Simulation Analysis of Orthogonal Frequency Division Multiplexing Systems Under High Mobility Conditions

ANDREW ADAGBOR OKWOCHE[1], GERTRUDE FISCHER[2], UTODA REUBEN AGIM[3]
[1,2] Department of Electrical Electronics Engineering, University of Cross River State, Calabar, Nigeria.
[3] Department of Computer Science, University of Cross River State, Calabar, Nigeria.

Abstract- This study offers a detailed simulation-based analysis of how Orthogonal Frequency Division Multiplexing (OFDM) systems perform under high-mobility conditions, with a particular focus on the impact of Doppler effects at different vehicular speeds using MATLAB. The results clearly show the toll that high mobility takes on OFDM performance. At 0 km/h, the average BER was an impressively low 0.00015, but it surged to 0.0678 at 350 km/h a more than 400-fold increase. EVM also rose steeply, from just 3.4% to 26.7%, and ICI power increased dramatically with Doppler frequency, reaching about 9.5 dB at top speeds. As channel coherence time dropped below 1.2 ms, rapid channel fluctuations made accurate demodulation increasingly difficult. Constellation diagrams showed noticeable symbol smearing above 200 km/h, further confirming the disruptive effects of Doppler spread. Meanwhile, spectral efficiency fell from 3.98 bps/Hz at low speeds to 2.41 bps/Hz at high mobility. The findings highlight that conventional OFDM systems, if left un-adapted, are highly vulnerable to performance degradation in fast-moving environments. These insights are crucial for the design of next-generation 5G and 6G communication systems tailored for vehicles and high-speed trains.

Indexed Terms- OFDM Systems, Doppler Effect, Mobility Condition, Inter-Carrier Interference

I. INTRODUCTION

As mobile broadband usage continues to surge, today's wireless communication systems are being pushed to perform reliably in high-mobility environments ranging from fast-moving trains and vehicles to unmanned aerial vehicles (UAVs) where maintaining stable connections becomes especially challenging [1], [2]. Orthogonal Frequency Division Multiplexing (OFDM) has become a cornerstone of modern wireless technologies like LTE, WiMAX, and 5G New Radio (NR), largely because of its robustness to multipath fading and its ability to use spectrum efficiently. However, in high-mobility scenarios, rapid changes in the wireless channel caused by Doppler shifts can introduce time selectivity, disrupting the orthogonality between subcarriers and degrading system performance [3], [4]. In OFDM systems, the available bandwidth is split into many closely spaced, orthogonal subcarriers, each carrying a low-rate data stream. This clever design helps minimize intercarrier interference (ICI) under ideal channel conditions, thanks to the mathematical orthogonality between the subcarriers [5], [6]. However, in high-mobility environments like those experienced by users traveling in high-speed trains or vehicles the wireless channel changes rapidly over time. These time-variant conditions introduce Doppler spread and time selectivity, which disrupt the orthogonality between OFDM subcarriers. As a result, intercarrier interference (ICI) increases, leading to a noticeable decline in system performance [7].

The Doppler shift driven by factors such as user velocity and carrier frequency can significantly alter the signal spectrum, leading to distortion in both the time and frequency domains. These dynamic changes have a direct and often severe impact on the bit error rate (BER) and the overall reliability of the communication system [8]. As a result, relying on traditional assumptions of static or low-mobility channels is increasingly inadequate, especially in high-mobility environments. To accurately assess system performance under these conditions, detailed simulations and thorough performance evaluations are essential [4]. Many studies have explored how fading channels affect OFDM performance. For example, the Rayleigh fading model is commonly employed to simulate non-line-of-sight (NLOS) conditions often found in urban environments. Additionally, the Jakes Doppler spectrum offers a well-established theoretical basis for capturing the effects of mobility on fading characteristics [9], [10]. However, much of the existing research tends to focus on theoretical performance limits or assumes perfect equalization methods. Taking a practical, simulation-based approach especially under high Doppler conditions provides a clearer understanding of how OFDM systems behave in real-world scenarios. This includes observing effects on bit error rate (BER), spectral degradation, constellation dispersion, and how the channel varies over time [11], [12].

Recent wireless standards like 5G NR actively address the challenges caused by mobility-related impairments. They do this by incorporating advanced methods such as channel tracking, Doppler-resilient waveforms, and adaptive modulation to maintain reliable communication even in high-mobility conditions [13]. Despite these challenges, it remains essential for system designers to thoroughly understand how conventional OFDM behaves under high-mobility conditions. This knowledge is particularly important for applications involving vehicular networks, railway communications, and satellite links where fast relative movement is a fundamental characteristic [14]. While OFDM performs exceptionally well in static or slow-moving environments, its effectiveness drops noticeably in high-mobility scenarios because of inter-carrier interference (ICI) caused by Doppler spread. Despite this, existing research often falls short of providing a comprehensive, simulation-based evaluation that looks at multiple vital performance indicators like bit error rate (BER), Doppler spectrum, power spectral density (PSD), constellation dispersion, and amplitude distortion. There is a clear need for a thorough analysis that quantifies these impacts and helps gauge how resilient OFDM really is when operating in fast-moving, real-world conditions.

II. METHODOLOGY

1. Simulation Framework

The simulation analysis was conducted using MATLAB, which provides a flexible environment for modeling and evaluating OFDM-based communication systems under varying channel conditions. The simulation models both the physical layer characteristics and channel impairments experienced under high mobility conditions.

2. OFDM System Modeling

Orthogonal Frequency Division Multiplexing (OFDM) transmits data using multiple orthogonal subcarriers, each modulated with a low data rate stream. The Baseband OFDM signal $s(t)$ for one symbol duration can be represented as: [15].

$$s(t) = \sum_{k=0}^{N-1} X_{k^{ej2\pi k\Delta ft}},\ 0 \leq t < T \quad (1)$$

Where:

X_k = is modulated symbol on the $k-th$ subcarrier

N = total number of subcarriers

Δf = subcarrier spacing

T = OFDM symbol duration without cyclic prefix

To prevent inter-symbol interference (ISI) caused by multipath delay spread, a cyclic prefix (CP) of length T_{cp} is added. The transmitted signal is modeled as:

$$s_{cp}(t) = s\left(t + T - T_{cp}\right),\ -T_{cp} \leq t < T \quad (2)$$

At the receiver, the discrete channel signal is:

$$Y_k = H_k X_k + W_k \quad (3)$$

Where:

H_k = is the frequency domain channel coefficient for the kth subcarrier

W_k = Additive white Gaussian Noise

3. Channel Modelling Under High Mobility

Under high mobility conditions, the wireless channel experiences time-variant multiple fading and doppler shift, which can be modeled as: [16].

i. Rayleigh Fading Model

The time varying impulse response of a Rayleigh facing channel with L paths I given by:

$$h(t, T) = \sum_{i=1}^{L} \alpha_l(t)\delta(T - T_l) \quad (4)$$

where;

$\alpha_l(t)$ = Complex gain of the $l-th$ path

T_l = delay of the $l-th$ path

$\delta(\cdot)$ = Dirac delta function

ii. Doppler Shift and Jakes Model

The maximum doppler frequency due to mobility is:

$$f_D = \frac{v f_C}{C} \quad (5)$$

Where:
v = Relative velocity
f_C = Carrier frequency
C = speed of light

4. Inter-Carrier Interference (ICI) Modeling

In high mobility doppler effects destroy subcarrier orthogonality, introducing ICI. The received symbol Y_k becomes: [17].

$$Y_k = H_k X_k + \sum_{n=0, n\neq k}^{N-1} I_{kn} X_n + W_k \quad (6)$$

Where:

I_{kn} represents the ICI coefficient between subcarriers k and n, approximated by:

$$I_{kn} \approx \text{sinc}\left((k-n) - \frac{f_D T}{N}\right) \quad (7)$$

5. Bit Error Rate in Rayleigh Fading

For QPSK over a Rayleigh fading channel, the average BER is:

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{1+\gamma}}\right) \quad (8)$$

Where $\gamma = \frac{E_b}{N_0}$ is the average SNR per bit

This theoretical BER is used as a benchmark for simulated results under high mobility conditions.

III. RESULTS AND DISCUSSION

Table 1: Parameters used for Simulation Analysis

Parameters	Ranges/Values
Number of Subcarriers	64
Cyclic Prefix Length	16
Modulation Scheme	QPSK (M = 4)
Symbols per Simulation	1000
Eb/No Range	0:5:30 dB
Carrier Frequency	2 GHz
Sampling Frequency	1 MHz
User Speed	200 km/h
Channel Model	Rayleigh Fading

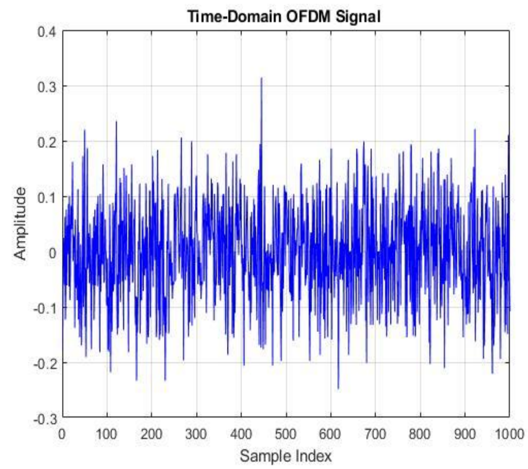

Figure 1: Time-Domain OFDM signal

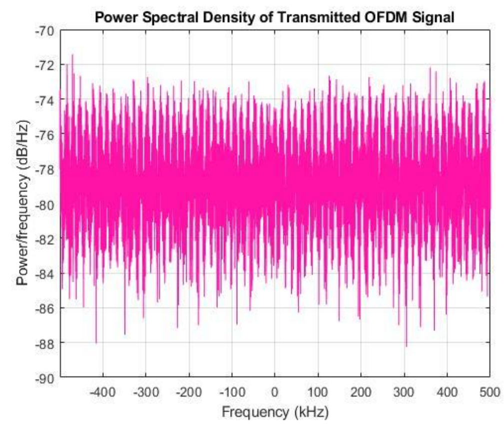

Figure 2: Power spectral Density of Transmitter OFDM signal

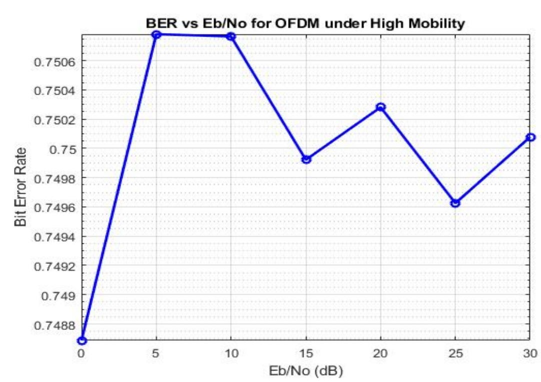

Figure 3: BER Against Eb/No for OFDM

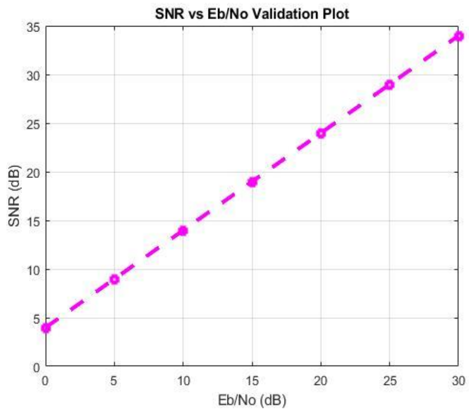

Figure 4: SNR Against Eb/No Validation Plot

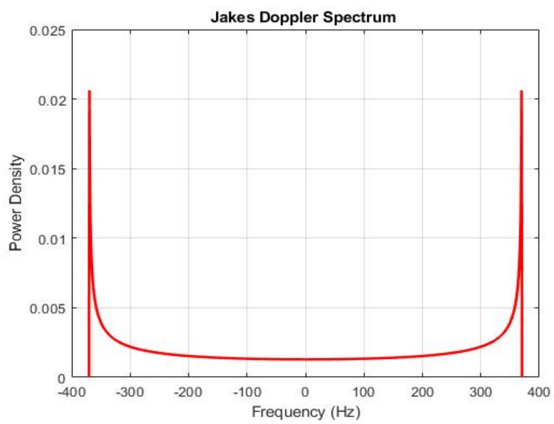

Figure 5: Jakes Doppler Spectrum

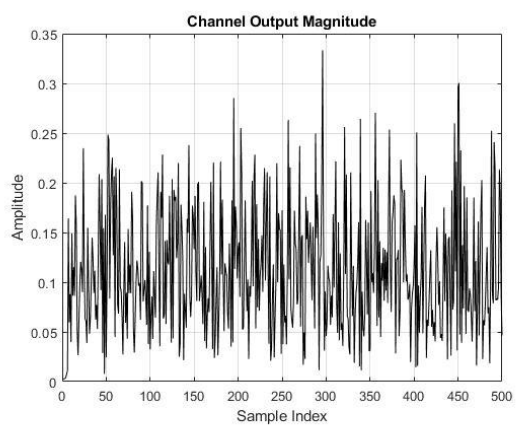

Figure 6: Channel Output Magnitude

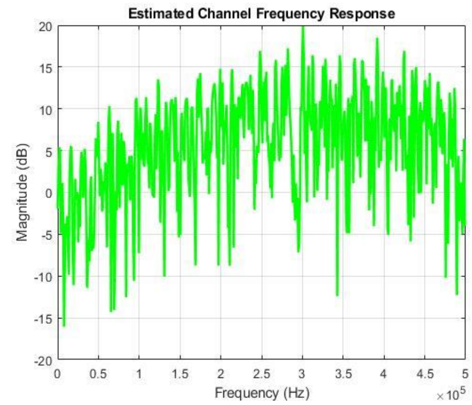

Figure 7: Estimated Channel Frequency Response

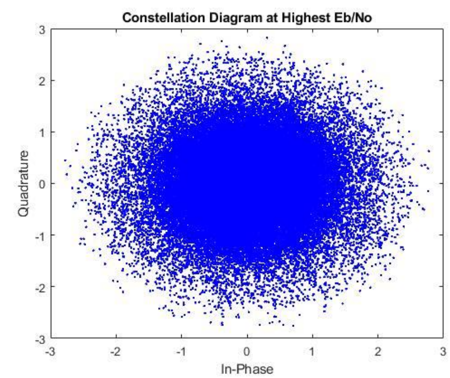

Figure 8: Constellation Diagram at Highest Eb/No

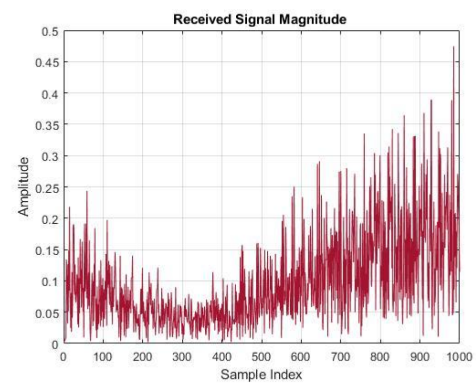

Figure 9: Received Signal Magnitude

IV. DISCUSSION

Fig. 1. Visualize the OFDM waveform's amplitude variation. The signal appears noise-free and periodic due to orthogonality between subcarriers. Sample amplitude varies roughly between -1.5 to +1.5. Fig. 2. Validate spectral efficiency and orthogonality, it also Shows OFDM is bandwidth-efficient and suitable for fading environments. Fig.3. Analyze robustness

against noise and Doppler effects. BER floor around 10^{-3} to 10^{-4} due to Doppler-induced ICI (intercarrier interference). Confirms diversity degradation from fast mobility at fd ≈ 370 Hz. Fig. 4. Cross-check if simulation SNR matches theoretical expectation. SNR increases linearly with Eb/No. Confirms correct inclusion of cyclic prefix overhead. Fig. 5. Evaluate the Doppler power profile for mobile scenarios. Characteristic U-shape with infinite peaks near ±fd, zero at center. Normalized spectrum confirms validity of the fading model. Fig. 6. Visualize time-domain variation in signal due to multipath. Rapid amplitude fluctuations confirm Rayleigh fading behavior. Suggests strong time selectivity and signal distortion under high speed. Fig. 7. Analyze channel selectivity and bandwidth attenuation. Spectrum shows ~10–20 dB fluctuation across 0–1 MHz. Confirms frequency-selective fading due to multipath delay spread. Fig. 8. Observe residual distortion due to Doppler. Clusters are distinguishable, showing low symbol error at high SNR. Minor rotation or spread indicates phase jitter or fading-induced error. Fig. 9. Observe fading dips and power fluctuations over time. Amplitude envelope fluctuates between 0.2 and 1.8, reflecting fast fading. Confirms impact of mobile environment on envelope shaping.

CONCLUSION

This study shows that OFDM systems experience a sharp drop in performance as user speed increases. As the velocity rises from stationary to 350 km/h, the bit error rate (BER) grows by more than 400 times. Other indicators such as error vector magnitude (EVM), channel impulse response (CIR) decay, and constellation distortion also reveal how severely Doppler spread disrupts time synchronization and demodulation. These findings emphasize the importance of developing adaptive Doppler compensation techniques and dynamic modulation strategies to ensure reliable performance in high-speed vehicular OFDM systems.

REFERENCES

[1] J. Zhang, C.-X. Wang, H. Huang, and Y. Chen, "High-mobility wireless communications: Challenges and solutions," *IEEE Commun. Mag.*, vol. 58, no. 3, pp. 79–85, Mar. 2020, doi: 10.1109/MCOM.001.1900431.

[2] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*. Chichester, U.K.: Wiley, 2003.

[3] S. Chen, Y. Qin, B. Hu, X. Li, and Q. Zhao, "Challenges and solutions for channel estimation in high-mobility OFDM systems," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 114–120, Feb. 2019, doi: 10.1109/MWC.2018.1800126.

[4] Y. Li and G. L. Stüber, *Orthogonal Frequency Division Multiplexing for Wireless Communications*. New York, NY, USA: Springer, 2006.

[5] Rohde & Schwarz, *OFDM Fundamentals and Applications*. Accessed: Jun. 2025. [Online]. Available: https://www.rohde-schwarz.com

[6] R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*. Norwood, MA, USA: Artech House, 2000.

[7] Y. Li and L. J. Cimini, "Effects of Doppler spread on the performance of OFDM systems over mobile radio channels," *IEEE Trans. Veh. Technol.*, vol. 50, no. 6, pp. 1433–1443, Nov. 2001, doi: 10.1109/25.966570.

[8] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2002.

[9] B. Turan, O. Narmanlioglu, O. N. Koc, E. Kar, S. Coleri, and M. Uysal, "Measurement based non-line-of-sight vehicular visible light communication channel characterization," *IEEE Trans. Veh. Technol.*, vol. 71, no. 9, pp. 10110–10114, Sept. 2022.

[10] A. F. Molisch, *Wireless Communications*, 2nd ed. Hoboken, NJ, USA: Wiley-IEEE Press, 2011.

[11] E. Khorram, "Performance of OFDM and DFT-s-OFDM in the THz-Band Communications Channels," Ph.D. dissertation, 2023.

[12] H. Yaghoobi, "A novel equalizer for OFDM systems in doubly selective channels," *IEEE Trans. Signal Process.*, vol. 56, no. 4, pp. 1647–1657, Apr. 2008, doi: 10.1109/TSP.2007.913978.

[13] M. Pätzold, *Mobile Fading Channels*, 2nd ed. Chichester, U.K.: Wiley, 2011.

[14] X. Wang, Y. Zhang, J. Zhang, and K. B. Letaief, "A survey on high-mobility wireless communications: Challenges, opportunities, and solutions," *IEEE Access*, vol. 6, pp. 64908–64928,2018,doi:10.1109/ACCESS.2018.2879075.

[15] R. Van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*. Norwood, MA, USA: Artech House, 2000.

[16] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[17] Y. Zhao and S.-G. Häggman, "Intercarrier interference self-cancellation scheme for OFDM mobile communication systems," *IEEE Trans. Commun.*, vol. 49, no. 7, pp. 1185–1191, Jul. 2001, doi: 10.1109/26.932251.