Doruntinë Berisha [1], Agnesë Avdiu [1], Mimoza Ibrani [1]

[1]University of Prishtina, Faculty of Electrical and Computer Engineering

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Evaluation of millimeter wave propagation parameters in fifth generation (5G) mobile systems

Abstract. *This paper analyzes the millimeter wave propagation parameters in 5G systems based on simulation results at 4 GHz, 28 GHz, and 73 GHz for different environments, urban and rural. The analyzed propagation parameters are path loss, shadow fading and path loss exponent for different scenarios with line-of-sight and non-line-of-sight. Additionally, we compared millimeter wave signal propagation from directional and omnidirectional antennas for the scenario when we have 100 receiving spots.*

Streszczenie:. *W artykule przeanalizowano parametry propagacji fal milimetrowych w systemach 5G na podstawie wyników symulacji dla częstotliwości 4 GHz, 28 GHz i 73 GHz dla różnych środowisk miejskich i wiejskich. Analizowanymi parametrami propagacji są utrata ścieżki, zanikanie cienia i wykładnik utraty ścieżki dla różnych scenariuszy z linią wzroku i bez linii wzroku. Dodatkowo porównaliśmy propagację sygnału fal milimetrowych z anten kierunkowych i dookólnych dla scenariusza, w którym mamy 100 punktów odbiorczych.* (***Ocena parametrów propagacji fal milimetrowych w systemach mobilnych piątej generacji (5G).***)
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Keyword: milimeter wave, mpropagation, 5G mobile system
Słowa kluczoqwe: fale milimetrowe, preopagacja, system mobileny 5G
Keywords

1. Introduction

The various services of wireless communications have become an integral part of our daily lives. The latest developments in this field are focusing on utilizing millimeter wave frequency band as the appropriate solution for the operation of the Internet of Things (IoT), in the fifth generation of mobile communications (5G) and beyond. The wide frequency band and communication capacity provided by millimeter waves, combined with the possibilities of operating with small cells as well as advanced signal processing techniques such as beamforming, make millimeter waves as optimal solution for dense networks and highly populated areas. There are also a few studies presenting results for application of millimeter waves for rural areas.

Even though millimeter waves provide a wide frequency range, it is not financially and technically reasonable to make measurements for its entire bandwidth. Millimeter wave signals are affected by high attenuation and propagation across many paths. Unlike signals at lower frequencies, millimeter waves are more susceptible to atmospheric effects and shadow fading and cannot propagate well through most mediums. Hence, these effects must be considered when modeling millimeter wave systems. These properties make them suitable for typical dense urban environments, even though there are studies analyzing their feasibility for rural areas as well. Parameters such as propagation loss, antenna directivity, and blocking sensitivity vary significantly in existing wireless communication systems compared to millimeter-wave based communication systems [1].

Signal losses caused by rainfall are significant in millimeter wave propagation. Losses resulting from rainfall and through the atmosphere are examined in [2], while the effects of water vapor absorption and oxygen absorption on signal attenuation on three millimeter waves frequencies (28 GHz, 30 GHz, and 60 GHz) appear in [3]. It is found that losses due to rain are negligible in millimeter waves at cell sizes of no more than 200 m [4].

In [5], extensive measurements were performed at the three different frequency bands covering a small cell scenario. According to their findings, the least-squares (LS) fitting graphs are similar to the 3GPP path loss model for antennas heights of 5m. Although numerous measurement campaigns have been carried out in the 28 GHz, 38 GHz, 60 GHz, and 72 GHz bands, the propagation characteristics of wideband millimeter waves remain largely unknown [6]. The study of millimeter waves can be done by performing simulations to estimate the loss characteristics during the propagation.

An effective millimeter wave communications system requires accurate modeling for the development of new techniques that can adapt to its propagation characteristics [6]. Several research papers have proposed channels models for carrier frequencies ranging from 2GHz to 100 GHz.

Channel models proposed for different short range propagation scenarios in the 60 GHz frequency band are presented in [7] and [8], while a 3D model for this band is suggested by the MiWEBA project in [9]. In [10], three stochastic models based on map and hybrid are proposed, together with the corresponding frequencies. A channel model from 3GPP that supports frequency bands up to 100 GHz is proposed in [11], where the frequency bands are supported over specific scenarios such as Dense Urban Macro (UMa), Urban Micro (UMi), Rural, Office, Device to Device (D2D), etc. And lastly, the 5G Channel Model (5GCM) proposed by NYU Wireless is a group of numerous channel models based on a wide set of measurements at 28 GHz, 38 GHz, 60 GHz and 73 GHz [12].

These various channel models may not adequately reflect all millimeter wave characteristics which is the main challenge recognized in [9]. A performance evaluation of the most popular channel models 3GPP and 5GCM and the different LOS probability and path loss models they utilize, showed that different channel models can lead to varied predictions for the channel performance metrics [13]. A demonstration of how the improved NYUSIM simulator 2.0 produces realistic data, making it a valuable measurement-based channel simulator for 5G communications is presented in [14]. The most appropriate channel model to reflect millimeter waves until now is channel model 5GCM [4]. Using this model, we performed our simulations for three different scenarios.

Our primary goal is analyzing and evaluating loss coefficients and propagation parameters of millimeter waves in 5G mobile systems in different network operation scenarios. We analyze how path loss (PL), shadow fading (SF) and path loss exponent (PLE) change in different frequency bands and environments. We examine the maximum distance between the transmitter and receiver for various scenarios, and inspect which case yields the better values of PLEdir-best (best possible link created in the directional path).

To achieve our goal, we used NYUSIM simulator (version 3.0) [15], and based on our research, we are the first paper to do so. The simulations have been performed for different environments like urban and rural areas, different frequency bands and scenarios. For each scenario a certain number of receivers and antenna characteristics are defined. For rural areas (RMa) the analyzed frequency band is 73 GHz, while urban ones are analyzed in UMi (Urban Microcell) in the 28 GHz frequency band and UMa (Urban Macrocell) in the 4 GHz frequency band. The 3-30 GHz super high frequency (SHF) spectrum, also known as centimeter-waves, has been referred to as millimeter waves due to its propagation characteristics in 5G, despite the commonly known 30-300 GHz band with 10-1 mm wavelengths [x]. The 4 GHz band is receiving attention as a 5G allocation, and we chose to use it for our simulations after reviewing literature and noting its use for testing and measurements in some countries[16]. The performance of each scenario is analyzed and compared for two cases, signal transmission from directional antennas as well as omnidirectional ones. The analyzed propagation parameters of the millimeter waves are path loss (PL), shadow fading (SF) as well as path loss exponent (PLE) for different scenarios in cases with line-of-sight (LOS) and non-line-of-sight (NLOS).

2. Simulation environments and scenarios

To achieve an in-depth analysis of millimeter wave propagation parameters, it is necessary to define the urban and rural environments, large scale propagation loss models and incorporate the line-of-sight probability model.

2.1. Environments

For the simulation environments, we focused on three different scenarios. 3GPP identified 10 deployment scenarios for the next generation access technologies [17], out of which we choose the dense urban (macro and micro layer) and the rural scenario.

Dense urban scenario has a high research importance since the density of 5G is projected to be 40-50 BS/km2, making it an ultra-dense network [18]. Dense urban environments are characterized by high traffic loads, outdoor and outdoor to indoor coverage [17]. The results for 73-GHz measurements in rural area are presented in [19] that are used to develop a new RMa path loss model that is accurate and easier to apply for varying transmitter antenna heights. Furthermore, carrier frequencies for macrocells are 4 GHz with a antenna height of 25 m and an ISD of 200 m, while for microcells the frequencies range from 30 to 70 GHz with a height of 10 m [20]. A lack of knowledge about millimeter wave propagation in rural areas makes it difficult to evaluate wireless signal coverage and interference. An important parameter to be considered in rural areas is the height of the base station [21]. Also, when analyzing the propagation patterns in rural areas, the distance between the transmitter and the receiver is much greater than in urban areas for cases with line of sight and non-line of sight. Inspired by the research done in [19], [21], the frequency band analyzed for rural areas will be 73 GHz with a bandwidth of 800 MHz and ISD up to 1732 m.

2.2. Channel models

Among the forementioned channel models in the Introduction section, the 5GCM and 3GPP channel models are mainly referred to in this paper. All simulations are run by the NYUSIM simulator version 3 [15], since based on [22], it has shown a higher accuracy than the 3GPP model. The NYUSIM simulator is based on the group of channel models known as 5GCM [12], taking advantage of field measurements in different cities.

Due to different propagation environments and obstacles, it is necessary to evaluate path loss separately over LOS and over NLOS. To forecast if a device will be within a clear line of sight of a base station, a LOS probability model is required [23]. The probability model for LOS is a function of transmitter-receiver distance, frequency independent and influenced on the layout of an environment [23]. To determine whether the receiver and transmitter are in a direct line of sight, [12] utilizes a map-based analysis emphasizing only the transmitter and receiver positions.

The simulations we performed for millimeter wave propagation in 5G mobile systems, are realized by considering the channel parameters and antenna characteristics. The two dense urban area scenarios and the rural scenario, are simulated using the NYUSIM simulator [15]. In NYUSIM, propagation loss is calculated using a Close-In (CI) approach that considers all the parameters that affect millimeter wave radiation. The propagation frequency varies from 0.5 GHz to 100 GHz, and scenarios like urban microcell and urban macrocell are supported. The LOS probabilities for RMA were not specified in [10] or [12], but the RMA model was adopted from the ITU-R [24], which was derived from the Winner RMa [25].

Table 1. Channel parameters and antenna characteristics at 28 GHz, 4 GHz and 73 GHz, UMi, UMa and RMa scenario.

Frequency	28GHz	4GHz	73 GHz
Bandwidth	800 MHz	200 MHz	800 MHz
BS height	25 m	25 m	110 m
Temperature	20 °C	20 °C	20 °C
Distance Tx-Rx	10-500(m)	10-500(m)	10-10000(m)
Receivers	100	100	100
Tx Power	30 dBm	30 dBm	30 dBm
Tx Array Type, Nt	Uniform Linear Array, 16	Uniform Linear Array, 8	Uniform Linear Array, 8
Rx Array Type, Rt	Uniform Linear Array, 4	Uniform Linear Array, 2	Uniform Linear Array, 8
Spacing of TX Antennas	0.5 λ	0.5 λ	0.5 λ
Spacing of RX Antennas	0.5 λ	0.5 λ	0.5 λ
Atmospheric pressure	1013.25 mbar	1013.25 mbar	1013.25 mbar
Humidity	50%	50%	50%

We present LOS probability results for UMi, UMa and RMa based on both LOS and NLOS propagation methods, with the TX-RX separation distance ranging from 10 to 500 meters. Atmospheric effects such as barometric pressure, humidity and temperature are included. The selected channel parameters and antenna characteristic for our simulations are given in Table 1.

The UMi scenario includes areas of high user density, as seen in Table 1., with BS height of 25 m and an ISD of 200 m or less. On the basis of the work in [4], UMi will operate at 28 GHz and employ 16 x 4 Uniform Linear Array (ULA) with 800 MHz bandwidth.

The UMa scenario is defined based on 3GPP with a BS height of 25 m, and an ISD up to 500 m, and operating frequency 4 GHz with a 200 MHz bandwidth and a range of 8x2 ULA antennas. And lastly RMa, usually with a BS height ranging from 10 to 150 m, and an ISD up to 5000 m. Operating frequency chosen for RMa is 73 GHz with an 800 MHz bandwidth and a range of 8x8 ULA antennas, even though for the rural area the presented level of BS height is high.

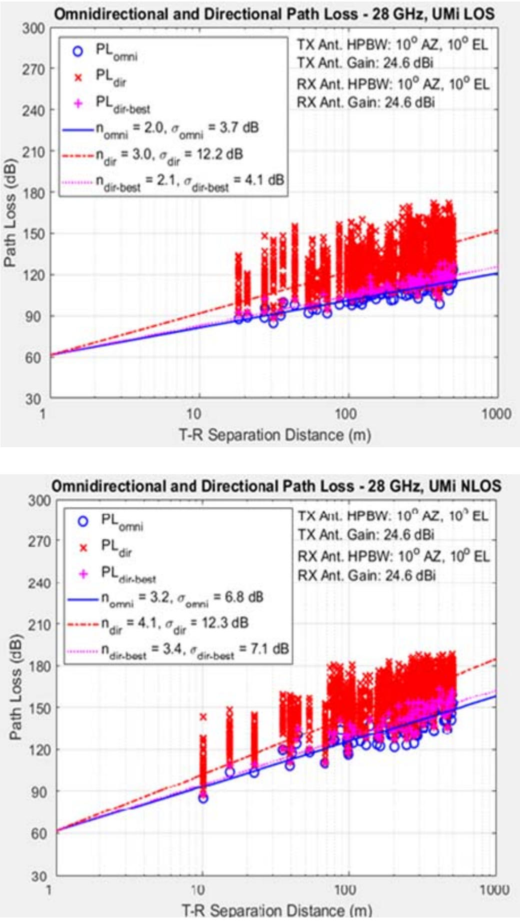

Fig. 1 Propagation losses simulated at 28 GHz for a) LOS scenario b) Propagation losses simulated for NLOS scenario at 28 GHz.

3. Results and discussions

3.1. Millimeter wave channel performance in the 28 GHz frequency band

We initially analyze the performance of the 5G system operating at 28 GHz in a dense urban environment (UMi).

In Fig.1 (a) and (b) are presented the simulation results from NYUSIM for the UMi scenario. Pathloss, Path loss exponent (PLE) and the best PLE are the analyzed parameters from directional and omnidirectional antennas in both LOS and NLOS. The performance of 100 receivers is shown, ranging from 10 m to 500 m as the lowest and highest distances from the transmitter, respectively.

With the increase of distance between the transmitter and receiver, it can be seen that propagation losses increase, and more so for the directional antennas.

The PLE at 3.0 for directional antennas, with shadow fading σ_{dir} = 12.2 dB is higher than PLE at 2.0 for omnidirectional antennas with shadow fading σ_{omni} = 3.7 dB. Nevertheless, the best PLE from directional antennas is similar to the best PLE for omnidirectional antennas for both LOS and NLOS. PLE at 28 GHz is higher for both NLOS and LOS cases, because of the non-optical alignment of antenna arrays on boresight, which can be avoided by using steerable beam antennas as presented in [26].

Delays along the propagation are greater in the case of signal transmission from omnidirectional antennas.

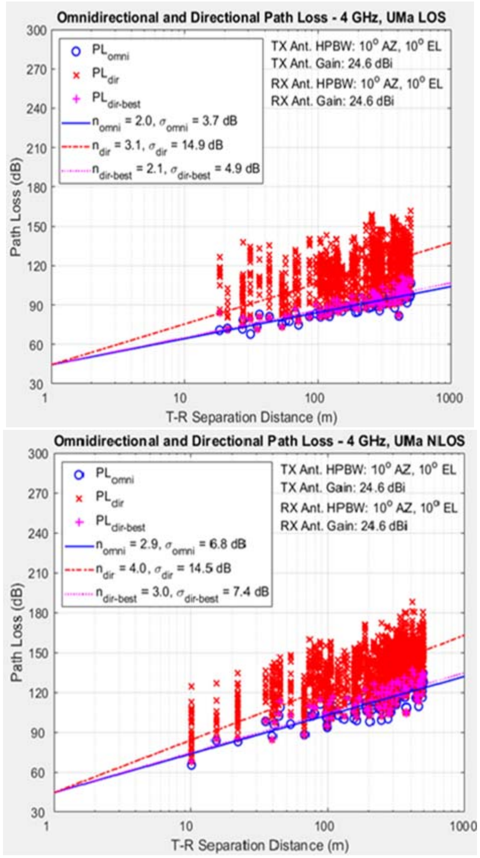

Fig. 2. a) Propagation losses simulated for LOS scenario at 4 GHz b) Propagation losses simulated for NLOS scenario at 4 GHz.

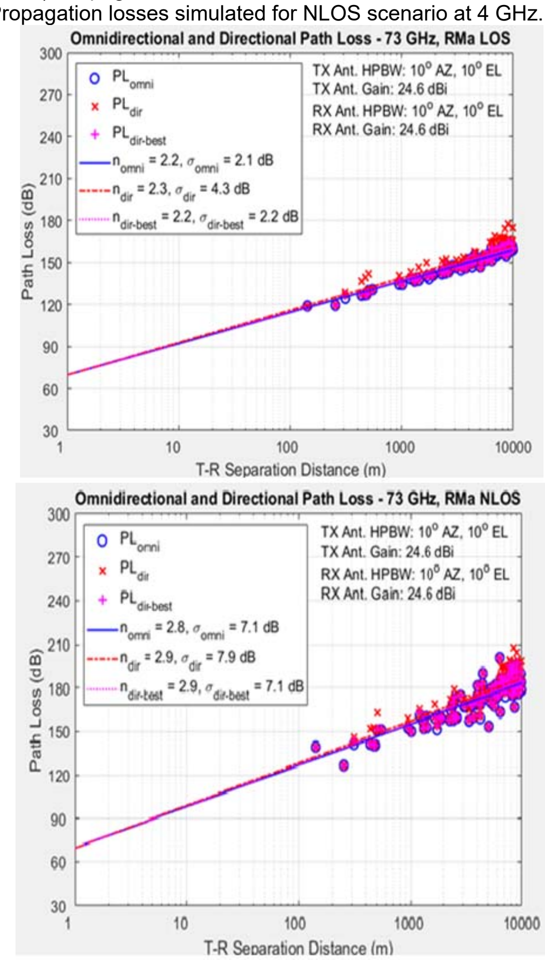

Fig. 3. a) Propagation losses simulated for LOS scenario at 73 GHz b) Propagation losses simulated for NLOS scenario at 73 GHz.

In UMi LOS scenario, for the directional antennas the average receiving power is -32.056 dBm, the average PL is 111.261 dB and the average PLE is 2.157, while for omnidirectional antennas the average receiving power turned out to be -77.553 dBm, the average PL is 107.553 dB and the average PLE is 1.99. From these parameter values it can be seen that average PLE and average PL are similar in values when we have transmissions from directional and omnidirectional antennas, but the average receiving power is much lower in the case of signal transmissions from omnidirectional antennas than from directional ones.

3.2. Millimeter wave Channel performance in 4 GHz frequency band

The second scenario we analyzed is the operation of 5G technologies in the 4GHz frequency band for dense macro urban UMa environments. Similar to the 28 GHz frequency band, through simulations we will analyze PL, PLE and best PLE at 4 GHz. The channel parameters and antenna characteristics are given in the Table 1.

For this scenario, propagation loss parameters are simulated for other channel conditions, than for UMi scenario. From the Fig.2 (a) and (b) it can be seen that the PLE of LOS and NLOS at 4 GHz is similar to 28 GHz. However, the shadow fading is 14.9 dB in the LOS case and 14.5 dB in the NLOS case which is much higher than at the 28 GHz frequency. Also, the best PLE in case we have transmission from directional antennas, or the best possible link created in the directional path is similar to PLE when we have transmission of signals from omnidirectional antennas in both LOS and NLOS scenarios.

In the simulations performed in the 4 GHz frequency band and the UMa LOS scenario when the signal transmissions are from the directional antennas, the average receiving power is -13.551 dBm, the average PL is 92.76 dB and the average PLE has turned out to be 2,083. For the case of signal transmissions from omnidirectional antennas the average receiving power is -61.031 dBm, the average PL is 90.619 dB and the average PLE is 1.988.

3.3. Millimeter wave channel performance in the 73 GHz frequency band

The frequency band used in the simulations for rural areas is 73 GHz. PL, PLE and PLE best are analyzed for this frequency band in the LOS and NLOS scenarios. Fig.3 (a) and (b) describe the performance at 100 receivers selected in NYUSIM ranging from 10 m to 10000 m, both the lower and upper limits from the transmitter.

From Fig.3 it can be seen that the losses along the propagation increase linearly with increasing distance and are greater for the signal propagation scenario from the directional antennas in both LOS and NLOS cases.

From these two figures it can be seen that the PLE in the LOS and NLOS scenario for the 73 GHz frequency band in RMa is lower than in the UMi and UMa scenarios. Also, the results obtained are comparable to the measurements made in [15]. Furthermore, the PLE at 2.3 for directional antennas and shadow fading σ_{dir} = 4.3 dB is higher than the PLE at 2.2 for omnidirectional antennas and σ_{omni} = 2.1 dB in the LOS scenario. The same applies to NLOS where PLE at 2.9 for directional antennas with shadow fading σ_{dir} = 7.9 dB is higher than PLE at 2.8 for omnidirectional antennas and σ_{omni}= 7.1 dB.

3.4. Comparative analysis of pathloss and Power delay profile

A comparative analysis of pathloss in dB, when we have signal transmission from directional and omnidirectional antennas in the LOS scenario, is illustrated in Fig.4 and Fig.5. These results were obtained by considering 100 signal receivers and the PL values are presented as they differ in each of these receivers.

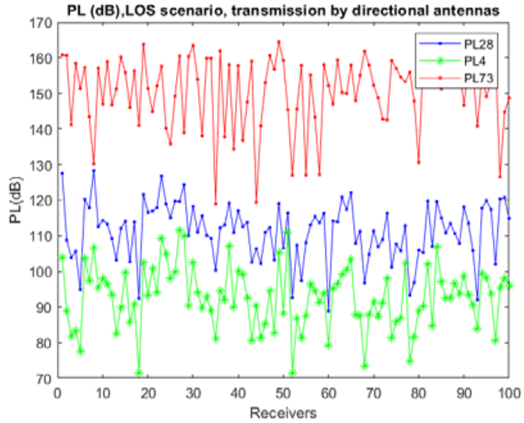

Fig. 4. PL (dB) during transmission from directional antennas for 28 GHz, 4 GHz and 73 GHz, LOS scenario

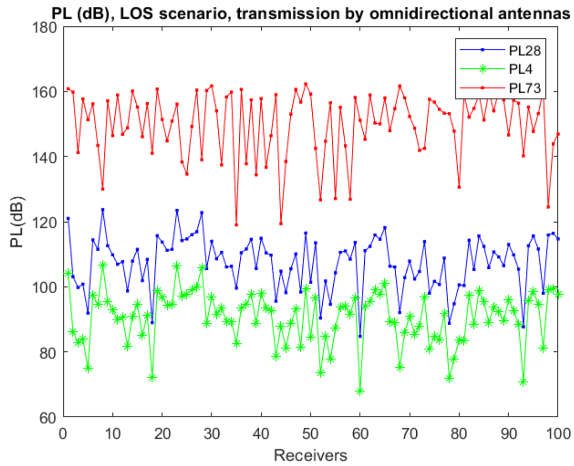

Fig. 5. PL (dB) during transmission from omnidirectional antennas for 28 GHz, 4 GHz and 73 GHz, LOS scenario

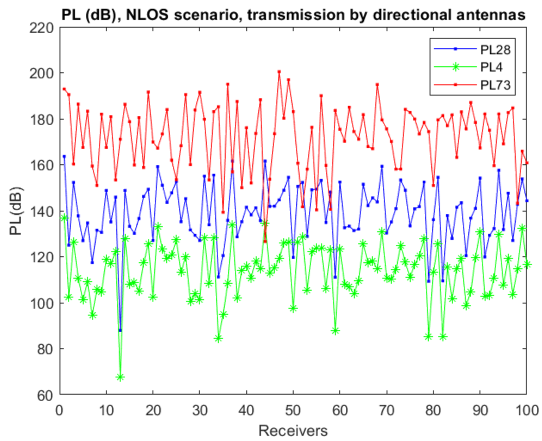

Fig. 6. PL (dB) during transmission from directional antennas for 28 GHz, 4 GHz and 73 GHz, NLOS scenario

From the figures it can be seen that the losses along the path are similar for transmissions from directional and omnidirectional antennas at frequencies 4 GHz and 28 GHz as well as for the frequency 73 GHz.

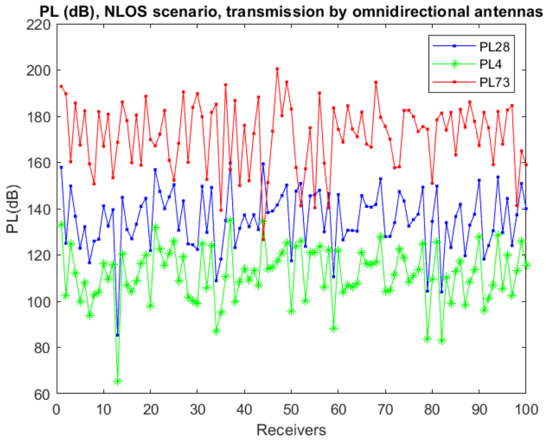

Fig. 7. PL (dB) during transmission from directional antennas for 28 GHz, 4 GHz and 73 GHz, NLOS scenario

PL at 73 GHz is higher than that at 4 GHz and 28 GHz for both directional and omnidirectional antenna transmissions (for different channel conditions between the scenarios analyzed above). Similarly, Fig. 6 and Fig. 7 present a comparative analysis of pathlosses in dB for UMi, UMa and RMa environments, for the NLOS scenario and for the case where we have signal transmission from directional and omnidirectional antennas. From the figures it can be seen that the values of losses along the propagation in dB are higher at the frequency of 73 GHz than those at 28 GHz and 4 GHz, for transmissions from directional antennas and omnidirectional antennas, for the channel conditions analyzed above. Also, the PL values are similar for both transmissions from directional antennas and transmissions from omnidirectional antennas for these three scenarios. According to our simulation results, PL in both LOS and NLOS propagation cases is within the allowed and negligible range for propagation.

Tables 2, 3, and 4 display the Power Delay Profiles data for each of the three scenarios, encompassing both LOS and NLOS propagation scenarios, and featuring both directional and omnidirectional antennas. In the UMi Dir instance, there is only a minor variation and time difference in the PL and RMS (root mean square) delay spread (σ_τ).

Table 2. Power Delay Profile for UMi scenario

UMi	T-R Separation	Pr (dBm)	PL (dB)	σ_τ (ns)
LOS Dir	199.2 m	-28.2	107.4	1.6
LOS Omni	199.2 m	-71.8	101.8	15.8
NLOS Dir	197.4 m	-54.6	133.9	2.7
NLOS Omni	197.4 m	-99.8	129.8	25.1

Table 3. Shows the Power Delay profile for the UMa case at 498-499.6 T-R separation. Although the Pathloss values remain comparable for both the LOS and NLOS scenarios, there is a considerable disparity between the omnidirectional and directional delay spread ratios.

Table 3. Power Delay Profile for UMa scenario

UMa	T-R Separation	Pr (dBm)	PL (dB)	σ_τ (ns)
LOS Dir	498.2 m	-30	109.2	0.2
LOS Omni	498.2 m	-76.6	106.5	6.9
NLOS Dir	499.6 m	-51.7	130.9	6.9
NLOS Omni	499.6 m	-96.4	127.9	51.6

Table 4. Power Delay Profile for RMa scenario

RMa	T-R Separation	Pr (dBm)	PL (dB)	σ_τ (ns)
LOS Dir	1758.3 m	-61.5	140.8	0
LOS Omni	1758.3 m	-108.5	138.5	1.4
NLOS Dir	1758.3 m	-74.5	153.7	0
NLOS Omni	1758.3 m	-121.3	151.3	1.9

Our findings are consistent with those of [27] and [4]. The results of our simulations suggest that utilizing cells smaller than 1732 m for 73 GHz, 200 m for 28 GHz, and up to 500 m for 4 GHz are suitable for transmission on 5G mobile systems.

3.5. General comparison of PL, PR and PLE

From the Power Delay Profile (PDP) results we got for directional and omnidirectional antennas in the three frequency bands we have done the comparison for three parameters PL, Pr and PLE. In the simulations conducted at the 28 GHz frequency, the antenna was positioned at a height of 25 meters, and the distance between the transmitter and receiver ranged from 10 to 500 meters. Similarly, at the 4 GHz frequency, the antenna height was 25 meters, and the distance between the Tx and Rx was between 10 to 500 meters. Finally, in the simulations carried out at the 73 GHz frequency band, the antenna was positioned at a height of 110 meters, and the distance between the Tx and Rx ranged from 10 to 10,000 meters.

Fig.8 illustrates the PL values obtained from directional and omnidirectional PDPs at 28 GHz, 4 GHz and 73 GHz for a randomly selected 100 RX locations under LOS and NLOS scenarios.

The path loss of both directional and omnidirectional conditions is similar for all of these simulated frequency bands, except for NLOS in UMa scenario, where the PL from omnidirectional antennas is significantly higher than from directional ones.

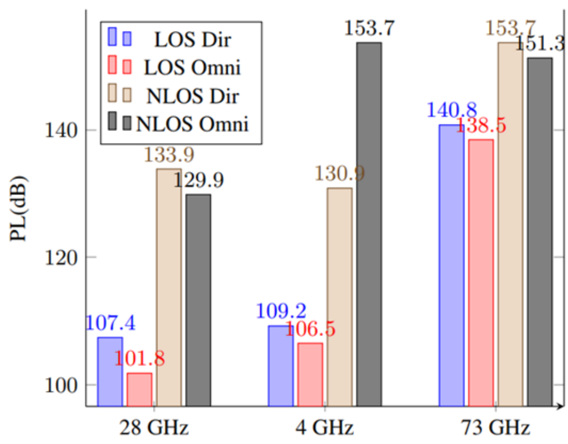

Fig. 8. Path Loss at 28 GHz, 4 GHz, and 73 GHz

Similar to Fig. 8, Fig. 9 shows the PLE values obtained from directional and omnidirectional PDPs for 28 GHz, 4 GHz and 73 GHz in the LOS/NLOS cases. Based on our results, the path loss exponent of both directional and omnidirectional conditions shows small difference for all of these frequency bands. From the simulations, it can be seen that the PL and PLE of the two cases (directional and omnidirectional) have a slight difference.

While in Fig.10 is shown the received signal power for 28 GHz, 4 GHz and 73 GHz in both LOS and NLOS cases. As a result of our simulations and results, the received signal power of omnidirectional antennas in both LOS and NLOS cases is significantly lower than that from directional antennas. The received signal power level below -150 dBm doesn't have practical sense if the required user equipment received power level is taken into consideration.

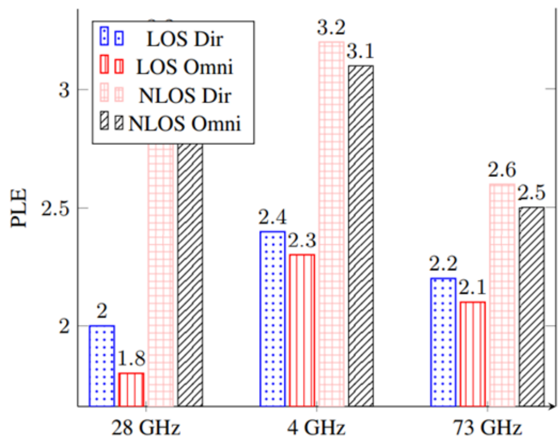

Fig. 9. Path Loss Exponent at 28 GHz, 4 GHz, and 73 GHz

These results are comparable to those reported in [16], [27], and [28]. These results indicate that LOS directional propagation does not differ significantly from omnidirectional propagation for cells up to 200 m at 28 GHz.

Based on other works carried out in this field and the results we obtained, the usability of these three frequency bands in the millimeter wave channel in 5G systems is quite high. The losses along the propagation in all three frequency bands and the analyzed scenarios will be greater in the case of NLOS compared to that of LOS and they increase linearly with increasing distance and are larger for the directional propagation, than from the omnidirectional one. Another reason why propagation losses decrease much faster with increasing distance in the NLOS scenario than in that LOS, is due to interference during signal propagation.

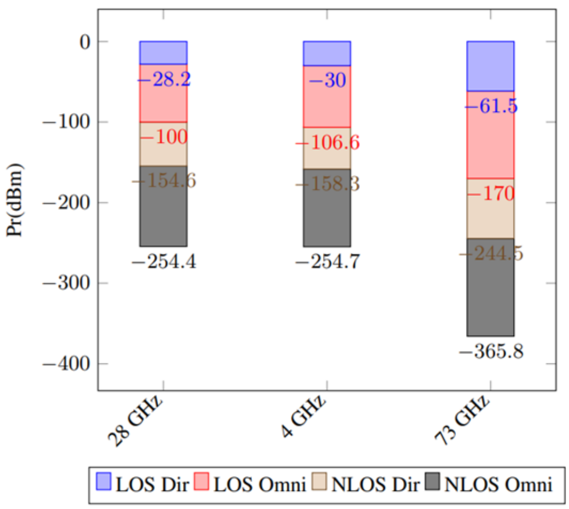

Fig. 10. Received Signal Power at 28 GHz, 4 GHz, and 73 GHz

The results suggest that higher PLE from directional antennas for both LOS and NLOS cases at 28 GHz is because very often the antenna arrays are not positioned to locate the targets and this problem can be addressed using direct antenna beams. Also, in all three frequency bands analyzed the reception power for the case of signal transmission from omnidirectional antennas is more than twice weaker than from the directional ones. The PLE of LOS and NLOS for UMa scenario is similar to the values in UMi. However, the SF is 14.9 dB in the LOS case and 14.5 dB in the NLOS case which is much higher than SF values at the 28 GHz frequency.

When modeling the millimeter wave channel in these three frequency bands the best PLE in case we have transmission from directional antennas, or the best possible link created in the directional path is similar to PLE when we have signal transmission from omnidirectional antennas in both LOS and NLOS scenarios. The results for the UMa scenario and the 4 GHz frequency band indicate that a large number of multipath components can be detected at 500 m in the NLOS scenario, with a PL comparable to other millimeter wave frequencies. In the RMa scenario and the 73 GHz frequency band, results show that directional antennas bring additional losses depending on the distance compared to omnidirectional antennas, as they act as space filters and lose power across many paths from directions where the antennas are not directed.

4. Conclusion

Wireless communication technology is growing rapidly, and the use of millimeter waves is considered and proposed to be the appropriate solution to accommodate the operation of the Internet of Things in the fifth generation of mobile communications.

This paper evaluates the parameters of millimeter wave propagation in fifth generation mobile systems for urban and rural environments. The simulations were performed through the NYUSIM simulator in the 28 GHz, 4 GHz and 73 GHz bands in 100 different urban and rural receiving locations, with LOS and NLOS. In these 100 locations, under different channel conditions, the current and average values of PL and PLE are determined. Our main contribution to this paper is the study of millimeter wave propagation characteristics in 5G systems using the NYUSIM simulator (v.3.0), where yet, based on our knowledge and research, there are not studies to date with these channel parameters and antenna characteristics with this upgraded version. The results presented in this paper can help inform the design and implementation of millimeter wave communication systems and can contribute to the development of more efficient and reliable 5G systems.

Authors
Doruntinë Berisha, doruntine.berisha@uni-pr.edu, PhD candidate; Agnesë Avdiu, agnese.avdiu@uni-pr.edu , PhD candidate (corresponding author); Prof. dr. Mimoza Ibrani, mimoza.ibrani@uni-pr.edu (corresponding author) , Faculty of Electrical and Computer Engineering, University of Prishtina, Street: Sunny Hill, nn, 10000, Prishtina, Republic of Kosovo

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