Investigating Reciprocity in the Millimeter Wave Channel

Technical Report
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Abstract

Millimeter wave (mmWave) technology is expected to play a major role in the deployment of 5G. As the demand for mobile data and cellular capacity increases, current cellular systems, based on microwave frequencies, are running out of available spectrum. It is expected that by the year 2020, some operators would face demand of about 130 x 1018 bits of data per year. A task that is unrealistic for today's cellular technology. However, bandwidth availability is much wider in the mmWave bands, and the available spectrum can be 200 times larger than all cellular allocations today. One of the challenges of mmWave communication is to gain full knowledge of the communication channel. In this project we investigate the reciprocity between the up link and the down link when communicating at the mmWave region of the spectrum and show a small presence of non reciprocity. Knowledge of the channels reciprocity is crucial when developing algorithms for channel estimation and link adaptation. We ran simulations for different scenarios to compare the received power, path loss exponent and the shadow fading standard deviation for the up link and the down link. We noticed that in most scenarios, there was a small difference in the results of the two links, which show a minor presence of non reciprocity.

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1 Introduction

The millimeter wave (mmWave) band of frequencies between 30 and 300 GHz is expected to host the next generation of wireless cellular networks [1]. As the demand for mobile data and cellular capacity increases, current cellular systems, based on microwave frequencies, are running out of available spectrum. It is expected that by the year 2020, some operators would face demand of about 130 x 1018 bits of data per year [2]. A task that is unrealistic for today's cellular technology. However, bandwidth availability is much wider in the mmWave bands, and the available spectrum can be 200 times larger than all cellular allocations today [3]. For this reason, researchers and engineers have started to show that mmWave will play a significant role in 5G cellular systems. Despite the potential of mmWave systems, there are a number of key challenges to be overcome. One of these challenges is to gain full knowledge of the communication channel in these systems. In this project we investigate the reciprocity between the up link and the down link when communicating at the mmWave region of the spectrum and show the presence of non reciprocity.

2 Problem Statement

Knowledge of the channels reciprocity is crucial when developing algorithms for channel estimation and link adaptation. Also, many existing transmission schemes assume full reciprocity, which hinders their performance when utilized with mmWave communication. We assume non reciprocity due to the nature of the waves. Since they operate at a high frequency, their wavelengths are short, making it susceptible to attenuation, severe shadowing, rapid channel fluctuations, intermittent connectivity and higher Doppler spreads. Reciprocity in this domain implies that if a transmitting antenna and a receiving antenna are functionally interchanged, the transfer characteristics of the channel remain unchanged. We name the communication from the transmitter to the receiver the Up Link, and the reverse communication, the Down Link, as can be seen in Figure [1].

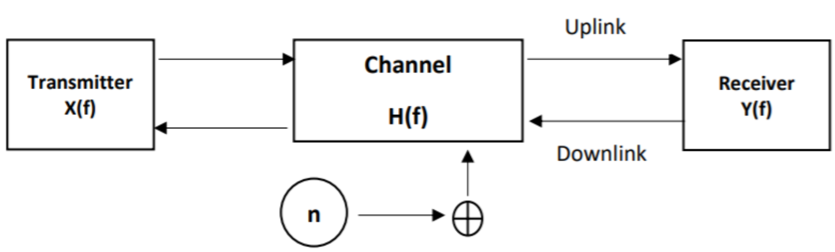

Figure 1: System Block Diagram

From figure [1] we can characterize the up link by the following equation:

$$Y(f) = X(f).H^{UL} + n(f) \tag{1}$$

where H^{UL} is the channel impulse response of the up link and $n(f)$ is the added Gaussian noise.

Similarly we can characterize the down link by the following equation:

$$Y(f) = X(f).H^{DL} + n(f) \tag{2}$$

where H^{DL} is the channel impulse response of the down link. The channel response $H(f)$ fully characterizes the channel, and one of its main components is the path loss model. In the next sections we detail the path loss model used for our channel model, and show how some experimental parameters in this model differ slightly between the up link and the down link.

3 Channel Model

Many existing models used for wireless communication are not adaptable in this project due to the uniqueness of the mmWave channel. Instead, it is modeled based on various measurements taken in a real environment, for many scenarios. In [4], researchers at NYU developed a broadband statistical spatial channel model (SSCM) based on numerous measurements in New York City. These measurements are provided through an open source simulator [5], that is used in our analysis.

3.1 Path Loss Model

The Path Loss model used for the simulator[5] is based on a close-in free space reference distane path loss model with a 1 m anchor point [6]. An extra attenuation term that accounts for various attenuation factors is also included. This path loss model is expressed as :

$$PL(f,d)[dB] = FSPL(f,1m)[dB] + 10n\log_{10}(\frac{d}{d_0}) + AT[dB] + \chi_\sigma \tag{3}$$

where f is the frequency in GHz, n represents the path loss exponent, d is the distance between the transmitter and receiver in meters, d_0 is the free space reference distance set to 1 m such that $d\ d_0$, AT is the attenuation term due to the effect of the atmosphere, χ_σ is a zero mean Gaussian random variable with a standard deviation of $\sigma[dB]$, and $FSPL(f,1m)$ is the free space path loss at a transmitter and receiver separation of 1 m at frequency f [6], it's expressed as :

$$FSPL(f,1m)[dB] = 20\log_{10}(\frac{4\pi f \times 10^9}{c}) \tag{4}$$

where c is the speed of light. Also, the attenuation term AT can be expressed as :

$$AT[dB] = \alpha[dB/m] \times d[m] \tag{5}$$

where α is the attenuation factor that includes attenuation effects form water vapor, dry air and haze [7].

4 Simulation Setup & Results

We will be running eight simulations on the NYUSIM [5] to gather information about the channel state. Specifically we will test the up link and down link communication at the Line of Sight (LOS) and Non-Line of Sight (NLOS) environments, at two different transmitter and receiver separation distances.The first four tests will be at separation of 750 meters, and the last four will be at separation of 1500 meters. The following test parameters were held constant through all the tests:

- Carrier frequency of 60 GHz
- RF Bandwidth of 800 MHz
- Transmission power of 30 dBm
- An Urban Micro Cell scenario
- Base Station height of 40 meters for both the transmitting and receiving antenna
- Barometric Pressure of 1013.25 mbar (sea level)
- Humidity level of 50%
- Temperature of 20 degrees Celsius
- Rain Rate of 0 mm/hr
- Co-Polarization between the transmitter and receiver
- No Foliage Loss
- Single Horn Antenna at each the transmitter and receiver
- Transmitting Antenna Azimuth HPBW of 10^o
- Transmitting Antenna Elevation HPBW of 10^o
- Receiving Antenna Azimuth HPBW of $45o$
- Receiving Antenna Elevation HPBW of 45^o

The graphs produced from the simulations are the following: An Angle of Arrival (AOA) and an Angle of Departure (AOD) Power Spectrum, a sample omni directional and directional Power Delay Profile (PDP), an omni directional and directional path loss plot over an entire distance range. Experimental parameters that are of our interest are the received power P_r, path loss PL, path loss exponent n and the shadow fading standard deviation σ for both the omni directional and directional cases.

4.1 Simulation 1

The variable parameters set in this simulation are as follows:

- Transmitter and Receiver separation Distance: 750 meters
- Communication Link: Up Link
- Environment : Line of Sight (LOS)

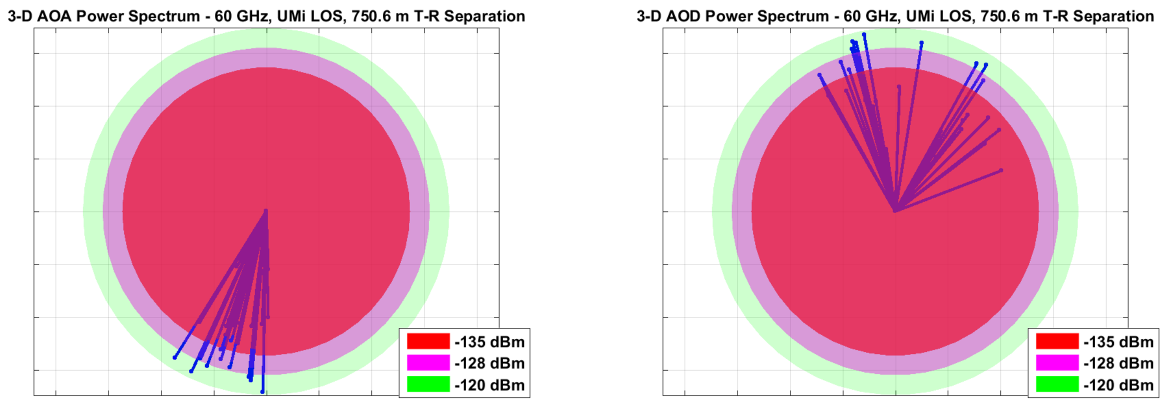

Figure 2: Up link AOA & AOD Power Spectrum at 750 m - 60 GHz - LOS

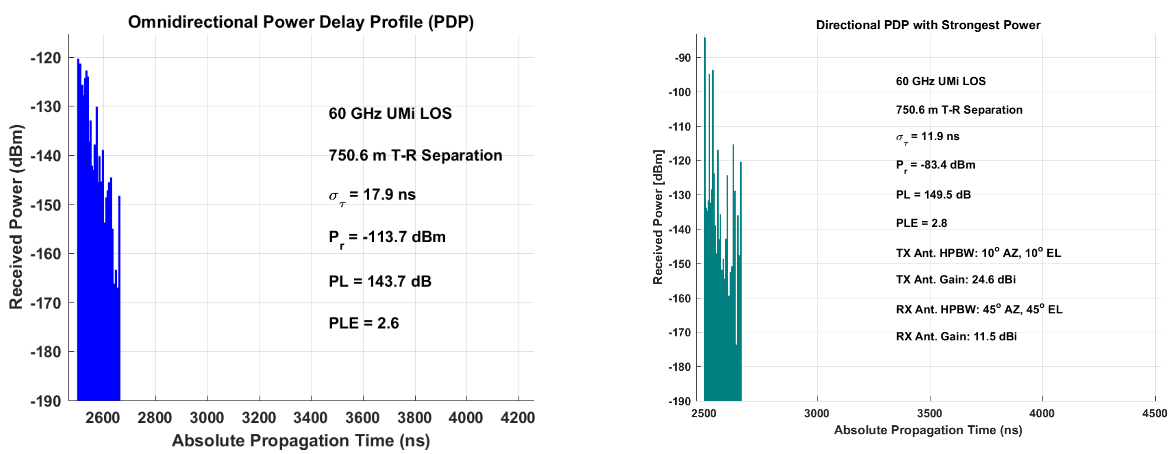

Figure 3: Up link Omni directional and Directional PDP at 750 m - 60 GHz - LOS

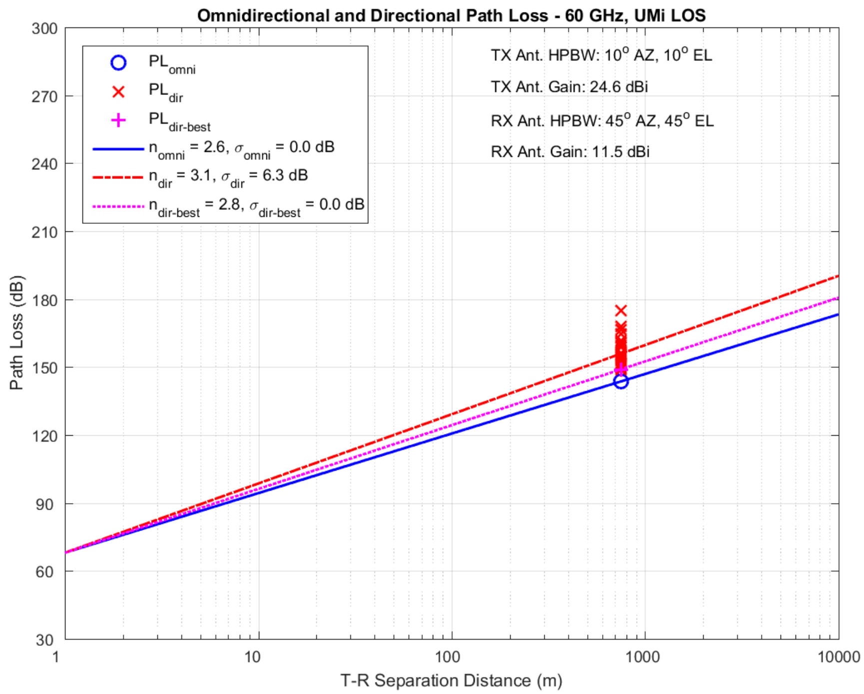

Figure 4: Up link Omni directional and Directional Path Loss - 60 GHz - LOS - 750 m

4.2 Simulation 2

The variable parameters set in this simulation are as follows:

- Transmitter and Receiver separation Distance: 750 meters
- Communication Link: Down Link
- Environment : Line of Sight (LOS)

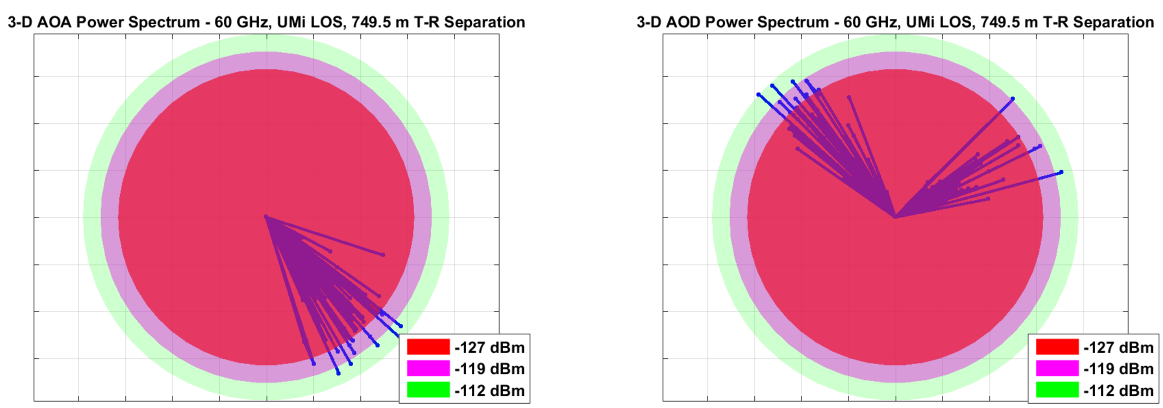

Figure 5: Down link AOA & AOD Power Spectrum at 750 m - 60 GHz - LOS

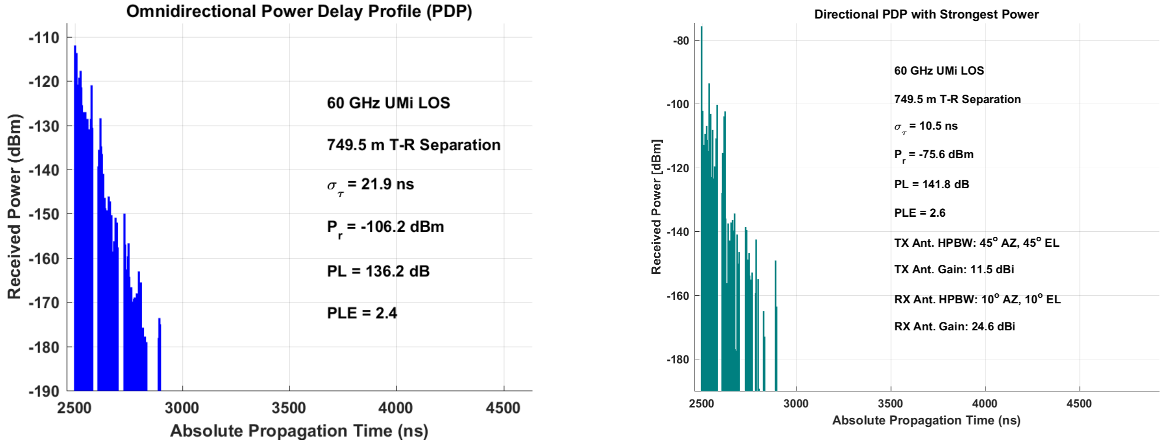

Figure 6: Down link Omni directional and Directional PDP at 750 m - 60 GHz - LOS

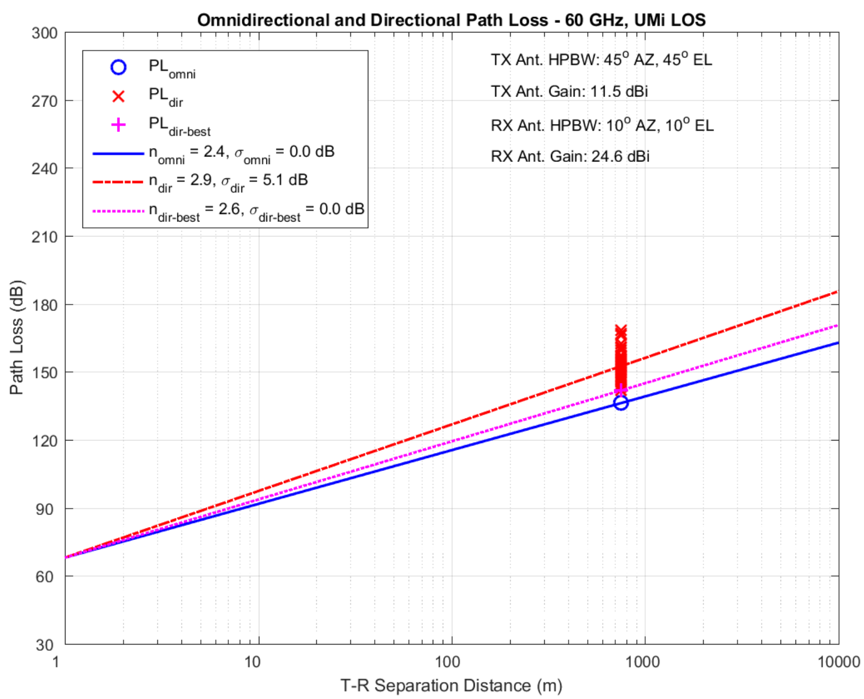

Figure 7: Down link Omni directional and Directional Path Loss - 60 GHz - LOS - 750 m

4.3 Simulation 3

The variable parameters set in this simulation are as follows:

- Transmitter and Receiver separation Distance: 750 meters
- Communication Link: Up Link

- Environment : Non Line of Sight (NLOS)

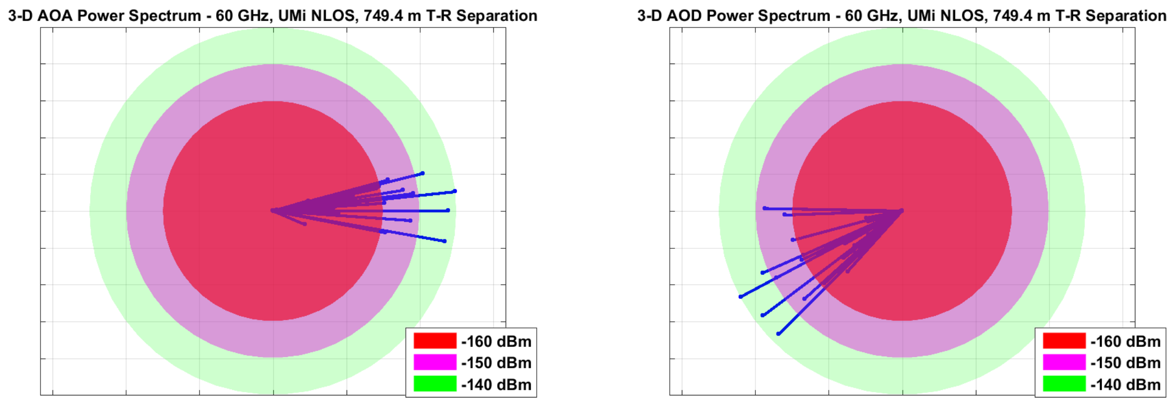

Figure 8: Up link AOA & AOD Power Spectrum at 750 m - 60 GHz - NLOS

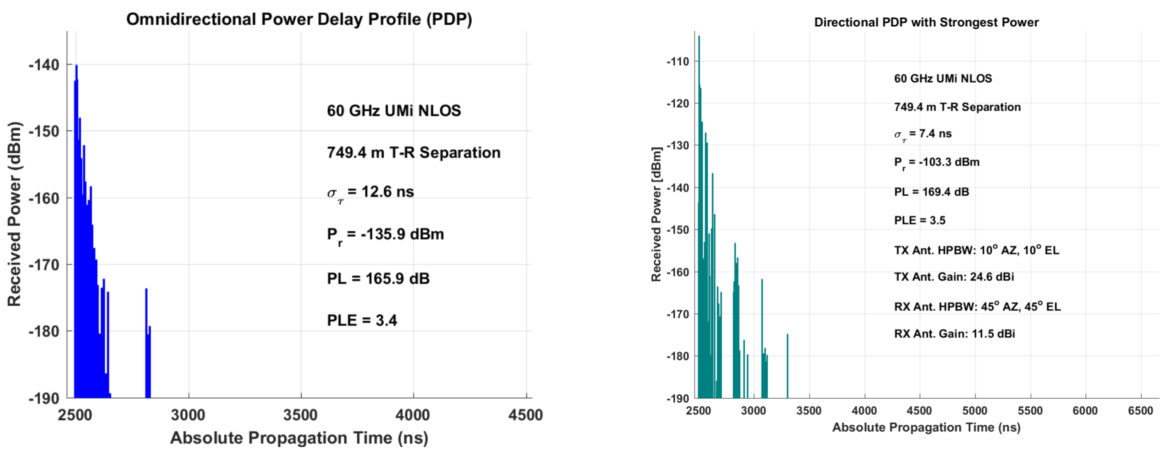

Figure 9: Up link Omni directional and Directional PDP at 750 m - 60 GHz - NLOS

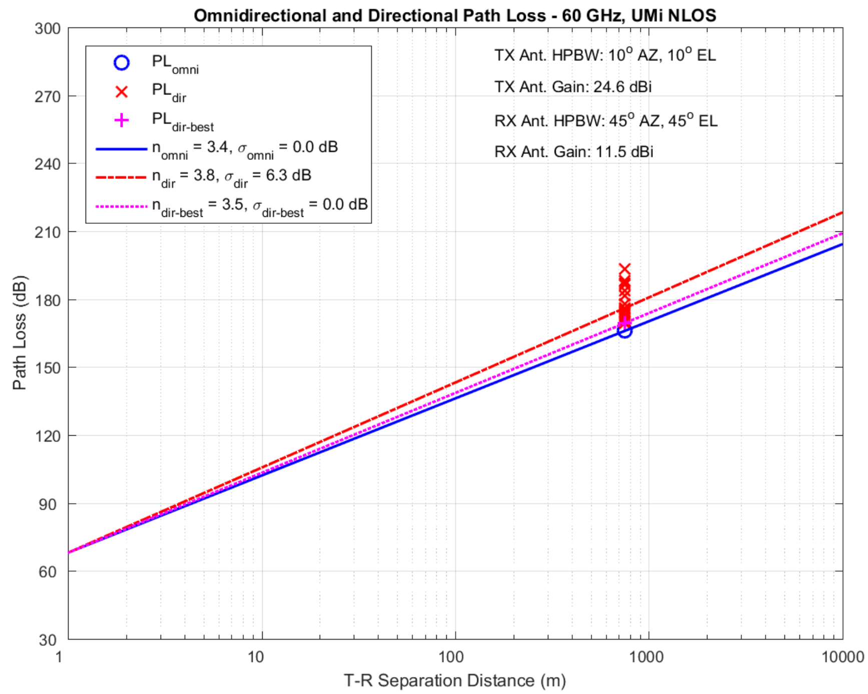

Figure 10: Up link Omni directional and Directional Path Loss - 60 GHz - NLOS - 750 m

4.4 Simulation 4

The variable parameters set in this simulation are as follows:

- Transmitter and Receiver separation Distance: 750 meters
- Communication Link: Down Link
- Environment : Non Line of Sight (NLOS)

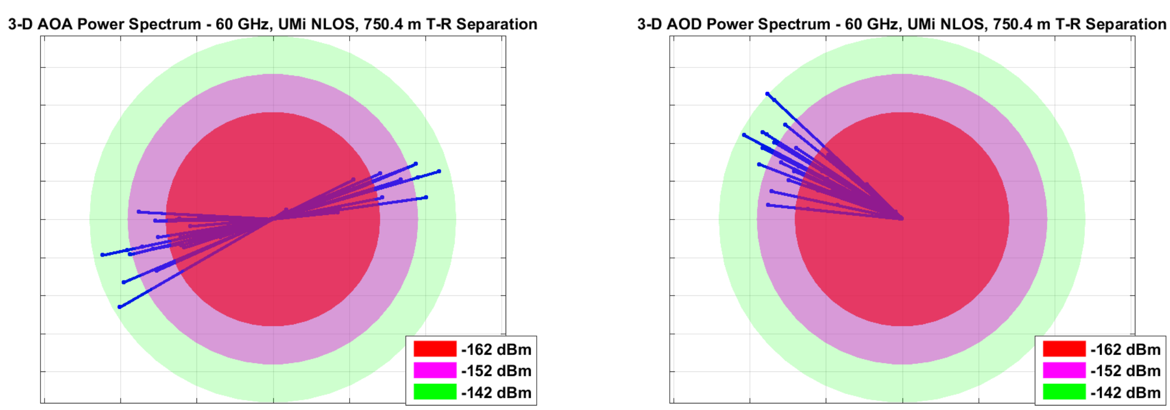

Figure 11: Down link AOA & AOD Power Spectrum at 750 m - 60 GHz - NLOS

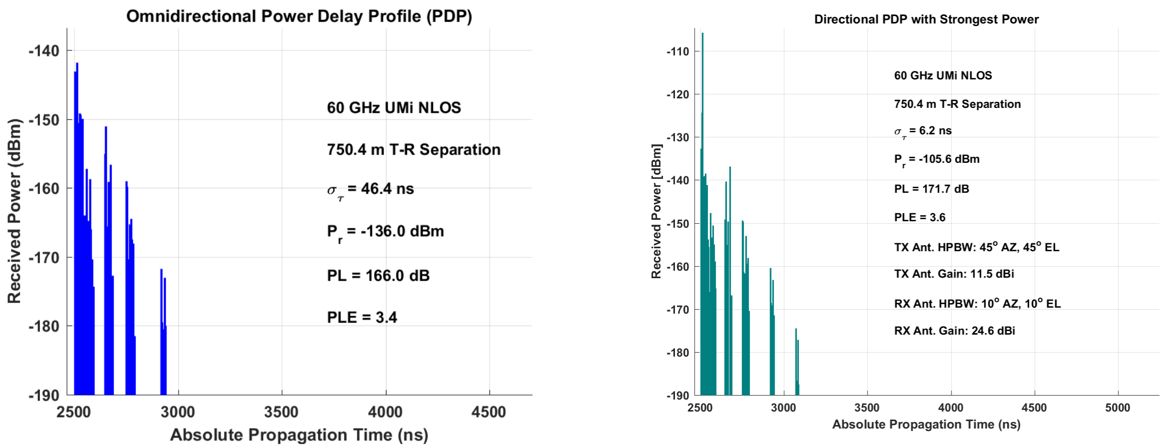

Figure 12: Down link Omni directional and Directional PDP at 750 m - 60 GHz - NLOS

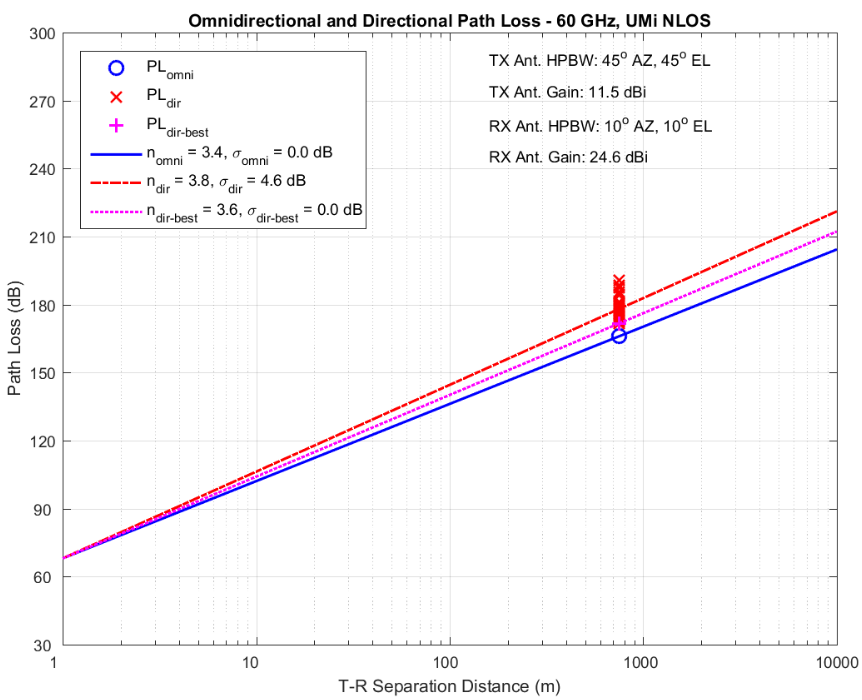

Figure 13: Down link Omni directional and Directional Path Loss - 60 GHz - NLOS - 750 m

4.5 Simulation 5

The variable parameters set in this simulation are as follows:

- Transmitter and Receiver separation Distance: 1500 meters
- Communication Link: Up Link

- Environment : Line of Sight (LOS)

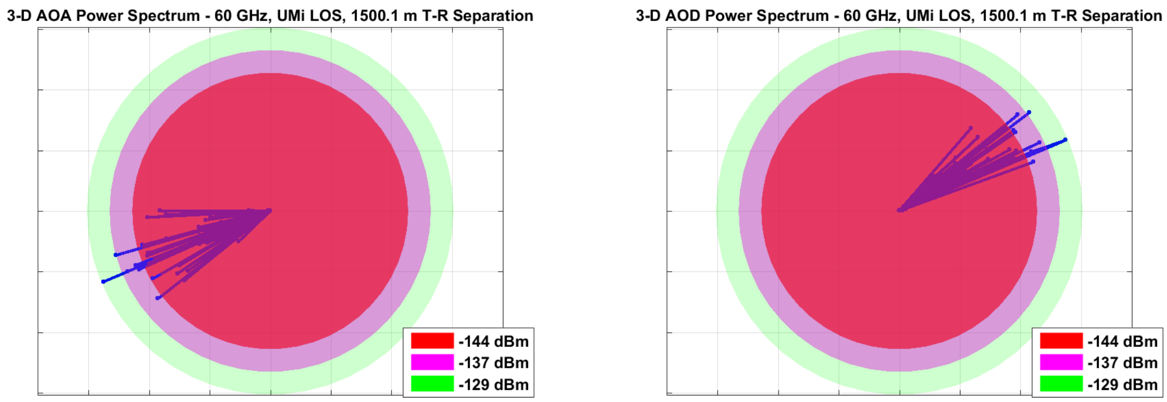

Figure 14: Up link AOA & AOD Power Spectrum at 1500 m - 60 GHz - LOS

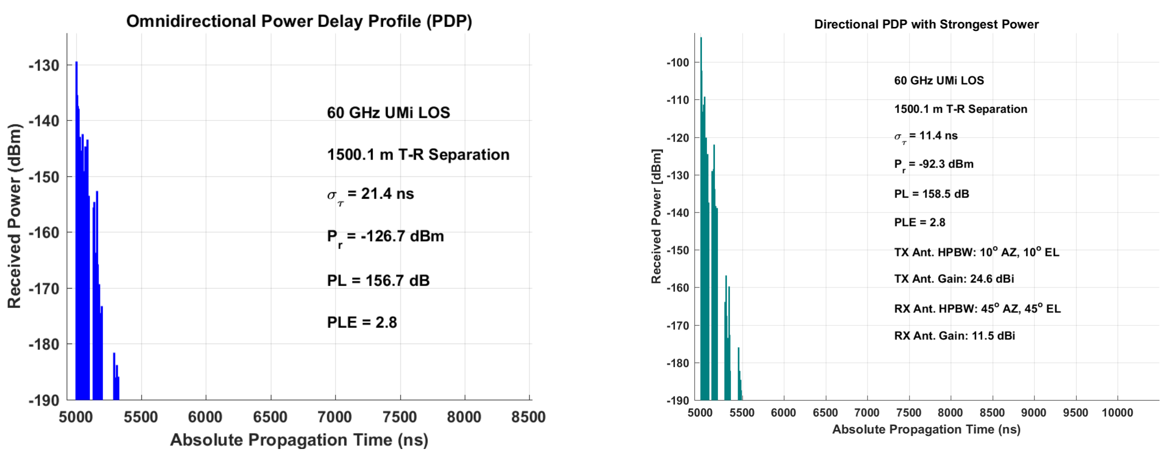

Figure 15: Up link Omni directional and Directional PDP at 1500 m - 60 GHz - LOS

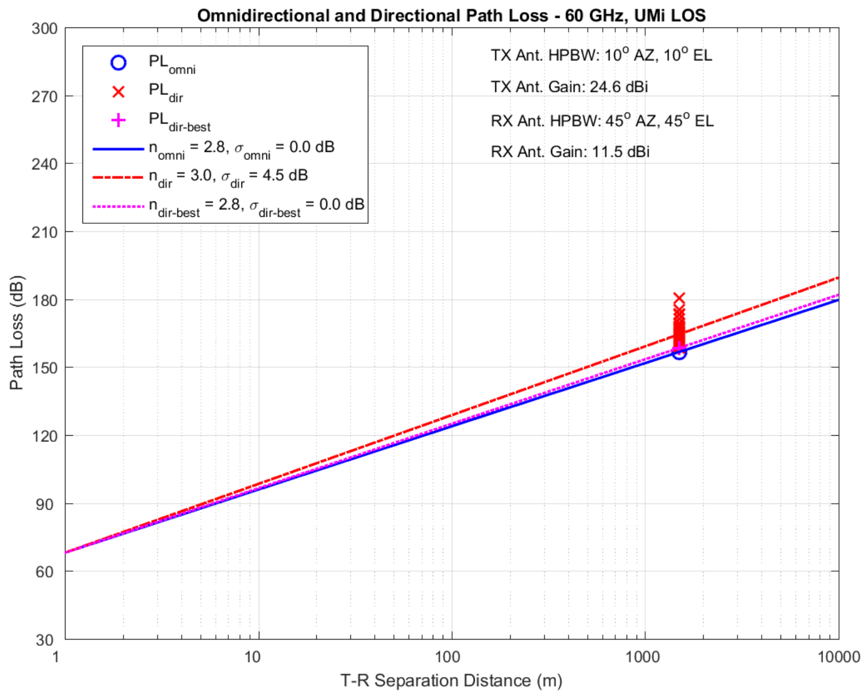

Figure 16: Up link Omni directional and Directional Path Loss - 60 GHz - LOS - 1500 m

4.6 Simulation 6

- Transmitter and Receiver separation Distance: 1500 meters
- Communication Link: Down Link
- Environment : Line of Sight (LOS)

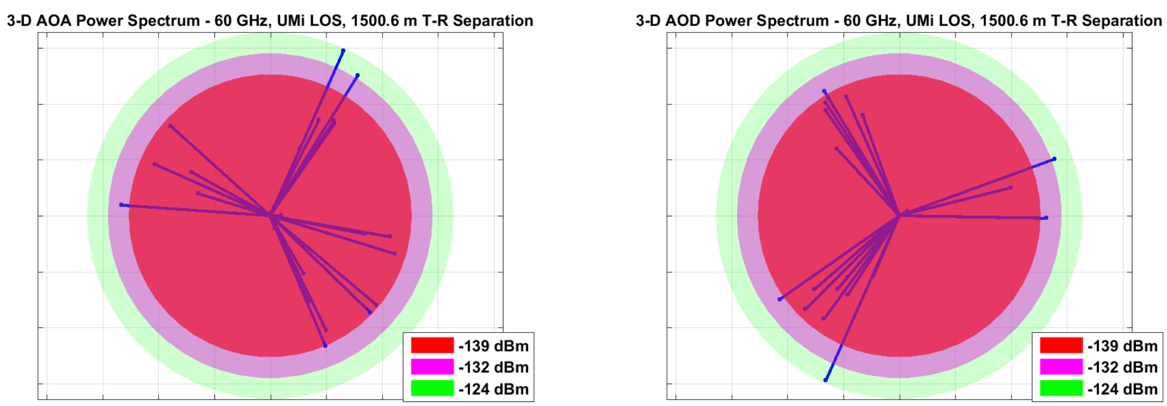

Figure 17: Down link AOA & AOD Power Spectrum at 1500 m - 60 GHz - LOS

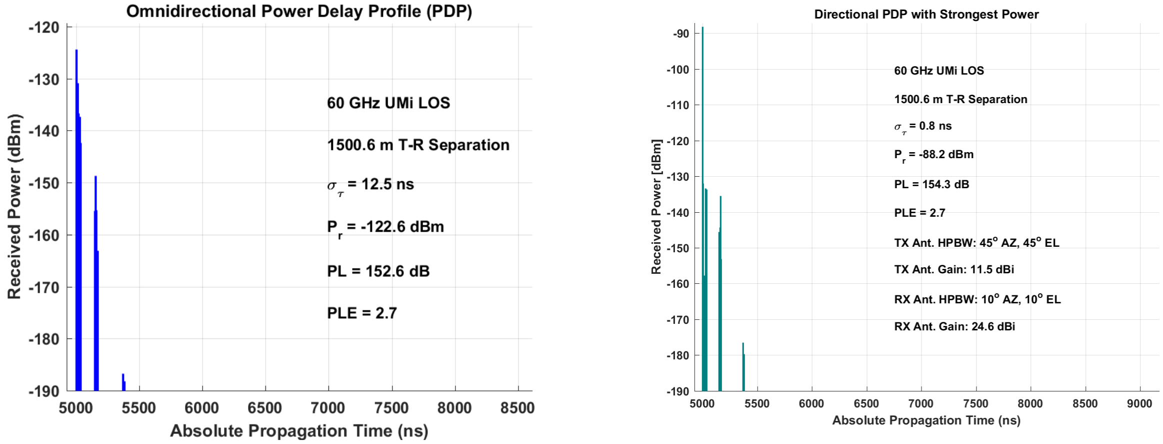

Figure 18: Down link Omni directional and Directional PDP at 1500 m - 60 GHz - LOS

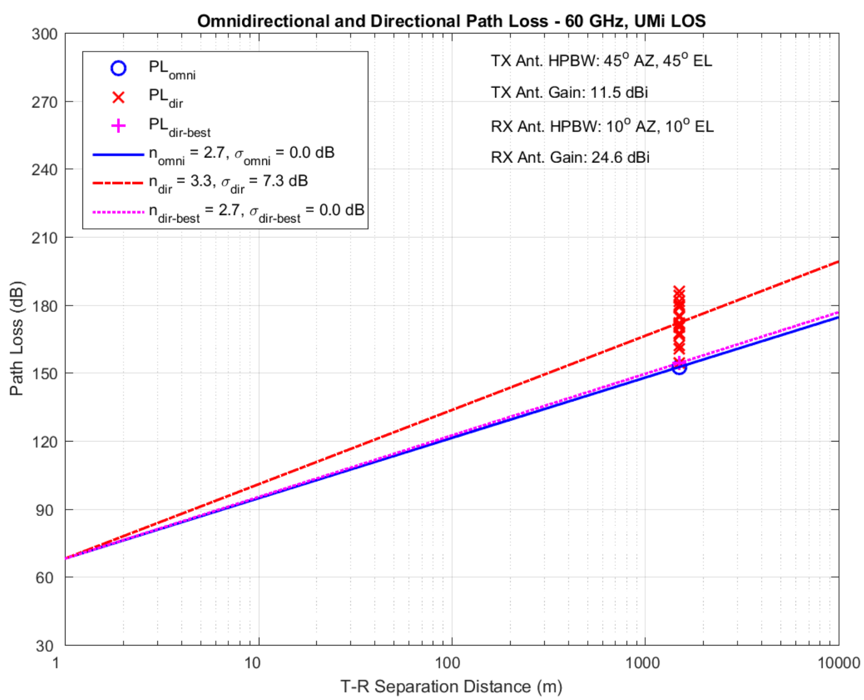

Figure 19: Down link Omni directional and Directional Path Loss - 60 GHz - LOS - 1500 m

4.7 Simulation 7

- Transmitter and Receiver separation Distance: 1500 meters
- Communication Link: Up Link
- Environment : Non Line of Sight (NLOS)

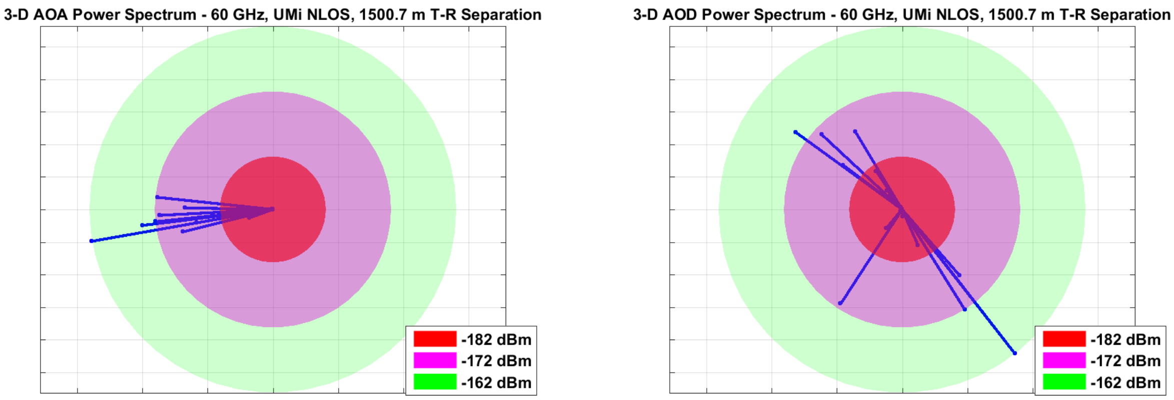

Figure 20: Up link AOA & AOD Power Spectrum at 1500 m - 60 GHz - NLOS

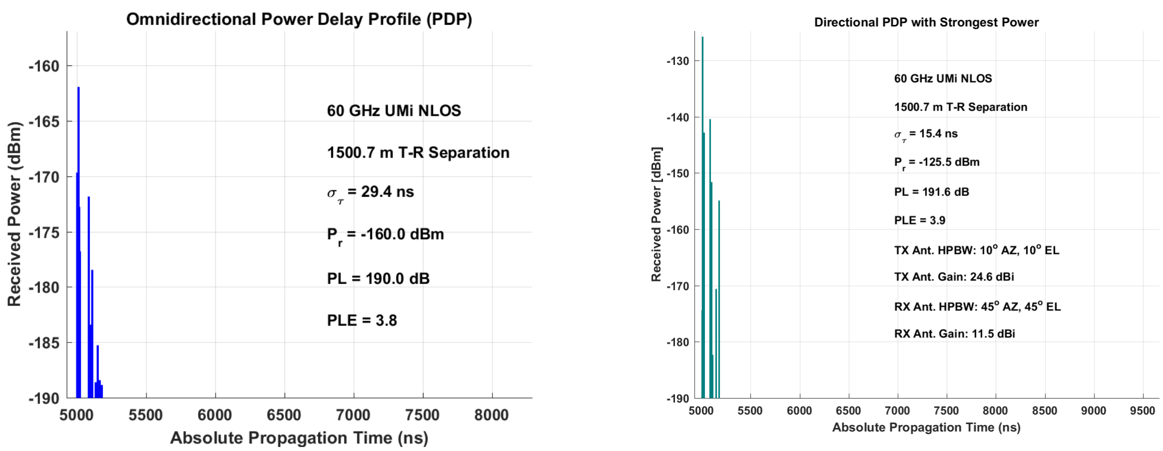

Figure 21: Up link Omni directional and Directional PDP at 1500 m - 60 GHz - NLOS

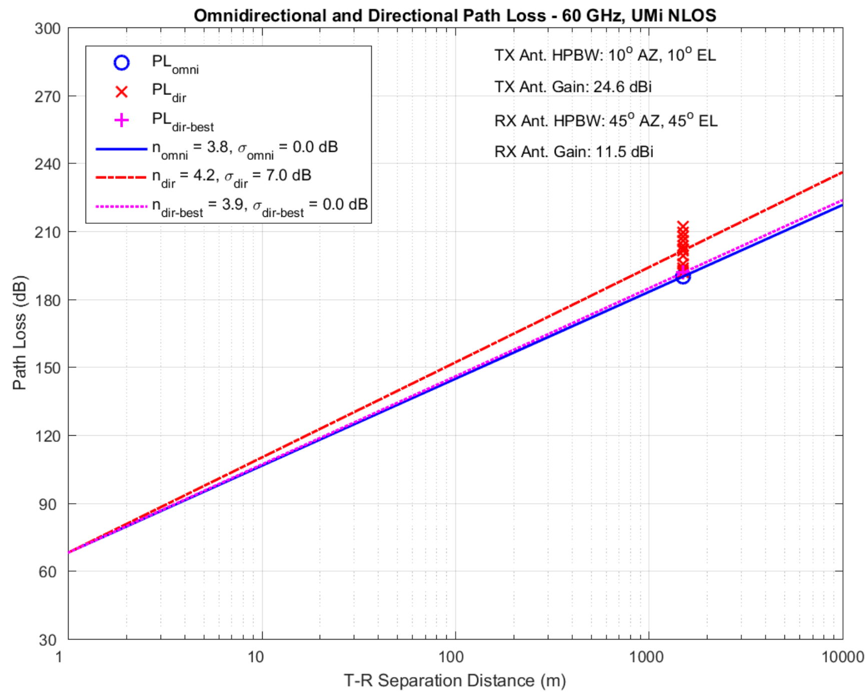

Figure 22: Up link Omni directional and Directional Path Loss - 60 GHz - NLOS - 1500 m

4.8 Simulation 8

- Transmitter and Receiver separation Distance: 1500 meters
- Communication Link: Down Link
- Environment : Non Line of Sight (NLOS)

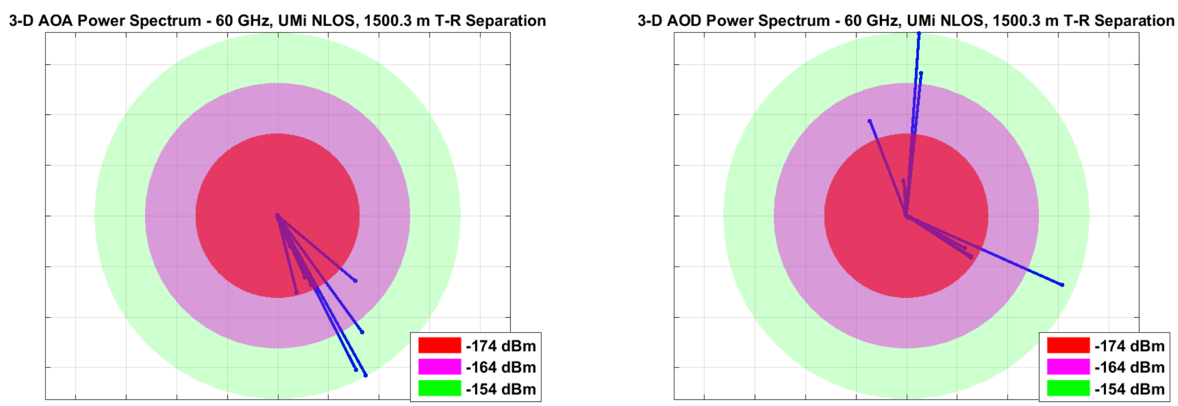

Figure 23: Down link AOA & AOD Power Spectrum at 1500 m - 60 GHz - NLOS

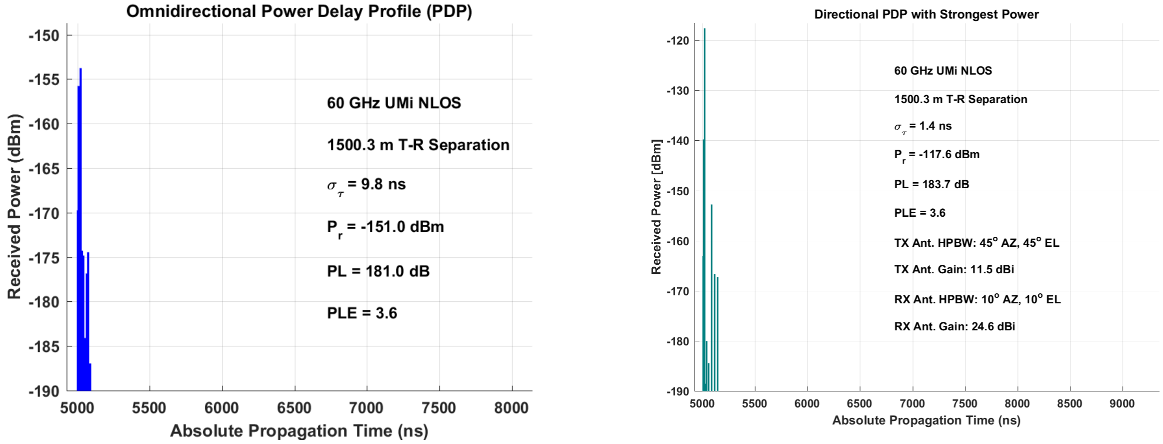

Figure 24: Down link Omni directional and Directional PDP at 1500 m - 60 GHz - NLOS

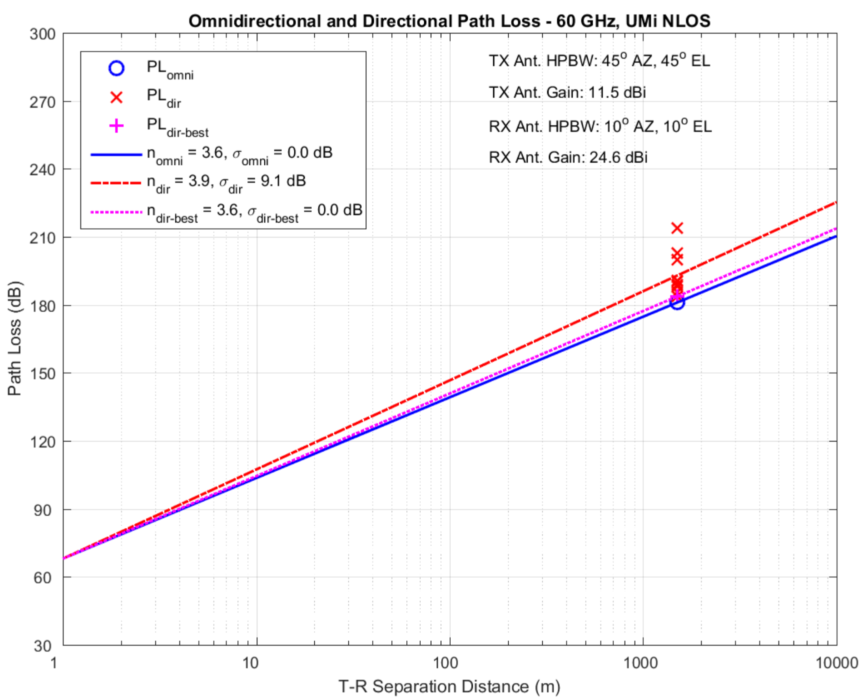

Figure 25: Down link Omni directional and Directional Path Loss - 60 GHz - NLOS - 1500 m

5 Discussion of Results

In order for us to show non reciprocity between the up link and the down link, the channel model parameters for both links need to differ. In our analysis we will compare the received power, path loss, path loss exponent and the shadow fading standard deviation for all our aforementioned scenarios. Table [1] & [2] summarize the obtained results for these parameters from the above

simulations.
The received power is measured in dBm, which is the power ratio in decibels. A less negative value indicates a better quality signal received. Therefore it is not unusual to see the received power decrease as the distance between the transmitter and receiver doubles from 750 m to 1500 m. Also, the received power decreases when switching between an omni directional (antenna transmits in all directions) and a directional (antenna transmits in a specific direction) antenna configuration, and from a LOS to a NLOS, as expected. However, we also notice that the received power is different between the up link and the down link, but the difference is not significant.

We also notice that the directional path loss and PLE are always larger than the omni directional case, the reason is that the directional channel is more lossy, since it will spatially filter out many multi path components due to its directional pattern [6], therefore the receiver antenna receives less multi path components, and less energy.

Table 1: Summary of Simulation Results - 750 m

Separation between Antennas d	Line of Sight (LOS)				Non Line of Sight (NLOS)			
	a) Uplink		b) Downlink		c) Uplink		d) Downlink	
750 m	Received Power (Omni directional)	-113.7 dBm	Received Power (Omni directional)	-106.2 dBm	Received Power (Omni directional)	-135.9 dBm	Received Power (Omni directional)	-136 dBm
	Received Power (Directional)	-83.4 dBm	Received Power (Directional)	-75.6 dBm	Received Power (Directional)	-103.3 dBm	Received Power (Directional)	-105.6 dBm
	Path Loss (Omni directional)	143.7 dB	Path Loss (Omni directional)	136.2 dB	Path Loss (Omni directional)	165.9 dB	Path Loss (Omni directional)	166 dB
	Path Loss (Directional)	149.5 dB	Path Loss (Directional)	141.8 dB	Path Loss (Directional)	169.4 dB	Path Loss (Directional)	171.7 dB
	Path Loss exponent (Omni directional)	2.6	Path Loss exponent (Omni directional)	2.4	Path Loss exponent (Omni directional)	3.4	Path Loss exponent (Omni directional)	3.4
	Path Loss (Directional)	3.1	Path Loss (Directional)	2.9	Path Loss (Directional)	3.8	Path Loss (Directional)	3.8
	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB
	Shadow Fading SD (Directional)	6.3 dB	Shadow Fading SD (Directional)	5.1	Shadow Fading SD (Directional)	6.3 dB	Shadow Fading SD (Directional)	4.6 dB

When comparing the PLE of the up link and the down link for all scenarios, we notice that theres a difference most of the time. Again, this isn't significant, however it shows theres a slight change in the channel condition. We also notice that the shadow fading standard deviation in the directional case is always different between the up link and the down link. The separation between antennas did not impact the PLE and shadow fading standard deviation as much for all scenarios.

Table 2: Summary of Simulation Results - 1500 m

Separation between Antennas d	Line of Sight (LOS)				Non Line of Sight (NLOS)			
	e) Uplink		f) Downlink		g) Uplink		h) Downlink	
1500 m	Received Power (Omni directional)	-126.7 dBm	Received Power (Omni directional)	-122.6 dBm	Received Power (Omni directional)	-160 dBm	Received Power (Omni directional)	-151 dBm
	Received Power (Directional)	-92.3 dBm	Received Power (Directional)	-88.2 dBm	Received Power (Directional)	-125.5 dBm	Received Power (Directional)	-117.6 dBm
	Path Loss (Omni directional)	156.7 dB	Received Power (Omni directional)	152.6 dB	Received Power (Omni directional)	190 dB	Received Power (Omni directional)	181 dB
	Path Loss (Directional)	158.5 dB	Received Power (Directional)	154.3 dB	Received Power (Directional)	191.6 dB	Received Power (Directional)	183.7 dB
	Path Loss exponent (Omni directional)	2.8	Path Loss exponent (Omni directional)	2.7	Path Loss exponent (Omni directional)	3.8	Path Loss exponent (Omni directional)	3.6
	Path Loss (Directional)	3	Path Loss (Directional)	3.3	Path Loss (Directional)	4.2	Path Loss (Directional)	3.9
	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB	Shadow Fading SD (Omni Directional)	0 dB
	Shadow Fading SD (Directional)	4.5 dB	Shadow Fading SD (Directional)	7.3 dB	Shadow Fading SD (Directional)	7 dB	Shadow Fading SD (Directional)	9.1 dB

6 Conclusion

In this project we investigated the reciprocity between the up link and the down link when communicating at a carrier frequency of 60 GHz, within the mmWave band. We ran simulations for different scenarios but with specific constant parameters to compare the received power, path loss exponent and the shadow fading standard deviation for the up link and the down link. We noticed that in most scenarios, there was a small difference in the results, which might show non reciprocity, but are still inconclusive. An extension to this work could be to run more simulations using different parameters, for example, including mobility between (i.e. base station and a mobile station), or using a higher carrier frequency.

References

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