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Performance Study of Multipath Effect in 5G Millimeter-Wave Channel

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***Abstract*— 5G has been essentially a buzzword for several years, but according to the experts, from 2022 onward, there will be an inflection point between network maturity and the availability of 5G. To make 5G a reality, we must minimize all propagation losses. One of the possible factors that reduces the performance of 5G transmission is the multipath effect. In this paper, we investigate the severity of the multipath effect in the 5G millimeter-wave (mmWave) channel and mitigate the multipath effect using adaptive equalization based on the least mean square (LMS) algorithm to improve the performance of 5G wireless signal transmission. A mmWave channel simulator, NYUSIM, provides complete data for all resolvable multipaths in a specific channel configuration. An analysis of bit-error-rate (BER) based on the minimum BER (MBER) and minimum mean square error (MMSE) optimization criterion is performed to measure the improved performance of a 5G data channel simulated under line-of-sight (LOS) and non-LOS (NLOS) paths. A good overall performance of BER based on the MBER and MMSE criteria is attained using the LMS equalization method in a micro-urban area at a maximum data rate of 50 Mbps. For both LOS and NLOS conditions, the increase in data rate to 55.56 Mbps and 62.5 Mbps causes a significant decrease in BER performance. In conclusion, the primary factor affecting the BER performance is the data rate, not the frequency or transmitter-to-receiver distance.**

***Keywords*— 5G; millimeter-wave; multipath; NYUSIM; bit-error-rate.**

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I. INTRODUCTION

5G, the fifth generation of cellular networks, is significant not just because it has the potential to revolutionize the world but also because it can handle millions of devices at once at incredible speeds [1] compared to the current 4G Long-Term Evolution (LTE) network [2]. According to the Global System for Mobile (GSM) Association, 5G will have more than 1.7 billion members worldwide by 2025 [3]. The 5G networks also connect to the emerging IoT ecosystem [4], which is used in various applications such as health care, agriculture, etc. [5]. Meanwhile, millimeter-wave (mmWave) is an exceptionally high-frequency band ranging from 30 GHz to 300 GHz that improves the performance of 5G wireless networks [6]. Since it is a relatively new band, its spectrum utilization is not congested with various existing wireless communications in narrowband and wideband, such as WiMax, GPS, WiFi, 4G, etc. Moreover, it can transport more information than the lower frequency waves and can be combined with multiple input multiple output (MIMO) antennas to provide a larger magnitude capacity than present communication systems [7]. The applications of 5G mmWave include radar systems, radio communication, and the upcoming 6G communication [8].

Several 5G experts have done extensive research on mmWave transmission. The authors of [9] investigated the difficulties and needs of developing mmWave 5G antennas for mobile devices. A tiny and low-profile 60 GHz array of antenna modules was created utilizing 3D planer mesh-grid antenna components. The authors of [10] also investigated the appropriateness of the mmWave spectrum for 5G cellular networks. They presented the recent developments in the system architectures of active beamforming arrays, beamforming integrated circuits, antennas for base stations and user terminals, system measurement and calibration, and channel characterization.

On the other hand, the authors of [11] addressed mmWave signal attenuation due to atmospheric gases, open space propagation, and other significant considerations for establishing mmWave communications in 5G. Throughout all the studies, a few specific mmWave frequencies are expected to be utilized for 5G, such as 28 GHz, 38 GHz, and 54 GHz. The channel characterization in terms of large-scale propagation, small-scale propagation, and interference analysis of these 5G mmWave signals has been presented in indoor and outdoor areas [12]. Extended analysis of the pace loss, especially in tunnels, has been presented in [13] by designing a directional horn antenna, and the challenges of the specific characteristics of mmWave propagation in massive MIMO mmWave systems have been addressed in [14].

Although 5G promises to provide a speedy transmission rate, the true performance of the network's speed is still under investigation, and the practical outcome is still far from the theoretical expectation. In [15], four major network providers from the United States, Verizon, AT&T, T-Mobile, and Sprint showed that their 5G speed performance can reach over 60 Mbps to 70 Mbps. For mmWave, the authors of [16] discussed the real-world performance of 5G fixed wireless broadband in an indoor-to-outdoor (I2O) environment. Two different NLOS path loss models were used: close-in (CI) free space reference distance and alpha-beta-gamma (ABG) models. The propagation signal through the NLOS channel at 19, 28, and 38 GHz was strong with a low delay; it was concluded that these bands are reliable for 5G systems in short-range applications. Similar research has been done [17] to find the best path loss models for indoor mmWave propagation. Besides that, research was done to study the internet speeds of 5G Internet of Things (IoT) mmWave at 38 GHz in an urban microcell condition [11]. This research mainly focused on the ability of mmWave route loss models. Based on CI-LOS V-V and FI-LOS V-V scenarios, the highest average throughput for a minimum of 10 users was 25 Mbps and 22 Mbps, respectively. For a single user, the highest average throughput that could be achieved was around 50 Mbps.

Increasing network capacity and channel bandwidth when using the mmWave spectrum in 5G introduces several channel propagation concerns that must be solved before they can be employed. Hence, selecting an appropriate channel model is important for studying the channel effect. 3GPP and NYUSIM are two well-known channel models utilized for wireless communication in 5G [18]. The research reported in [19] concluded that NYUSIM provided a more uniform spectral efficiency and eigenvalue distribution for mmWave bands, and a more accurate and reliable set of simulation results compared to the 3GPP channel model in an urban area. The multipath effect and path loss in mmWave have been studied [20], [21]. Both studies indicate a loss of signal quality and transmission coverage due to multipath propagation. Especially in [20], the multipath effect on the investigated parameters reduced the received power and increased the path losses to approximately their double values by using lower frequencies of 28 and 39 GHz mmWave.

On the other hand, [21] studied the signal strength, shadow fading, etc. of a 40 GHz mmWave signal for LOS and NLOS paths in an indoor environment scenario. The NLOS path was found to lose the majority of the signal energy when compared to the LOS path. Another similar work has also been reported in [22] to investigate the effect of multipath propagation in an indoor environment, which covers the mmWave frequencies from 28 GHz to 100 GHz. In addition, the authors of [23] showed that the multipath effects are more severe in urban areas, and broadband, high gain circularly polarised antennas were preferred to reduce effects.

One possible way to mitigate the multipath effect is adaptive equalization. The least mean square (LMS) algorithm is one of the most popular types of adaptive filtering. Two major advantages of the LMS filter are its simplicity of design and high-performance effectiveness, which have made it extremely useful in a wide range of applications [24]. However, an equalization algorithm needs to employ an acceptable optimization criterion to find the equaliser's coefficients. The minimal mean square error (MMSE) optimization criterion is one of the most commonly employed approaches [25] due to its simplicity and capability to reduce both inter-symbol interference (ISI) and noise at the same time. A downfall of the MMSE criterion is that it is optimum because mean square error (MSE) is not the true indicator of performance in digital communications. The BER, on the other hand, is a true indicator, which is used in the minimum bit error rate (MBER) criterion [26]. Studies have been done using the advanced version of MBER to reduce signal distortion due to interference and multipath propagation in other applications, such as those reported in [26, 27]. For example, a minimum symbol error rate (MSER) criterion was used to design the equalizer of underwater acoustic (UWA) communication [27], and a generalised-MBER (G-MBER) equalizer was designed to mitigate multi-user access interference (MAI) in an ultra-wideband multipath channel (UWB) [26].

Therefore, in this paper, a series of steps involving the NYUSIM 5G mmWave simulator are performed to evaluate the effect of multipath in the mmWave channel. NYUSIM is chosen since it provides reliable and accurate results to generate the multipath channel components used for the 5G transceiver simulation. The mmWave signal will then propagate through this multipath channel, resulting in a distorted signal at the receiver. A study of the adaptive equalization using the LMS algorithm to mitigate the distorted signal's multipath effect is then performed. Result analysis is carried out based on the MBER and MMSE optimization criteria by investigating the bit-error-rate (BER) performance at different channel configurations such as mmWave frequencies, transmitter-to-receiver distances, data rates, and LOS and NLOS environments. Exploiting the multipath effect on the mmWave and mitigating the effect are essential since they enable a more reliable and efficient signal transmission for handling the excessive data demand that will rise in 5G networks in the near future.

In the rest of this paper, section 2 discusses the project methodology by describing the sequence of simulations performed to obtain and include multipath in a 5G millimeter wave channel. It also discusses the adaptive equalization techniques used to mitigate multipath effects. Section 3 presents the results of multiple simulations with different channel configurations. It includes a performance analysis of the LMS equalization based on the MBER and MMSE optimization criteria and a discussion on the overall effectiveness of the LMS equalization in a micro-urban area. Lastly, Section 4 includes a summary of the study of the multipath effect in the 5G mmWave channel and future recommendations.

II. MATERIAL AND METHOD

The complete design process involves four phases. The block diagram of the design process carried out throughout the research is shown in Fig. 1. The first step is to obtain multipaths from NYUSIM. Next, multipaths are sampled at a desired time interval to achieve a specific data rate. A 5G transceiver implementing LMS adaptive equalization is developed using MATLAB to study the effect of multipath and the ability of LMS equalization to mitigate the effect of multipath. Finally, performance analysis is done based on the MBER and MMSE criteria.

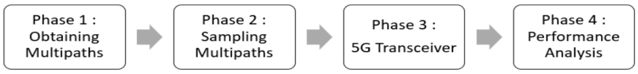

Fig. 1 Block diagram of the design process

A. NYUSIM - Millimeter-Wave Channel Simulator

The NYUSIM channel simulator includes a complete statistical channel model and simulation code and an intuitive interface for creating realistic spatial and temporal wideband channel impulse responses. New York University's (NYU) broadband statistical spatial channel model (SSCM) serves as the foundation for NYUSIM [18]. The simulation of NYUSIM provides complete data on all multipaths for the specific scenario and channel parameter configuration. The channel simulator includes 49 input parameters, which are classified as channel parameters, antenna properties, human blockage parameters, and spatial consistency parameters. In this paper, parameter configuration only involves the channel parameters. Antenna properties are set to default values, whereas spatial consistency and human blockage are turned off.

Table 1 shows all the critical channel parameter configurations used in this research for multiple findings of 5G signal transmission performance in different scenarios. The 28 GHz and 38 GHz mmWave frequencies are potential candidates for use in 5G and Beyond-5G systems [28]. 54 GHz is another common frequency chosen to study 5G signal transmission at higher frequencies. A transmit power of 30 dBm is chosen based on [19], which discussed mmWave base station diversity. The transmit power of 30 dBm is commonly used in ultra-micro urban areas. Almost every specification for a 5G device states co-polarization as a primary and mandatory feature. Thus, co-polarization is used. Standard distances of 50, 100, and 500 meters are selected for simulation analysis.

TABLE 1
CHANNEL PARAMETER CONFIGURATIONS

Channel Parameters	**Configuration**
Scenario	Ultra-micro urban area
Frequency	28 GHz, 38 GHz ,54 GHz
Environment	LOS, NLOS
Tx-Rx separation distance	50 m, 100 m, 500 m
Transmit power	30 dBm
Polarization	Co-polarization

After running the simulation, NYUSIM provides complete data on all resolvable multipath in the directional power delay profile (PDP) output file named "DirPDPInfo.txt". The PDP provides the received signal's intensity and phase through a multipath channel as a function of time delay. Once multipaths are successfully obtained, sampling of multipaths is carried out, as shown in Fig. 2.

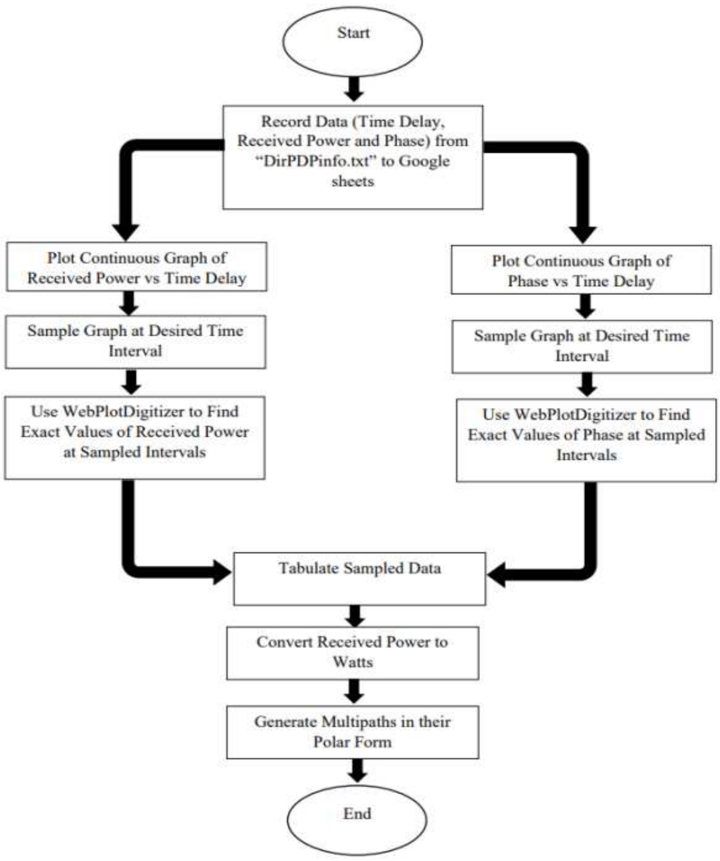

Fig. 2 Block diagram of sampling process

The recorded data, which includes the received power, phase, and time delay, is imported to Google Sheets. Continuous graphs are plotted separately for received power vs. time delay and phase vs. time delay to apply a graphical method called WebPlotDigitizer to sample and extract the values of the multipath components at different time intervals. The sampling time, t_s, affects the data transmission rate, given as data rate = $1/t_s$.

Examples of sampled graphs are shown in Fig. 3 and Fig. 4. The power and phase of each multipath are plotted into two separate continuous line graphs and sampled at 20 ns to achieve a data rate of 50 Mbps. This data rate is chosen since it is the average data rate that can be achieved practically in a micro-urban environment, as mentioned previously [11].

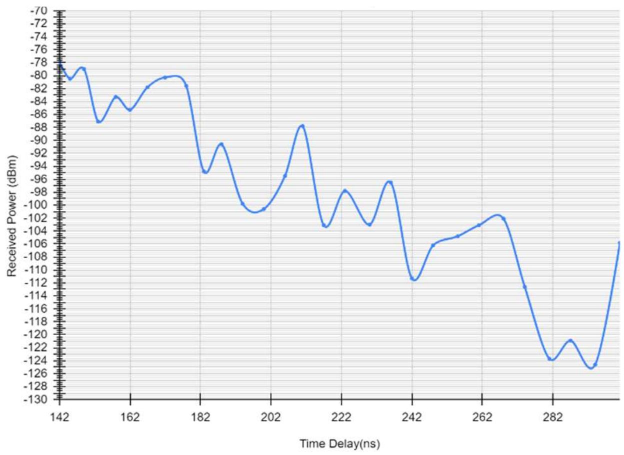

Fig. 3 Sampling of received power at 20ns interval

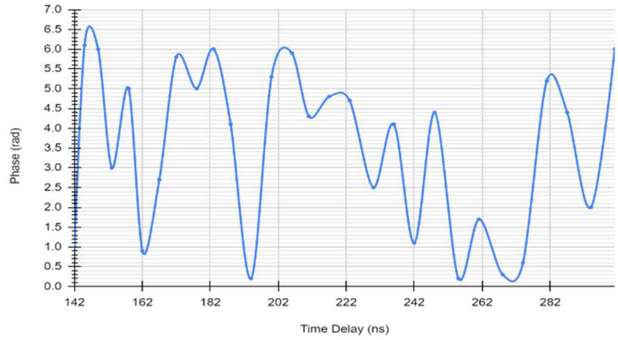

Fig. 4 Sampling of phase at 20ns interval

Upon sampling, the multipaths at specific time intervals are tabulated according to their corresponding sampled values of received power, P_{dbm} and phase, $Phase_{rad}$. The received power, P_{dbm} is then converted from dBm to mW using the following equation,

$$P_{mW} = 10^{\frac{P_{dbm}}{10}} \text{mW} \tag{1}$$

The final step is to generate the multipath in their polar form, given as follows:

$$z(n) = P_{mW}(n) \cdot cos(Phase_{rad}(n)) + jP_{mW}(n) \cdot sin(Phase_{rad}(n)) \tag{2}$$

where n is the total number of sampled multipaths.

B. 5G Transceiver

The mmWave signal is modulated using quadrature phase shift keying (QPSK) [24] before a 5G transceiver can transmit it. The QPSK signal can be generated on the transmitter side based on the block diagram shown in Fig. 5.

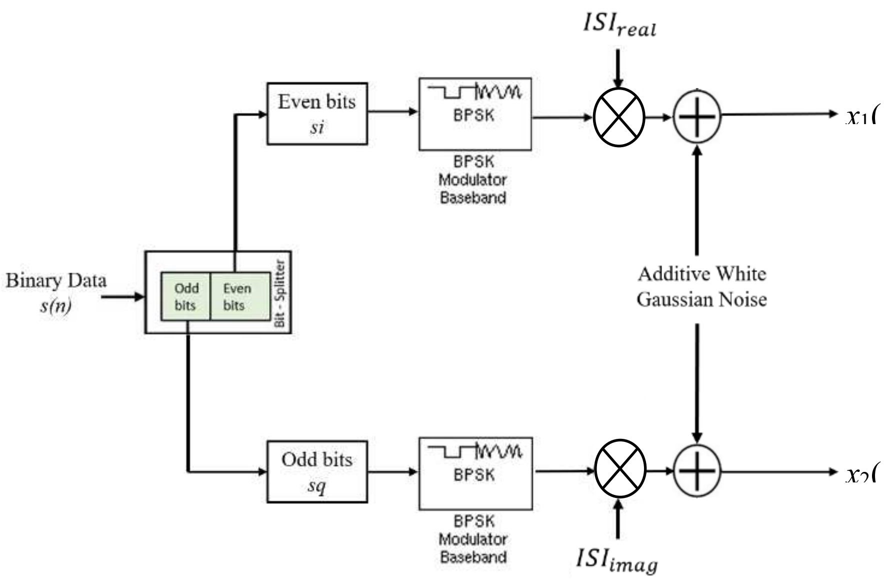

Fig. 5 Block diagram of a transmitter

The binary information data, $s(n)$ is separated by a bit splitter into even bits, s_i and odd bits, s_q. Both even and odd bits undergo baseband binary phase shift keying (BPSK) modulation. The even bits transmitted undergo convolution with the real inter-symbol interference (ISI) values, ISI_{real} generated, whereas the odd bits are convoluted with the imaginary ISI values, ISI_{imag}. Additive white Gaussian noise (AWGN) is added to both bit streams. This results in one in-phase distorted output signal, $x_1(n)$, and one quadrature distorted output signal, $x_2(n)$. The ISI values are generated from the multipath given as follows:

$$ISI_{real} = \frac{1}{\sqrt{\sum \mathrm{Re}(z_m)^2}} \cdot \mathrm{Re}(z_m) \quad (3)$$

$$ISI_{imag} = \frac{1}{\sqrt{\sum \mathrm{Im}(z_m)^2}} \cdot \mathrm{Im}(z_m) \quad (4)$$

where $z_m = \{z(1), z(2), \cdots, z(n)\}$ are all the sampled multipath components, Re(•)is the real part and Im(•)is the imaginary part.

As shown in Fig. 6, both distorted output signals are fed into the adaptive equalizer based on the LMS algorithm at the receiver end. The equalizer's outputs, $y_1(n)$ and $y_2(n)$, undergo baseband BPSK demodulation, resulting in received even bits, de_s_i and odd bits, de_s_q. The even and odd bits are joined back together in the same order they were split. The final combined even and odd bit streams result in the received signal, $r(n)$.

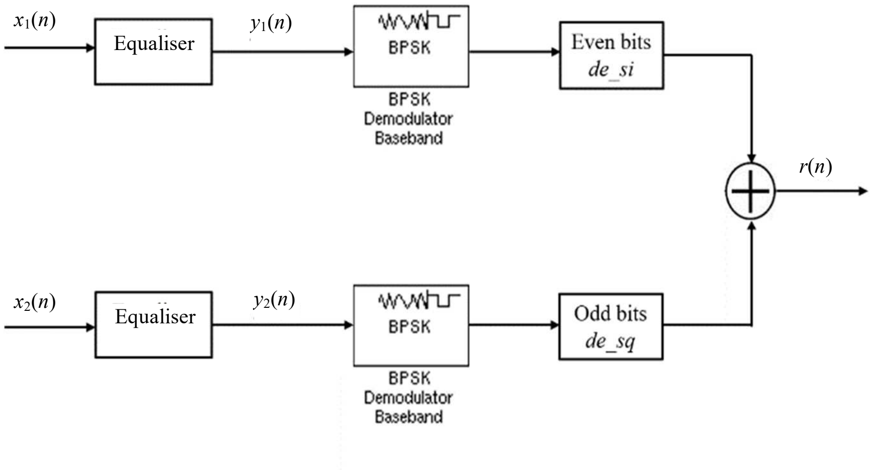

Fig. 6 Block diagram of receiver

The equalizer used in this research applies the LMS algorithm, a stochastic gradient descent method for adaptive signal processing. LMS updates the N-tap equalizer's tap weight, $W(n)$ using the following formula [24]:

$$W(n+1) = W(n) + \mu \Delta F(\bullet) \quad (5)$$

where μ is a step size parameter that impacts the filter weights' convergence behavior, Δ is a gradient, and $F(\bullet)$is an object function.

The equalizer's output is then formulated as,

$$y(n) = W^T x(n) \quad (6)$$

The objective function is determined based on the optimization criteria used to search for an optimum solution to minimize the distortion effect of the received signal. This paper considers MMSE and MBER criteria since MMSE is the most commonly used criterion [30], whereas MBER is deemed to have a better solution [26].

Therefore, the equalizer's tap weight, $W(n)$ is updated using the MMSE criterion given as [30],

$$W(n+1) = W(n) + \mu \Delta F(\bullet) \quad (7)$$

where $e(n) = d(n) - y(n)$ is the difference between the desired signal, $d(n)$ and the equalizer's output. Meanwhile, the equalizer's tap weight, $W(n)$ is updated using the MBER criterion given as [26],

$$W_{MBERE}(n+1) = W(n) + \mu \Delta P_E \quad (8)$$

where ΔP_E is the gradient of a probability of error. After obtaining the received signal $r(n)$, performance analysis can be done by comparing the BER, which will be discussed in the next section.

III. Result and Discussion

At first, the most suitable equalizer's tap length is chosen as $N = 7$ for higher frequency resolution, which in turn means narrower filters and steeper roll-offs, and the step size is selected as $\mu = 0.001$ since a smaller step size produces better BER performance [30]. Performance analysis is done at different frequencies, transmitter-to-receiver (Tx-Rx) distances and data rates for LOS conditions using the determined tap length and step size. Finally, performance analysis in NLOS conditions is also performed at multiple data rates.

A. Performance Analysis on Millimeter-wave Frequencies Testing

Fig. 7 and Fig. 8 present the BER performance of MBER and MMSE equalizer at different frequencies.

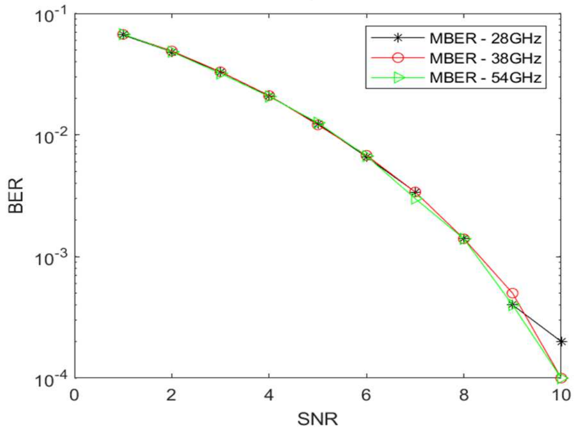

Fig. 7 BER performance of MBER at different frequencies

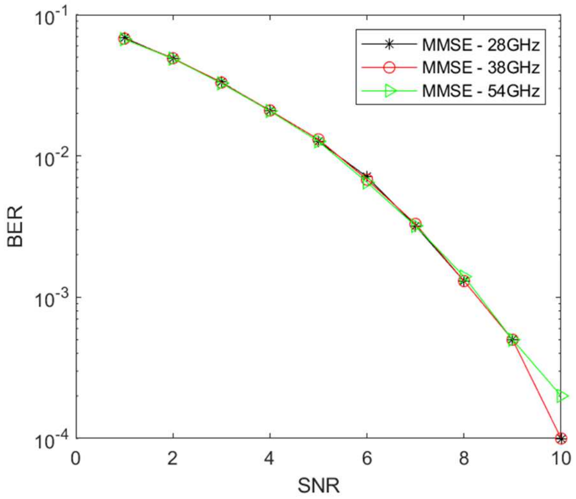

Fig. 8 BER performance of MMSE at different frequencies

The channel configurations remain as in Table 1, except that the Tx-Rx distance used is 100 m, and the environment is LOS. Simulation is run at 28 GHz, 38 GHz, and 54 GHz mmWave frequencies for the 5G network. Based on the results, the BER performances are almost the same at frequencies of 28 GHz, 38 GHz, and 54 GHz, respectively, for both the MBER and MMSE equalizers. All of them are able to achieve a BER of 10^{-4} at a signal-to-noise ratio (SNR) of 10 dB. The results indicate that the changes from a lower 28 GHz frequency to a higher 38 GHz and 54 GHz frequency waves do not affect the multipath effect. There is no noticeable performance difference between the MMSE and the MBER criteria.

B. Performance Analysis on Tx-Rx Distances

Fig. 9 and Fig. 10 present the BER performance of MBER and MMSE equalizers at different Tx-Rx distances. The channel configurations remain in Table 1, except that the mmWave frequency used is 38 GHZ, and the environment is LOS. Simulations are run at distances of 50 m, 100 m, and 500 m.

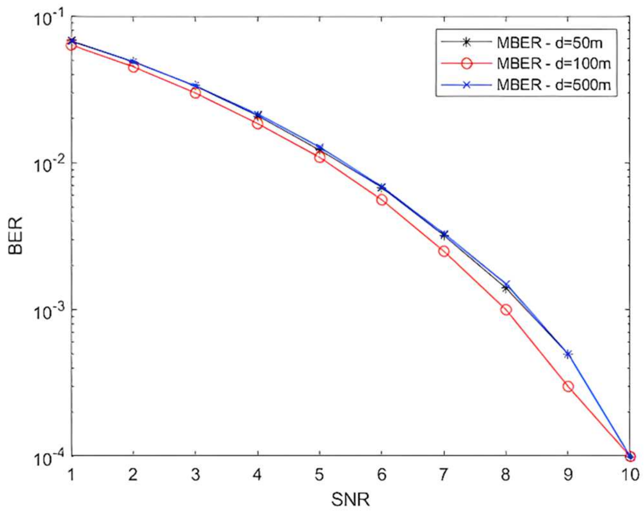

Fig. 9 BER performance of MBER at different Tx-Rx distances

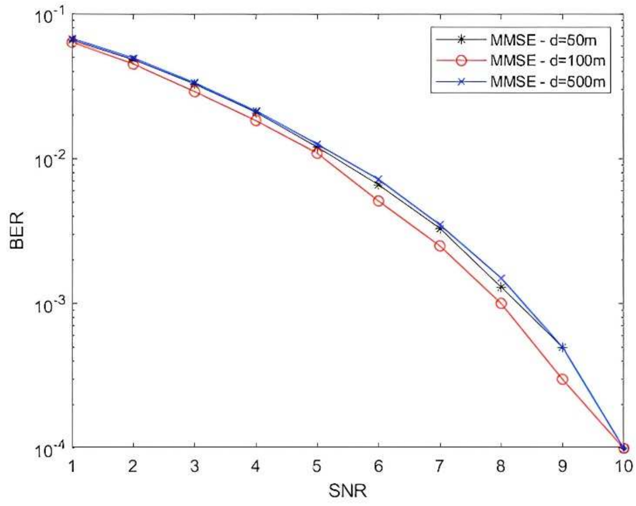

Fig. 10 BER performance of MMSE at different Tx-Rx distances

Based on the results, good overall BER performance is achieved at all transmitter-receiver distances of 50, 100, and 500 meters in both the MBER and MMSE equalizers. All of them are able to achieve a BER of 10^{-4} at a SNR of 10 dB. The results indicate that the 5G mmWave signal is able to travel distances of 50 m to 500 m without suffering a severe multipath effect.

C. Performance Analysis on Data Rates

In the last analysis, both the performance of LOS and NLOS environments is evaluated. Fig. 11 and Fig. 12 present the BER performance of MBER and MMSE equalizers simulated in a LOS environment at different data rates. The channel configurations remain in Table 1, except that the mmWave frequency used is 38 GHZ, and the Tx-Rx distance is set to 100 m. Simulation is run at 50 Mbps, 55.56 Mbps, and 62.5 Mbps data rates.

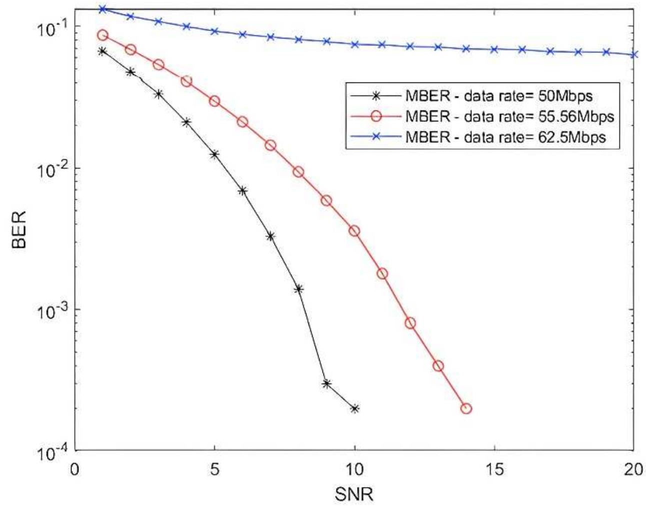

Fig. 11 BER performance of MBER simulated under LOS at different data rates

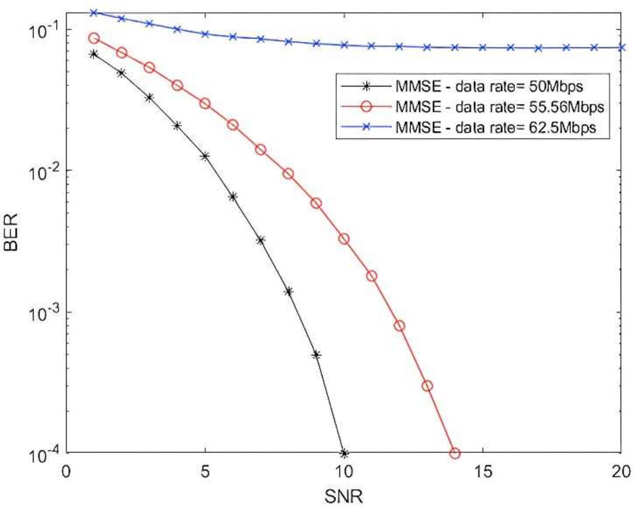

Fig. 12 BER performance of MMSE simulated under LOS at different data rates

For both MBER and MMSE equalizers, the best performance of BER is attained at a lower data rate of 50 Mbps. A BER of 10^{-4} is achieved at approximately SNR = 10 dB and SNR = 14 dB, respectively, when the data rate is 55 Mbps and 55.56 Mbps. At 62.5 Mbps, a poor BER is attained. The result matches the average data rate that can be achieved practically in a micro-urban environment. Moreover, it seems that there is no difference in terms of BER performance between the MBER and MMSE equalizers.

On the other hand, Fig. 13 and Fig. 14 present the BER performance of MBER and MMSE equalizers simulated under the NLOS environment at different data rates. The channel configurations remain as in Table 1, except that the mmWave frequency used is 38 GHZ, and the Tx-Rx distance is 10 m. The propagation loss and multipath effect in the NLOS path are more severe than in the LOS path, and hence, the transmission distance of the mmWave signal is limited to a maximum distance of 10 m only. Simulation is run again at 50 Mbps, 55.56 Mbps, and 62.5 Mbps data rates.

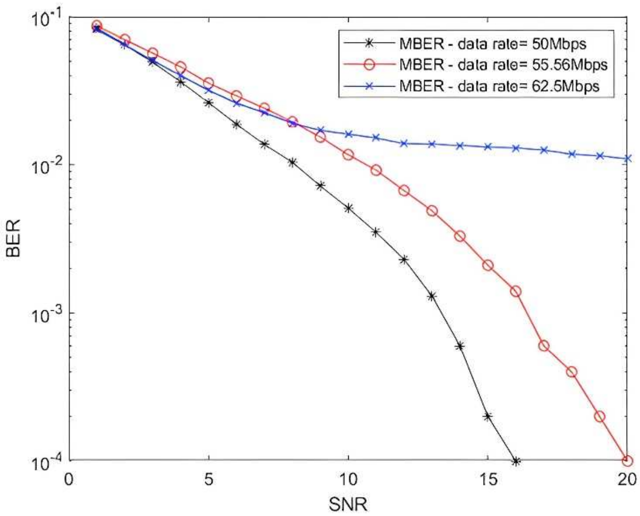

Fig. 13 BER performance of MBER simulated under NLOS at different data rates

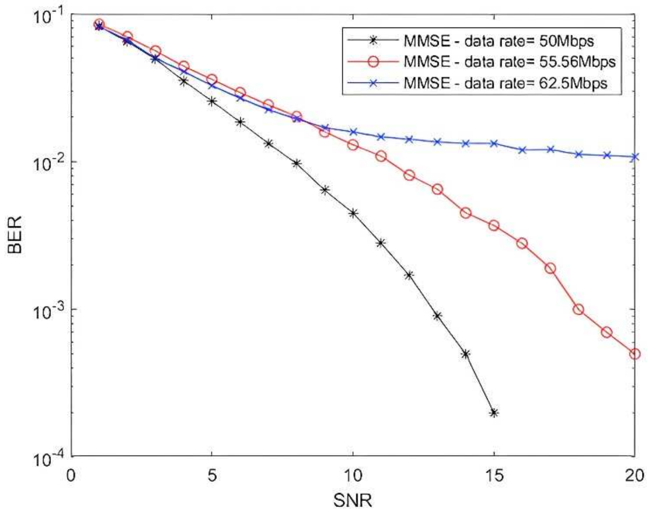

Fig. 14 BER performance of MMSE simulated under NLOS at different data rates

For both MBER and MMSE equalizers, the best performance of BER is again attained at a lower data rate of 50 Mbps, with a BER of 10^{-4} achieved at around SNR = 16 dB. However, when the data rate increases to 55.56 Mbps, only the MBER equalizer attains a good BER performance, with a BER of 10^{-4} achieved at around SNR = 20 dB. Meanwhile, the MMSE cannot perform similarly when SNR is less than 20 dB. At 62.5 Mbps, both equalizers attain poor BER performances. Thus, the BER performance of the MBER equalizer outperforms the MMSE equalizer under the NLOS environment, which exhibits a severe multipath effect.

IV. CONCLUSION

In this paper, the effect of multipath in a 5G mmWave channel has been successfully studied in a micro-urban area. The multipath components were generated from the NYUSIM, a 5G mmWave channel simulator, for the specific scenario and channel parameter configuration. A 5G transceiver has been developed using LMS adaptive equalization based on the MBER and MMSE criteria. The adaptive equalizer has proven to be able to reduce signal distortion due to the effect of multipath in a 5G mmWave channel at different frequencies and transmitter-receiver distances with an average data rate of 50 Mbps. This allows 5G signal transmission to perform better without the degradation caused by multipath propagation. In addition, it was found that the frequency and the transmitter-receiver distance did not affect the ability of the LMS equalizer to mitigate the multipath effect. However, the data rate of signal transmission and NLOS condition are the two main factors causing a drop in the BER performance of a 5G millimeter-wave channel. Meanwhile, MBER has a better performance in the NLOS environment than MMSE.

This research is limited to an average data rate of 50 Mbps. Although the performance of 5G is not up to its theoretical performance in most places now, there is a high possibility of the technology providing higher data speeds with more coverage areas across the globe shortly. Future work to attain good BER performance via equalization at a higher data rate can be done by using various advanced adaptive algorithms, such as the Normalized Least Mean Square (NLMS) algorithm. On the other hand, higher-order modulation may be implemented, allowing for greater bandwidth utilization or the ability to deliver higher data rates within a given bandwidth. Nevertheless, this research study can extend to multiple transmitter and receiver systems in different environments to provide a more accurate and reliable BER performance analysis.

References

[1] M. Attaran, and S. Attaran, "Digital transformation and economic contributions of 5G networks," International Journal of Enterprise Information Systems, vol. 16, no. 4, pp. 58–79, 2020, doi: 10.4018/IJEIS.2020100104.

[2] C. Dikki, A. R. Fauzi, A. Siska, and F. K. Andre, "Effect of modulation on throughput of 4G LTE network frequency 1800 MHz," International Journal of Advanced Science Computing and Engineering, vol. 5, no. 1, pp. 44–53, 2023, doi: 10.30630/ijasce.5.1.121.

[3] R. Dangi, P. Lalwani, G. Choudhary, I. You, and G. Pau, "Study and investigation on 5G technology: A systematic review," Sensors, vol. 22, no. 1, p. 26, 2022, doi: 10.3390/s22010026.

[4] S. Wijethilaka, and M. Liyanage, "Survey on network slicing for Internet of Things realization in 5G networks," IEEE Communications Surveys & Tutorials, vol. 23, no. 2 pp. 957–994, 2021, doi: 10.1109/COMST.2021.3067807.

[5] A. Dogra, R. K. Jha, and S. Jain, "A survey on beyond 5G network with the advent of 6G: Architecture and emerging technologies IEEE Access, vol. 9, 2020, doi: 10.1109/ACCESS.2020.3031234.

[6] M. Pant, and L. Malviya, "Design, developments, and applications of 5G antennas: a review," International Journal of Microwave and Wireless Technologies, pp. 1–27, 2022, doi: 10.1017/S1759078722000095.

[7] Y. N. R. Li, B. Gao, X. Zhang, and K. Huang, "Beam management in millimeter-wave communications for 5G and beyond," IEEE Access, vol. 8, pp. 13282–1329, 2020, doi: 10.1109/ACCESS.2019.2963514.

[8] N. K. Mallat, M. Ishtiaq, A. Ur Rehman, and A. Iqbal, "Millimeter-wave in the face of 5G communication potential applications," IETE Journal of Research, vol. 68, no. 4, pp. 2522–2530, 2022, doi: 10.1080/03772063.2020.1714489.

[9] W. Hong, K. H. Baek, and S. Ko, "Millimeter-wave 5G antennas for smartphones: Overview and experimental demonstration," IEEE Transactions on Antennas and Propagation, vol. 65, no. 12, pp. 6250–6261, 2017, doi: 10.1109/tap.2017.2740963.

[10] T. Hong, S. Zheng, R. Liu, and W. Zhao, "Design of mmWave directional antenna for enhanced 5G broadcasting coverage," Sensors, vol. 21, no. 3, 2021, p. 746, doi: 10.3390/s21030746.

[11] F. Qamar, M. N. Hindia, T. Abd Rahman, R. Hassan, K. Dimyati, and Q. N. Nguyen, "Propagation characterization and analysis for 5G mmWave through field experiments," Comput. Mater. Contin., vol. 68, no. 2, pp. 2249–2264, 2021, doi: 10.32604/cmc.2021.017198.

[12] L. Azpilicueta, P. Lopez-Iturri, J. Zuñiga-Mejia, M. Celaya-Echarri, F. A. Rodríguez-Corbo, C. Vargas-Rosales, and F. Falcone, "Fifth-generation (5G) mmwave spatial channel characterization for urban environments' system analysis," Sensors, vol. 10, no. 18, p. 5360, 2020, doi: 10.3390/s20185360.

[13] W. Hong, Z. H. Jiang, C. Yu, D. Hou, H. Wang, C. Guo, and J. Y. Zhou, "The role of millimeter-wave technologies in 5G/6G wireless communications," IEEE Journal of Microwaves, vol. 1, no. 1, pp. 101–122, 2021, doi: 10.1109/JMW.2020.3035541.

[14] K. Hassan, M. Masarra, M. Zwingelstein, and I. Dayoub, "Channel estimation techniques for millimeter-wave communication systems: Achievements and challenges," IEEE Open Journal of the Communications Society, vol. 1, pp. 1336–1363, 2020, doi: 10.1109/OJCOMS.2020.3015394.

[15] N. Ord, "Ookla's Newest 5G speed tests show AT&T leading while Verizon stumbles," HotHardware, 20 Jan. 2021. [Online]. Available: https://hothardware.com/news/mobile-network-stats-for-q4-2020-released-by-ookla.

[16] A. M. Al-Samman, M. H. Azmi, Y. A. Al-Gumaei, T. Al-Hadhrami, T. Abd. Rahman, Y. Fazea, and A. Al-Mqdashi, "Millimeter wave propagation measurements and characteristics for 5G system," Applied Sciences, vol. 10, no. 1, p. 335, 2020, doi: 10.3390/app10010335.

[17] T. T. Oladimeji, P. Kumar, and N. O. Oyie, "Propagation path loss prediction modelling in enclosed environments for 5G networks: A review," Heliyon, vol. 8, no. 11, 2022, doi: 10.1016/j.heliyon.2022.e11581.

[18] S. Mohebi, F. Michelinakis, A. Elmokashfi, O. Grøndalen, K. Mahmood, and A. Zanella, "Sectors, beams and environmental impact on the performance of commercial 5G mmWave cells: An empirical study," IEEE Access, vol. 10, pp. 133309–133323, 2022, doi: 10.1109/ACCESS.2022.3229588.

[19] A. A. Budalal, and M. R. Islam, "Path loss models for outdoor environment—with a focus on rain attenuation impact on short-range millimeter-wave links," e-Prime-Advances in Electrical Engineering, Electronics and Energy, vol. 3, p. 100106, 2023, doi: 10.1016/j.prime.2023.100106.

[20] M. M. Abdulwahid, O. A. S. Al-Ani, M. F. Mosleh, and R. A. Abd-Alhameed, "Investigation of millimeter-wave indoor propagation at different frequencies," in Proc. 4th Scientific International Conference Najaf (SICN), April 2019, pp. 25–30, doi: 10.1109/sicn47020.2019.9019358.

[21] H. Zhang, Y. Zhang, J. Cosmas, N. Jawad, W. Li, R. Muller, and T. Jiang, "mmWave indoor channel measurement campaign for 5G new radio indoor broadcasting," IEEE Transactions on Broadcasting, vol. 68, no. 2, pp. 331–344, 2022, doi: 10.1109/tbc.2021.3131864.

[22] A. Al-Saman, M. Cheffena, O. Elijah, Y. A. Al-Gumaei, S. K. Abdul Rahim, and T. Al-Hadhrami, "Survey of millimeter-wave propagation measurements and models in indoor environments," Electronics, vol. 10, no. 14, p. 1653, 2021, doi: 10.3390/electronics10141653.

[23] T. Nahar, and S. Rawat, "A review of design consideration, challenges and technologies used in 5G antennas," Wireless Personal Communications, vol. 129, no. 3, pp. 1585–1621, 2023, doi: 10.1007/s11277-023-10193-x.

[24] K. Kumar, R. Pandey, M. L. N. S. Karthik, S. S. Bhattacharje, and N. V. George, "Robust and sparsity-aware adaptive filters: A review," Signal Processing, vol. 189, p. 108276, 2021, doi: 10.1016/j.sigpro.2021.108276.

[25] U. Easwaran, and V. Krishnaveni, "Analysis of phase noise issues in millimeter wave systems for 5G communications," Wireless Personal Communications, vol. 126, no. 2, pp. 1601–1619, 2022, doi: 10.1007/s11277-022-09810-y.

[26] G. C. Chung, M. Y. Alias, and J. J. Tiang, "Bit-error-rate optimization for CDMA ultra-wideband system using Generalized Gaussian approach," International Journal of Electrical and Computer Engineering, vol. 7, no. 5, p. 2661, 2017, doi: 10.11591/ijece.v7i5.pp2661-2673.

[27] T. Zheng, L. Jing, C. Long, C. He, and H. Yin, "Frequency domain direct adaptive turbo equalization based on block normalized minimum-SER for underwater acoustic communications," Applied Acoustics, vol. 205, p. 109266, 2023, doi: 10.1016/j.apacoust.2023.109266.

[28] A. Bani-Bakr, M. N. Hindia, K. Dimyati, Z. B. Zawawi, and T. F. T. M. N. Izam, "Caching and multicasting for fog radio access networks," IEEE Access, vol. 10, pp. 1823–1838, 2021, doi: 10.1109/access.2021.3137148.

[29] G. R. MacCartney, and T. S. Rappaport, "Millimeter-wave base station diversity for 5G coordinated multipoint (CoMP) applications," IEEE Transactions on Wireless Communications, vol. 18, no. 7, pp. 3395–3410, 2019, doi: 10.1109/twc.2019.2913414.

[30] B. Sklar, and F. Harris, Digital communications: fundamentals and applications. Prentice Hall., 2020.