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Analisis Kanal Multipath pada Frekuensi 30 GHz untuk Jaringan Nirkabel 6G Berdasarkan Kinerja BER

Multipath Channel Analysis at 30 GHz for 6G Wireless Networks Based on BER Performance

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Abstrak

Karakterisasi kanal merupakan tahapan penting dalam mengevaluasi performa sistem komunikasi gelombang milimeter 6G pada lingkungan propagasi yang realistis. Penelitian ini menganalisis karakteristik kanal multipath pada frekuensi 30 GHz di lingkungan Urban Microcell (UMi) Non-Line-of-Sight (NLOS) menggunakan simulator NYUSIM serta mengevaluasi pengaruhnya terhadap performa Bit Error Rate (BER) pada sistem Orthogonal Frequency Division Multiplexing (OFDM) yang menerapkan modulasi 64-QAM dan convolutional coding dengan code rate 1/2. Channel Impulse Response (CIR) hasil simulasi NYUSIM diintegrasikan ke dalam sistem OFDM untuk mengevaluasi BER pada rentang SNR 0–20 dB. Hasil simulasi menunjukkan propagasi spasial yang terkelompok dengan lintasan pertama yang dominan, path loss sebesar 127 dB, dan RMS delay spread sebesar 14,6 ns. Nilai BER menurun dari sekitar 4,8 × 10^{-1} pada 0 dB menjadi kurang dari 10^{-3} pada 16 dB, yang menunjukkan komunikasi yang andal pada kondisi propagasi multipath yang realistis. Nilai RMS delay spread yang relatif kecil mampu mengurangi inter-symbol interference (ISI) melalui cyclic prefix pada OFDM. Temuan ini menunjukkan hubungan langsung antara karakteristik kanal multipath dan performa BER, sehingga memberikan evaluasi yang lebih representatif bagi sistem komunikasi gelombang milimeter 6G.

Kata kunci: 6G, BER, Convolutional Codes, mmWave, NYUSIM, OFDM

Abstract

Channel characterization enables the evaluation of future 6G millimeter-wave communication systems operating in realistic propagation environments. This research investigates the multipath channel characteristics of a 30 GHz Urban Microcell (UMi) Non-Line-of-Sight (NLOS) environment using the NYUSIM channel simulator and evaluates their influence on the Bit Error Rate (BER) performance of an Orthogonal Frequency Division Multiplexing (OFDM) system employing 64-QAM modulation and rate-1/2 convolutional coding. The NYUSIM-generated Channel Impulse Response (CIR) was integrated into the OFDM system to evaluate BER over an SNR range of 0–20 dB. The simulation results reveal clustered spatial propagation with a dominant first-arrival path, a path loss of 127 dB, and an RMS delay spread of 14.6 ns. The BER decreases from approximately 4.8 × 10^{-1} at 0 dB to below 10^{-3} at 16 dB, demonstrating reliable communication under realistic multipath propagation conditions. The relatively small RMS delay spread effectively suppresses inter-symbol interference through the adopted cyclic prefix. These findings establish a direct relationship between multipath channel characteristics and BER performance, providing a more representative evaluation of OFDM systems for future 6G millimeter-wave wireless communications.

Keywords: 6G, BER, Convolutional Code, mmWave, NYUSIM, OFDMIntroduction

I. INTRODUCTION

The rapid evolution of wireless communication technologies has accelerated research toward sixth-generation (6G) networks, which are expected to provide terabit-per-second data rates, ultra-low latency, massive connectivity, and intelligent communication services for emerging applications such as extended reality (XR), digital twins, holographic communications, and autonomous systems [1], [2]. To satisfy these stringent requirements, the utilization of millimeter-wave (mmWave) spectrum has become one of the most promising solutions due to its abundant available bandwidth and capability to support high-capacity wireless communications [2].

Among the potential mmWave bands, the 30 GHz frequency has attracted increasing attention as a promising candidate for beyond-5G and early 6G systems. Compared with conventional sub-6 GHz bands, the 30 GHz band offers significantly larger bandwidth while maintaining more favorable propagation characteristics than higher mmWave and sub-terahertz frequencies. Nevertheless, signal propagation at this frequency is highly susceptible to severe path loss, blockage, and multipath propagation, particularly in dense urban environments operating under Non-Line-of-Sight (NLOS) conditions [2], [4]. These propagation impairments directly affect communication reliability by increasing delay dispersion, signal attenuation, and fading.

The performance of mmWave communication systems is therefore highly dependent on the propagation channel characteristics. In Urban Microcell (UMi) NLOS environments, received signals are composed of multiple reflected and scattered components arriving through different propagation paths. Such multipath propagation introduces delay spread, frequency-selective fading, and inter-symbol interference (ISI), all of which can significantly degrade the Bit Error Rate (BER) performance of broadband communication systems [2], [5]. Consequently, accurate channel characterization is essential for designing reliable 6G wireless communication systems.

To realistically model mmWave propagation, the New York University Simulator (NYUSIM) has become one of the most widely adopted statistical channel simulators. Developed from extensive real-world propagation measurements, NYUSIM is capable of generating realistic channel parameters, including Angle of Arrival (AOA), Angle of Departure (AOD), Power Delay Profile (PDP), path loss, received power, and delay spread for various deployment scenarios [3]. These channel characteristics provide valuable information for evaluating wireless system performance under realistic propagation environments.

Several previous studies have investigated mmWave propagation characteristics using NYUSIM or measurement-based channel models. Most of these studies primarily focused on channel characterization by analyzing propagation parameters such as path loss, PDP, AOA, AOD, and delay spread [3]. Other studies evaluated BER performance of OFDM systems under simplified statistical fading models such as Rayleigh or Rician channels. However, only limited studies have quantitatively investigated how realistic multipath channel characteristics generated by NYUSIM influence BER performance in practical OFDM communication systems. Furthermore, studies specifically addressing the 30 GHz Urban Microcell NLOS scenario remain relatively limited despite its relevance for future 6G deployments.

Therefore, the research gap addressed in this work lies in the lack of comprehensive analysis linking realistic multipath channel characteristics generated by NYUSIM with BER performance evaluation of OFDM-based communication systems operating at 30 GHz under Urban Microcell NLOS conditions. Existing studies generally report channel characteristics and communication performance separately, whereas the relationship between both aspects has not been sufficiently discussed.

The novelty of this work is the integration of realistic NYUSIM-generated multipath channel characteristics into the evaluation of OFDM communication performance employing 64-QAM modulation and rate $\frac{1}{2}$ convolutional coding at 30 GHz. Instead of only reporting statistical channel parameters or conventional BER results, this study analyzes how channel characteristics, including path loss, Power Delay Profile (PDP), Angle of Arrival (AOA), Angle of Departure (AOD), and RMS delay spread, are associated with communication reliability measured by BER.

II. LITERATURE REVIEW

Research on 6G channel propagation characteristics at 95 GHz has been performed using NYUSIM across both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions within Urban Microcell (UMi) environments [6]. The study analyzed critical parameters including AoA, AoD, PDP, path loss, received power, and propagation delay. The findings established that propagation conditions heavily dictate the received signal quality, underscoring channel characterization as a fundamental step in designing millimeter-wave 6G architectures. Nevertheless, that research remained limited to basic parameter characterization and did not investigate transmission performance regarding BER. [6].

6G networks are anticipated to yield terabit-per-second data rates alongside vastly superior spectral efficiency compared to earlier generations [6]. Achieving this requires robust channel models that depict propagation realistically to enable precise design and evaluation frameworks. Given that mmWave bands are bounded by massive bandwidths, sharp directional beamforming, severe path loss, and blockage vulnerabilities, statistical channel simulators like NYUSIM have become indispensable assets in 6G research. [6].

Furthermore, the "Intelligent Network of Everything" paradigm introduces a holistic 6G vision integrating communication, computing, sensing, and Artificial Intelligence (AI) into a unified ecosystem. This integration is critical to drive futuristic applications like holographic interactions, digital twins, and autonomous control systems that demand extreme capacities and ultra-low latencies [7].

The underlying 6G architecture is also evolving toward user-centric topologies where networks dynamically allocate resources based on user behavior, utilizing AI for automatic optimization, mobility management, and real-time decision-making. Within this framework, channel propagation characteristics remain a determining factor that directly dictates transmission reliability and Quality of Service (QoS). [8].

Comprehensive overviews of mmWave and Terahertz 6G platforms highlight that while high-frequency bands present wider bandwidth resources for high-speed transmission, they face steep path losses and intricate multipath fading. Accurate performance assessments thus dictate the use of realistic channel models. [9], [10].

Existing literature has extensively mapped out architectural concepts, AI resource allocation, and baseline channel profiles (AoA, AoD, PDP). However, direct evaluations linking these precise channel profiles to the resulting BER are still scarce. Consequently, this study bridges this gap by focusing on 30 GHz multipath characterizations via NYUSIM and evaluating their explicit impacts on a 64-QAM OFDM system with rate-1/2 Convolutional Coding.

A. Multipath Channels at mmWave Frequencies

Signal propagation at mmWave frequencies is radically distinct from conventional bands. Transmitted waves encounter reflections, scattering, and diffractions off physical structures, reaching the receiver through multiple paths over varying time frames. This multipath propagation produces time dispersion (delay spread) and severe signal power fluctuations, which degrade digital transmission quality and increase bit error hazards. [12].

The severity of multipath propagation is commonly characterized using parameters such as Angle of Arrival (AOA), Angle of Departure (AOD), Power Delay Profile (PDP), path loss, and RMS delay spread. These parameters provide valuable information regarding the spatial and temporal characteristics of the wireless propagation channel and play an essential role in designing robust broadband communication systems.

B. Power Delay Profile (PDP)

The Power Delay Profile (PDP) maps out the distribution of received signal power against its relative delay time across a channel. It characterizes multipath environments by isolating the individual power contributions of different signal paths. PDP data helps derive critical parameters such as the mean excess delay and RMS delay spread. A higher delay spread intensifies the likelihood of Inter-Symbol Interference (ISI), severely hampering overall throughput. [11].

Among these parameters, RMS delay spread is particularly important because it determines the degree of temporal dispersion experienced by transmitted signals. Larger RMS delay spread generally results in stronger inter-symbol interference (ISI), whereas coherence bandwidth indicates the frequency range over which the channel response remains highly correlated. Consequently, both parameters directly influence the performance of broadband multicarrier systems such as OFDM.

C. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multicarrier transmission technique that partitions a wide communication channel into multiple orthogonal subcarriers. By transmitting low-rate symbol streams across these subcarriers, OFDM successfully mitigates frequency-selective fading and ISI. Its high resilience against severe multipath channels makes it a foundational modulation scheme for high-speed modern communication, spanning 5G and future 6G structures. [2].

These characteristics make OFDM particularly suitable for wireless channels exhibiting frequency-selective fading, including mmWave multipath environments. Consequently, OFDM has been widely adopted in modern broadband wireless communication systems such as LTE, 5G New Radio, and prospective 6G networks.

D. Bit Error Rate (BER)

BER serves as a standard metric to gauge digital communication fidelity, defined as the ratio of incorrectly received bits to the total transmitted bits. Mathematically, it is expressed as:

$$BER = \frac{N_e}{N_t}$$

where N_e represents the number of bit errors and N_t denotes the total number of transmitted bits. Lower BER parameters signal superior transmission quality. In this study, BER is utilized to monitor how 30 GHz multipath channels impact an OFDM system's performance. [12].

In multipath wireless channels, BER is strongly influenced by propagation impairments including path loss, delay spread, fading, and additive noise. Therefore, BER provides a quantitative measure of how channel characteristics affect communication reliability and is widely used to evaluate the effectiveness of modulation, coding, and equalization techniques.

E. 64-Quadrature Amplitude Modulation (64-QAM)

64-QAM is a digital modulation scheme that varies both the amplitude and phase of a carrier wave to encode data. It synthesizes orthogonal In-phase (I) and Quadrature (Q) components to define specific constellation points. Containing 64 unique constellation points, each transmitted symbol represents 6 bits of information based on the logarithmic relation:

$$log_2(64) = 6$$

This high-order mapping grants 64-QAM a superior spectral efficiency over QPSK or 16-QAM, making it ideal for broadband networks like LTE, 5G, Wi-Fi, and 6G development. However, its closely packed constellation coordinates make it highly susceptible to noise and fading, requiring strict channel quality to perform optimally. The 64 symbols are organized in an 8 × 8 matrix where the relationship between constellation size M and bits per symbol k satisfies:

$$k = log_2(M)$$

For 64-QAM:

$$k = log_2(64) = 6\ bits/symbol$$

While this enables large-scale data capacities, the heightened spectral efficiency demands a higher Signal-to-Noise Ratio (SNR) to preserve an acceptable BER.

To improve transmission reliability, rate-1/2 convolutional coding is employed before modulation. The encoded sequence is decoded at the receiver using the Viterbi algorithm, enabling error correction caused by noise and multipath fading. The combination of convolutional coding and OFDM provides both frequency diversity and coding gain, making it suitable for evaluating communication performance over realistic mmWave multipath channels generated by NYUSIM.

III. RESEARCH METHOD

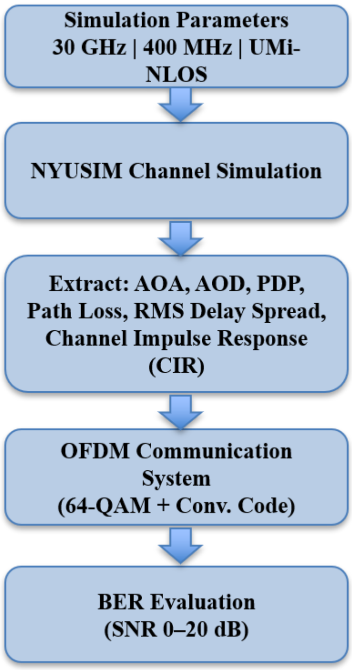

Figure 1. Research Framework for Channel Characterization and BER Evaluation.

Figure 1 shows the research framework adopted in this study. The methodology consists of two sequential stages: multipath channel characterization using the NYUSIM simulator and communication system performance evaluation using an OFDM transceiver.

In the first stage, the NYUSIM channel simulator is configured with a carrier frequency of 30 GHz, a radio-frequency bandwidth of 400 MHz, and an Urban Microcell (UMi) Non-Line-of-Sight (NLOS) propagation scenario. Based on these parameters, NYUSIM generates realistic millimeter-wave propagation characteristics, including the Angle of Arrival (AOA), Angle of Departure (AOD), Power Delay Profile (PDP), path loss, RMS delay spread, and the corresponding Channel Impulse Response (CIR). These parameters represent the spatial and temporal behavior of the wireless propagation channel and provide the basis for subsequent communication system evaluation.

This integrated simulation framework enables the evaluation of BER performance under realistic 30 GHz multipath propagation conditions generated by NYUSIM, rather than relying on simplified statistical fading models. Consequently, the relationship between channel characteristics and communication reliability can be analyzed more accurately for future 6G wireless communication systems.

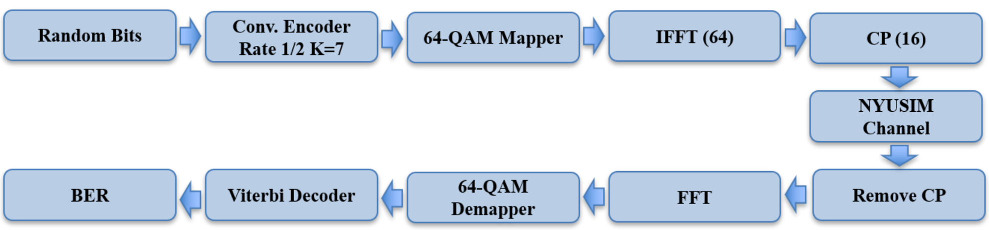

Figure 2. Block Diagram of The OFDM Communication System for BER Evaluation Using The NYUSIM Channel.

Figure 2 shows the block diagram of the OFDM communication system employed in this study. The communication process begins with random binary bit generation, followed by rate-1/2 convolutional encoding with a constraint length of 7 to improve transmission reliability. The encoded bits are then mapped using 64-QAM modulation and transformed into OFDM symbols through a 64-point Inverse Fast Fourier Transform (IFFT). A cyclic prefix (CP) of 16 samples is subsequently inserted to mitigate inter-symbol interference caused by multipath propagation.

The OFDM signal is transmitted through the NYUSIM-generated multipath channel using the exported Channel Impulse Response (CIR). At the receiver, the cyclic prefix is removed before FFT processing, followed by 64-QAM demapping and Viterbi decoding to recover the transmitted information bits. Finally, the decoded bit sequence is compared with the original transmitted sequence to calculate the BER over an SNR range of 0–20 dB.

This transmitter–receiver architecture enables the BER performance to be evaluated under realistic 30 GHz multipath propagation conditions, allowing the communication performance to be directly related to the channel characteristics obtained from NYUSIM.

IV. RESULT AND DISCUSSION

A. Channel Simulation Configurations

The NYUSIM simulator was configured to model a realistic 30 GHz millimeter-wave propagation channel under an Urban Microcell (UMi) Non-Line-of-Sight (NLOS) scenario. To better represent the propagation environment in Semarang, Indonesia, several environmental parameters, including barometric pressure, temperature, relative humidity, and rainfall intensity, were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) of Semarang and incorporated into the simulation setup. These parameters were selected to represent the prevailing atmospheric conditions during the simulation, thereby improving the realism of the generated propagation channel. The complete simulation configuration is showed in Table I.

Table I. Parameters for Simulator Input

Parameter	**Value**	**Parameter**	**Value**
Scenario	Umi	Number of Rx Location	100
Frequency	30 GHz	Barometric Pressure	1013 mbar
RF Bandwidth	400 MHz	Humidity	69.80
Distance Range	Standart	Temperature	28.7ºC
Environment	NLOS	Polarization	Co-Pol
Lower Bound	10 m	Rain Rate	9.7 mm/hr
Upper Bound	50 m	Foliage Loss	No
Tx Power	30 dBm	Spatial consistency	OFF
Base Station Height	30 m	Human Blockage	OFF
User Terminal Height	1.5 m		

The selected simulation parameters represent a typical outdoor urban microcell deployment for future 6G communications at 30 GHz. The carrier frequency of 30 GHz with a 400 MHz RF bandwidth enables the investigation of wideband millimeter-wave propagation, while the UMi-NLOS scenario captures the effects of dense urban environments where signal transmission is dominated by reflected and scattered multipath components. The transmitter and receiver antenna heights of 30 m and 1.5 m correspond to a practical base station and user equipment deployment, respectively. Furthermore, the use of actual environmental parameters obtained from BMKG Semarang allows the simulated channel characteristics to better reflect local atmospheric conditions, providing a more representative basis for subsequent channel characterization and BER performance evaluation.

B. Spatial and Power Delay profile Performance Analysis

Figure 3 shows the simulated Angle of Arrival (AOA) and Angle of Departure (AOD) power spectra generated by NYUSIM for a 30 GHz Urban Microcell (UMi) Non-Line-of-Sight (NLOS) environment with a transmitter–receiver separation of 42.6 m. The color scale represents the received power level of each multipath component, ranging from approximately –118 dBm to –98 dBm.

As shown in Figure 3(a), the AOA distribution is concentrated within a limited angular region, indicating that most received multipath components arrive from a small number of dominant reflection paths. Similarly, Figure 3(b) shows that the transmitted energy is primarily directed toward several dominant departure angles rather than being uniformly distributed across all directions. This clustered spatial distribution is a typical characteristic of millimeter-wave propagation, where the received signal is mainly composed of a few strong reflected components due to the limited diffraction capability and severe

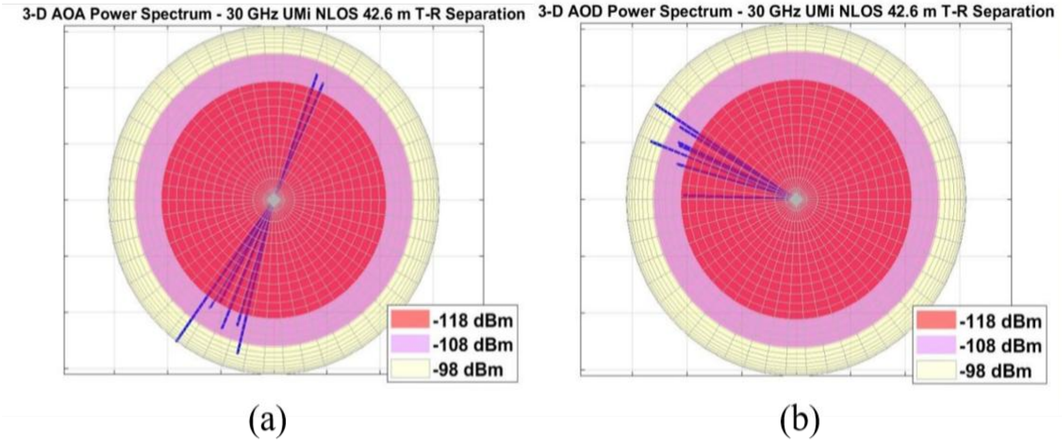

Figure 3. (a) Angle of Arrived (AOA); (b) Angle of Departure (AOD)

penetration loss at high frequencies.

The observed directional behavior is consistent with previous millimeter-wave channel measurement studies, which reported that propagation at frequencies around 30 GHz is dominated by a limited number of spatial clusters rather than rich isotropic scattering. Consequently, beamforming and directional transmission become essential to concentrate signal energy toward dominant propagation paths and improve communication reliability in dense urban environments.

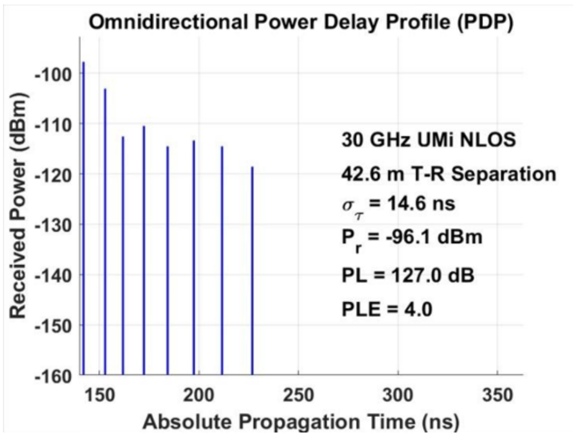

Figure 4. Simulated Power Delay Profile (PDP)

Figure 4 presents the omnidirectional Power Delay Profile (PDP) obtained from 100 channel realizations generated by NYUSIM under the same UMi-NLOS scenario. The PDP characterizes the temporal distribution of the received multipath components by showing the received power as a function of propagation delay.

The first arriving path exhibits the highest received power of approximately –96.1 dBm at an absolute propagation time of about 145 ns, indicating the dominant propagation component. Subsequent multipath components arrive with progressively lower power levels, reaching approximately –118 dBm at delays approaching 230 ns. This gradual power decay reflects the attenuation experienced by reflected and scattered propagation paths after multiple interactions with surrounding buildings and urban obstacles.

The simulated channel exhibits an RMS delay spread of 14.6 ns and a path loss of 127 dB. The relatively small RMS delay spread indicates that the dominant multipath energy is concentrated within a short temporal interval, resulting in a limited delay dispersion. Consequently, the temporal spread remains considerably shorter than the adopted cyclic prefix length of 16 samples in the OFDM system, thereby reducing the possibility of severe inter-symbol interference (ISI). This characteristic is beneficial for maintaining reliable symbol detection at the receiver.

Overall, the obtained PDP confirms that the 30 GHz UMi-NLOS channel is dominated by a small number of strong reflected paths followed by several weaker delayed components. Such temporal characteristics are consistent with the propagation behavior of millimeter-wave channels reported in previous studies and provide the basis for interpreting the BER performance presented in the following section. Specifically, the relatively small delay spread observed in the simulated channel is expected to support improved BER performance because the OFDM system can effectively mitigate the remaining multipath effects using the cyclic prefix.

C. BER Performance Analysis

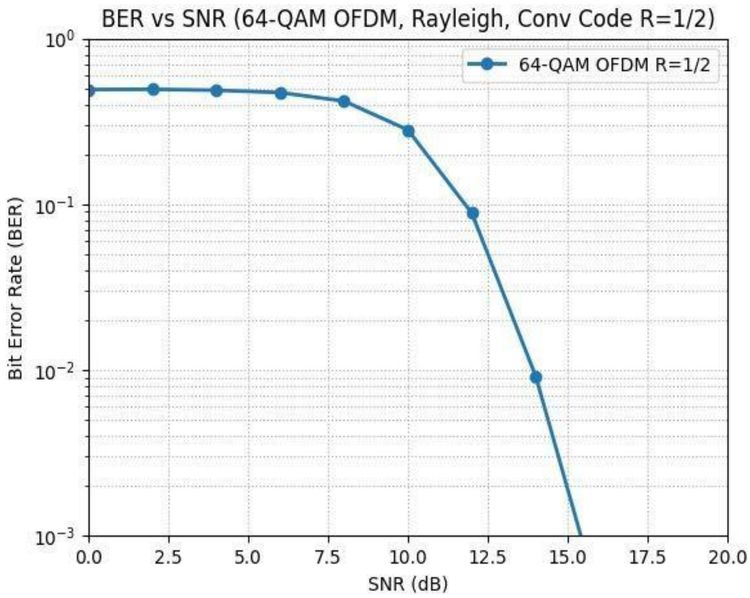

Figure 5. BER Performances for the OFDM System Using 64-QAM and Convolutional Coding.

Figure 5 shows the BER performance of the OFDM communication system employing 64-QAM modulation and rate-1/2 convolutional coding over the NYUSIM-generated multipath channel. The BER is evaluated over an SNR range of 0–20 dB to investigate the communication reliability under realistic 30 GHz Urban Microcell (UMi) Non-Line-of-Sight (NLOS) propagation conditions.

At low SNR values (0–8 dB), the BER remains relatively high, varying between approximately $4.8 \times 10^{-1}$and 4.2×10^{-1}. In this region, the received signal is significantly affected by channel attenuation, multipath fading, and additive white Gaussian noise (AWGN). Consequently, the Euclidean distance between adjacent 64-QAM constellation points becomes insufficient for reliable symbol detection, causing a large number of symbol decision errors. Although the rate-1/2 convolutional encoder provides forward error correction, the decoder is unable to recover most erroneous symbols because the received signal quality remains below the decoding threshold.

As the SNR increases, the BER decreases gradually and reaches approximately 2.8×10^{-1}at 10 dB and 9×10^{-2}at 12 dB. A pronounced waterfall region is observed between 12 dB and 16 dB, where the BER drops by several orders of magnitude. This behavior indicates that the received signal quality becomes sufficiently high for the Viterbi decoder to effectively correct transmission errors while the OFDM modulation suppresses the remaining multipath distortion through orthogonal subcarrier transmission. Beyond an SNR of 16 dB, the BER falls below $10^{-3}$and approaches zero, demonstrating highly reliable communication with negligible error probability.

The observed BER trend is closely related to the spatial and temporal channel characteristics discussed in the previous subsection. The NYUSIM simulation produces a dominant first-arrival path followed by several weaker delayed multipath components, resulting in an RMS delay spread of 14.6 ns. Since the delay spread is shorter than the cyclic prefix duration adopted in the OFDM system, inter-symbol interference

(ISI) can be effectively mitigated before FFT processing. Consequently, the receiver is able to recover the transmitted symbols with high accuracy, allowing the convolutional decoder to operate more effectively as the SNR increases. This explains the significant BER improvement observed beyond approximately 14 dB.

The obtained BER characteristics are consistent with previous studies on millimeter-wave OFDM communication systems, where a rapid BER reduction is commonly observed once the SNR exceeds the decoding threshold of convolutionally coded 64-QAM transmission. However, unlike conventional BER evaluations based on simplified Rayleigh or Rician fading models, this study employs the realistic multipath channel generated by NYUSIM. Therefore, the obtained BER performance reflects practical propagation phenomena, including directional propagation, path loss, and delay dispersion, making the evaluation more representative of future 6G urban deployment scenarios.

The integration of NYUSIM channel characterization with BER evaluation demonstrates that realistic multipath propagation has a direct influence on communication reliability. The spatial distribution of dominant propagation paths and the relatively small delay spread generated by NYUSIM enable the OFDM system with convolutional coding to achieve reliable transmission at moderate-to-high SNR values. These findings confirm that incorporating realistic channel characteristics into BER analysis provides a more comprehensive assessment of OFDM performance for future 6G millimeter-wave communication systems than evaluations based solely on idealized statistical channel models.

V. CONCLUSION

This research investigated the multipath channel characteristics of a 30 GHz Urban Microcell (UMi) Non-Line-of-Sight (NLOS) environment using the NYUSIM channel simulator and evaluated their influence on the BER performance of an OFDM communication system employing 64-QAM modulation and rate-1/2 convolutional coding. The simulation results revealed clustered spatial propagation with a dominant first-arrival path, a path loss of 127 dB, and an RMS delay spread of 14.6 ns, reflecting the directional and highly attenuated characteristics of millimeter-wave propagation in dense urban environments. The BER analysis demonstrated a substantial improvement in communication reliability as the SNR increased, with the BER decreasing from approximately 4.8×10^{-1}at 0 dB to below 10^{-3}at 16 dB. The relatively small RMS delay spread remained within the cyclic prefix duration, enabling the OFDM receiver to effectively suppress inter-symbol interference while enhancing the error-correction capability of the rate-1/2 convolutional coding scheme. The integration of NYUSIM-based channel characterization with BER evaluation demonstrates that realistic multipath propagation characteristics have a direct influence on communication reliability. By employing a site-representative channel generated by NYUSIM instead of simplified statistical fading models, this research provides a more realistic assessment of OFDM performance in 30 GHz urban propagation environments. Furthermore, this research establishes a direct relationship between spatial and temporal channel characteristics, particularly the Power Delay Profile (PDP) and RMS delay spread, and the resulting BER performance. These findings provide a more comprehensive understanding of how realistic multipath propagation affects communication reliability and offer a valuable reference for the design, simulation, and performance evaluation of future 6G millimeter-wave OFDM communication systems.

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AUTHOR CONTRIBUTION

RD constructed the study design. IU and RA performed and analyzed the data. TT prepared the manuscript and revised the final version of the paper. RD, IU, and RA have read the final manuscript and approved the submission. RD, TT, IU, and RA are the abbreviation of First, Second, Third and Fourth Author respectively.

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