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Analysis of MIMO Channel Capacity at 28/73 GHz with NYUSIM Channel Simulator

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Abstract

5G and beyond systems will meet the demand for high data rates in mobile communication with millimeter wave (mmWave) technology. The use of high frequencies reduced signal strength, changed path loss patterns, and increased the effect of atmospheric attenuation. Therefore, using old channel models became impossible, and new channels had to be created. Analyzing the channel models to be produced is also critical for 5G system performance. This study investigated the effects of 28 GHz and 73 GHz frequencies, the number of transmitting and receiving antennas, and LOS/NLOS parameters on 5G channel capacity using the NYUSIM channel simulator. As a result of the analysis, changing from a 2x2 to a 64x64 antenna structure for 28 GHz increased capacity by 29.78 times for LOS and 26.91 times for NLOS. When changing the MIMO configuration from 2x2 to 64x64 at 73 GHz, the channel capacity rises 36.88 times for LOS and 29.00 times for NLOS. With a 64x64 antenna structure, the channel capacity for 28 GHz and LOS is 8.81 times higher than for 73 GHz and 12.56 times higher for NLOS. For the 28 GHz 64x64 structure and LOS condition, the channel capacity is 215.69 times higher than the NLOS condition, while this value is 307.7 times for 73 GHz. It has been recognized that it is critical to adjust the LOS status in communication in urban areas where disruption effects from the use of mmWaves are common. Furthermore, as frequency increases, communication efficiency decreases. Various MIMO configurations can compensate for this reduction.

Keywords
“mmWave, Channel Modeling, Channel Capacity, NYUSIM”

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1. Introduction

The increasing number of users, mobile traffic, and user demands for high-data-rate applications has created a need for high data rates in wireless communication. Communication with developing technology began between people and everything, such as innovative home technologies, IoT, virtual reality, cloud technologies, high-definition multimedia, vehicle-to-vehicle (V2V), device to device (D2D), but instead mobile lines. Each innovation added to the wireless communication channel creates a new data rate requirement. The current frequency spectrum would not be able to meet the demands of this rapidly evolving technology (Yang, Xiao, Xiao, & Li, 2019). Radio/TV, mobile communication, satellite, and Wi-Fi systems are currently in the sub-6 GHz frequency region. Because of the extreme density of these frequency ranges, the ITU has identified the millimeter-wave region for fifth-generation (5G) and beyond systems. Using frequency bands ranging from 30-300 GHz, 5G communication, and beyond technologies can achieve data transmission rates of 10 Gbps and higher with very low latency and data loss. In 5G technology, using multiple-input multiple-output (MIMO) and massive MIMO antenna technologies to transmit signals in multiple ways improves communication quality and efficiency. The orthogonal frequency-division modulation (OFDM) technique first appeared in fourth-generation (4G) systems and has also been used in 5G and beyond technologies. Deep fading regions in the frequency selective channel at bandwidths of up to 800 MHz significantly reduce communication efficiency in 5G. With OFDM, the interruptive effect of the channel can be reduced.

The evolution of wireless communication systems since 4G has resulted in new differentiation (Qi, Hunukumbure, Nekovee, Lorca, & Sgardoni, 2016). The channel models will change significantly with the implementation of mmWave to mobile communication. This is because high frequencies will be used for the first time, and the properties of signals with these frequencies will be discovered. Before creating communication systems, channel models are also required to predict how the channel will react in various situations. Therefore, new 5G channel models and computer-aided channel simulators are required to generate these models. In literature, many channel models have been investigated as 5G technology progresses, and many channels and channel simulators have been designed for 5G and beyond systems (Lübke et al., 2021). In 2017, Rappaport made the NYUSIM channel simulator open source as a MATLAB GUI file developed by New York University (Sun, MacCartney, & Rappaport, 2017). There are many studies in the literature using the NYUSIM. Many studies examine the power delay profile and path loss models produced directly by the software (Hasan, Mowla, Rashid, Hosain, & Ahmad, 2019; Mowla, Dutty, & Ahmad, 2019; Zekri & Ajgou, 2019). Also, the effect of system parameters on received power is shown in (Al-Shuwaili & Jamel, 2021; Surahio, Hafeez, & Bohra, 2020). There have also been studies modeled using NYUSIM and capacity analysis, but the effect of channel parameters on capacity has not been investigated thoroughly (Abdullah-Al-Nahid et al., 2021; Hikmaturokhman, Suryanegara & Ramli, 2019; Kurniawan, Danisya, & Isnawati, 2020; Prasetyo, Suryanegara, & Asvial, 2019)[10-13]. In this study, the effects of 28 GHz and 73 GHz frequencies, the number of transmitter and receiver antennas, and whether there is direct sight between the receiver and the transmitter (line of sight, non-line of sight) on the 5G channel capacity was investigated using the NYUSIM simulator.

2. Wireless Channel Model

NYUSIM simulator performs Monte Carlo simulations and has two modes; spatial consistency mode on or off. When spatial consistency is enabled, it creates time and frequency-selective channels. In the off mode used in this study, a time-selective channel consisting of delayed and fading multipath components (MPCs) is established between the stationary transceiver, independent of the channel Doppler shift (Ju, Kanhere, Xing, & Rappaport, 2019). Aside from the basic parameters such as frequency, bandwidth, communication distance, line of sight (LOS), non-line of sight (NLOS) factor, and signal strength, the NYUSIM simulator can determine environmental factors such as rain, humidity, pressure, and temperature, the type of environment where communication will take place (urban, rural, microcell, macrocell), and antenna characteristics. In the NYUSIM, the channel coefficient of each MIMO-OFDM subcarrier is expressed by equation (1).

$$h_{m,k}(f) = \sum_{p} \alpha_{m,k,p} e^{j\Phi} e^{-j2\pi f\tau} e^{-j2\pi d_T m \sin(\emptyset)} e^{-j2\pi d_R k \sin(\varphi)} \tag{1}$$

Here, m is the transmitting, k is the receiving antenna number, and f is the subcarrier frequency. Resolvable MPCs are denoted by p; thus, the multipath components of the noise level can be ignored. α is the amplitude of the antenna gain, Φ indicates the phase of each MPC, τ the delay of the MPCs, d_T and d_R are the distance between each antenna in the antenna groups for the transmit and receive antenna groups, respectively. $\emptyset$ and φ is the angel of departures (AOD) and an angel of arrivals (AOA). The channel matrix is the matrix $h_{m,k}$, each of which represents a channel coefficient.

The close-in free space reference distance (CI) path loss model used by NYUSIM is given in equation (2), which changes according to various atmospheric conditions, taking 1 meter as a reference. Using the CI parameter and the path loss exponent simultaneously provides excellent stability under different environmental conditions (Ju et al., 2019).

$$\mathrm{PL^{CI}(f,d) = FSPL(f,1m)[dB] + 10nlog_{10}(d) + AT[dB] + X_{\sigma}} \tag{2}$$

Here n represents the degree of path loss, which is set to 2 for free space. The distance between the transmitter and the receiver is shown with d. X_{σ} is called shadow fading. The free space path loss model (FSPL) is expressed by equation (3).

$$\mathrm{FSPL(f,1m)[dB]} = 20\log_{10}\left(\frac{4\pi f \times 10^{9}}{c}\right) = 32.4[\mathrm{dB}] + 20\log_{10}(f) \tag{3}$$

f represents the carrier frequency in GHz, and c represents the speed of light. Equation (4) represents atmospheric attenuation.

$$\mathrm{AT[dB]} = \alpha[\mathrm{dB/m}] + d[\mathrm{m}] \tag{4}$$

Here, α denotes the attenuation coefficient for dry air, vapor, haze, fog, and rain. The received signal power is directly related to the Friis relation and, as shown in (5), to the path loss.

$$\mathrm{P_r|dBm| = P_t|dBm| + G_t|dB|G_r|dB| \times PL(d)|dB|} \tag{5}$$

P_t transmit antenna power, G_t and G_t represents transmit and receive antenna gains, respectively. The average path loss is denoted by $PL(d)$.

Channel capacity analysis can be used to assess the impact of a communication channel on communication quality. Equation (6) gives the capacity expression for MIMO channels.

$$C = B\log_2[\det(I_m + SNR.H.H')] \tag{6}$$

Here, B denotes the bandwidth, SNR is the signal-to-noise ratio, N_t transmitting, N_r is the receiving antenna number, H represents the channel matrix, H' is the conjugate transpose of the channel matrix, I_m represents the identity matrix of $N_t \times N_r$ dimensions. Equation (6) can be arranged as given below (7).

$$C = B\sum_{1}^{r}\log_2(1 + SNR.\lambda_i^2) \tag{7}$$

Here, λ_i^2, represents the eigenvalues of the $H.H'$ matrix. This operation is carried out because the relationships of the eigenchannels are used in the channel capacity, as demonstrated by equation (8).

$$\lambda_i^2 = \mathrm{eig}(H.H') \tag{8}$$

Capacity analysis can be carried out in either the time or frequency domain. By analyzing each MPCs, capacity can be calculated in the time domain. It is possible to calculate capacity in the frequency domain by analyzing all OFDM subcarriers, and this method was used in this study.

Version 3.1 of the NYUSIM simulator was used in this study. Table 1 lists the channel parameters that were used in the NYUSIM simulations. The table shows that 28 GHz and 73 GHz frequencies were used in the analysis. 28 GHz is currently licensed in existing 5G communication networks. 73 GHz, on the other hand, was chosen because it has the lowest local atmospheric attenuation and is one of the potential 5G/6G communication frequencies. An example of a channel obtained with these parameters is shown in Fig. 1. The equivalent of the channel in the frequency domain is given in Fig. 2. The bandwidth in the NYUSIM is 800 MHz, and each OFDM subcarrier is divided into 500 kHz channels, with channel capacity analyses performed.

Table 1. NYUSIM Channel Parameters

Parameter	Scenario A	Scenario B	Scenario C	Scenario D
Frequency	28 GHz	28 GHz	73 GHz	73 GHz
Environment	LOS	NLOS	LOS	NLOS
Bandwidth	800 MHz	800 MHz	800 MHz	800 MHz
Scenario	UMi	UMi	UMi	UMi
Distance	200 m	200 m	200 m	200 m
Tx Power	30 dB	30 dB	30 dB	30 dB
Pressure	1013.13 mbar	1013.13 mbar	1013.13 mbar	1013.13 mbar
Temperature	20 ℃	20 ℃	20 ℃	20 ℃
Humidity	%80	%80	%80	%80
Rain Rate	60 mm/hr	60 mm/hr	60 mm/hr	60 mm/hr
Antenna number	2x2 - 64x64	2x2 - 64x64	2x2 - 64x64	2x2 - 64x64

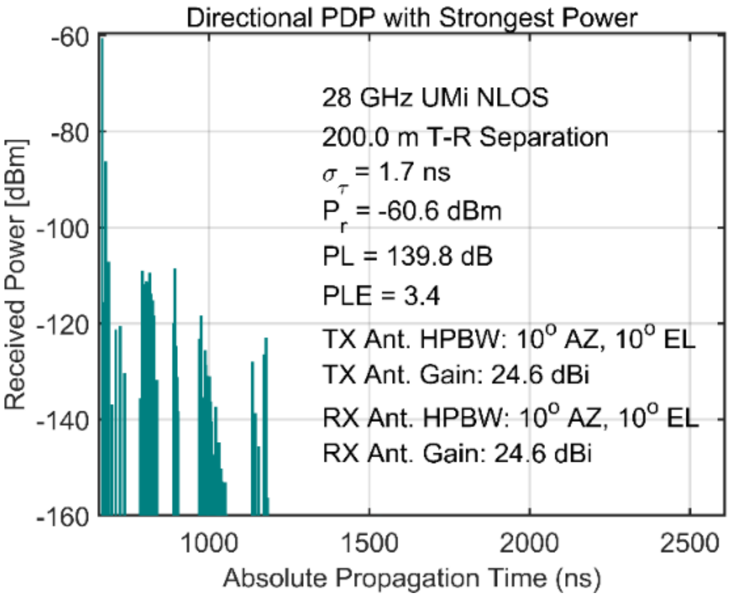

Figure 1. A sample of channel impulse response value in time-domain

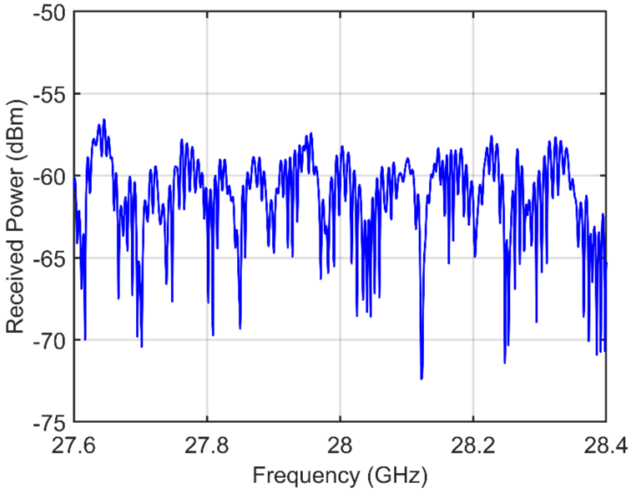

Figure 2. An example of OFDM subcarrier placement in the frequency domain.

Because NYUSIM generates a stochastic model, analyses in this study were performed by repeating each channel simulation 2000 times. The capacity of each generated channel was calculated, and the analysis used the average of 2000 different channel capacity values. After setting 28 GHz and 73 GHz as operating frequencies in the channel simulators, channel capacity analyses were performed for LOS and NLOS. All the channel capacity analyzes were made by selecting the receiver and transmitter antenna numbers of 2x2, 4x4, 8x8, 16x16, 32x32, and 64x64.

3. Simulation Results

This study made channel capacity analyses for frequency, antenna number, and LOS/NLOS situations in this study. For the 28 GHz frequency, channel capacity analyses for LOS and NLOS status were obtained, and the variation of capacity with SNR is shown in Fig. 3. Fig. 3 shows that the channel capacity grows exponentially as the SNR increases. It is also seen that the channel capacity calculated for LOS is much higher than for NLOS. For LOS, 2x2 MIMO structure, and 40 dB, channel capacity is 0,6336 (Table II contains all capacity ratings for 40 dB). This value is 18.8687 for 64x64, and the increase in channel capacity is 29.78 times compared to 2x2 MIMO. For NLOS, 2x2 MIMO structure and 40 dB, channel capacity is 0,00325. For 64x64, this value is 0.08748, and the difference between 2x2 is 26.92 times. For 64x64 MIMO, 40 dB, LOS channel capacity is 215.69 times higher than NLOS condition.

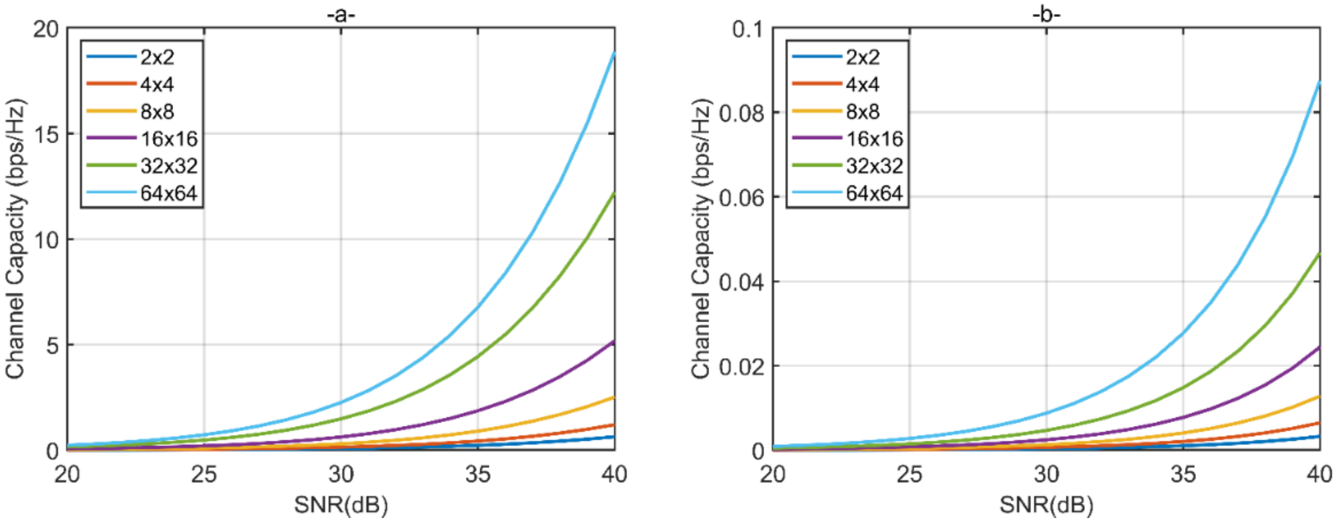

Figure 3. Channel capacity for 28 GHz in condition a) LOS b) NLOS

The changes in channel capacity with SNR for LOS and NLOS at 73 GHz frequency are given in Fig. 4. For 73 GHz, all MIMO models and LOS/NLOS implementations used at 28 GHz have been re-examined. The capacity of the 2x2 MIMO channel with the LOS transmission line is calculated as 0.05806 for 40 dB SNR in the NYUSIM model. This value is 2.14164 for 64x64, and the increase in channel capacity is 36.88 times compared to the 2x2 structure. For NLOS, 40 dB, 2x2 MIMO, the channel capacity is

0.00024, this value is 0.00696 for 64x64, and the amount of increase in the channel capacity is 29 times. For 40 dB, 64x64 MIMO, LOS, channel capacity is 307.7 times higher than NLOS. In NLOS cases, it has been demonstrated that channel capacity drops so dramatically that communication quality suffers significantly in areas with high urbanization. The distances between the antennas must be reduced or the disruptive effects minimized to avoid this. Furthermore, in such environments, increasing the number of base stations and reflective antennas, bringing them closer, and converting communication to LOS conditions will improve efficiency. For 64x64, 40 dB, LOS, 28 GHz frequency, the channel capacity is 8.81 times more than 73 GHz. For NLOS, this value is 12.56 times. The channel capacity decreases as the frequency increases due to both a decrease in signal strength and an increase in atmospheric attenuation. But this decrease is not as much as in the LOS/NLOS case. Therefore, the capacity decreasing with frequency can be compensated by various MIMO implementations or, more simply.

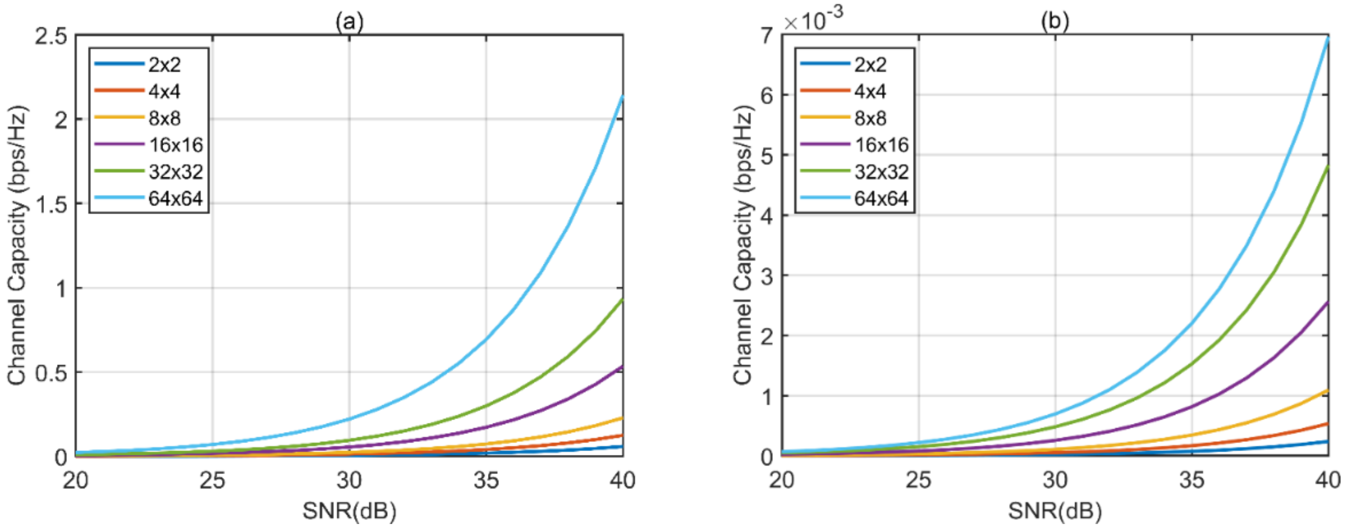

Figure 4. Channel capacity for 73 GHz in condition a) LOS b) NLOS

Table II shows channel capacity values for all MIMO antenna structures, 28 GHz and 73 GHz, and LOS/NLOS conditions are given for the 40 dB SNR value. As can be seen from Table II, the channel capacity also increases depending on the increasing number of transceiver antennas. When the number of transceiver antennas is doubled, the increase in capacity varies between 1.54 and 2.35 times for 28 GHz and LOS, while this value range is between 1.87 and 1.99 for NLOS. For 73 GHz and LOS, this range is 1.74 - 2.34, while it is 1.44-2.20 for NLOS. In short, doubling the MIMO antennas increases channel capacity by approximately twofold. This result was obtained as predicted by equation (7). Communication at high frequencies, where signal strengths and, thus, channel capacities are low, can be carried out much more efficiently with an increase in the number of transceiver antennas. It is also seen from Table II that the amount of increase in channel capacity changes depending on the frequency and LOS/NLOS conditions depending on the increasing MIMO structure. For example, when increasing MIMO configuration from 2x2 to 4x4, channel capacity increases 1.90 times for 28GHz LOS, while NLOS is 1.99 times. While it is 2.14 times for 73 GHz LOS, it is 2.20 times for NLOS.

Table 2. Channel Capacity Analysis

MIMO	**Channel Capacity (for 40 dB)**			
	28 GHz		**73 GHz**	
	LOS	**NLOS**	**LOS**	**NLOS**
2x2	0.6336	0.00325	0.05806	0.00024
4x4	1.2055	0.00647	0.12453	0.00053
8x8	2.5119	0.01277	0.22799	0.00109
16x16	5.1755	0.02442	0.53439	0.00205
32x32	12.2122	0.04673	0.93330	0.00483
64x64	18.8687	0.08748	2.14164	0.00696

4. Conclusion

This study investigates different channel models created for millimeter-wave communication systems using the NYUSIM channel simulator. The created channels were analyzed for carrier frequencies of 28/73 GHz, MIMO antenna configurations from 2x2 to

64x64, and LOS/NLOS parameters. Based on the results, the highest channel capacity was obtained for the 28 GHz frequency and 64x64 MIMO structure and LOS state condition. The channel capacity increased to 36.88 times when changing from 2x2 to 64x64, up to 12.56 times when 28 GHz was used instead of 73 GHz, and up to 307.7 times when LOS was used instead of NLOS. Based on these results, it is clear that high frequencies for 5G and beyond systems are critical. Increasing the frequency reduces channel efficiency directly. As a result, the use of higher frequencies requires the use of large MIMO antenna arrays. Furthermore, the location of base stations and reflective antennas in urban areas can be adjusted, increasing the probability of LOS in communication and thus significantly increasing channel efficiency.

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