHz
CA2	FR1	1:1	0	20 MHz
CA3	FR1	1:0	0	20 MHz
CA4	FR1	1:0	0	20 MHz
PDSCH and PUSCH Configuration				
MCS Table	QAM64			
CSI Report Configuration				
CQI Table	TABLE1			
Channel Model				
Pathloss Model	None			

- Frequency range FR1, Numerology = 0, Bandwidth = 20 MHz with QAM 64 MCS table represents a 4G configuration.
- Set Uplink speed and Downlink speed as 10000 Mbps and BER as 0 in all wired links.
- Set Tx Antenna Count as 2 and Rx Antenna Count as 1 in eNB > Interface LTE > Physical Layer.
- Set Tx Antenna Count as 1 and Rx Antenna Count as 2 in UE > Interface LTE > Physical Layer.
- Configure 40 applications with Source id as 3 and Destination id as 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43 and 44 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 applications.

Table 4-24: *Application properties*

Application Properties	
Frame Per Sec	50
Pixel Per Frame	50000
Mu	1
Start Time	1s

- Run simulation for 2 sec. After simulation completes go to results window and note down throughput and delay value from application metrics.

Increase the number of UE's and number of applications as 40, 80, 120, 160, 200, 240 and 280 and note down throughput and delay value from application metrics.

4.6.2 5G

Under 5G click on 40 Nodes Sample, the following network diagram illustrates what the NetSim UI displays when you open the example configuration file.

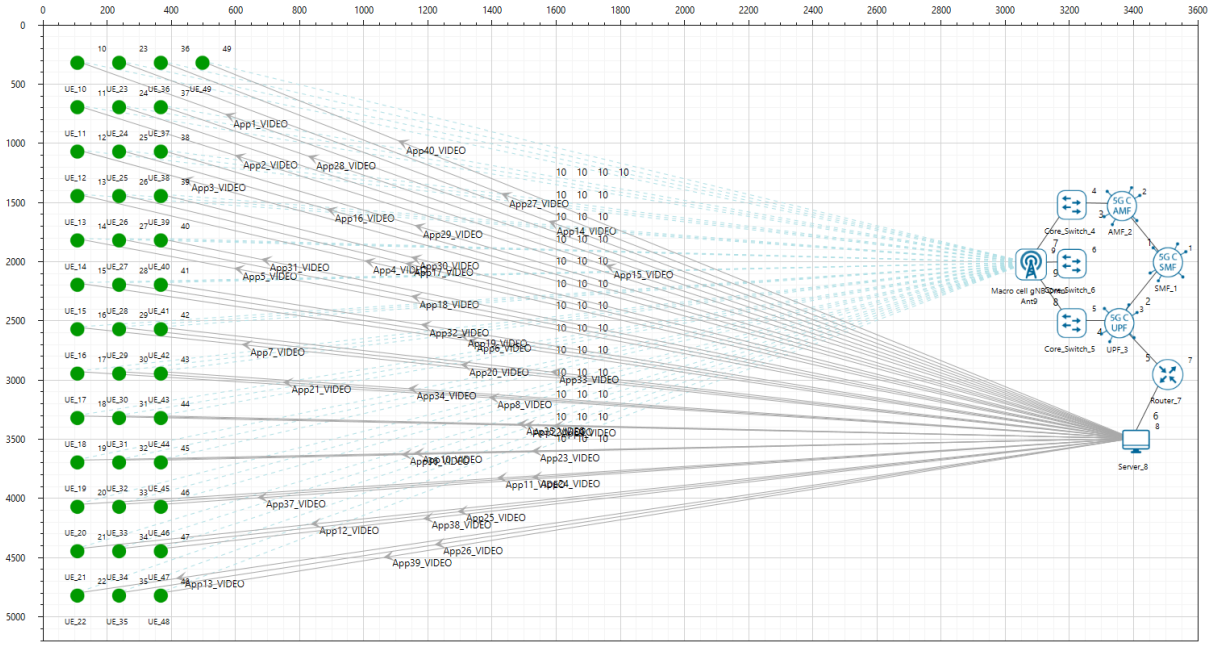


Figure 4-32: *Network setup for studying the 5G.*

Settings done in example config file:

- For the above 5G scenario set the following given properties.

Table 4-25: *gNB > Interface (5G RAN) > Physical layer properties*

gNB Properties → Interface (5G RAN)				
CA Type	Intra Band Contiguous CA			
CA Configuration	CA n258G			
	DL UL Ratio	Frequency Range	Numerology	Channel Bandwidth (MHz)
CA1, CA2	1:1	FR2	3	400
PDSCH and PUSCH Configuration				
MCS Table	QAM256			
CSI Report Configuration				
CQI Table	TABLE2			
Channel Model				
Pathloss Model	None			

- The Tx Antenna Count was set to 2 and Rx Antenna Count was set to 1 in gNB > Interface 5G RAN > Physical Layer.
- The Tx Antenna Count was set to 1 and Rx Antenna Count was set to 2 in UE > Interface 5G RAN > Physical Layer.
- Frequency range FR2, Numerology = 3, Bandwidth = 400 MHz with QAM 256 MCS table represent a 5G configuration
- The Uplink and Downlink speed was set to 10000 Mbps and BER as 0 in wired links.
- Run simulation for 2 sec. After simulation completes go to results window and note down throughput and delay value from application metrics.

- Increase number of UE's and number of applications as 40, 80, 120, 160, 200, 240 and 280 and note down throughput and delay value from application metrics.

$$Throughput\ Per\ User\ (Mbps) = \frac{Sum\ of\ throughputs\ (Mbps)}{Number\ of\ User} \tag{81}$$

$$Delay\ Per\ User\ (\mu s) = \frac{Sum\ of\ Delays\ (\mu s)}{Number\ of\ User} \tag{82}$$

4.6.2.1 Theoretical PHY Rate Calculation

The 4G/5G PHY data rate is given by the expression

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

where $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$

This expression gives the PHY rate; the application throughput would be lower than the PHY rate given the overheads in the various layers.

4G:

Number of carriers: 4, Number of layers = $\min(N_t\ (gNB),\ N_r(UE)) = \min(2, 2) = 2$, Numerology: 0. The BW per carrier is 20 MHz, with each carrier having 100 PRBs. In this experiment settings the DL:UL Ratio is 1:1 for 2 carriers and 1:0 for 2 carriers. Avg DL:UL ratio is 3:1 and hence the DL fraction = $\frac{3}{3+1} = \frac{3}{4}$.

Applying the 4G PHY data rate formula

$$PHY\ Rate = 10^{-6} \left(2 \times 6 \times 1 \times \frac{948}{1024} \times \frac{100 \times 12}{\left(\frac{10^{-3}}{14 \cdot 2^{0}}\right)} \times (1 - 0.25) \right) \times 4 = 559.40 \text{ Mbps} \tag{83}$$

Where 4 is the number of carriers

Multiplying by the DL fraction we obtain the downlink PHY rate as $559.40 \times \frac{3}{4} = 419.93$ Mbps

5G:

Number of carriers: 4, Number of layers = $\min(N_t\ (gNB),\ N_r(UE)) = \min(2, 2) = 2$, Numerology: 3. The BW per carrier is 400 MHz with each carrier having 264 PRBs. In this experiment settings, the DL:UL Ratio: 1:1 for both carriers

Applying the 5G PHY data rate formula, we get

$$PHY\ Rate = 10^{-6} \left(2 \times 8 \times 1 \times \frac{948}{1024} \times \frac{264 \times 12}{\left(\frac{10^{-3}}{14 \cdot 2^{3}}\right)} \times (1 - 0.18) \right) \times 2 = 7568.22 \text{ Mbps} \tag{84}$$

Where 2 is the number of carriers

Multiplying by the DL fraction we obtain the downlink PHY rate as $7568.22 \times \frac{1}{2} = 3784.11$ Mbps.

We vary the UE count from 40 to 280 in steps of 40. Each UE is downloading video at a rate of 2.5 Mbps. Post simulation, we plot the throughput per UE for 4G and 5G as the UE count is increased from 40 to 280.

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4.6.2.2 Results:

Table 4-26: *Aggregated and Average throughput and delay per user with different number of users for LTE 4G and 5G NR*

	4G (Devices downloading video)			5G (Devices downloading video)		
Users	**Per user (Mbps)**	**Agg. (Mbps)**	**Avg delay (μs)**	**Per user (Mbps)**	**Agg. (Mbps)**	**Avg delay (μs)**
40	2.43	97.23	3669.92	2.45	98.08	392.12
80	2.44	195.41	6613.61	2.44	195.69	649.40
120	2.44	293.13	9538.82	2.44	293.29	908.43
160	2.41	386.24	65498.56	2.45	392.18	1171.72
200	2.06	412.68	153012.12	2.44	489.94	1430.69
240	1.71	412.53	211389.46	2.44	587.86	1689.47
280	1.47	412.31	253392.03	2.44	685.70	1946.88

In the earlier section, we had predicted a PHY rate of 419 Mbps. We observe that the aggregate application throughput of 4G saturates at 407 Mbps. The $\approx$ 10% difference is due to the overheads in the various layers. The required rate for each video application is $\approx$ 2.5 Mbps and we see that 4G is able to support full rate for upto 160 UEs. At 200 UEs the capacity required is $\approx 200 \times 2.5 = 500$ Mbps which is more than what is available. Therefore, the rate per user starts decreasing for UE counts of 200, 240 and 280. In line with this, we see that the average delay increases exponentially from 200 UEs onwards.

On the other hand, 5G can handle a PHY rate of 3784 Mbps or $\approx$ 3400 Mbps of application throughput. Thus, we see that 5G is easily able to provide full rate of $\approx$ 2.5 Mbps to each UE even when the total UE count is 280.

Throughput per user vs. Number of users for 4G and for 5G

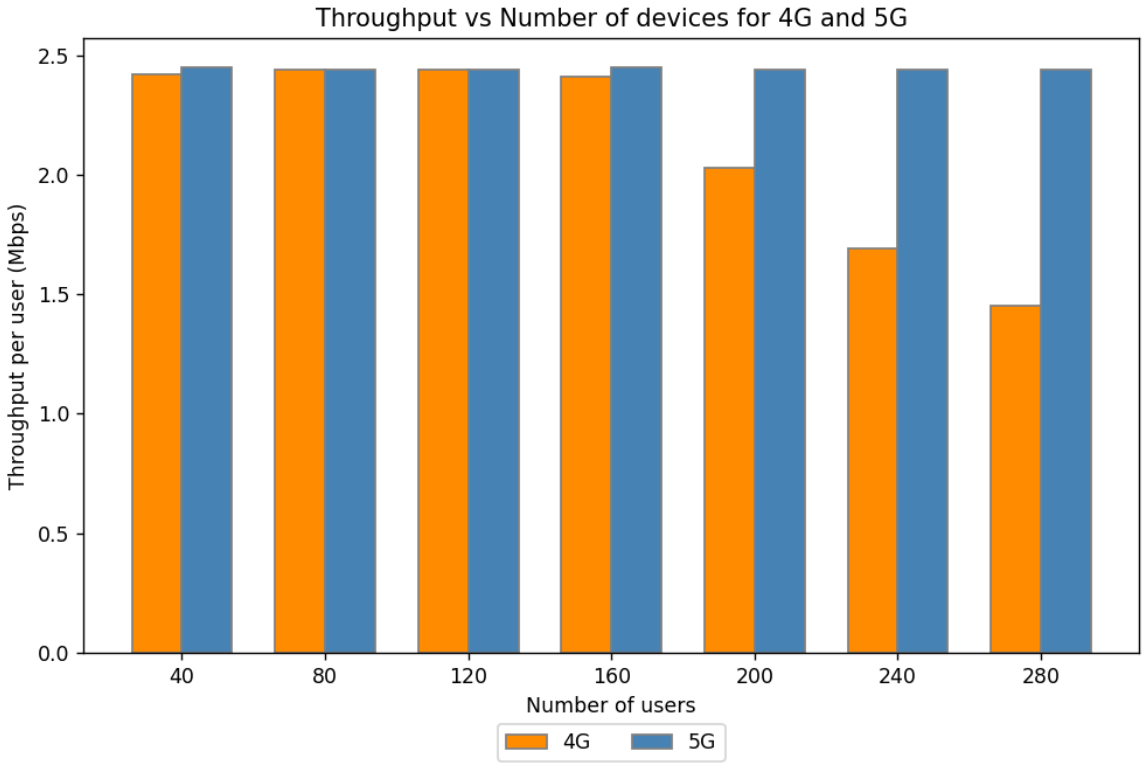


Figure 4-33: *Throughput per user vs Number of Devices for 4G and 5G. The 4G per user throughput starts falling after 160 devices.*

Average delay vs. Number of users for 4G and for 5G

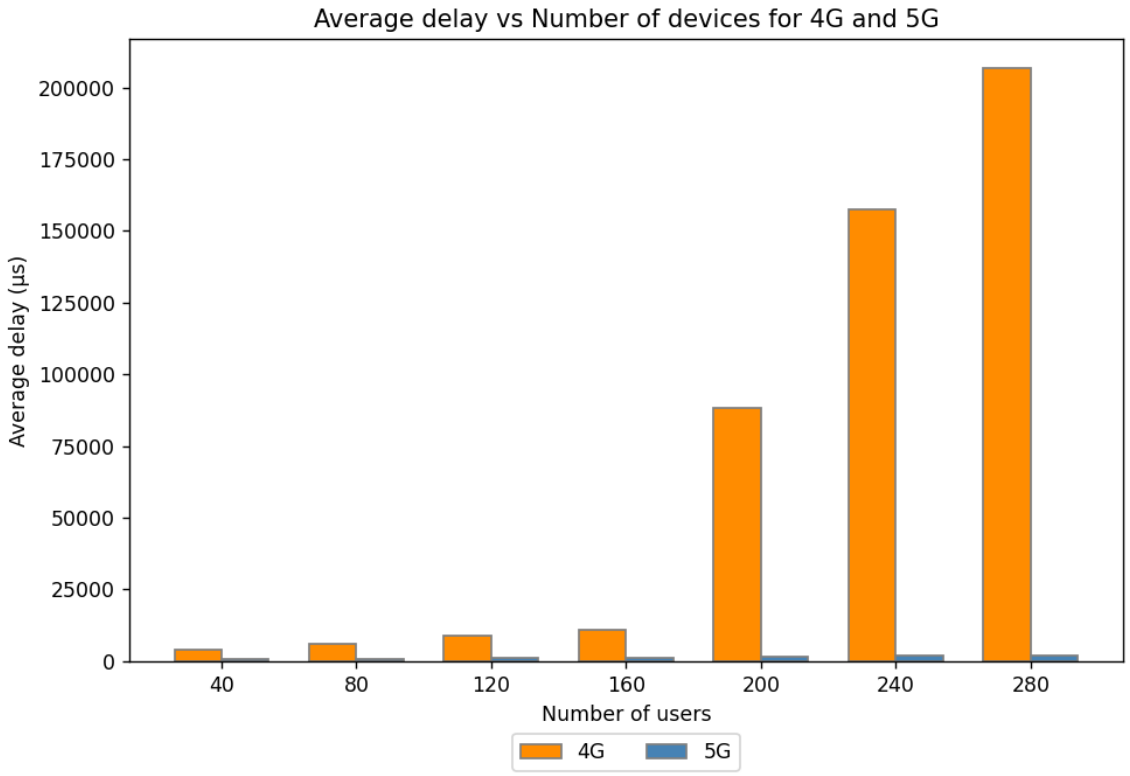


Figure 4-34: *Delay vs Number of Devices. The 5G Network average delay is insignificant i.e., many orders of magnitude lower, and hence not visible in the plot.*

4.7 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

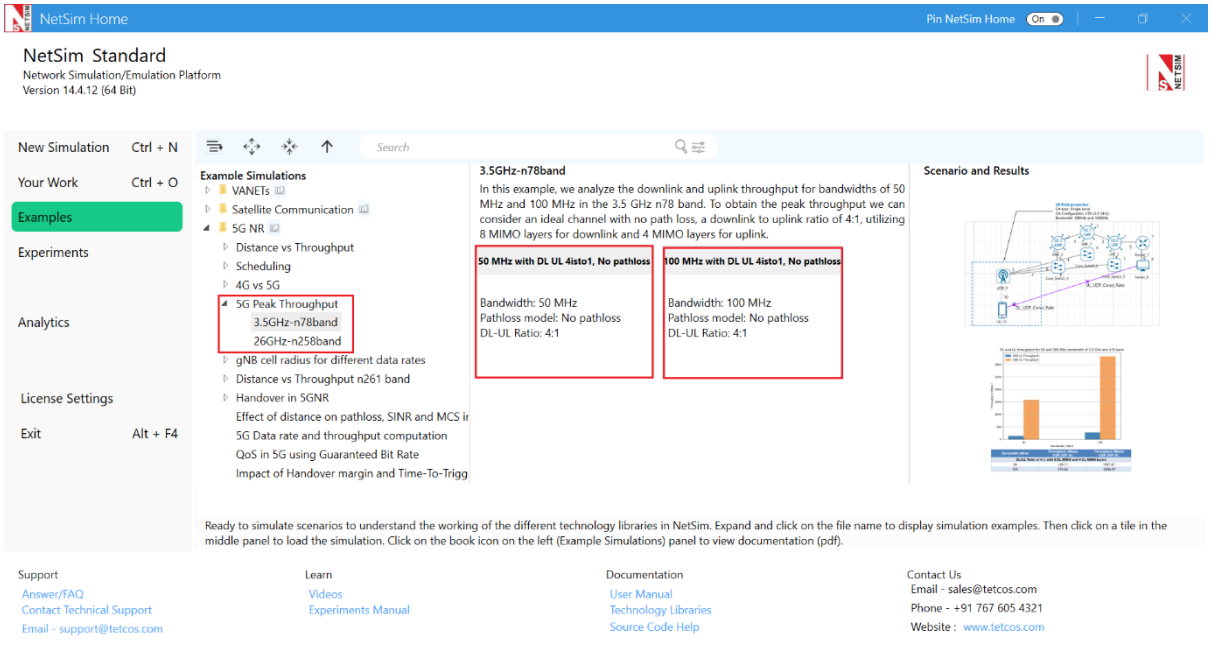


Figure 4-35: *List of scenarios for the example of 5G Peak Throughput*

4.7.1 3.5 GHz n78 band

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

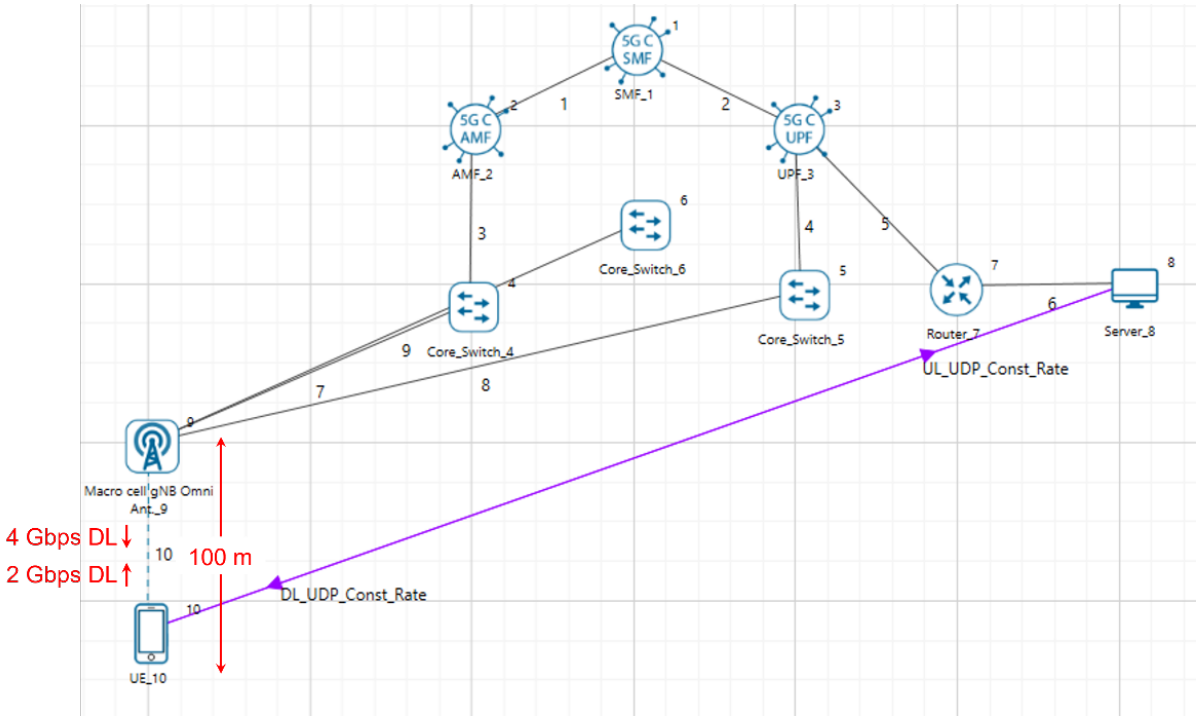


Figure 4-36: *Network setup for studying the 5G Peak Throughput*

Settings done in example config file:

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

Table 4-27: *gNB > Interface (5G RAN) > Physical layer properties*

gNB Properties → Interface (5G RAN)	
CA Type	Single Band
CA Configuration	n78
CA1	
Frequency Range	FR1
DL/UL Ratio	4:1
Numerology	2
Channel Bandwidth	50 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM256
CSI Report Configuration	
CQI Table	TABLE2
Channel Model	
Pathloss Model	None

- The Tx Antenna Count was set to 8 and Rx Antenna Count was set to 4 in gNB > Interface 5G RAN > Physical Layer.
- The Tx Antenna Count was set to 4 and Rx Antenna Count was set to 8 in UE > Interface 5G RAN > Physical Layer.
- Set 2 applications Downlink source node as 8, and destination node as 10, Uplink source node as 10, and destination node as 8. Transport Protocol is set to UDP in all the applications.

Table 4-28: *Application properties*

Application Properties	
App CBR UDP DL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (μs)	2.92
App CBR UDP UL	
Start Time (s)	1
Packet Size (Byte)	1460
Inter Arrival Time (μs)	5.84

- Enable the Throughput vs time plot under Application and link and run simulation for 1.1 sec. After simulation completes go to results 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:

Table 4-29: *Results Comparison*

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	128.71	1597.47
100	270.62	3366.87

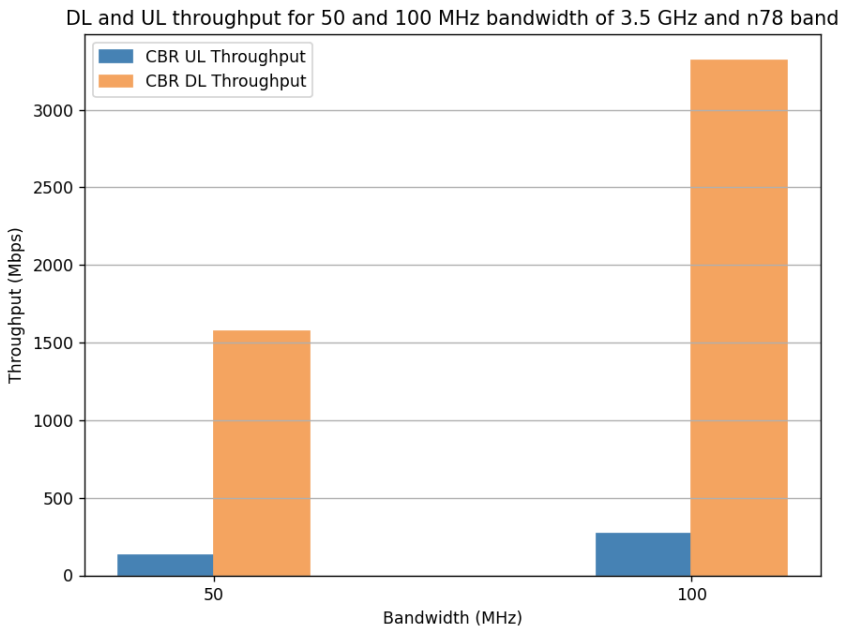


Figure 4-37: *Plot for DL and UL throughput for 50 and 100 MHz bandwidth of 3.5 GHz and n78 band*

4.7.2 26 GHz n258 band

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

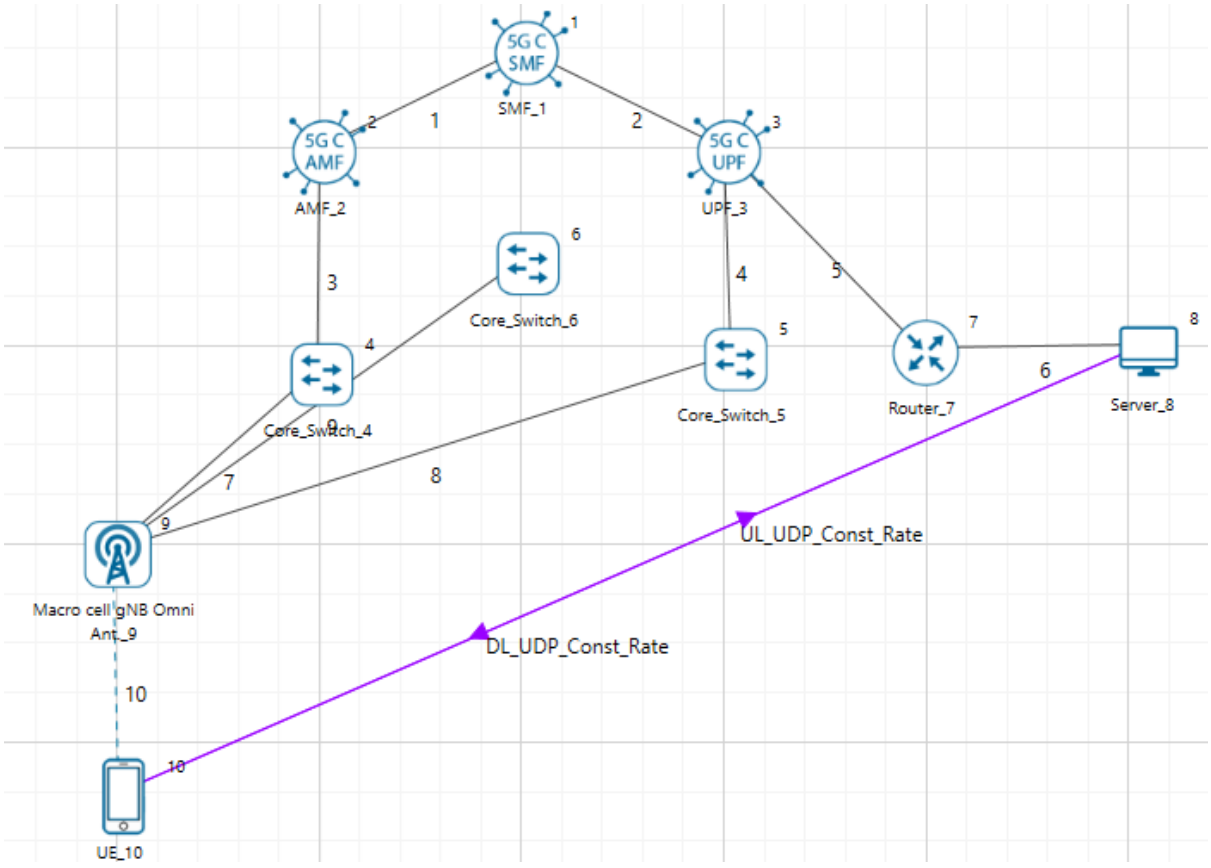


Figure 4-38: *Network setup for studying the 5G Peak Throughput*

Settings done in example config file:

- Set the following property as shown in below Table.

Table 4-30: *gNB > Interface (5G RAN) > Physical layer properties*

gNB Properties → Interface (5G RAN)	
CA Type	Single Band
CA Configuration	n258
Component Carrier 1	
DL/UL Ratio	4:1
Frequency Range	FR2
Numerology	3
Channel Bandwidth	200 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM256
CSI Report Configuration	
CQI Table	TABLE2
Channel Model	
Pathloss Model	None

- The Tx Antenna Count was set to 8 and Rx Antenna Count was set to 4 in gNB > Interface 5G RAN > Physical Layer.
- The Tx Antenna Count was set to 4 and Rx Antenna Count was set to 8 in UE > Interface 5G RAN > Physical Layer.
- Set 2 applications Downlink source node as 8 destination node as 10, Uplink source node as 10 destination node as 8. Transport Protocol is set to UDP in all the applications.

Table 4-31: *Application properties*

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

- After simulation completes go to results 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:

Table 4-32: *Results Comparison*

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	518.35	6283.72
400	1041.15	11648.46

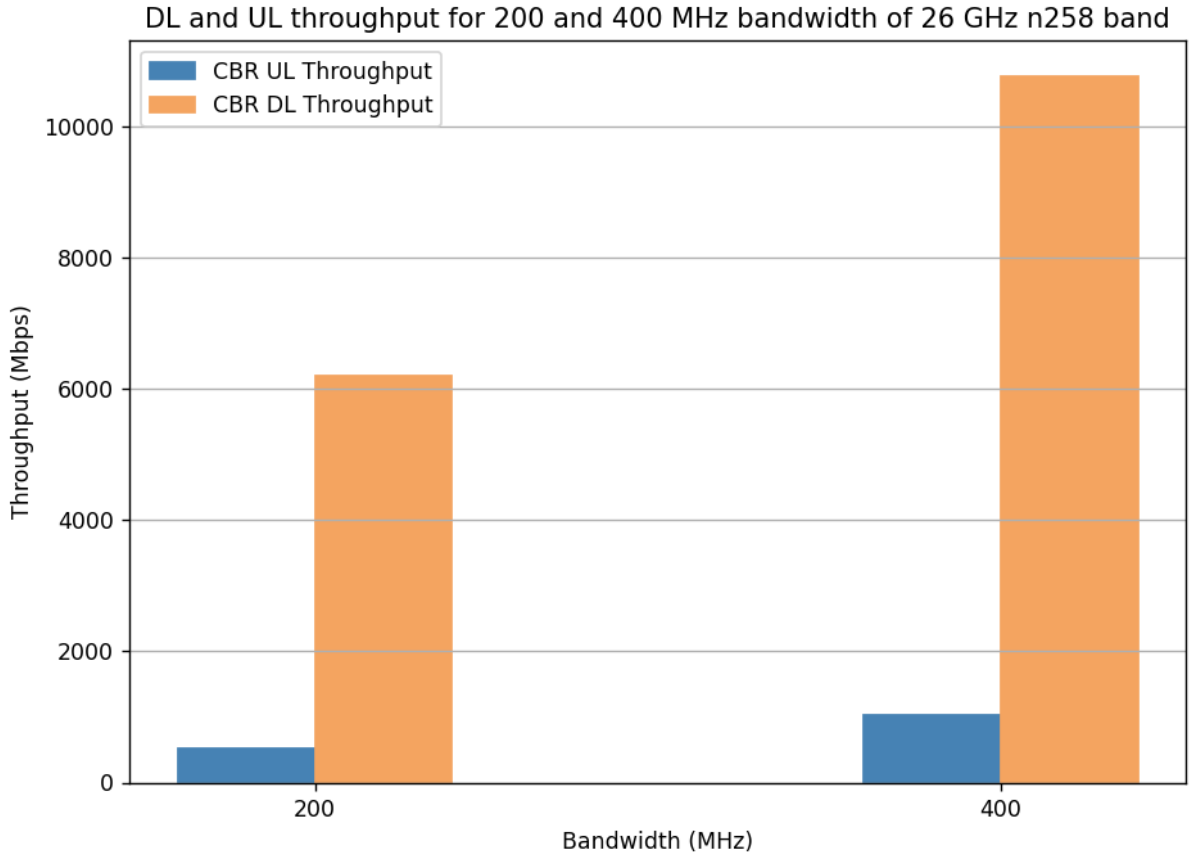


Figure 4-39: *Plot for DL and UL throughput for 200 and 400 MHz bandwidth of 26 GHz and n258 band*

4.8 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

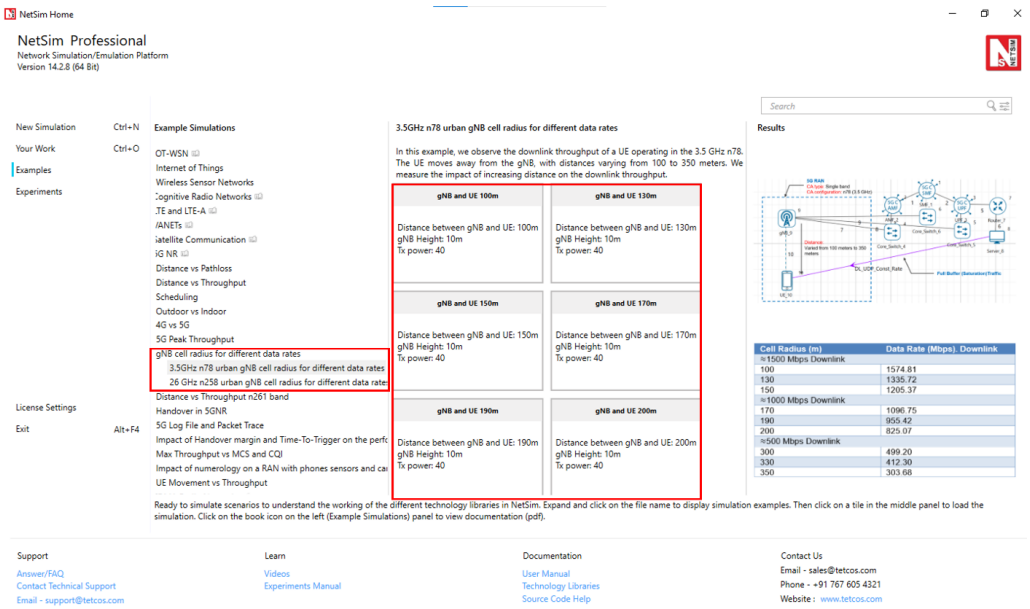


Figure 4-40: *List of scenarios for the example of gNB cell radius for different data rates*

4.8.1 3.5 GHz n78 urban gNB cell radius for different data rates

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

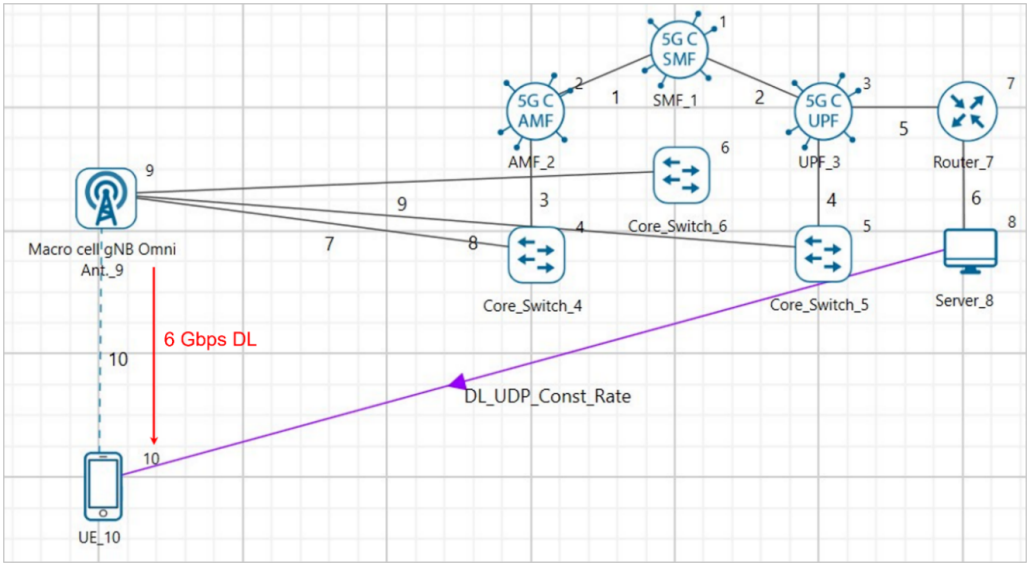


Figure 4-41: *Network setup for studying the gNB cell radius for different data rates.*

Setting done in example config file:

- Set the following property as shown in below Table.

Table 4-33: *gNB > Interface (5G RAN) > Physical layer properties*

gNB Properties → Interface (5G RAN)	
Property	**Value**
gNB Height	10 m
Tx Power	40
CA Type	Single Band
CA Configuration	n78
Component Carrier 1	
DL: UL	4:1
Numerology	2
Channel Bandwidth	50 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM256
CSI Report Configuration	
CQI Table	TABLE2
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS NLOS Selection	3GPP TR 38.901-Table7.4.2-1
Shadow Fading Model	None
Fast Fading Model	No Fading

- Set the Tx Antenna Count as 8 and Rx Antenna Count as 1 in gNB > Interface 5G RAN > Physical Layer.
- Set the Tx Antenna Count as 1 and Rx Antenna Count as 8 in UE > Interface 5G RAN > Physical Layer.
- Set the following application properties:

Table 4-34: *Application properties*

App_1_CBR	**Value**
Source Id	8
Destination Id	10
Packet Size	1460
IAT	1.94 μs
Start time	1 s
Transport Protocol	UDP
Generation Rate	6 Gbps

- Run simulation for 1.1 sec. After simulation completes go to results window and note down throughput value from application metrics.

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Go back to the Scenario and change distance between gNB and UE to 100 m, 130 m, 150 m, 170 m, 190 m, 200 m, 300 m, 330 m, and 350 m and run simulation for 1.1 sec.

Result:

Table 4-35: *Results Comparison*

Cell Radius (m)	Data Rate (Mbps). Downlink
1500 Mbps Downlink	
100	1597.47
130	1421.22
150	1278.02
1000 Mbps Downlink	
170	1167.76
190	969.44
200	925.40
500 Mbps Downlink	
300	506.79
330	418.61
350	374.57

4.8.2 26 GHz n258 urban gNB cell radius for different data rates

Setting done in example config file:

- Set the following property as shown in below given table:

Table 4-36: *gNB > Interface (5G RAN) > Physical layer properties*

gNB Properties → Interface (5G RAN)	
Property	**Value**
gNB Height	10 m
Tx Power	40
CA Type	Single Band
CA Configuration	n258
Component Carrier 1	
DL: UL	4:1
Numerology	2
Channel Bandwidth	200 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM256
CSI Report Configuration	
CQI Table	TABLE2
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS_NLOS Selection	3GPP TR 38.901-Table7.4.2-1
Shadow Fading Model	None
Fast Fading Model	No Fading

- Set the Tx Antenna Count as 8 and Rx Antenna Count as 1 in gNB > Interface 5G RAN > Physical Layer.
- Set the Tx Antenna Count as 1 and Rx Antenna Count as 8 in UE > Interface 5G RAN > Physical Layer.
- Set the following application properties:

Table 4-37: *Application properties*

App 1 CBR	**Value**
Source Id	8
Destination Id	10
Packet Size	1460
IAT	1.94 μs
Start time	1 s
Transport Protocol	UDP
Generation Rate	6 Gbps

- Run simulation for 1.1 sec. After simulation completes go to results window and note down throughput value from application metrics.

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Go back to the Scenario and change distance between gNB and UE to 20 m, 110 m, and 150 m and run simulation for 1.1 sec.

Result:

Table 4-38: *Results Comparison*

Cell Radius (m)	Data Rate (Mbps). Downlink
6000 Mbps Downlink	
20	5989.03
1000 Mbps Downlink	
110	735.48
500 Mbps Downlink	
150	302.86

4.9 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.

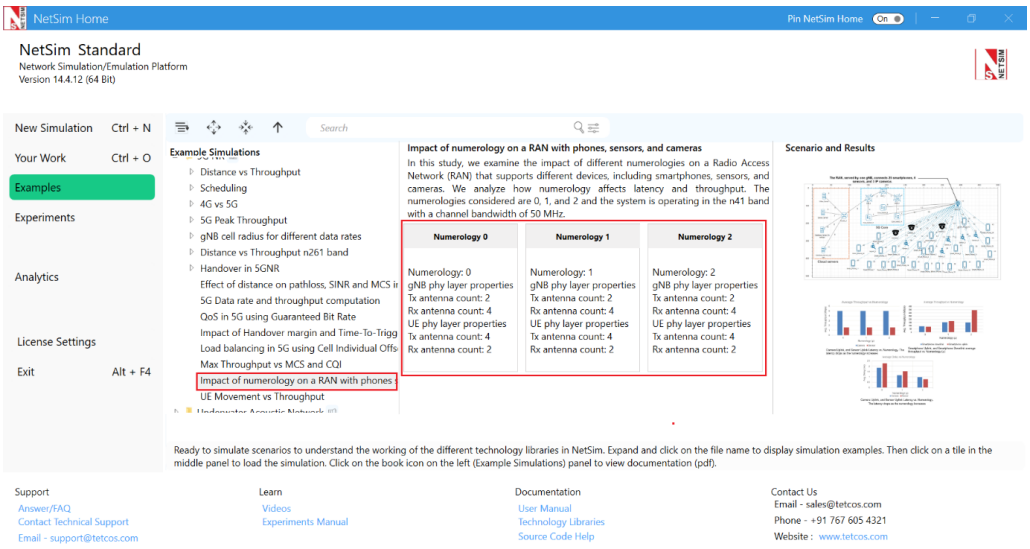


Figure 4-42: *List of scenarios for the example of Impact of numerology on a RAN with phones sensors and cameras*

Network Scenario: To model a real-world scenario, we base our simulation on the setup shown in the Figure below. 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 100 MHz and Round Robin MAC Scheduler. The position of the devices in the reference scenario depicted in the Figure is quasi-random.

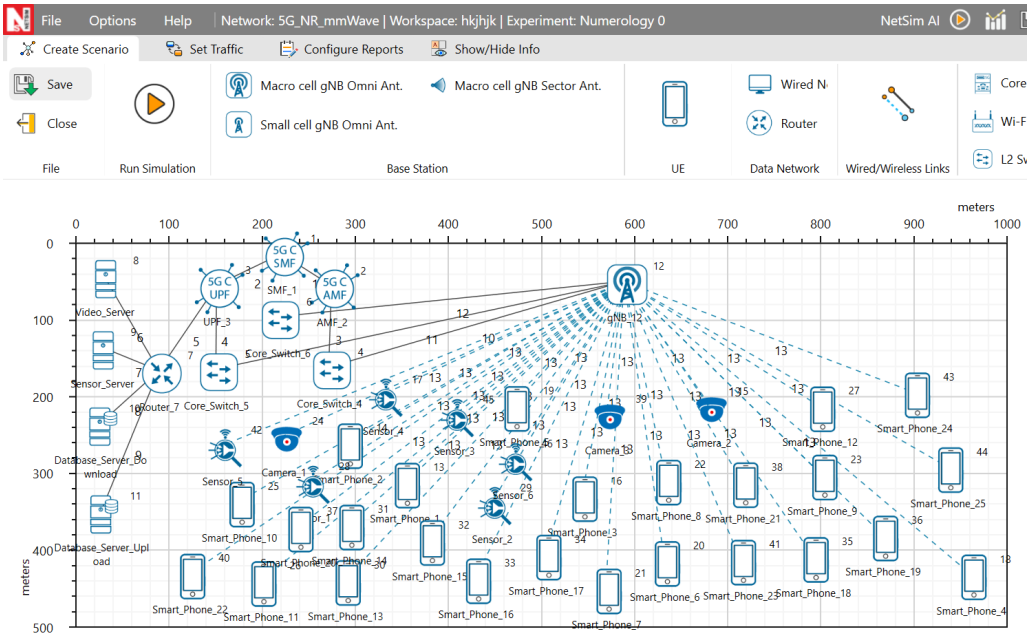


Figure 4-43: *Network setup for studying with 25 smartphones, 6 sensors and 3 cameras communicating with respective cloud servers.*

In terms of application data traffic, the camera (video) and sensor nodes have one UDP flow each, that goes in the UL towards a remote node on the Internet. These flows are fixed-rate flows: we have a continuous transmission of 5 Mb/s for the video nodes, to simulate a 720p24 HD video, and the sensors transmit a payload of 500 bytes each 2.5 ms, that gives a rate of 1.6 Mb/s. For smartphones, we use TCP as the transmission protocol. These connect to database 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.

Table 4-39: *Various parameters of the Traffic flow models for all the devices*

	Flows (No of devices)	Traffic Rate (Mbps)	Segment / File Size (B)	RAN Dir.	TCP ACK Dir.
Camera (UDP)	3	5	500	UL	–
Sensor (UDP)	6	1.6	500	UL	–
Smartphone Upload (TCP)	25	–	1,500,000	UL	DL
Smartphone Download (TCP)	25	–	25,000,000	DL	UL

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 analyzed are a) Throughput of TCP uploads & downloads, and b) Latency of the UDP uploads.

Settings done in example config file:

- For the above scenario set the following given properties:

Table 4-40: *gNB > Interface (5G RAN) > Physical layer properties*

Property	Value
Pathloss Model	None
CA Type	Inter Band CA
CA Configuration	CA_2DL_2UL_n40_n41
CA1	
DL UL Ratio	1:4
Frequency Range	FR1
Numerology	0, 1, and 2
Channel Bandwidth	50 MHz
CA2	
DL UL Ratio	1:4
Frequency Range	FR1
Numerology	0, 1, and 2
Channel Bandwidth	50 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM64
CSI Report Configuration	
CQI Table	TABLE1
Channel Model	
Pathloss Model	None

- The following Application properties set to the above scenario:

Table 4-41: *Sensor Application Properties for UL UDP*

Sensor UL UDP	Value
Generation Rate (Mbps)	1.6
Transport Protocol	UDP
Application Type	Custom
Packet Size (Bytes)	500
Inter Arrival Time (μs)	2500

Table 4-42: *Camera Application Properties for UL UDP.*

Camera UL UDP	Value
Generation Rate (Mbps)	5
Transport Protocol	UDP
Application Type	Custom
Packet Size (Bytes)	500
Inter Arrival Time (μs)	800

Table 4-43: *Phone Application Properties for DL TCP*

Phone DL TCP	Value
Transport Protocol	TCP
Start Time (s)	0, 1, 2, . . . , 48
Stop Time (s)	95
File Size (Bytes)	25,000,000
Inter Arrival Time (s)	200 (Simulation ends at 110 s and hence only one file is sent)
Application Type	FTP

Table 4-44: *Phone Application Properties for UL TCP*

Phone UL TCP	Value
Application Type	FTP
Transport Protocol	TCP
Start Time (s)	$4.5 + 4(i - 1)$ Where, $i = 1, 2, \ldots, 25$
Stop Time (s)	100
File Size (Bytes)	1,500,000
Inter Arrival Time (s)	200 (Simulation ends at 110 s and hence only one file is sent)

- The Tx Antenna Count was set to 2 and Rx Antenna Count was set to 4 in gNB > Interface 5G RAN > Physical Layer.
- The Tx Antenna Count was set to 4 and Rx Antenna Count was set to 2 in UE > Interface 5G RAN > Physical Layer.
- Run simulation for 110 sec. After simulation completes go to results window and note down throughput and delay value from application metrics.

Result and Analysis:

Table 4-45: *Throughput and delay for Camera, Sensors and Smartphones, when $\mu = 0$*

Camera Uplink Throughput (Mbps)	Delay (μs)	Sensor Uplink Throughput (Mbps)	Delay (μs)	Smartphone Downlink Throughput (Mbps)	Uplink Throughput (Mbps)
5.00	1801.94	1.60	2252.64	101.68	86.32
5.00	1803.13	1.60	2254.25	101.68	86.32
5.00	1804.67	1.60	2256.92	101.68	86.32
		1.60	2256.38	101.68	86.32
		1.60	2257.37	101.68	86.32
		1.60	2254.70	101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
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				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32
				101.68	86.32

Table 4-46: *Throughput and delay for Camera, Sensors and Smartphones, when $\mu = 1$*

Camera Uplink Throughput (Mbps)	Delay (μs)	Sensor Uplink Throughput (Mbps)	Delay (μs)	Smartphone Downlink Throughput (Mbps)	Uplink Throughput (Mbps)
5.00	901.86	1.60	1502.24	156.43	172.61
5.00	902.57	1.60	1503.20	156.43	172.61
5.00	903.47	1.60	1505.04	156.43	172.61
		1.60	1504.59	156.43	172.61
		1.60	1505.48	156.43	172.61
		1.60	1503.65	156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
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				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61
				156.43	172.61

Table 4-47: *Throughput and delay for Camera, Sensors and Smartphones, when $\mu = 2$*

Camera Uplink Throughput (Mbps)	Delay (μs)	Sensor Uplink Throughput (Mbps)	Delay (μs)	Smartphone Downlink Throughput (Mbps)	Uplink Throughput (Mbps)
5.00	451.78	1.60	751.98	151.75	345.10
5.00	453.33	1.60	752.68	151.75	345.10
5.00	456.98	1.60	754.26	151.75	345.10
		1.60	753.81	151.75	345.10
		1.60	754.71	151.75	345.10
		1.60	753.12	151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.11
				151.75	345.10
				151.75	345.10
				151.75	345.10
				151.75	345.10

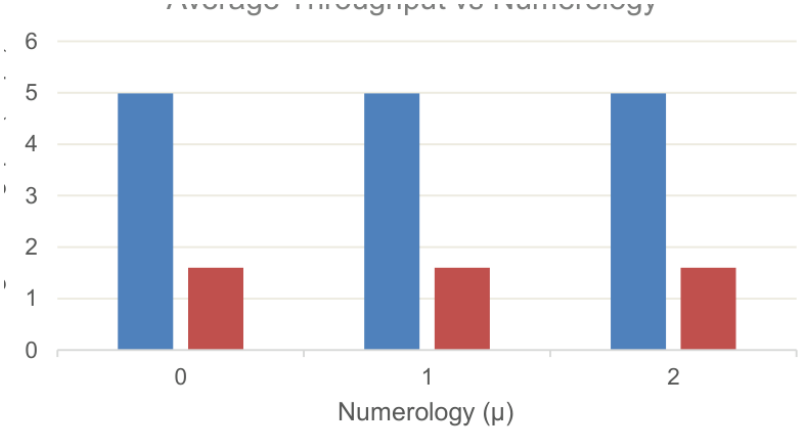


Figure 4-44: *The average uplink throughput for camera and sensors remains the same as numerology is increased. This is because the flow is UDP.*

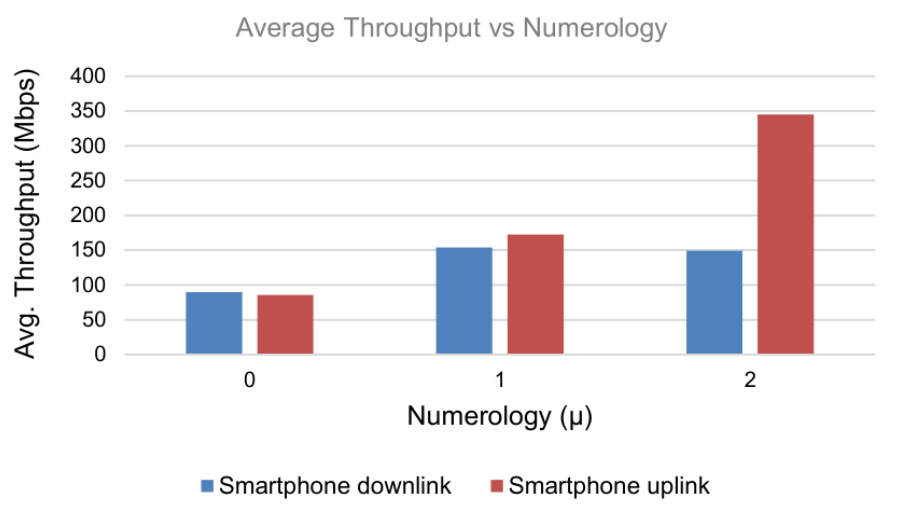


Figure 4-45: *Smartphone Uplink, and Smartphone Downlink average throughput vs. Numerology (μ)*

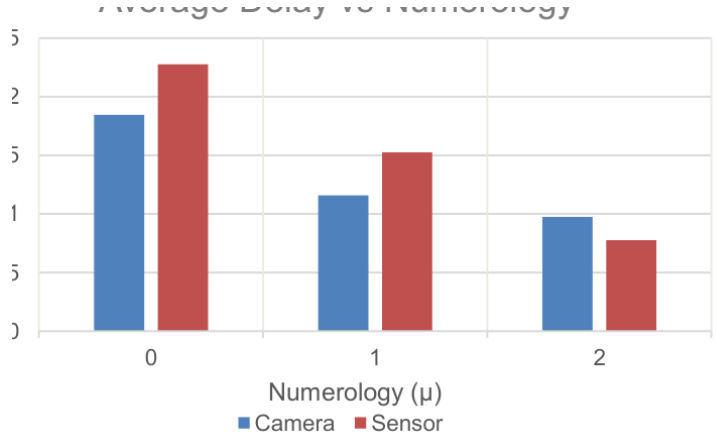


Figure 4-46: *Camera Uplink, and Sensor Uplink Latency vs. Numerology. The latency drops as the numerology increases*

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:

Table 4-48: *Variation of delay vs. numerology for Camera and Sensors*

	Avg Delay (Camera)	Avg Delay (Sensor)
$\mu = 0$	1.838 ms	2.26 ms
$\mu = 1$	0.930 ms	1.51 ms
$\mu = 2$	0.476 ms	0.75 ms

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.

4.10 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.

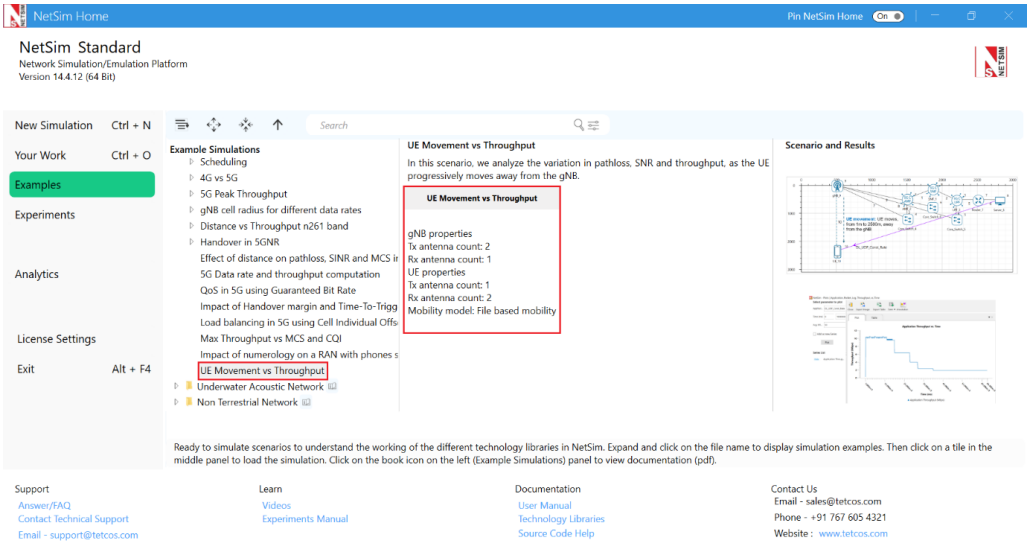


Figure 4-47: *List of scenarios for the example of UE Movement vs Throughput*

NetSim UI displays the configuration file corresponding to this experiment as shown below.

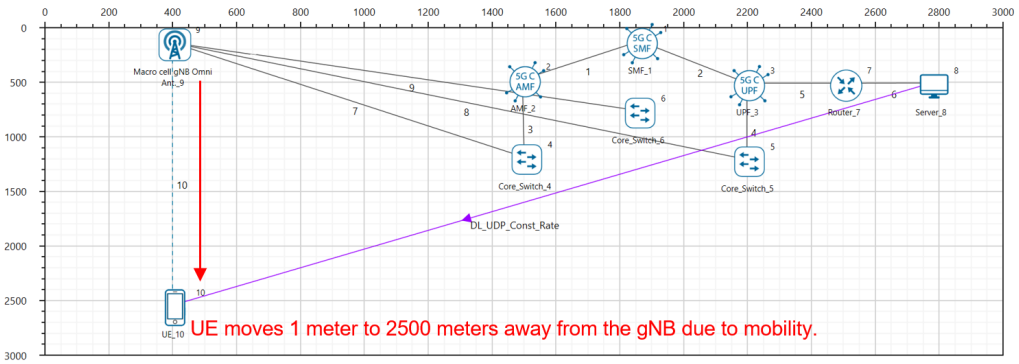


Figure 4-48: *Network setup for studying Throughput vs. UE Movement*

The following set of procedures were done to generate this sample:

Step 1: A network scenario is designed in NetSim GUI consisting 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 7000 m × 3500 m.

Step 3: The device positions are set as per the table given below.

Table 4-49: *Device general properties*

Device	UE_10	gNB_9
x-axis	500	500
y-axis	600	0

Step 4: The following properties were set in Interface (5G RAN) of gNB

Table 4-50: *gNB > Interface (5G RAN) > Physical layer properties*

Parameter	Value
Tx Power	40
gNB Height	10 m
CA Type	Single Band
CA Configuration	n78
Component Carrier 1	Component Carrier 1
DL-UL Ratio	4:1
Numerology	0
Channel Bandwidth	10 MHz
PDSCH and PUSCH Configuration	
MCS Table	QAM64LOWSE
CSI Report Configuration	
CQI Table	TABLE3
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Propagation Model	Urban Macro
LOS NLOS Selection	User Defined
LOS Probability	0
Shadow Fading Model	None
Fast Fading Model	No Fading

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 Position Properties of UE 8, set Mobility Model as File Based Mobility

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	10	500	601	0
4	10	500	701	0
8	10	500	801	0
12	10	500	901	0
16	10	500	1001	0
20	10	500	1101	0
24	10	500	1201	0
28	10	500	1301	0
32	10	500	1401	0
36	10	500	1501	0
40	10	500	1601	0
44	10	500	1701	0
48	10	500	1801	0
52	10	500	1901	0
56	10	500	2001	0
60	10	500	2101	0
64	10	500	2201	0
68	10	500	2301	0
72	10	500	2401	0
76	10	500	2501	0
80	10	500	2601	0
84	10	500	2701	0
88	10	500	2801	0
90	10	500	2901	0
92	10	500	3001	0
94	10	500	2601	0
96	10	500	2701	0
98	10	500	2801	0
100	10	500	2901	0
102	10	500	3001	0
104	10	500	3101	0

Figure 4-49: *mobility.csv file.*

Step 8: A CBR Application was generated from set traffic tab in top ribbon between Wired node and UE 10 (Source as Server and destination as UE) with Packet Size of 1460 Bytes and Inter Arrival Time of 1168 μs.

Step 10: The Transport Protocol is set to UDP. Additionally, the "Start Time(s)" parameter is set to 1 s. To configure it, click on created application, change the properties accordingly in

the right-side property panel.

Step 11: Application throughput vs time plot under Application and Link performance is enabled from the configure reports tab in plots tab in the NetSim GUI. Additionally, LTE Radio measurements log is enabled for detailed analysis.

Step 12: Run simulation for 105 s.

Results:

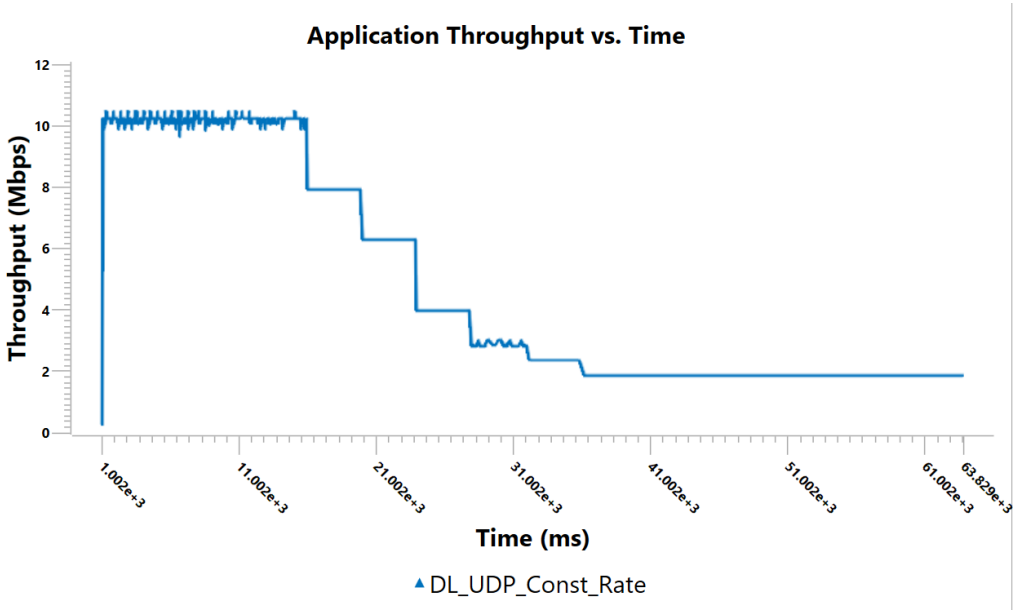


Figure 4-50: *Plot of Throughput (Mbps) vs Time (sec).*

Discussion

As the UE moves away from the gNB, the Application throughput starts reducing. The maximum throughput of 10 Mbps is obtained until 11.9 sec. At 16 s the UE is 1000 m away from the gNB, then the throughput drops to 6.30 Mbps and at time 36.6 sec (when UE is 1800 m away from gNB), the throughput drops to 1.86 Mbps and subsequently keeps dropping as till the end of the simulation as the UE continues to move further away from the gNB.

4.11 Simulate and study the 5G Handover procedure

4.11.1 Introduction

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. Ericsson Research). The algorithm enables each UE to connect to that gNB which provides the highest Reference Signal Received Power (RSRP). Therefore, a handover occurs the moment a better gNB (adjacent cell has offset stronger RSRP, measured as SNR in NetSim) is detected.

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 event Triggered since NetSim is a discrete event simulator and not a continuous time simulator.

This algorithm is susceptible to ping-pong handovers; continuous handovers between the serving and adjacent cells on account of changes in RSRP due mobility and shadow-fading. At one

instant the adjacent cell's RSRP 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:

1. Hysteresis (Hand-over-margin, HOM) which adds a RSRP threshold (Adjacent cell RSRP – Serving cell RSRP > Hand-over-margin or hysteresis), and
2. Time-to-trigger (TTT) which adds a time threshold.

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

4.11.2 Network Setup

Open NetSim and click on Examples > 5G NR > Handover in 5GNR > Handover Algorithm then click on the tile in the middle panel to load the example as shown in below Figure.

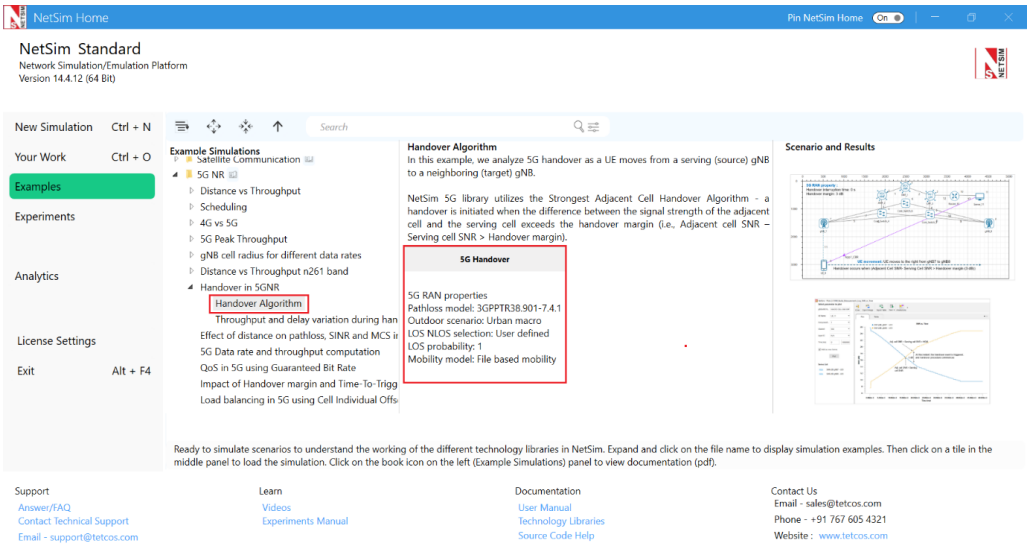


Figure 4-51: *List of scenarios for the example of Handover in 5GNR*

4.11.3 Handover Algorithm

NetSim UI displays the configuration file corresponding to this experiment as shown below.

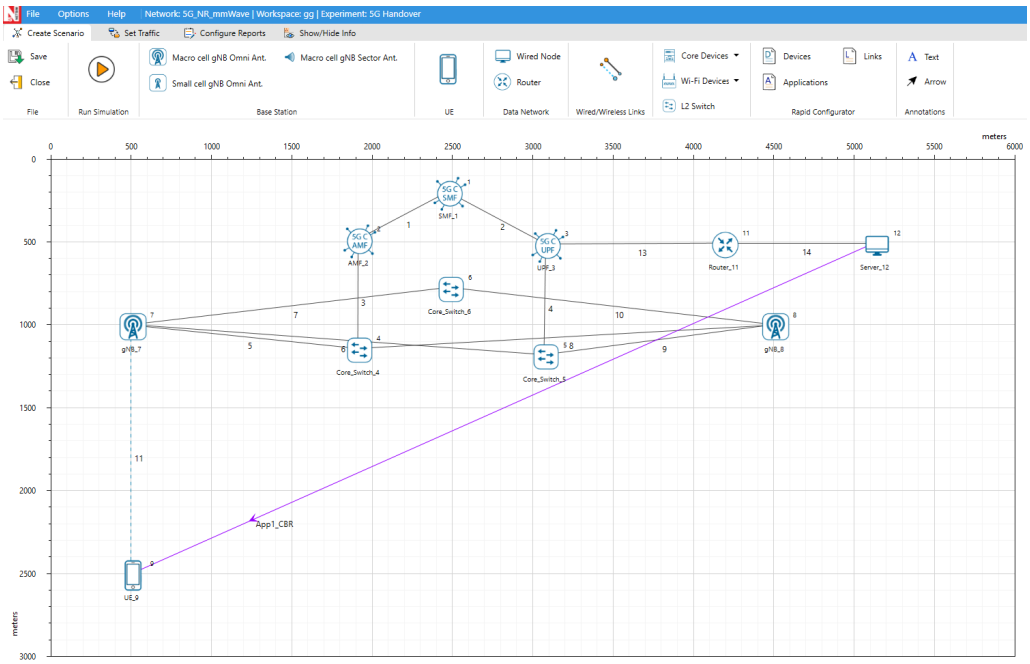


Figure 4-52: *Network setup for studying the 5G handover*

Procedure for 5G Handover

The following set of procedures were done to generate this sample:

Step 1: A network scenario is designed in NetSim GUI consisting of 5G-Core devices, 2 gNBs, and 1 UE in the "5G NR" Network Library.

Step 2: The device positions are set as per the table given below.

Table 4-51: *Device positions*

	gNB 7	gNB 8	UE 9
X Coordinate	500	4500	500
Y Coordinate	1000	1000	2500

Step 3: In the Position properties of UE 9, set Mobility Model as File Based Mobility.

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 0.5 sec with distance 50 m.

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

Table 4-52: *mobility.csv file*

#Time(s)	Device ID	X	Y	Z
0	9	550	2500	0
0.5	9	1000	2500	0
1	9	1050	2500	0

#Time(s)	Device ID	X	Y	Z
1.5	9	1100	2500	0
2	9	1150	2500	0
2.5	9	1200	2500	0
3	9	1250	2500	0
3.5	9	1300	2500	0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
38	9	3900	2500	0
39	9	3950	2500	0
40	9	4000	2500	0

Step 4: Click on the gNB 7 and expand the right-side property panel and set as following Table.

Table 4-53: *gNB 7 > 5G RAN Interface Properties Window*

Interface 4 (5G RAN) Properties	Value
CA Type	Single Band
CA Configuration	n78
CA Count	1
Component Carrier 1	
DL UL Ratio	4:1
Numerology	0
Channel Bandwidth (MHz)	10
PRB Count	52
PDSCH Configuration	
MCS Table	QAM64LOWSE
X Overhead	XOH0
PUSCH Configuration	
MCS Table	QAM64LOWSE
CSI Report Configuration	
CQI Table	Table 3
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS NLOS Selection	User Defined
LOS Probability	1
Shadow Fading Model	None
Fast Fading Model	No Fading
O2I Building Penetration Model	Low_loss_model
Additional Loss Model	None

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Similarly, it is set for gNB 8.

Step 5: The Tx Antenna Count was set to 2 and Rx Antenna Count was set to 1 in gNB > Interface (5G RAN) > Physical Layer.

Step 6: The Tx Antenna Count was set to 1 and Rx Antenna Count was set to 2 in UE > Interface (5G RAN) > Physical Layer.

Step 7: Configure CBR application from Server 12 to UE 9 by clicking on the set traffic tab in ribbon on the top. Then, click on the created application and expand the application property on the right and set the start time to 40 seconds, and QOS to UGS.

Step 8: Packet Trace is enabled by clicking on Configure reports tab. At the end of the simulation, a very large .csv file contains all the packet information and is available for the users to perform packet level analysis.

Step 9: LTENR Radio measurement, Handover log and SNR vs Time plot under LTENR Radio Measurements plots are enabled by clicking on plots/logs from right panel for detailed analysis.

Step 10: Run the Simulation for 50 Seconds.

Results and Discussion

Handover Signaling

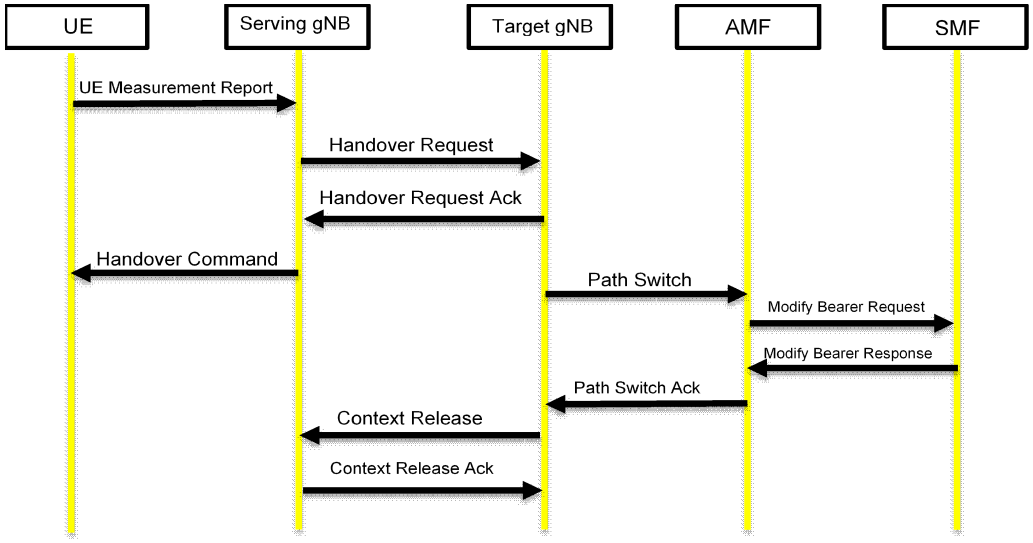
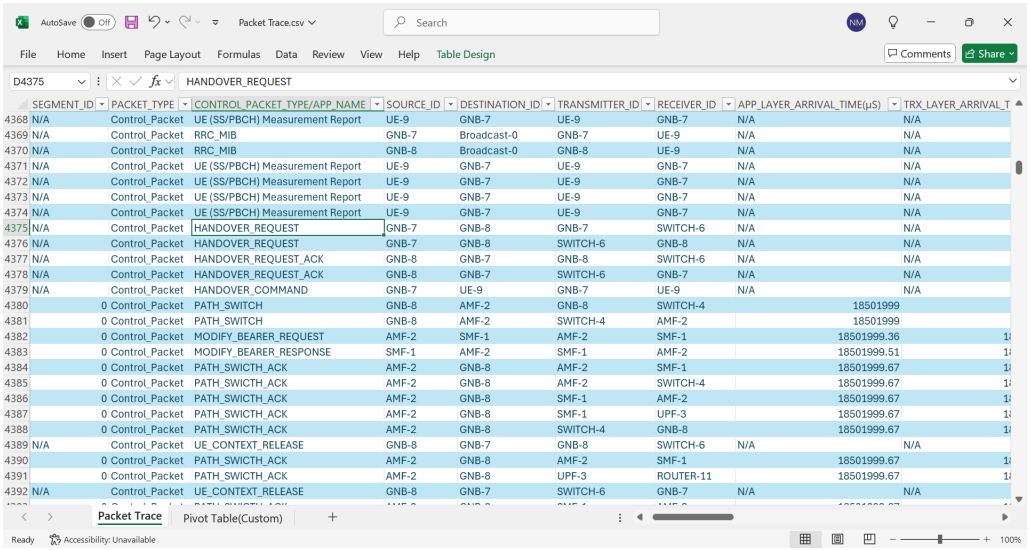


Figure 4-53: *Control packet flow in the 5G handover process*

The packet flow depicted above can be observed from the packet trace.

- UE will send the UE MEASUREMENT REPORT every 5 ms to the connected gNB
- The initial UE-gNB connection and UE association with the core takes place by transferring the RRC and Registration, session request response packets.
- As Per the configured file-based mobility, UE 9 moves towards gNB 8.
- After 18.5 s gNB 7 sends the HANDOVER REQUEST to gNB 8.
- gNB 8 sends back HANDOVER REQUEST ACK to gNB 7.
- After receiving HANDOVER REQUEST ACK from gNB 8, gNB 7 sends the HANDOVER COMMAND to UE 9

- After the HANDOVER COMMAND packet is transferred to the UE, the target gNB will send the PATH SWITCH packet to the AMF via Switch 4.
- When the AMF receives the PATH SWITCH packet, it sends MODIFY BEARER REQUEST to the SMF
- The SMF on receiving the MODIFY BEARER REQUEST provides an acknowledgement to the AMF.
- 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 via Switch 4.
- The target gNB sends CONTEXT RELEASE to source gNB, and the source gNB sends back CONTEXT RELEASE ACK to target gNB. The context release request and ack packets are sent between the source and target gNB via Switch 6.
- RRC Reconfiguration will take place between target gNB and UE 9.
- The UE 9 will start sending the UE (SS/PBCH) MEASUREMENT REPORT to gNB 8.



	SEGMENT_ID	PACKET_TYPE	CONTROL_PACKET_TYPE/APP_NAME	SOURCE_ID	DESTINATION_ID	TRANSMITTER_ID	RECEIVER_ID	APP_LAYER_ARRIVAL_TIME(µS)	TRX_LAYER_ARRIVAL_T
4368	N/A	Control_Packet	UE (SS/PBCH) Measurement Report	UE-9	GNB-7	UE-9	GNB-7	N/A	N/A
4369	N/A	Control_Packet	RRC_MIB	GNB-7	Broadcast-0	GNB-7	UE-9	N/A	N/A
4370	N/A	Control_Packet	RRC_MIB	GNB-8	Broadcast-0	GNB-8	UE-9	N/A	N/A
4371	N/A	Control_Packet	UE (SS/PBCH) Measurement Report	UE-9	GNB-7	UE-9	GNB-7	N/A	N/A
4372	N/A	Control_Packet	UE (SS/PBCH) Measurement Report	UE-9	GNB-7	UE-9	GNB-7	N/A	N/A
4373	N/A	Control_Packet	UE (SS/PBCH) Measurement Report	UE-9	GNB-7	UE-9	GNB-7	N/A	N/A
4374	N/A	Control_Packet	UE (SS/PBCH) Measurement Report	UE-9	GNB-7	UE-9	GNB-7	N/A	N/A
4375	N/A	Control_Packet	HANDOVER_REQUEST	GNB-7	GNB-8	GNB-7	SWITCH-6	N/A	N/A
4376	N/A	Control_Packet	HANDOVER_REQUEST	GNB-7	GNB-8	SWITCH-6	GNB-8	N/A	N/A
4377	N/A	Control_Packet	HANDOVER_REQUEST_ACK	GNB-8	GNB-7	GNB-8	SWITCH-6	N/A	N/A
4378	N/A	Control_Packet	HANDOVER_REQUEST_ACK	GNB-8	GNB-7	SWITCH-6	GNB-7	N/A	N/A
4379	N/A	Control_Packet	HANDOVER_COMMAND	GNB-7	UE-9	GNB-7	UE-9	N/A	N/A
4380	0	Control_Packet	PATH_SWITCH	GNB-8	AMF-2	GNB-8	SWITCH-4	18501999	
4381	0	Control_Packet	PATH_SWITCH	GNB-8	AMF-2	SWITCH-4	AMF-2	18501999	
4382	0	Control_Packet	MODIFY_BEARER_REQUEST	AMF-2	SMF-1	AMF-2	SMF-1	18501999.36	1
4383	0	Control_Packet	MODIFY_BEARER_RESPONSE	SMF-1	AMF-2	SMF-1	AMF-2	18501999.51	1
4384	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	AMF-2	SMF-1	18501999.67	1
4385	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	AMF-2	SWITCH-4	18501999.67	1
4386	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	SMF-1	AMF-2	18501999.67	1
4387	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	SMF-1	UPF-3	18501999.67	1
4388	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	SWITCH-4	GNB-8	18501999.67	1
4389	N/A	Control_Packet	UE_CONTEXT_RELEASE	GNB-8	GNB-7	GNB-8	SWITCH-6	N/A	N/A
4390	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	AMF-2	SMF-1	18501999.67	1
4391	0	Control_Packet	PATH_SWICTH_ACK	AMF-2	GNB-8	UPF-3	ROUTER-11	18501999.67	1
4392	N/A	Control_Packet	UE_CONTEXT_RELEASE	GNB-8	GNB-7	SWITCH-6	GNB-7	N/A	N/A

Figure 4-54: *Screenshot of NetSim packet trace file showing the control packets involved in handover. Some columns have been hidden before the last column.*

Plot of SNR vs. Time

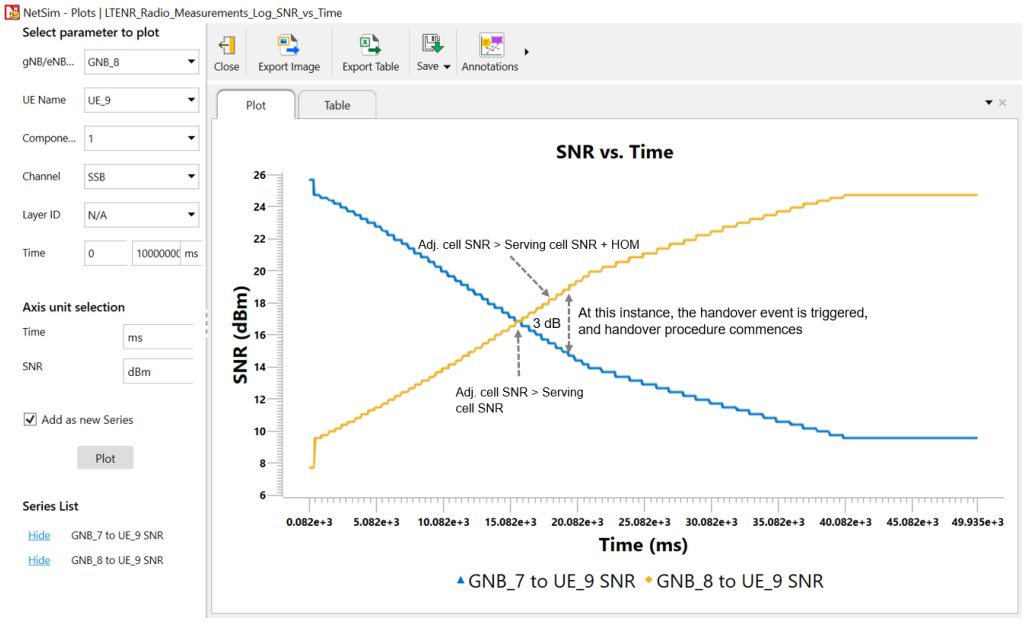


Figure 4-55: *Plot of the DL SNR over time seen by the UE from the serving cell (gNB 7) and the target cell (gNB 8). The handover process does not commence with Adj. cell SNR is greater than Serving cell SNR but only commences with Adj. cell SNR is greater than Serving cell SNR by the Handover margin (3 dB in this case).*

This chart can be obtained in NetSim by enabling the option to plot SNR vs. time prior to the simulation. First, plot the SNR curve for gNB7 and UE9 keeping the channel as SSB. Then select "Add as new series" and select the gNB/eNB as gNB8 and UE name as UE9. Click on plot, and you would then obtain the above "stacked" plot

- At 15.6 seconds, the signal-to-noise ratio (SNR) from both gNB7 and gNB8 is 16.84 dB. This is the point where the SNR curves for both gNBs intersect.
- At 18.6 seconds, the SNR from gNB7 is 15.21 dB and the SNR from gNB8 is 18.54 dB. This is the point where Adj cell RSRP from gNB8 exceeds the serving cell RSRP by the handover margin (HOM) of 3 dB.

4.11.4 Throughput and delay variation during handover

NetSim UI displays the configuration file corresponding to this experiment as shown below.

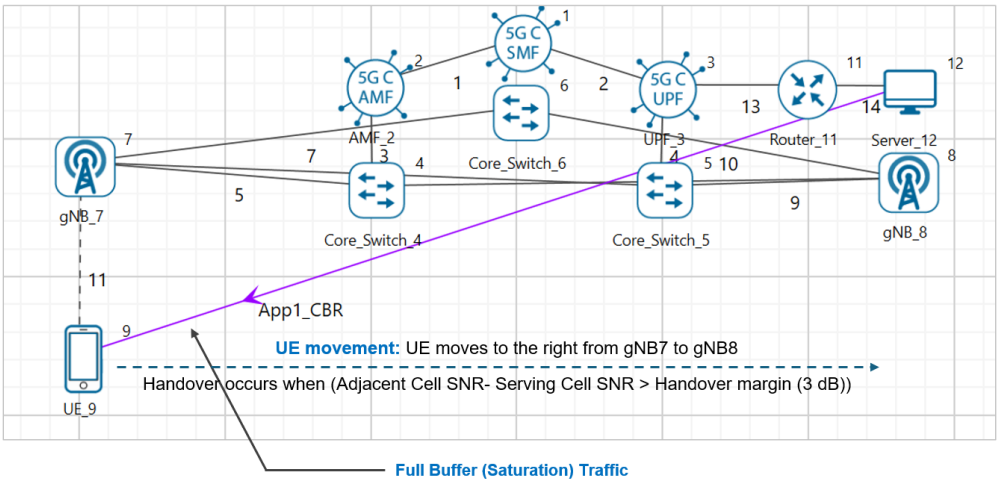


Figure 4-56: *Network set up for studying the Throughput and delay variation during handover.*

Procedure for Effect of Handover on Delay and Throughput

The following set of procedures were done to generate this sample:

Step 1: A network scenario is designed in NetSim GUI consisting of 2 gNBs, 5G Core, 1 Router, 1 Wired Node and 1 UE in the "5G NR" Network Library.

Step 2: The device positions are set as per the table given below.

Table 4-54: *Device positions*

	gNB 7	gNB 8	UE 9
X Coordinate	500	4500	500
Y Coordinate	500	500	1000

Sep 3: Click on the gNB 7 and expand the right-hand side properties, and set as following

Table 4-55: *gNB 7 > Interface(5G RAN) Properties Setting*

Interface (5G RAN) Properties	Value
CA Type	Single Band
CA Configuration	n78
CA Count	1
Component Carrier 1	Component Carrier 1
DL UL Ratio	4:1
Numerology	0
Channel Bandwidth (MHz)	10
PRB Count	52
PDSCH Configuration	
MCS Table	QAM64
X Overhead	XOH0
PUSCH Configuration	

Interface (5G RAN) Properties	Value
MCS Table	QAM64
CSI Report Configuration	
CQI Table	Table 1
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS_NLOS Selection	User Defined
LOS Probability	1
Shadow Fading Model	None
Fast Fading Model	No Fading
Additional Loss Model	None

Similarly, it is set for gNB 8.

Step 4: The Tx Antenna Count was set to 2 and Rx Antenna Count was set to 1 in gNB > Interface (5G RAN) > Physical Layer.

Step 5: The Tx Antenna Count was set to 1 and Rx Antenna Count was set to 2 in UE > Interface (5G RAN) > Physical Layer.

Step 6: In the position properties of UE 9, set Mobility Model as File Based Mobility.

Step 7: The BER and propagation delay was set to zero in all the wired links.

Step 8: Configure application between server and UE by selecting an application from Set Traffic Tab. Click on the application flow App1 CBR, expand the application property panel on the right and set the start time to 1 s, QOS to UGS and Inter arrival time to 233.6 μs by keeping the packet size as default.

Additionally, the "Start Time(s)" parameter is set to 1, 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 0.5 sec with distance 50 m.

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

Table 4-56: *mobility.csv file*

#Time(s)	Device ID	X	Y	Z
0	9	500	1000	0
0.5	9	750	1250	0
1	9	1000	1500	0
1.5	9	1250	1750	0
2	9	1500	2000	0
2.5	9	1750	2250	0
3	9	2000	2500	0
3.5	9	2250	2750	0

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#Time(s)	Device ID	X	Y	Z
4	9	2500	3000	0
4.5	9	2750	2750	0
5	9	3250	2250	0
5.5	9	3500	2000	0
6	9	3750	1750	0
6.5	9	4000	1500	0
7	9	4250	1250	0
7.5	9	4500	500	0

Step 9: The LTENR Radio measurement log file can be enabled per the information provided in Section 3.22 of this document. Also enable the Latency vs. Time and Throughput vs. Time application performance plots.

Step 10: Run the Simulation for 20 Seconds.

Results and Discussion

UDP Throughput Plot

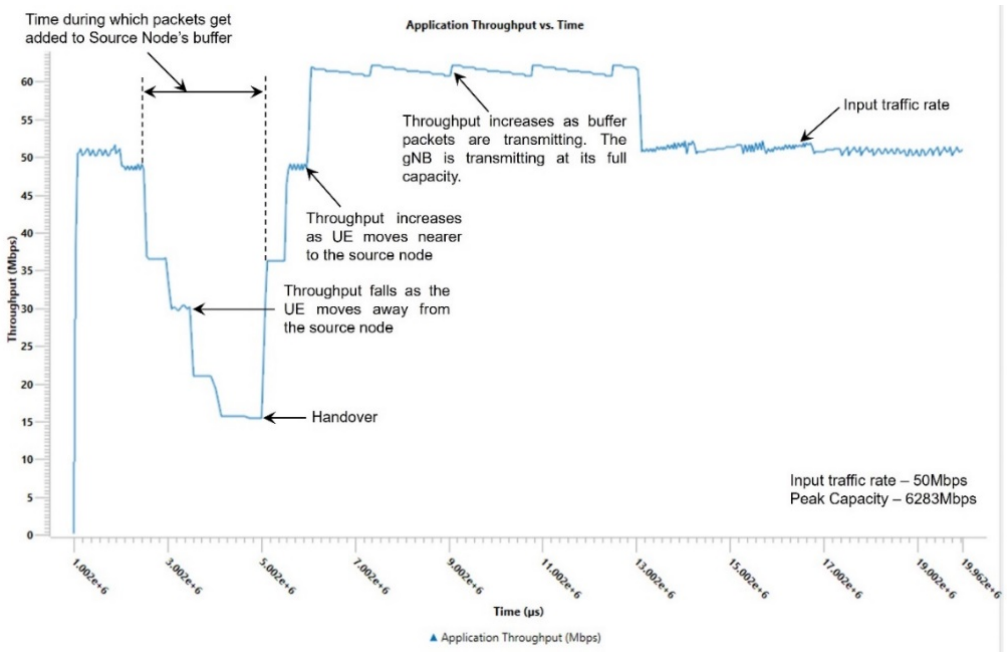


Figure 4-57: *We see how throughput varies with time, and the reasons for this variation, as the UE moves from the source gNB to the target gNB.*

The application starts at 1 s. The generation rate is 50 Mbps and we see the network is able to handle this load, and the throughput is equal to the generation rate. We then observe that the throughput starts dropping from 2.5 s onwards because the UE is moving away from the gNB. As it moves as the SNR falls, and therefore a lower MCS is chosen leading to reduced throughput. At 3 s there is a further drop in throughput and then a final dip at 3.9 s. The time the handover occurs is 5.04 sec. At this point we see the throughput starts increasing once UE attaches to gNB8. The throughput for a short period of time is greater than 50 Mbps because of the transmission of queued packets in the s-gNB buffer which get transferred to the t-gNB buffer over the Xn interface.

UDP Delay Plot

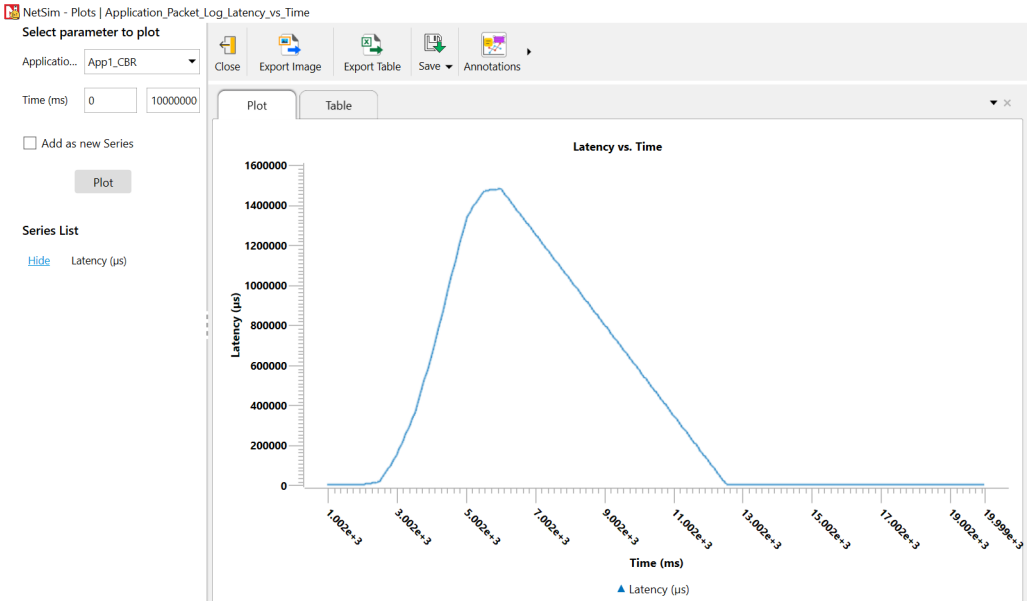


Figure 4-58: *Plot of Delay vs. Time*

Since the application starts at 1 s, the UDP plot begins at 1000 ms. The initial UDP delay is ≈ 1 ms, and hence the curve is seen as close to 0 on the Y axis. We then see that the packet delay starts increasing as the UE moves away from the gNB. This is because the link capacity drops as the CQI falls. The peak delay experienced shoots up to ≈1.1 s at ≈5.5 s when the handover occurs. Once the handover is complete the delay starts reducing and returns to ≈ 1 ms. The reason is that as the UE moves closer to the gNB its CQI increases and hence the 5G link can transmit at a higher rate.

4.12 Impact of Handover margin and Time-To-Trigger on the performance of a 5G heterogeneous network

In a 5G heterogeneous network we analyze how the handover margin and time-to-trigger parameters influence two performance metrics: the number of handovers and the sum throughput (aggregate throughput of all UEs).

Open NetSim, Select Examples → 5G NR → Impact of Handover margin and Time-To-Trigger on the performance of a 5G heterogeneous network, then click on the tile in the middle panel to load the example as shown in below screenshot.

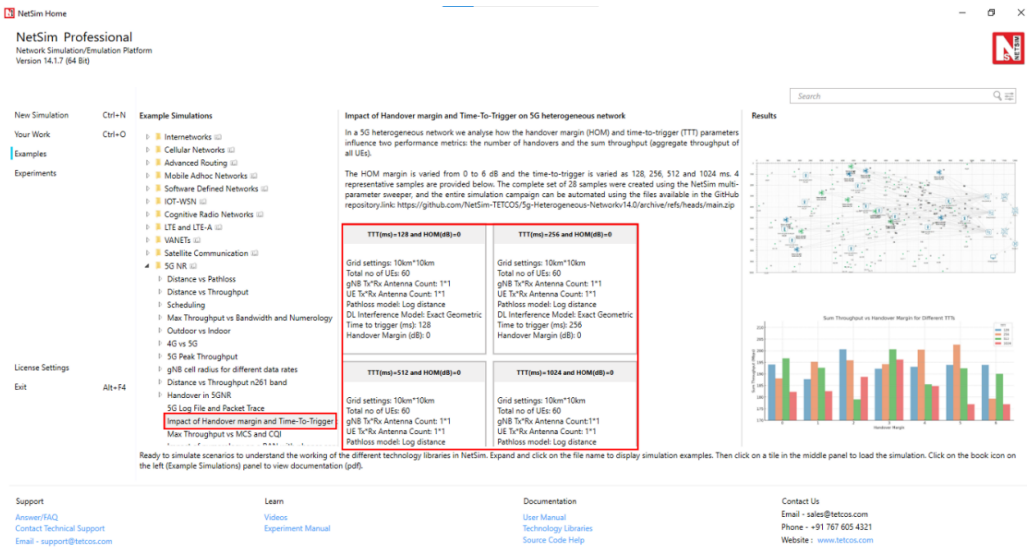


Figure 4-59: *List of scenarios for the example of a 5G heterogeneous network*

The following network diagram illustrates what the NetSim UI displays while opening the example configuration file.



Figure 4-60: *Network setup for studying 5G heterogeneous network.*

System model

The study is based on a 3-tier 5G HetNet simulation. The network comprises gNB tiers at 1.5 GHz, 2.1 GHz, and 3.5 GHz.

Table 4-57: *System parameters for the gNBs in the three different tiers*

gNB tiers	Frequency (GHz)	Pathloss Exponent (-)	Transmit Power (dBm)	Antenna Type	Antenna Height (m)	Channel Bandwidth (MHz)
Tier 1 gNBs	1.5	2.9	37	Sector (3 Nos)	30	10
Tier 2 gNBs	2.1	2.9	37	Sector (3 Nos)	30	15
Tier 3 gNBs	3.5	3.9	30	Omni-Directional	20	50

Each tier has a specific pathloss exponent influencing signal attenuation. The transmit power, antenna types (sector and omni-directional), and antenna heights vary across tiers. The simulation area is 10 km^2, with 60 User equipments (UEs) distributed randomly and 18 tier-I gNBs, 18 tier-II gNBs, and 12 tier-III gNBs distributed randomly. The gNBs across tiers will not interference since they operate at different frequencies.

Simulation parameters include gNB and UE antenna configurations, pathloss models, interference models, and mobility settings. Shadowing effects are modeled using a lognormal distribution with a standard deviation of 5 dB.

Table 4-58: *System parameters for the scenario being simulated*

Parameter	Value
Simulation Area	10 km × 10 km
Number of UEs	60 (distributed randomly)
Number of Tier 1 gNBs	18 (distributed randomly)
Number of Tier 2 gNBs	18 (distributed randomly)
Number of Tier 3 gNBs	12 (distributed randomly)
gNB Tx×Rx Antenna Count	1×1
UE Tx×Rx Antenna Count	1×1
gNB Pathloss Model	Log Distance
Downlink Interference Model	Exact Geometric Model
Mobility Model	Random Walk
Velocity	33 m/s
Calculation (update) interval for mobility	0.12 s (120 ms)
Measurement Interval (ms)	160
Shadowing	Lognormal. Std. dev. = 5 dB
Time to trigger (ms)	Varies; 128, 256, 512, 1024
Handover Margin (dB)	Varies; 0, 1, 2, 3, 4, 5, 6
Handover model	A3 event based
Simulation Time	30 s
Traffic model	Saturated (full buffer) DL

The Time to Trigger (TTT) and Handover Margin (HO Margin) are variables in the study. An A3 event-based handover model is used. An Event A3-based HO is triggered when,

- The SINR of a user from target gNB becomes higher than the SINR of the user from the serving gNB by an offset. This offset is termed as handover margin.
- And this condition (C1) is maintained for a duration known as the time to trigger.

The model focuses on the interaction of these parameters and their effect on network performance, measured in terms of handover count and sum throughput.

Procedure to simulate the scenario using Multiparameter Sweeper

- Click on the first experiment tile to open the scenario in NetSim. Save this scenario and open the experiment in the file explorer and open Configuration.netsim in Visual Studios.

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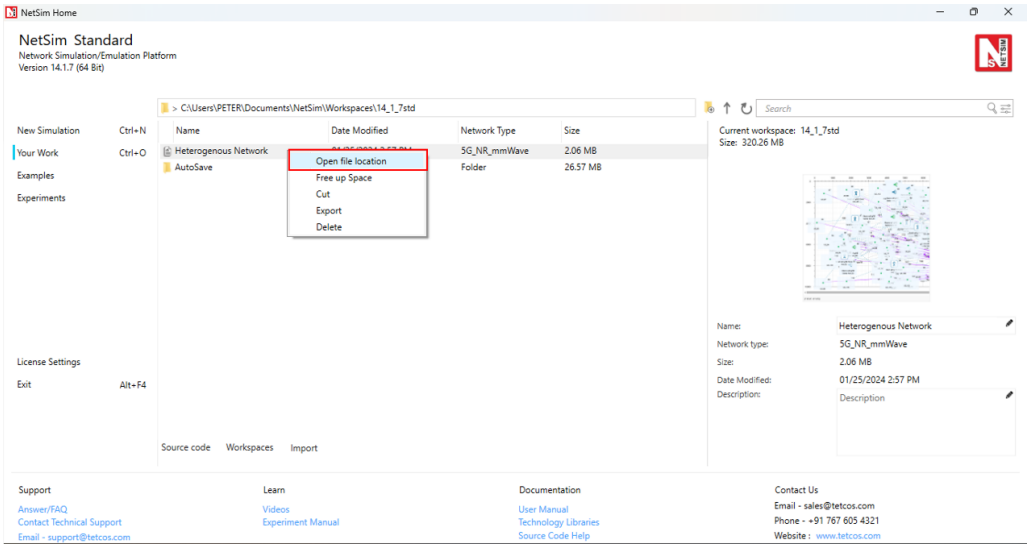


Figure 4-61: *Opening saved file location from 'Your Work' window.*

- Within the Datalink Layer of all gNB, in HANDOVER tag replace the HANDOVER_MARGIN="{1}" and TIME_TO_TRIGGER="{0}" representing an input variable for the multi-parameter sweeper.

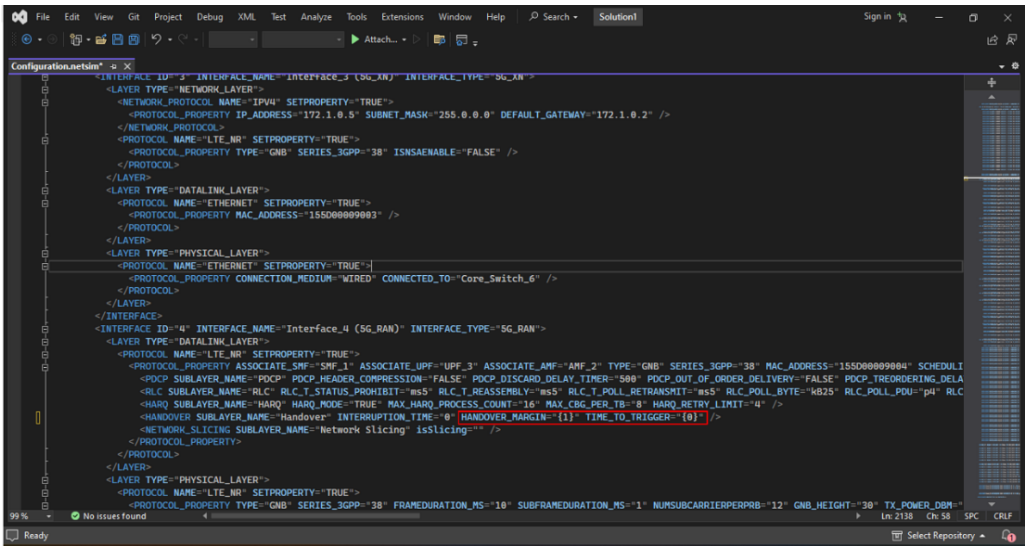


Figure 4-62: *input variables for Multi-Parameter Sweeper*

- Save the configuration file and rename it as input.xml.
- Download the multi-parameter sweeper from the link https://github.com/NetSim-TETCOS/5G-Heterogeneous-Network-v15.1/archive/refs/heads/main.zip
- Paste input.xml, the Config support folder, and the default folder into the 5G-Heterogeneous-Network-v15.1 folder.
- Open the multi-parameter-sweeper.py file in text editor, change the NETSIM_PATH suitably (line #14).

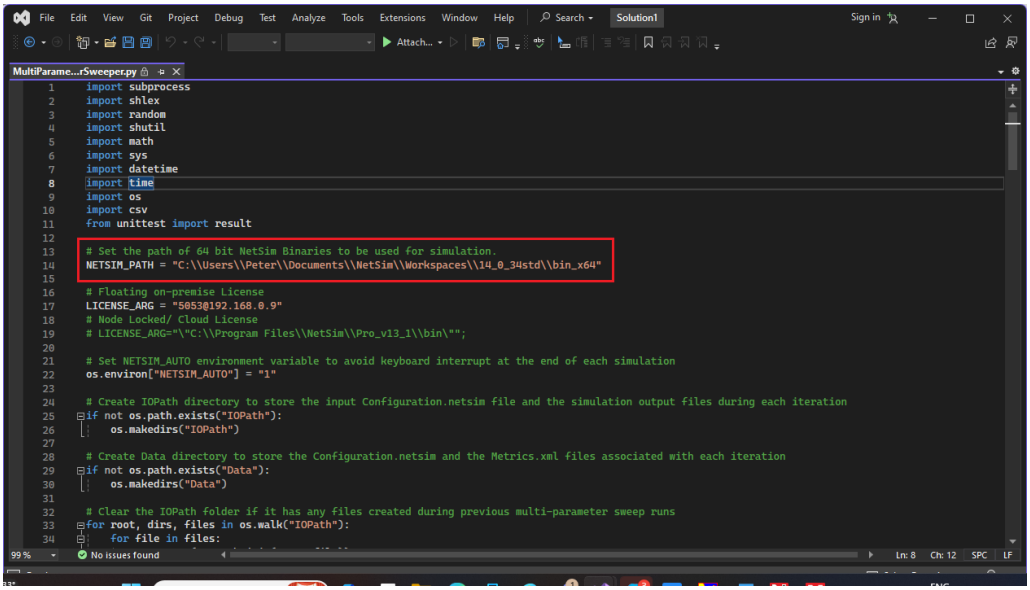


Figure 4-63: *Changing the NETSIM_PATH in multi-parameter-sweeper.py*

- Run via CLI from the 5G-Heterogeneous-Network-v15.1 folder as shown below.

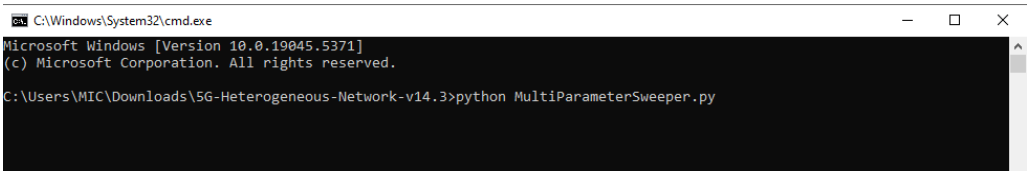


Figure 4-64: *Running the multi-parameter sweeper via CLI*

- The multi-parameter sweeper runs a total of 28 simulations, varying handover margin from 0 to 6 dB and time to trigger from 128, 256, 512, 1024 for all gNB's. It generates an output file named "result.csv" which stores sum throughputs of all applications and the handover count. (It took us approximately 4 hours to complete all 28 simulations; we used a machine with a i5 processor and with 8 GB RAM).

Results and discussion

We tabulate below the handover count and sum throughput for various values of time to trigger (ms) and Handover margin (dB) which is obtained in result.csv file in multiparameter sweeper folder.

Table 4-59: *Table demonstrates Sum Throughput and Handover Count variation with changes in Handover Margin and Time to Trigger (TTT).*

Time-to-trigger (ms)	Handover margin (dB)	Sum throughput (Mbps)	Handover count
128	0	231.31	389
128	1	221.53	334
128	2	221.28	261
128	3	224.08	207
128	4	231.43	168
128	5	227.70	133

(continued)

Time-to-trigger (ms)	Handover margin (dB)	Sum throughput (Mbps)	Handover count
128	6	225.96	86
256	0	223.96	165
256	1	228.79	154
256	2	230.18	106
256	3	228.59	71
256	4	224.22	54
256	5	224.85	38
256	6	228.19	23
512	0	222.10	48
512	1	238.50	34
512	2	223.26	26
512	3	217.94	26
512	4	231.28	20
512	5	237.94	17
512	6	224.19	11
1024	0	221.02	20
1024	1	235.19	18
1024	2	224.49	14
1024	3	228.35	8
1024	4	229.39	9
1024	5	225.89	7
1024	6	224.64	3

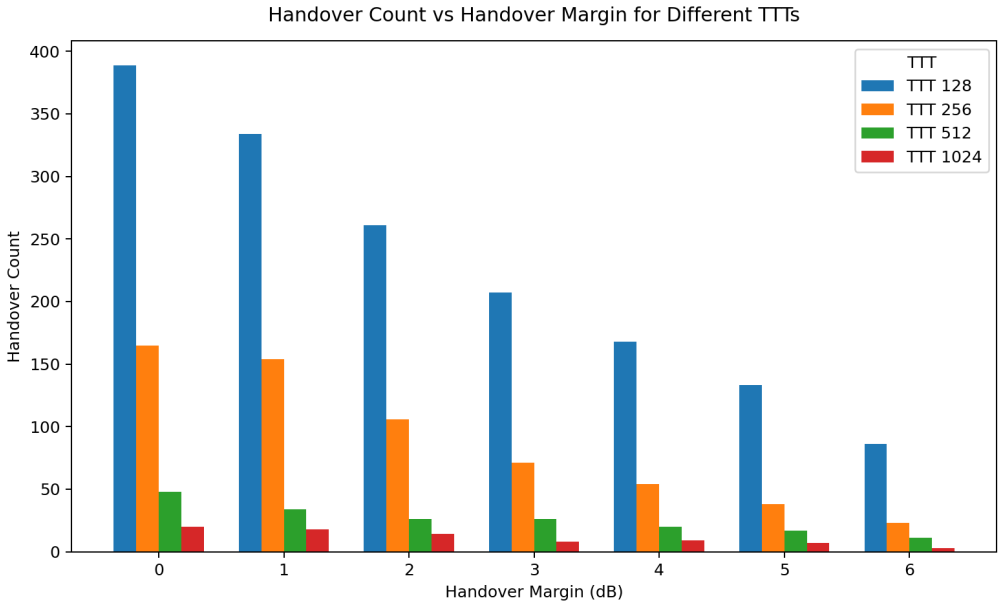


Figure 4-65: *Plot representing Handover Count vs Handover Margin for different TTTs.*

It is evident from the plot that the handover count decreases as the handover margin increases. This trend is consistent across different TTT values, suggesting that a higher handover margin generally results in fewer handovers. The rationale behind this trend is that increased handover

margin leads to more stringent conditions for handover and thereby reduces the frequency of handover occurrences.

We also observe that the handover count decreases as TTT increases. Shorter TTT values lead to quicker responses to signal changes, resulting in more frequent handovers, while longer TTT values delay the handover process, thereby reducing the handover count. The plot highlights the effects of both the handover margin and the TTT on handover count.

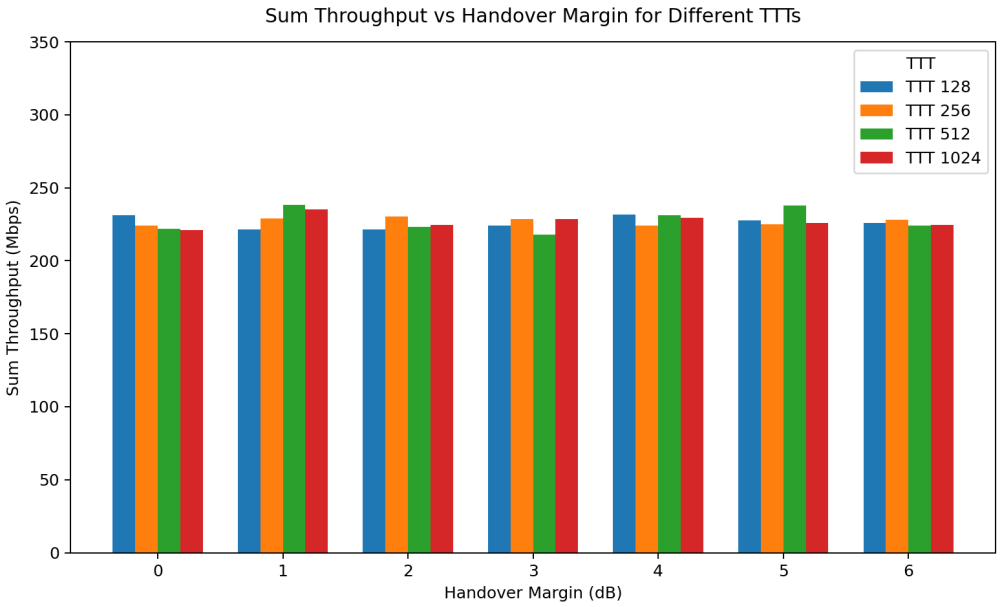


Figure 4-66: *Plot representing Sum Throughput vs Handover Margin for Different TTTs*

In the second chart we see that sum throughput generally rises and then falls with the increasing handover margin. For each handover margin we see the throughput again roughly increases and then drops as TTT increases. Initially, with a higher handover margin and/or higher TTT unnecessary and frequent handovers between cells are avoided. This leads to better throughput, but only to a certain extent. Beyond a point, a high handover margin and/or high TTT causes delayed handovers. Users stay connected to a weaker cell longer, despite being closer to a stronger cell, leading to poorer signal quality and thus lowering throughput.

4.13 QoS in 5G using GBR

4.13.1 Introduction

This experiment explores a new approach to providing Quality of Service (QoS) guarantees in 5G networks by modifying the traditional Proportional Fair Scheduling (PFS) algorithm. The study focuses on implementing Guaranteed Bit Rate (GBR) requirements using index bias (Lagrange multiplier) in the scheduler, and understanding how this modification impacts network performance under various scenarios.

The experiment investigates three cases: First, a baseline scenario using standard PFS where all User Equipment (UEs) are static but at different distances from the gNB (base station). Second, the same setup but with the modified PFS algorithm incorporating GBR guarantees for one UE. Finally, the study examines how the GBR mechanism performs when one UE is mobile. In all cases, we simulate Rayleigh fading channels between the gNB and UEs, creating dynamic channel conditions that reflect real-world wireless propagation.

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Through these scenarios, the experiment demonstrates how the scheduler dynamically adjusts resource allocation to maintain throughput guarantees for specific UEs, at the expense of reducing resources to other users. The study is particularly useful for understanding how modern 5G networks can provide differentiated services and maintain quality guarantees in real-world conditions, where users may be at varying distances from the base station and potentially mobile.

4.13.2 Methodology

Open NetSim and click on Examples > 5G NR > QoS in 5G using GBR then click on the tile in the middle panel to load the example as shown below

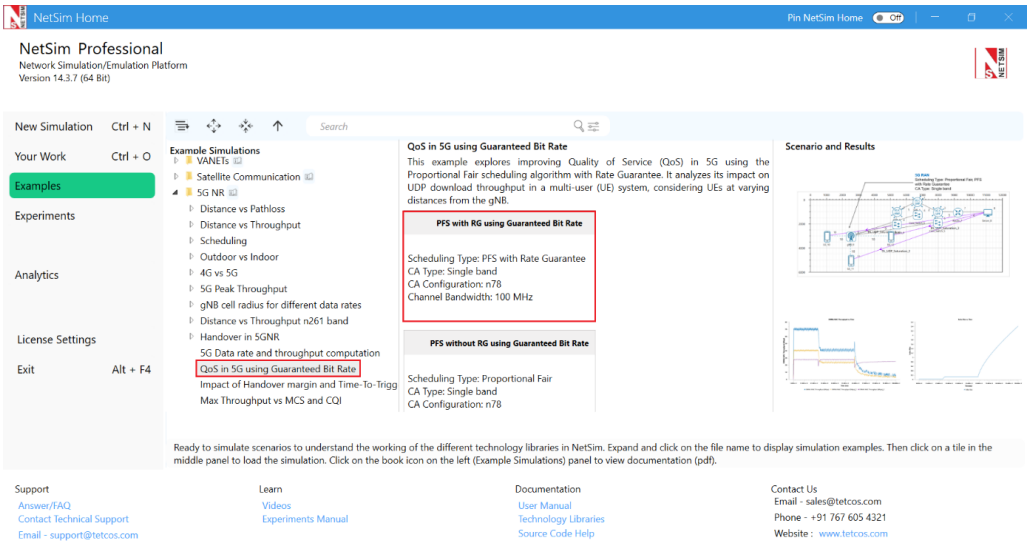


Figure 4-67: *List scenarios for the example of a QoS in 5G using GBR network*

4.13.3 Case 1: Proportional Fair Scheduling (PFS). All UEs are static

NetSim UI displays the configuration file corresponding to this experiment as shown below

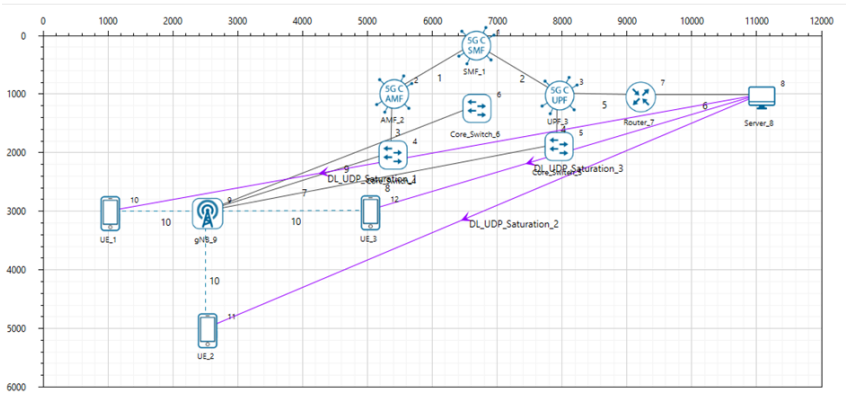


Figure 4-68: *Network scenario*

- Set grid length as 6000 m and width as 12000 m from grid property panel on the right.
- Set distance as follows:

  - gNB 9 to UE 10 = 1500 m
  - gNB 9 to UE 11 = 2000 m, and
  - gNB 9 to UE 12 = 2500 m

- Go to gNB properties → Interface (5G RAN), set the following properties as shown below Table. In the first case the scheduling type is set to PFS.

Table 4-60: *gNB > Interface (5G RAN) > Datalink and Physical layer properties*

Properties	Value
Datalink Layer Properties	
Scheduling Type	PFS, PFS with RG
Physical Layer Properties	
CA Type	Single band
CA Configuration	n78
CA1	
Numerology	1
Channel Bandwidth	100 MHz
Channel Model	
Pathloss Model	3GPP TR 38.901-7.4.1
Outdoor Scenario	Urban Macro
LOS NLOS Selection	User defined
LOS Probability	1
Shadow Fading Model	None
Fast Fading Model	No fading

- Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in gNB properties.
- Set Tx Antenna Count as 1 and Rx Antenna Count as 1 in all the UEs.
- Go to the Set Traffic tab in the top ribbon and create a CBR application as shown in the table below. To change the transport protocol, QoS, and IAT click on the application and change the properties in the right-side property panel.

Table 4-61: *Application properties*

Application Properties	Application 1	Application 2	Application 3
Application Type	CBR	CBR	CBR
Source ID	8	8	8
Destination ID	10	11	12
QoS	UGS	UGS	UGS
Transport Protocol	UDP	UDP	UDP
Packet Size	1460 Bytes	1460 Bytes	1460 Bytes
Inter-arrival time	58.4 μs	58.4 μs	58.4 μs
Start Time	1 s	1 s	1 s

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- Make sure you enable these two plots under plots section as shown in figure

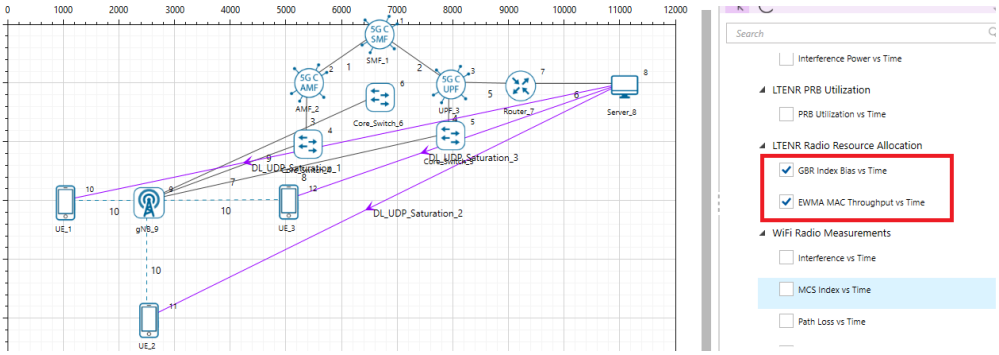


Figure 4-69: *Enabling the plots*

- Run Simulation for 100 s and note down throughput value in the results window for each UE.
- Here, we can see the resulting plots of the case:

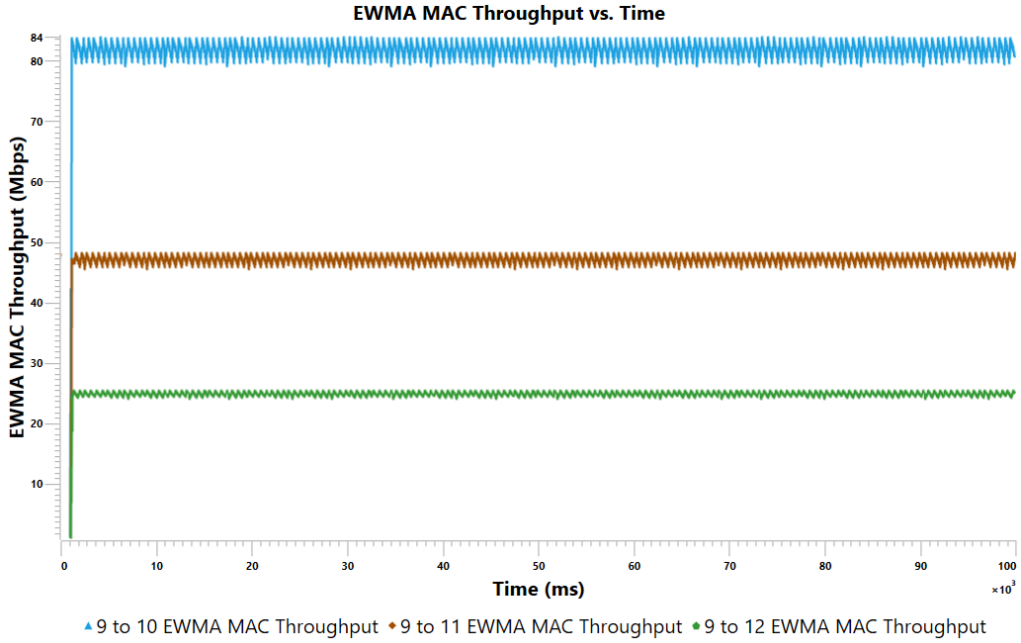


Figure 4-70: *EWMA MAC Throughput vs Time*

4.13.4 Case 2: PFS with RG using Guaranteed Bit Rate (GBR). All UEs are static.

- Now, for the same scenario above we just need to disable the GBR Configuration.
- For doing that we need to change the Scheduling algorithm from Proportional Fair to PFS with RG as shown below.

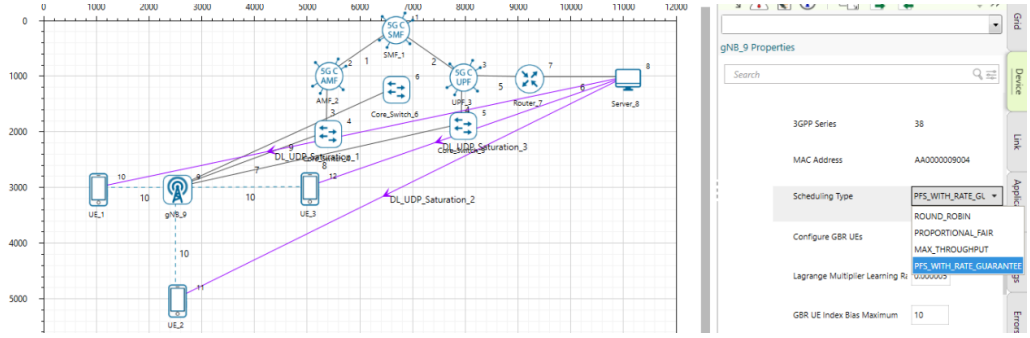


Figure 4-71: *Changing the Scheduling Algorithm*

- Then, Configure GBR UEs via GUI as shown below. Change the Downlink of UE12 to 27.57 Mbps and click on update.

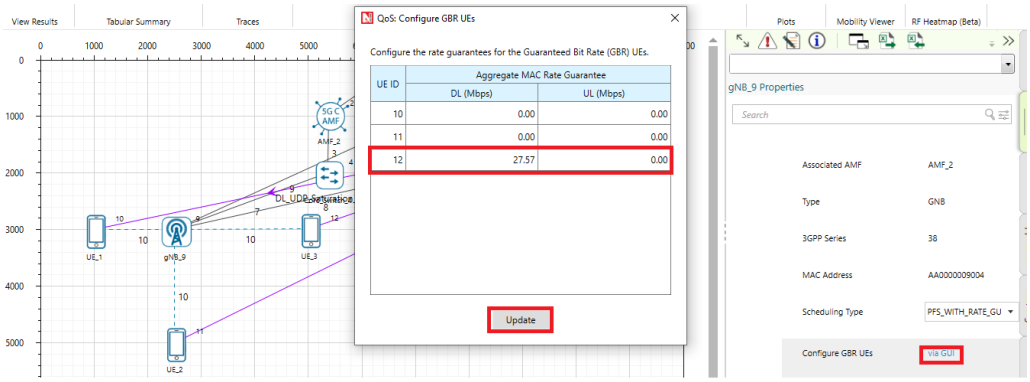


Figure 4-72: *Adding GBR DL to UE*

- Now, run the scenario for 100 s.
- Now plot the values using plots section in Results dashboard.

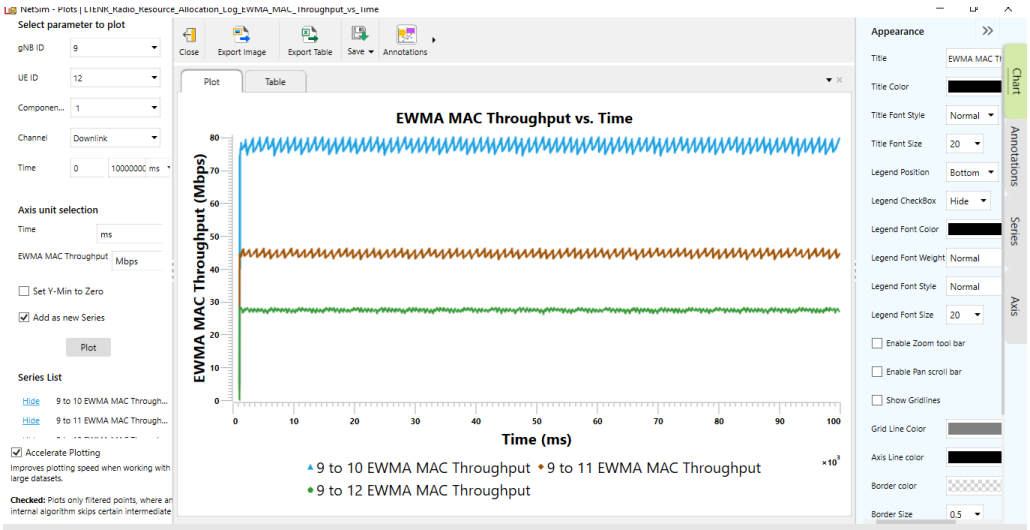


Figure 4-73: *EWMA MAC Throughput vs Time*

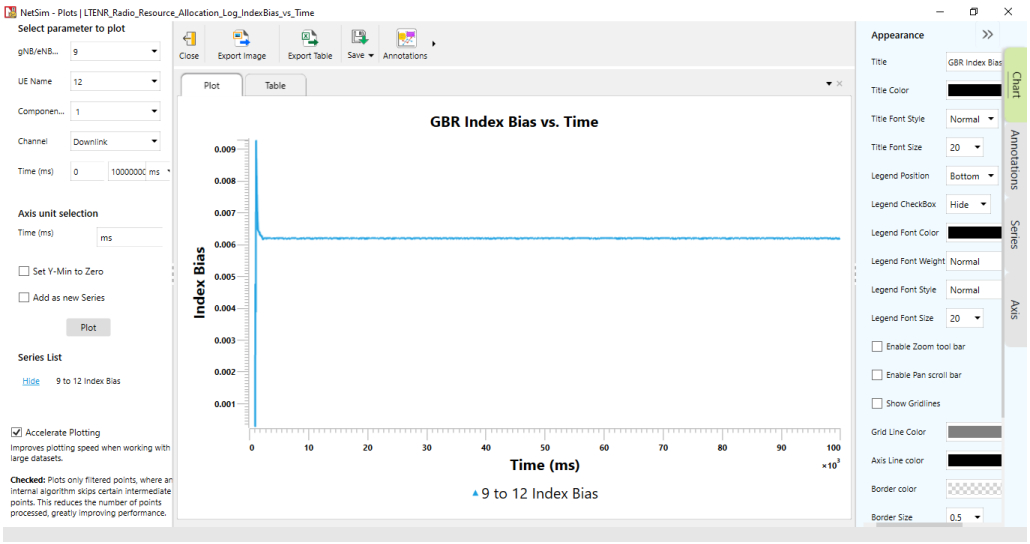


Figure 4-74: *Index Bias vs Time*

4.13.5 Case 3: PFS with RG using GBR. One of the UE's is mobile.

- In this case we are working with GBR again.
- Now we need to add Mobility for UE-12, click on UE-12 then select Position → Mobility Model → File Based Mobility → via File.

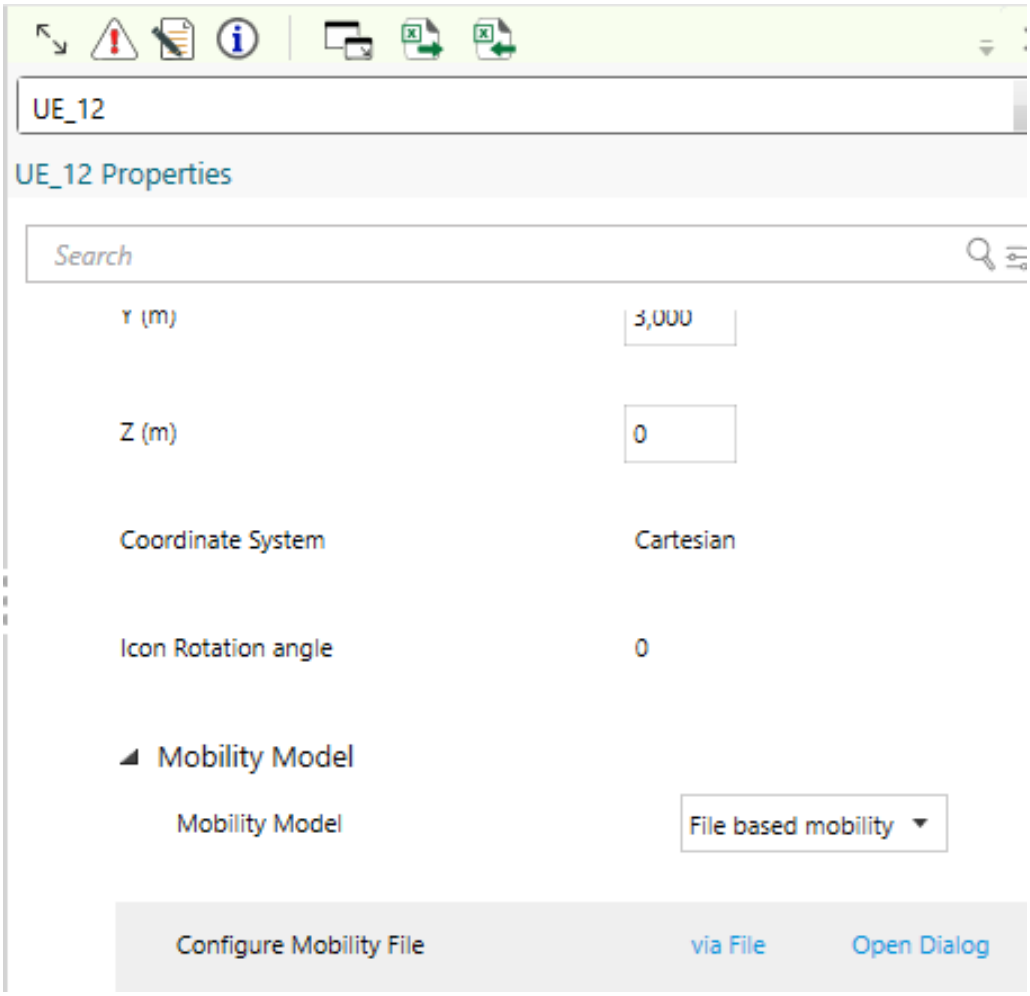


Figure 4-75: *Adding file-based mobility to UE*

- Now add Mobility as shown below:

1	#Time(s)	Device ID	X	Y	Z
2	0	12	5000	3000	0
3	1	12	5010	3000	0
4	2	12	5020	3000	0
5	3	12	5030	3000	0
6	4	12	5040	3000	0
7	5	12	5050	3000	0
8	6	12	5060	3000	0
9	7	12	5070	3000	0
10	8	12	5080	3000	0
11	9	12	5090	3000	0
12	10	12	5100	3000	0

Figure 4-76: *Mobility.csv file*

- In this way, you can add mobility by increasing 10 m of distance in the interval of 1 s and keep adding up to 100 s then save the file.
- Now, run the simulation for 100 s.
- The plots are obtained from results dashboard:
- So, we can see a lot of spike variations in plots due to mobility in UE 3.

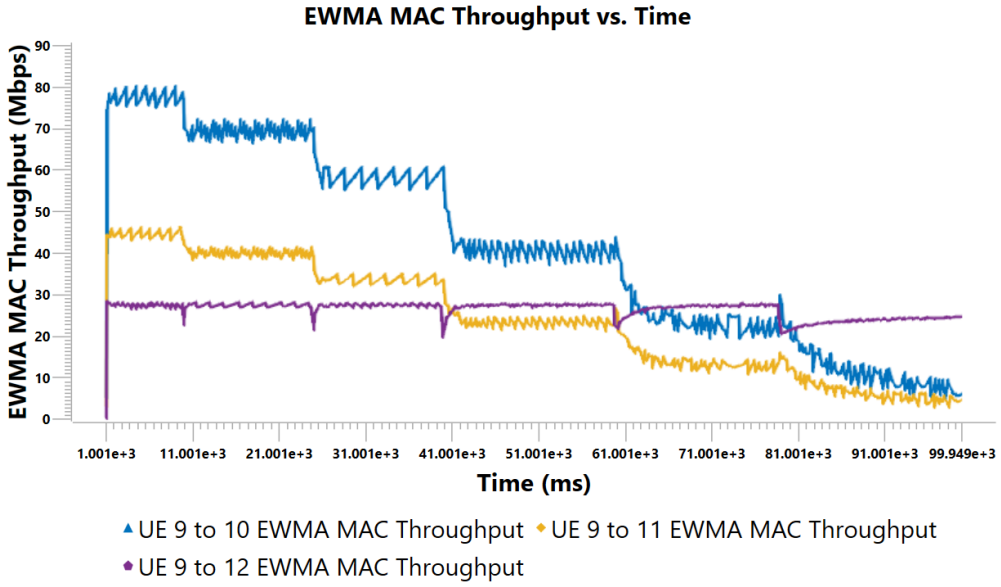


Figure 4-77: *EWMA MAC Throughput vs Time*

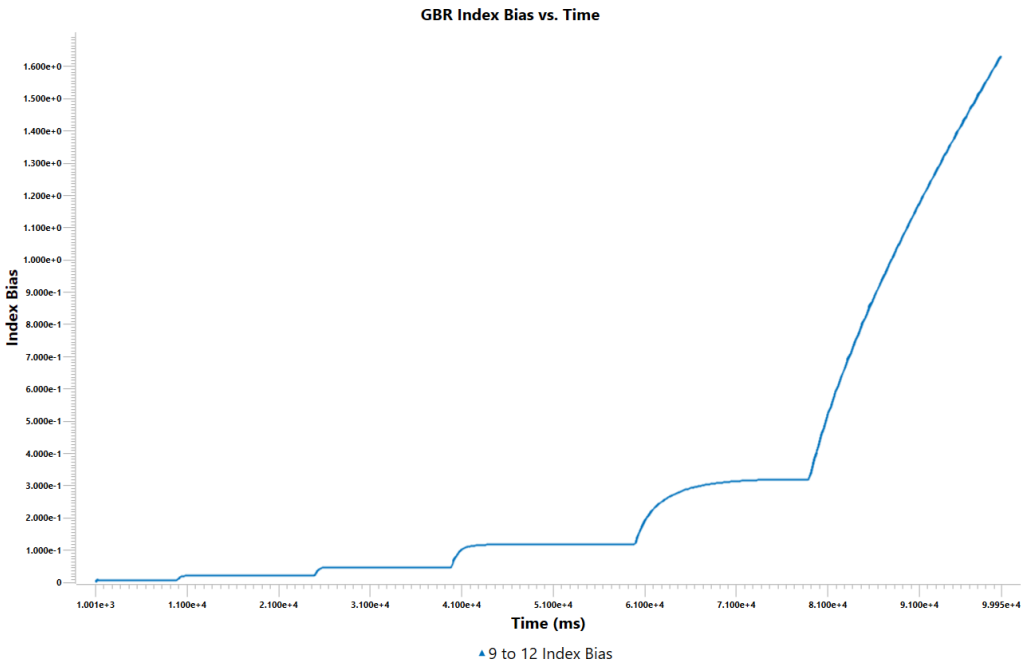


Figure 4-78: *Index Bias vs Time*

4.13.6 Obtaining the EWMA MAC Throughput and Resource share

Now, let's see the MAC Throughputs, to obtain them follow the steps:

- Select the Logs section in Result Metrics, then click on LTENR Radio Resource Allocation.csv log file as shown below.

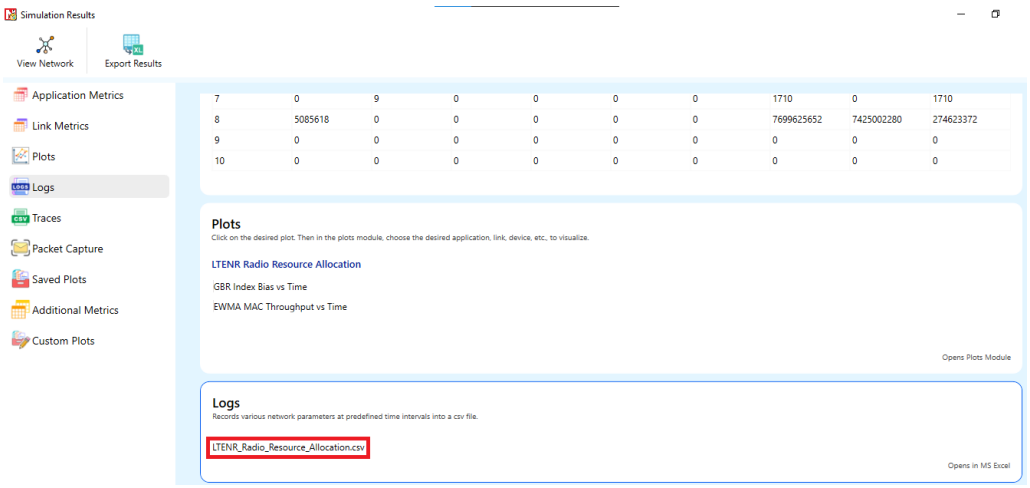


Figure 4-79: *Results dashboard window*

- After the log file is loaded into the excel sheet, select on the pivot table section below and select the checkboxes of UE ID and EWMA MAC throughput on the right side.
- Now drag the UE ID to the rows and EWMA MAC throughput to the values of the table and change the values from sum to average by right clicking on that column head as shown below.

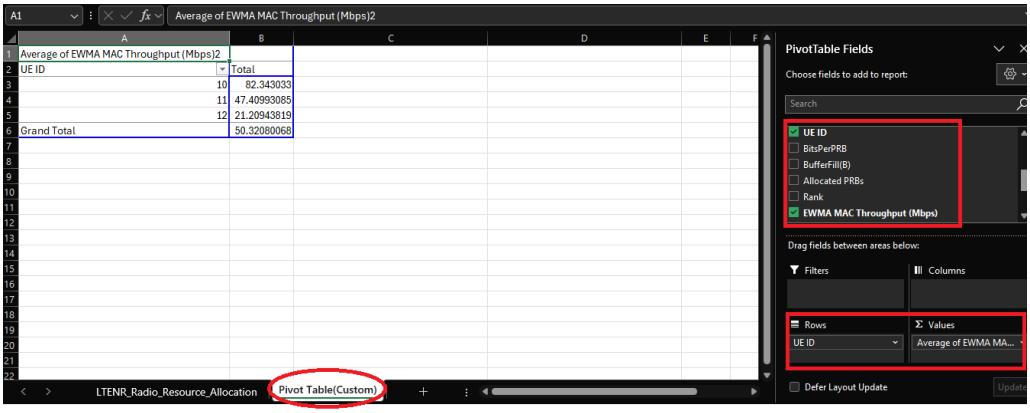


Figure 4-80: *Average of EWMAC Throughput*

- Now in the sheet table, you can see the MAC Throughput values of respective UEs to the right side of them under the 'Total' named column.
- In this way, you can obtain the MAC Throughput values of 3 UEs in all the three cases using the LTENR Radio Resource Allocation.csv log file.
- The values obtained from all the cases are tabulated in Results.

Now, to obtain Allocated PRBs percentage:

- Follow step 1, and then instead of adding EWMA MAC Throughput add Allocated PRBs to Values section.
- Now, right click on the values and select 'show values as' section then select '% of Grand Total' and click on OK as shown below.

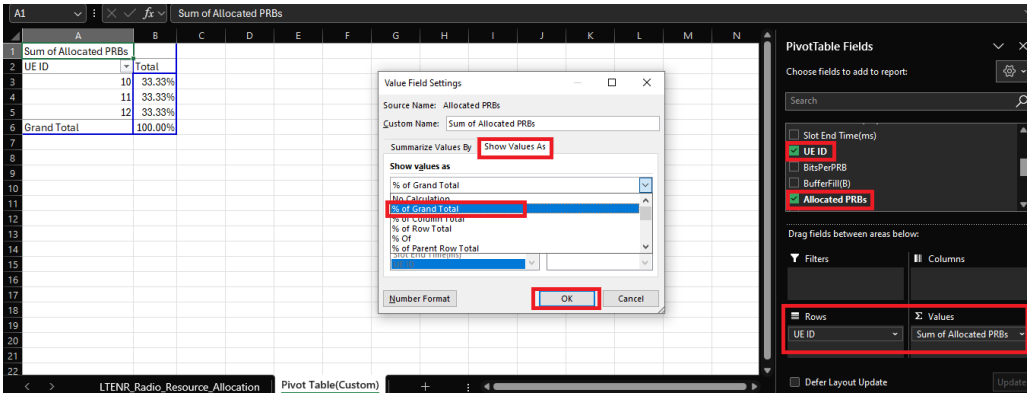


Figure 4-81: *Obtaining Resource Utilization*

- On the left side table, you can see the values.
- The values obtained from all the cases are tabulated in Results.

4.13.7 Results and Discussion

Let's analyze the Application Throughputs and MAC Throughputs obtained by 3 UEs in results dashboards in all the three different cases discussed above:

Table 4-62: *Application Throughputs*

Case #	Description	UE1 (Mbps)	UE2 (Mbps)	UE3 (Mbps)
1	Proportional Fair Scheduling (PFS). All UEs static.	64.65	37.22	19.59
2	PFS with RG using Guaranteed Bit Rate (GBR). All UEs static.	61.26	35.27	21.64
3	PFS with RG using GBR. UE 3 is mobile.	33.23	19.13	20.83

Table 4-63: *MAC Throughputs*

Case #	Description	UE1 (Mbps)	UE2 (Mbps)	UE3 (Mbps)
1	Proportional Fair Scheduling (PFS). All UEs static.	82.34	47.40	24.95
2	PFS with RG using GBR. All UEs static.	78.03	44.92	27.56
3	PFS with RG using GBR. UE 3 is mobile.	42.34	24.38	26.53

Table 4-64: *Resource allocation*

Case #	Description	UE1 (%)	UE2 (%)	UE3 (%)
1	Proportional Fair Scheduling (PFS). All UEs static.	33.33	33.33	33.33
2	PFS with RG using GBR. All UEs static.	31.59	31.59	36.83
3	PFS with RG using GBR. UE 3 is mobile.	17.14	17.14	65.73

Case-1: Proportional Fair (PF) Algorithm

- Under standard PFS, the algorithm distributes Physical Resource Blocks (PRBs) uniformly among the three UEs, with each receiving approximately 33.33% of the resources. This results in decreasing throughputs as distance from the gNB increases – UE1 achieves 64.65 Mbps, UE2 gets 37.22 Mbps, and UE3 receives 19.59 Mbps at the application layer.

Case-2: GBR with Static UEs

- When GBR is enabled for UE3 with a target rate of 27.57 Mbps, we observe the index bias mechanism actively working to guarantee this rate. The scheduler increases the bias factor for UE3, resulting in its PRB allocation increasing from 33.33% to 36.83%.
- This resource reallocation successfully raises UE3's throughput from 19.59 Mbps to 21.64 Mbps at the application layer, achieving the target MAC layer throughput of 27.56 Mbps.
- However, this comes at the cost of reduced resources for other UEs – UE1's throughput drops from 64.65 Mbps to 61.26 Mbps, and UE2's decreases from 37.22 Mbps to 35.27 Mbps.

Case-3: GBR with Mobile UE

- As UE3 begins moving away from the gNB, we observe a complex interplay between distance, channel conditions, and the index bias mechanism.
- Initially, as UE3's throughput starts dropping due to increased distance, the index bias increases to compensate, pulling more resources from UE1 and UE2. Their throughputs drop significantly – UE1 falls to 33.23 Mbps and UE2 to 19.13 Mbps.
- As UE3 moves even further away, the scheduler dramatically increases the index bias in an attempt to maintain the GBR. This results in UE3 being allocated nearly 65.73% of all PRBs, leaving only about 17.14% each for UE1 and UE2.
- Despite this extreme resource reallocation, UE3's throughput still falls to 20.83 Mbps, unable to meet the GBR target due to poor channel conditions at the increased distance. Meanwhile, the throughputs of UE1 and UE2 are severely impacted due to their minimal resource allocation.

This behavior demonstrates both the power and limitations of the index bias mechanism in GBR implementation – while it can effectively guarantee bit rates under most conditions by redistributing resources, there are physical limitations that cannot be overcome simply by increasing resource allocation when channel conditions become too poor.

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5 Omitted Features

- The omitted features in the PHY layer are mentioned in Section 3.9.24.
- 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 References

[1] A. Goldsmith, Wireless Communications. Stanford University. [Online]. Available: https://web.stanford.edu/class/archive/ee/ee359/ee359.1062/cup_mimo.pdf [Accessed: Nov. 20, 2020.]

[2] M. Viswanathan, "Ricean flat-fading channel," in *Wireless Communication Systems in MATLAB*, Gaussian Waves, 2020, pp. 172–173.

[3] E. Telatar, "Capacity of Multi-antenna Gaussian Channels," [Online]. Available: http://web.mit.edu/18.325/www/telatar_capacity.pdf. [Accessed 08 11 2020].

[4] N. Patriciello, S. Lagen, L. Giupponi and B. Bojovic, "5G New Radio Numerologies and their Impact on the End-To-End Latency," IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2018.

[5] M. Mezzavilla, M. Zhang, M. Polese, R. Ford, S. Dutta, S. Rangan and M. Zorzi, "End-to-End Simulation of 5G mmWave Networks," IEEE Communication Surveys & Tutorials, Vol 20, No. 3, Third Quarter, 2018.

[6] A. Duran, M. Toril, F. Ruiz and A. Mendo, "Self-Optimization Algorithm for Outer Loop Link Adaptation in LTE," IEEE Communications Letters, 2015.

[7] E. Makridis, "Reinforcement Learning for Link Adaptation in 5G-NR Networks," KTH Royal Institute of Technology, Sweeden, 2020.

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