Understanding 5G NR (3GPP) pathloss models

Objective

In the elementary case of 1gNB communicating with 1UE over a 5G NR network, in a rural setting, we study the question: How does the UE-gNB pathloss vary with the distance between the UE and the gNB and the gNB height? What is the optimal height of a gNB?

Motivation

We start with a non-technical explanation of the objective. A mobile phone (in the hands of an individual) is the UE; the cell tower is the gNB. Assume the person is in a rural area and is outdoors. Pathloss would determine the signal strength displayed on the phone; a higher loss means a lower signal strength. Mobile network operators (think of the top service providers in our country) invest large sums in setting-up the towers. They wish to know the tower height[1] that gives users the highest signal strength. The answer is not obvious: the more the height of the gNB, the more likely it is that there exists a line-of-sight path to a given UE, but the signal has to traverse a longer distance, incurring a higher path loss. The cell radius might also play a role here: perhaps a lower height is better for smaller sized cells, and a greater height is better for large cells. In this experiment, we will understand these trade-offs.

The 5G pathloss equations

To answer these questions, we look at the 5G pathloss equations for a rural scenario as defined in the 3GPP 38.901 standards:

Scenario	LOS/ NLOS State	Pathloss (dB) (f_c in GHz and d in meters)	Shadow Fading (σ)	Parameter values and ranges
	LOS	$PL_{RMA_{LOS}} = \begin{cases} PL_1, 10m \le d_{2D} \le d_{BP} \\ PL_2, d_{BP} \le d_{2D} \le 10Km \end{cases}$ $\mathrm{PL_1} = 20\log_{10}(40\pi d_{3D} f_c/3) + \min(0.03h^{1.72}, 10)\log_{10}(d_{3D}) - \min(0.044h^{1.72}, 14.77) + 0.002\log_{10}(h)d_{3D}$ $PL_2 = PL_1(d_{BP}) + 40\log_{10}(\frac{d_{3D}}{d_{BP}})$	$\sigma_{SF} = 4$ $\sigma_{SF} = 6$	$h_{BS} = 35m$ $h_{UT} = 1.5m$ $W = 20m$ $h = 5m$

[1] The antenna can be placed at different heights on the cell tower. Hence the term "Antenna height" would be technically precise.

Rural Macro	NLOS	$PL_{RMa_{NLOS}} = \max\left(PL_{RMa_{LOS}}, \quad PL_{RMa'_{NLOS}}\right)$ For $10m \leq d_{2D} \leq 5Km$ $PL_{RMa'_{NLOS}} = 161.04 - 7.1 * \log_{10}(W) + 7.5 * \log_{10}(h) - \left(24.37 - 3.7 * \left(\frac{h}{h_{BS}}\right)^2\right) * \log_{10}(h_{BS}) + (43.42 - (3.1 * \log_{10}(h_{BS})^2)) * (\log_{10}(d_{3D}) - 3) + 20 * (\log_{10}(f_c)) - (3.2 * (\log_{10}(11.75 * h_{UT}))^2 - 4.97)$	$\sigma_{SF} = 8$	$5m \leq h \leq 50m$ $5m \leq W \leq 50m$ $10m \leq h_{BS} \leq 150m$ $1m \leq h_{UT} \leq 10m$

NOTE:

1. Break point distance[2] $d_{BP} = 2\pi h_{BS} h_{UT} f_c / c$, where fc is the centre frequency in Hz, $c = 3.0 * 10^8\ m/s$ is the propagation velocity in free space, and hBS and hUT are the antenna heights at the BS and the UT, respectively.
2. fc denotes the centre frequency normalized by 1 GHz, all distance related values are normalized by 1 m, unless stated otherwise.

Table 1: Pathloss equations for Rural Macro environment for LOS and NLOS states

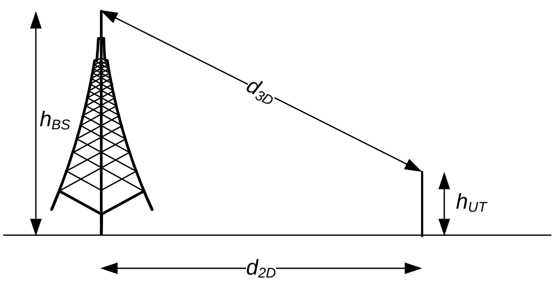

Fig 1: Definition of d_{2D} and d_{3D} for outdoor UEs

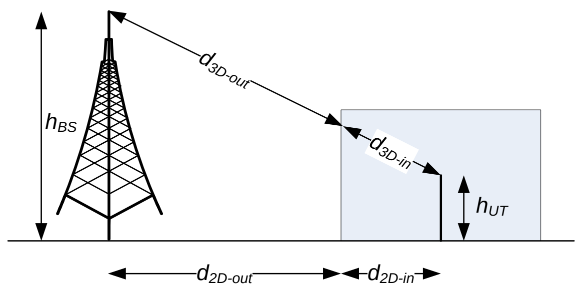

Fig 2: Definition of $d_{2D\text{-}out}$, $d_{2D\text{-}in}$ and $d_{3D\text{-}out}$, $d_{3D\text{-}in}$ for indoor UEs

Note that,

$$d_{3D_{out}} + d_{3D_{in}} = \sqrt{\left(d_{2D_{out}} + d_{2D_{in}}\right)^2 + (h_{BS} - h_{UT})^2}$$

[2] A question for the reader: Why is it called break point?

Observing the above equations, we see that the pathloss is not a simple expression in terms of gNB height. The other parameters affecting the pathloss are a) the UE-gNB 2D distance and b) the UE state[3].

Consequently, we investigate the revised question: how does the UE-gNB pathloss vary for *combinations* of gNB height, UE-gNB 2D distance, and UE states (LOS/NLOS)?

Procedure:

1. Use the following download Link to download a compressed zip folder which contains the workspace.
   https://github.com/NetSim-TETCOS/5G_Experiments_v13.0/archive/refs/heads/main.zip
2. Extract the zip folder.
3. The extracted project folder consists of a NetSim workspace file (*.netsim_wsp).
4. Go to NetSim Home window, go to Your Work and click on workspace options.

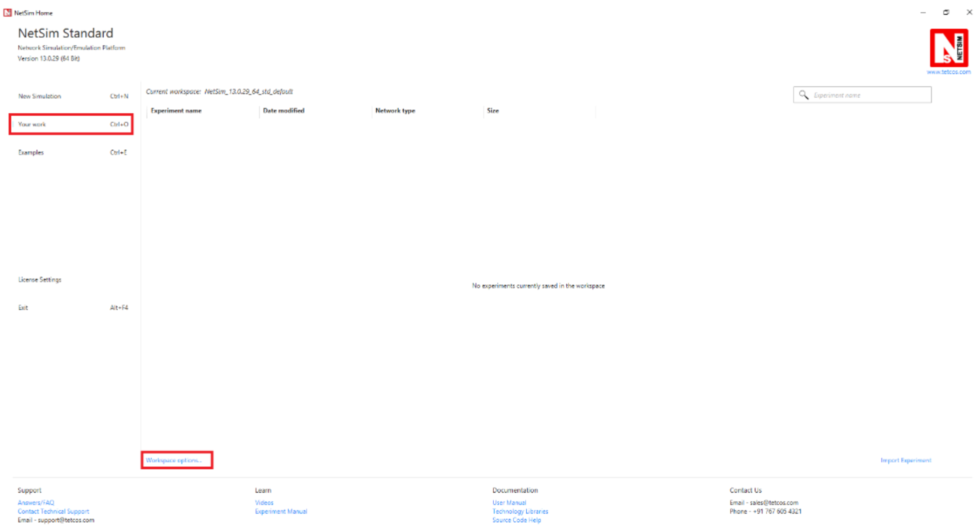

Fig 3: NetSim Home Window

5. Select more options.

[3] Can the UE directly see the gNB? If yes, it is in a Line-of-sight (LOS) state and if not, it is in the NLOS state.

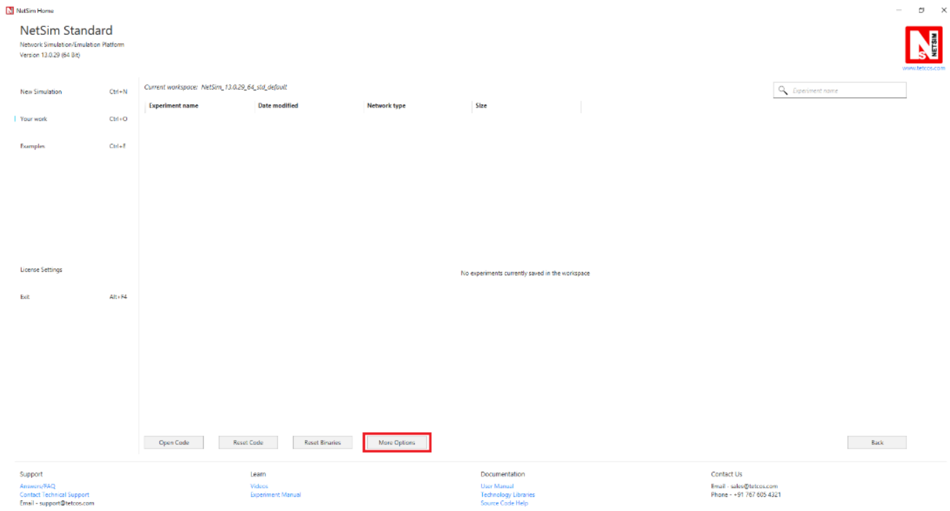

Fig 4**:** NetSim Your Work window

6. Click on Import.

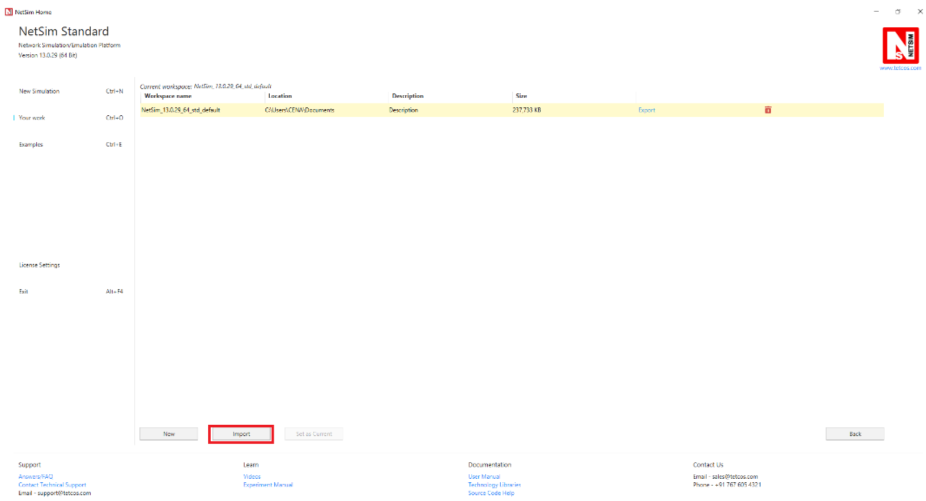

Fig 5**:** NetSim Your Work Window to import a workspace

7. In the Import Workspace Window that appears browse and select the *.netsim_wsp file from the extracted directory and for the Destination path browse to select a path in your system where you want to set up the workspace folder.

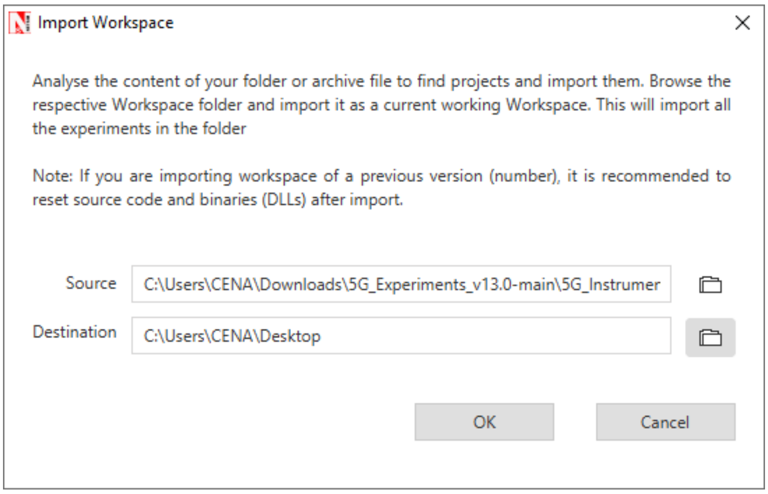

Fig 6: NetSim Import Workspace Window

8. While importing the workspace, if a warning message indicating a software version mismatch is displayed, it can be ignored by clicking on OK.

9. The Imported Project workspace will automatically be set as the current workspace.

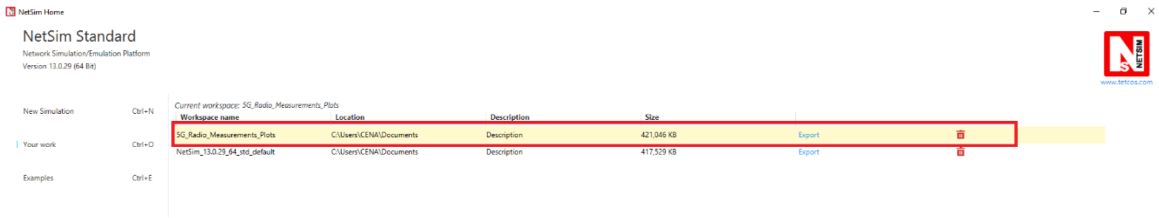

Fig 7: NetSim Your work window with list of workspaces

Network scenario:

NetSim UI would display the following network topology when you open the example configuration file as shown below screenshot.

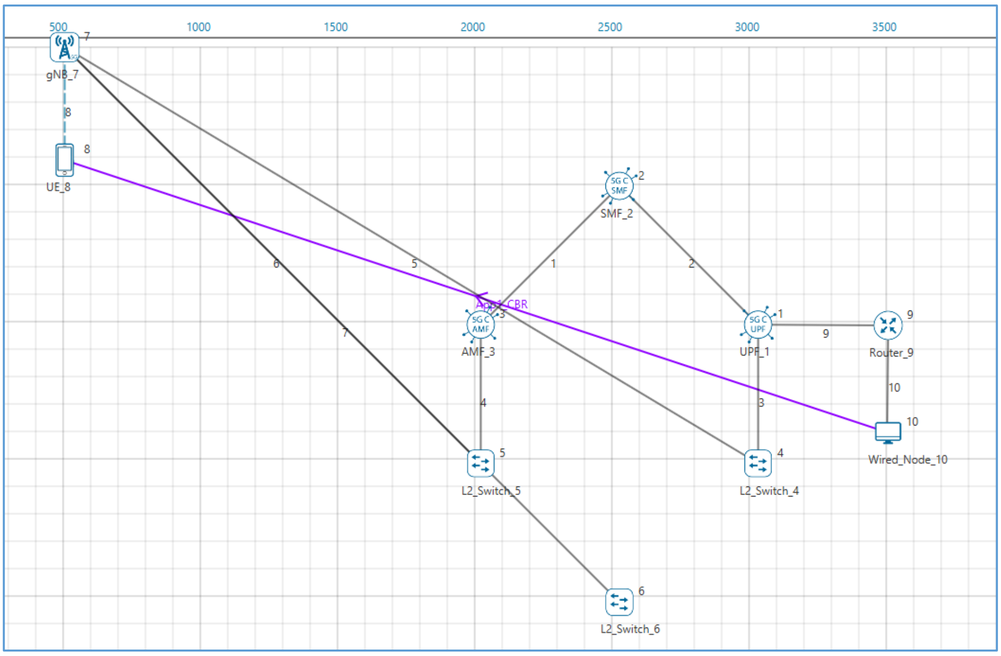

Fig 8: Network topology in this experiment

Settings:

The following settings were configured in the network setup.

1. The UE was placed 50m away from the gNB.
1. The following properties were set in Interface 5G RAN, Physical Layer of gNB.

gNB Interface 5G RAN	
gNB Height (m)	Varied from 10 to 150
Tx Power (dBm)	40
Tx Antenna Count	2
Rx Antenna Count	2
CA Type	Single Band
CA Configuration	n78
DL: UL Ratio	4:1
F_Low (MHz)	3300
F_High (MHz)	3800
Central Frequency (MHz)	3550
Numerology	0
Channel Bandwidth (MHz)	10
MCS Table	QAM64
CQI Table	TABLE1
Outdoor Scenario	Rural Macro
Indoor Office Type	Mixed Office
Pathloss Model	3GPPTR38.901-7.4.1

LOS Mode	User Defined
LOS Probability	0 or 1
Shadow Fading Model	None
Fading and Beamforming	No Fading
O2I Building Penetration Model	LOW LOSS MODEL

Table 2**:** gNB properties

2. Tx Antenna Count = Rx Antenna Count = 2 in UE > Interface 5G RAN > Physical Layer
3. A downlink CBR application was configured from Wired Node to UE with Packet Size 1460B and IAT 1168µs and the start time was set to 1s.
4. Run simulation for 2s.
5. In Case 2, set the LOS probability to 0 and run simulation for various gNB heights.
6. In case 3, place the UE 1000m away from the gNB and repeat the above procedure.
7. In case 4, set the LOS probability to 0 and run simulation for 2s.
8. After the simulation, note down the Pathloss from the log file generated for various gNB heights.

Results

1. After simulation, open 5G Parameter Log file from NetSim Result dashboard.

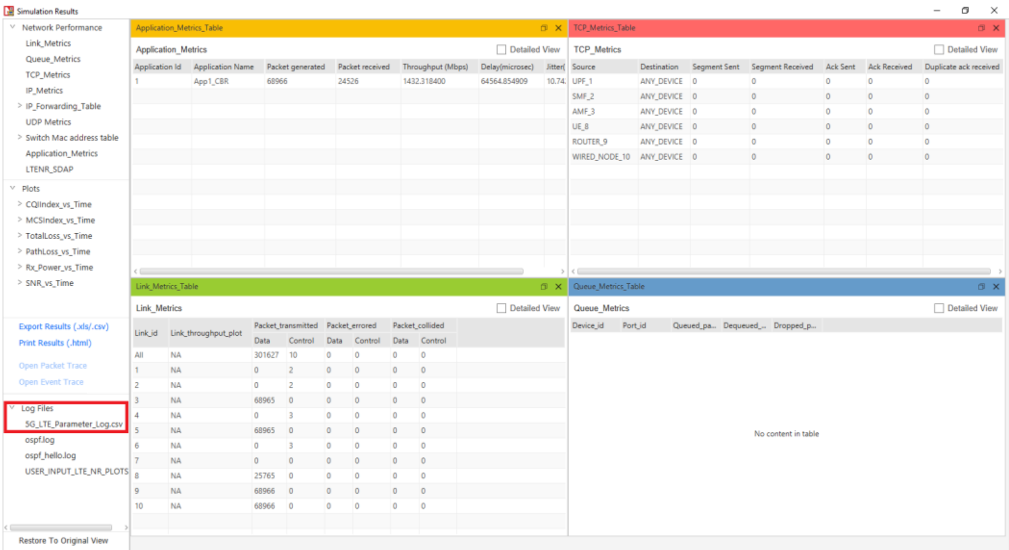

Fig 9**:** NetSim Results window

2. Note down the Pathloss value for each gNB height setting

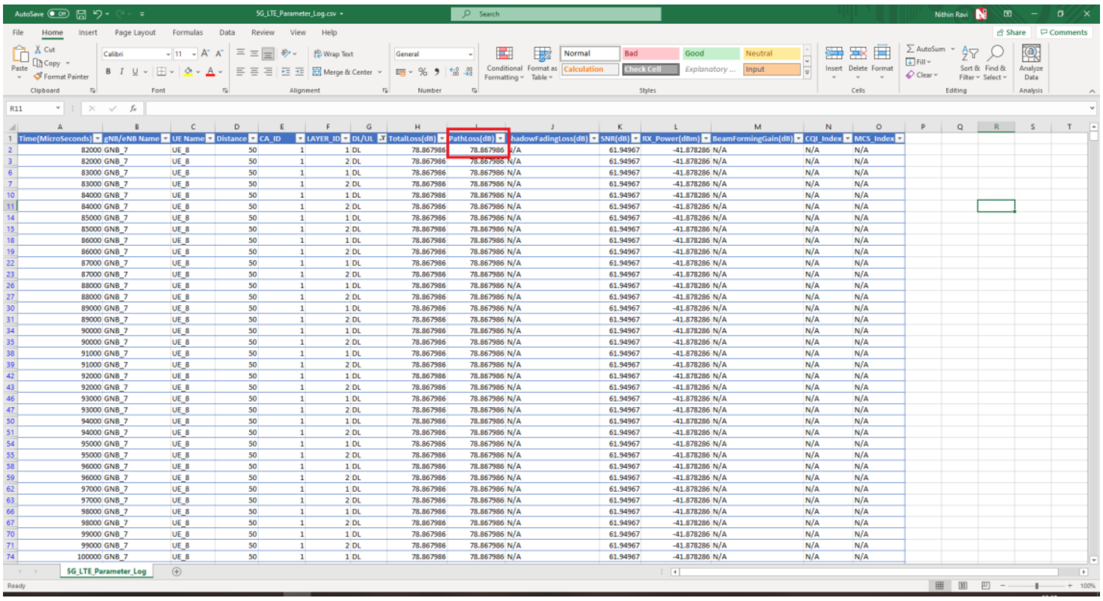

Fig 10: NetSim 5G Log file

Upon running simulations, we can obtain the following table below which contains pathloss values for:

- gNB height varying from 10m to 150m in steps of 20m.
- UE placed at 50m, 500m and 1000m away from gNB, and
- UE states: LOS, NLOS

gNB Height(m)	Pathloss (dB)					
	UE 50m, LOS	UE 50m, NLOS	UE 500m, LOS	UE 500m, NLOS	UE 1 km, LOS	UE 1km, NLOS
10	77.73	92.39	98.71	132.47	105.57	144.60
30	78.86	84.04	98.73	120.54	105.58	132.21
50	80.58	82.56	98.76	115.30	105.58	126.72
70	82.35	82.72	98.80	111.92	105.60	123.15
90	83.98	83.98	98.86	109.45	105.62	120.51
110	85.44	85.44	98.93	107.52	105.64	118.41
130	86.75	86.75	99.02	105.95	105.66	116.67
150	87.91	87.91	99.12	104.66	105.69	115.20

Table 3: Pathloss values for various combinations. The gNB heights are shown in Column 1. Other columns shows the gNB-UE 2D distance (50m, 500m and 1Km) and the UE state (LOS/NLOS)

Verification of two cases

In this section we hand calculate the pathloss per the 5G pathloss formula for two cases to verify NetSim's output.

Symbol	Description	Value
d_{BP}	$Breakpoint\ distance$	
h_{BS}	$Height\ of\ Base\ Station$	$10m$
h_{UT}	$Height\ of\ UE$	$1.5m$
f_c	$Central\ Frequency\ in\ Hz$	$3550 * 10^6 Hz = 3.55GHz$
c	$Speed\ of\ light$	$3 * 10^8 m/s$
W	$Street\ width$	$20m$
h	$Building\ Height$	$5m$

Table 4: Various parameters used in the pathloss calculations and their values

Case 1: gNB height = 10m, UE State is LOS and UE-gNB 2D Distance = 50m

Breakpoint Distance:

$$f_c = \frac{F_{Low}+F_{High}}{2} = \frac{3300+3800}{2} = 3550\ MHz = 3550 * 10^6 Hz$$

$$d_{Bp} = 2 * \ \pi * h_{BS} * h_{UT} * (f_c * \ 1000000000)\ /\ c)$$

$$d_{BP} = 2 * 3.14 * 10 * 1.5 * \left(\frac{3.55 * 1000000000}{3 * 10^8}\right) = 1114.7m$$

Pathloss Calculation

$$d_{2D} = 50m,\ d_{3D} = \sqrt{(d_{2D})^2 + (H_{BS} - H_{UT})^2} = \sqrt{(50)^2 + (10 - 1.5)^2} = 50.71m$$

If $(10 \le d_{2D} \le d_{BP})$

$$PL1 = (20 * log10(40 * PI * distance3D * fc_{(GHz)}\ /\ 3)) + fmin((0.03 * pow(h, 1.72)), 10) * log10(distance3D) - fmin((0.044 * pow(h, 1.72)), 14.77) + (0.002 * log10(h) * distance3D)$$

$$= \left(20 * log_{10}\left(40 * 3.14 * 50.71 * \frac{3.55}{3}\right)\right) + f_{min}\left((0.03 * pow(5,1.72)), 10\right) * log_{10}(50.71) - f_{min}\left((0.044 * pow(5,1.72)), 14.77\right) + (0.002 * log_{10}(5) * 50.71) = 77.73\ dB$$

Pathloss = 77.73 dB (matches NetSim result)

Case 2: gNB height = 10m, UE State is NLOS and UE-gNB 2D Distance = 50m

Breakpoint Distance:

$$f_c = \frac{F_{Low}+F_{High}}{2} = \frac{3300+3800}{2} = 3550\ MHz = 3550 * 10^6 Hz$$

$$d_{Bp} = 2 * \ \pi * h_{BS} * h_{UT} * (f_c * \ 1000000000)\ /\ c)$$

$$d_{BP} = 2 * 3.14 * 10 * 1.5 * \left(\frac{3.55 * 1000000000}{3 * 10^8}\right) = 1114.7m$$

Pathloss Calculation

$$d_{2D} = 50m$$

$$d_{3D} = \sqrt{(d_{2D})^2 + (H_{BS} - H_{UT})^2} = \sqrt{(50)^2 + (10 - 1.5)^2} = 50.71m$$

If $(10 \leq d_{2D} \leq 5Km)$

$$PL_{NLOS} = \max(PL_{LOS}, PL'_{NLOS})$$

Where,

$PL'_{NLOS} = 161.04 - 7.1 * \log_{10}(W) + 7.5 * \log_{10}(h) - \left(24.37 - 3.7 * \left(\frac{h}{h_{BS}}\right)^2\right) * \log_{10}(h_{BS}) + (43.42 - (3.1 * \log_{10}(h_{BS})^2)) * (\log_{10}(d_{3D}) - 3) + 20 * (\log_{10}(f_c)) - (3.2 * (\log_{10}(11.75 * h_{UT}))^2 - 4.97)$

$= 161.04 - (7.1 * \log_{10}(20)) + 7.5 * (\log_{10}(5)) - (24.37 - 3.7 * \left(\frac{5}{10}\right)^2) * (\log_{10}(10)) + (43.42 - (3.1 * \log_{10}(10)^2)) * (\log_{10}(50.71) - 3) + 20 * (\log_{10}(3.55)) - (3.2 * (\log_{10}(11.75 * 1.5))^2 - 4.97) = 92.39\ dB$

$PL_{LOS} = (20 * log10(40 * PI * distance3D * fc_{(GHz)} / 3)) + fmin((0.03 * pow(h, 1.72)), 10) * log10(distance3D) - fmin((0.044 * pow(h, 1.72)), 14.77) + (0.002 * log10(h) * distance3D)$

$= \left(20 * log_{10}\left(40 * 3.14 * 50.71 * \frac{3.55}{3}\right)\right) + f_{min}\left((0.03 * pow(5,1.72)), 10\right) * log_{10}(50.71) - f_{min}\left((0.044 * pow(5,1.72)), 14.77\right) + (0.002 * log_{10}(5) * 50.71) = 77.73\ dB$

$$PL_{NLOS} = \max(PL_{LOS}, PL'_{NLOS}) = \max(77.73, 92.39)$$

Pathloss = 92.39 dB (matches NetSim result)

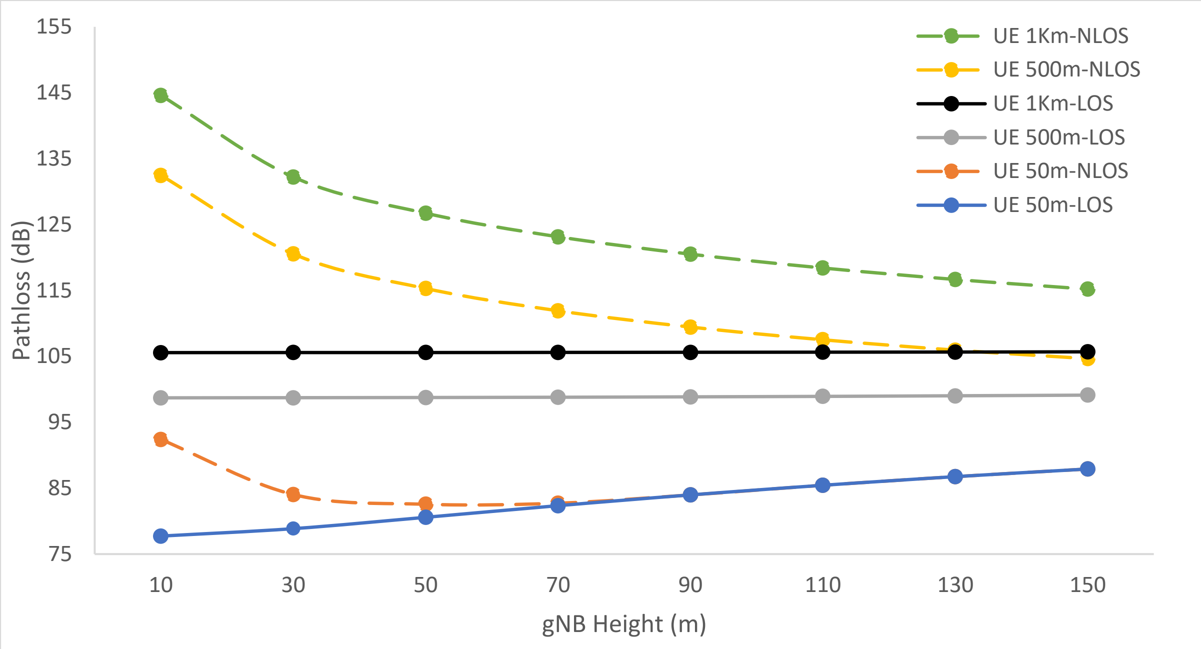

Fig 11: Plots of Pathloss vs. gNB height for different UE-gNB 2D Distances and UE States (LOS, NLOS)

Discussion

We explain the results in the plots above from the specifics of the pathloss formulas.

- In the LOS plots, the pathloss is flat for different gNB heights when the gNB-UE distance is high, i.e 500m and 1 km. When the gNB-UE distance is low i.e 50m, the pathloss increases with gNB height.
- Observe from the LOS pathloss formula that pathloss is proportional to $\log(D_{3d})$. D_{3d} of the 3D distance between the UE and the gNB and is defined as $d_{3D} = \sqrt{(d_{2D})^2 + (h_{BS} - h_{UT})^2}$. It is the hypotenuse of the right triangle with the base being the gNB-UE 2D distance.
  - Since the length of the hypotenuse is sensitive to the height of the triangle, when the base is small, we see the pathloss increasing with gNB height when the UE is 50m away.
  - Inversely, the length of the hypotenuse is almost insensitive to the triangle height when the base is much larger than the height. Therefore, when the UE is far, the gNB's height does not have a noticeable impact. Pathloss is flat when the UE is 500m and 1 km away.
- Let us turn to the NLOS results.
  - The NLOS pathloss decreases with gNB height when the gNB-UE distance is high i.e 500m and 1000m.
  - When the UE is near, i.e 50m, the NLOS pathloss first decreases and then increases with gNB height.

   - The reason for this kind of variation is the NLOS pathloss formulas in which that pathloss has terms proportional to:
     - $\log(h_{BS})$, $\log((h_{BS})^2)$
     - $\log(d_{3d})$
     - The reciprocal of $(h_{BS})^2$
- We see that at larger distances LOS pathloss is almost flat and NLOS pathloss decreases, as gNB height increases. From the plots one sees that the optimal gNB height would be between 125m to 150m in the example discussed above.

Exercises

1. Make a separate plot with the UE distance on the X-axis and show the behavior for three different values of the gNB height. Recommend the gNB height for different cell radii. Does your recommendation make practical sense?
2. Use MATLAB or Python to plot similar curves from the standard pathloss formulas. Compare your results against the NetSim results.
3. (For the Instructor or TA) Generate *personalized* exercises where the student can be asked to
   a. Recommend the gNB height given the cell radius
   b. Recommend gNB height given the transmit power.
   c. Find the cell radius given the gNB height, transmit power and noise figure.