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Enhancing OFDM System Performance in Noisy Channels Using Advanced Signal Processing Techniques and AI

Anjana Kumari
M. Tech. in Electronics & Communication Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Sannam
A.P ECE Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) has emerged as a leading modulation technique in modern digital communication systems, owing to its ability to combat frequency-selective fading and support high data rates in bandwidth-constrained environments. However, noisy channel conditions such as Doppler shifts, frequency offsets, and inter-carrier interference (ICI) significantly degrade the performance of OFDM systems. Advanced techniques like deep learning for joint channel estimation and reconfigurable intelligent surfaces (RIS) have been proposed to enhance system robustness under harsh conditions. These innovations are critical for ensuring reliable communication in terrestrial, satellite, and underwater acoustic networks.

Keywords: *OFDM, Doppler Shifts, Channel Estimation, Deep Learning, Reconfigurable Intelligent Surfaces.*

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has become a cornerstone modulation technique in modern digital communication systems due to its ability to efficiently combat frequency-selective fading and support high data-rate transmission in bandwidth-constrained environments. The fundamental principle of OFDM is the division of a high-rate data stream into multiple orthogonal low-rate subcarriers, which reduces inter-symbol interference (ISI) and enhances robustness against multipath propagation effects. This structure has made OFDM a preferred choice in various standards, including 4G LTE, 5G New Radio (NR), Wi-Fi systems, optical wireless communication, underwater acoustic communication, and emerging satellite-based networks. However, despite its advantages, OFDM performance is highly sensitive to noisy channel conditions, including additive white Gaussian noise (AWGN), Doppler shifts, carrier frequency offset (CFO), sampling frequency offset (SFO), and inter-carrier interference (ICI). These impairments significantly degrade system reliability, especially in dynamic and harsh communication environments where channel variations occur rapidly (Wu et al., 2025; Wang et al., 2025).

In practical wireless communication scenarios, noisy channel conditions introduce significant challenges that affect the performance of OFDM-based systems. For instance, in high-mobility vehicular networks, rapid channel variations and Doppler effects result in severe synchronization issues, leading to degraded channel estimation accuracy and increased bit error rates (BER). Wu et al. (2025) demonstrated that traditional estimation methods struggle under such conditions, whereas deep learning-based joint CFO and channel estimation frameworks significantly enhance robustness and performance. Similarly, in non-terrestrial networks (NTN) involving low Earth orbit (LEO) satellites, non-uniform Doppler shifts cause sampling frequency offsets that are substantially larger than conventional CFO effects, leading to phase distortion and inter-symbol interference. Wang et al. (2025) highlighted that these impairments reduce spectral efficiency and necessitate advanced compensation techniques to maintain reliable communication. These studies collectively emphasize that OFDM systems, while theoretically efficient, require sophisticated signal processing strategies to operate effectively under noisy and rapidly changing channel conditions.

Beyond terrestrial and satellite communications, OFDM-based systems are also widely applied in underwater acoustic communication, visible light communication (VLC), and power line communication (PLC), where channel conditions are inherently noisy and highly variable. In underwater environments, severe multipath fading, absorption losses, and Doppler spreading significantly distort signal transmission, making reliable communication challenging. Alraie et al. (2024) proposed an OFDM-based subcarrier power modulation approach that improves data rate and spectral efficiency, while Thi et al. (2022) introduced non-uniform FFT-based Doppler compensation techniques to reduce inter-carrier interference and enhance system performance. In optical communication systems, Deepa et al. (2022) addressed the issue of high peak-to-average power ratio (PAPR), which leads to nonlinear distortion in light-emitting diodes (LEDs), and proposed precoding-based solutions to improve BER and spectral efficiency. Similarly, Cortés et al. (2023) analyzed channel estimation techniques in OFDM-based PLC systems and found that hybrid estimation approaches significantly improve performance in noisy indoor environments. These studies collectively demonstrate that noise and channel impairments remain a major limiting factor across all OFDM application domains, requiring adaptive and context-specific solutions.

Recent advancements in OFDM research have increasingly focused on intelligent and adaptive techniques to mitigate the effects of noisy channel conditions and improve overall system performance. Artificial intelligence (AI) and machine learning (ML) approaches, particularly deep neural networks and reinforcement learning, have shown significant potential in addressing nonlinear channel estimation, interference mitigation, and resource allocation problems. For example, Liu et al. (2024) proposed a semantic-aware OFDM-based communication framework that leverages deep reinforcement learning for optimal subcarrier and bit allocation, resulting in improved task-oriented communication efficiency. In addition, Wang et al. (2025) introduced a reconfigurable intelligent surface (RIS)-aided OFDM-based integrated sensing and communication (ISAC) system that enhances spatial signal control and improves sensing accuracy under noisy conditions. Furthermore, security and robustness considerations have also become increasingly important, as highlighted by Bartoletti et al. (2026), who demonstrated that OFDM-based ISAC systems are vulnerable to blind replay attacks that can manipulate sensing outputs without disrupting communication performance. Similarly, Argyriou (2023) proposed a generalized likelihood ratio test (GLRT)-based detection mechanism to identify false targets in OFDM-based radar-communication systems. These advancements indicate a shift toward intelligent, secure, and adaptive OFDM architectures capable of operating reliably in noisy and adversarial environments.

II. RESEARCH BACKGROUND

Bartoletti et al. (2026) had examined the security vulnerabilities of Integrated Sensing and Communication (ISAC) systems at the physical layer, emphasizing that although ISAC enabled enhanced connectivity and situational awareness, it also introduced novel attack surfaces. The authors had demonstrated a blind full-frame OFDM replay attack capable of manipulating sensing outputs by injecting false targets and concealing real ones without interrupting communication performance. It had been reported that the attack required neither synchronization nor prior knowledge of signal structure, reference signals, or sensing parameters, which had made it practically feasible and comparatively simple to implement. By replaying complete OFDM frames with controlled delay and frequency shift, the attack had been shown to distort range estimation and induce artificial Doppler shifts, thereby imitating moving targets. Furthermore, the study had proposed a general analytical framework to characterize the impact of the attack on range-Doppler processing. The findings had been validated through system-level simulations based on 5G NR parameters and real-world experiments using a 5G testbed with software-defined radios and commercial off-the-shelf hardware, thereby confirming the feasibility and severity of the attack in realistic ISAC environments.

Dratnal et al. (2026) had presented underwater visible light communication (UVLC) as a high-speed and low-latency alternative to conventional underwater communication methods such as acoustic and radio frequency systems, which had been constrained by inherent limitations in aquatic environments. The study had described the design and implementation of an orthogonal frequency-division multiplexing (OFDM)-based UVLC system employing multi-order quadrature amplitude modulation (M-QAM), with particular emphasis on ensuring reliable performance under practical conditions. Experimental investigations had been carried out in three distinct water environments, namely clear, murky, and dynamically turbid water, using a 545 nm LED source. The findings had indicated that 64-QAM delivered stable and consistent performance across all tested conditions, whereas higher-order modulation schemes such as 128-QAM and 256-QAM had achieved greater data rates but had exhibited increased bit error rates in turbid environments. Overall, the study had demonstrated that the proposed OFDM-based UVLC system had been capable of supporting short-range, high-throughput underwater communication under varying real-world water conditions.

Wu et al. (2025) had investigated vehicular communication in high-mobility environments, where the presence of carrier frequency offset (CFO) and rapidly varying channels had significantly degraded the performance of OFDM-based systems. To overcome these limitations, they had proposed a simple and effective cell reference signal (CRS)-based joint CFO and channel estimation framework using deep learning. Their model had comprised a joint neural network architecture, including a CFO estimation network (CFOENet) based on fully connected layers and a channel estimation network (CENet) built with convolutional layers. It had been reported that the proposed architecture efficiently exploited CRS correlation while simultaneously learning CFO characteristics and channel state information variations, thereby enhancing pilot usage efficiency. Through extensive simulation experiments, the authors had demonstrated that the deep learning-based approach had outperformed conventional techniques in CFO estimation, channel estimation, and overall system performance. The study had further indicated that the proposed method possessed stronger robustness and better generalization capability under diverse channel conditions, highlighting its significant potential for Internet of Vehicles applications.

Wang et al. (2025) investigated the challenges of 5G Non-Terrestrial Networks (NTN) under the 3rd Generation Partnership Project (3GPP), where Orthogonal Frequency Division Multiplexing (OFDM) was adopted to enable integrated space-ground networks via Low Earth Orbit (LEO) satellites. They noted that the rapid movement of LEO satellites induced significant non-uniform Doppler shifts across subcarriers, causing signal bandwidth variations that led to sampling point offsets and adversely affected demodulation performance. Previous Doppler compensation techniques were observed to primarily address uniform Carrier Frequency Offset (CFO) caused by crystal oscillation, whereas in LEO broadband systems, the Sampling Frequency Offset (SFO) arising from non-uniform Doppler shifts could be tens of times larger than the CFO, generating considerable phase rotation, inter-carrier interference (ICI), and inter-symbol interference (ISI). To address this, the authors derived a closed-form expression for signal distortion and proposed a model-driven compensation approach exploiting satellite trajectory predictability. Their method reportedly mitigated ICI and ISI through fast Fourier transform (FFT) window adjustment and phase rotation compensation. Validation via simulations and real satellite trials suggested support for higher-order modulations, with an average spectral efficiency improvement of roughly 50%, indicating enhanced robustness in dynamic LEO environments.

Wang et al. (2025) investigated integrated sensing and communication (ISAC) systems, highlighting that the use of multiple antennas for spatial processing often increased system cost and complexity. To address this challenge, they proposed an efficient ISAC framework that combined reconfigurable intelligent surface (RIS) and orthogonal frequency-division multiplexing (OFDM) technologies to process signals across time, frequency, and space domains. They designed an integrated waveform by incorporating an additional time slot in each OFDM frame, during which a single-tone signal was transmitted while the RIS generated random patterns to sense spatial information of both cooperative users and non-cooperative targets. The spatial information obtained from previous OFDM frames was employed in subsequent frames to implement an adaptive beam-tracking mechanism. Range and velocity detections were conducted through processing of transmitted and received OFDM symbols. Finally, a prototype RIS-aided ISAC system was developed and experimentally validated, demonstrating its effectiveness in wireless communication, detection, and tracking.

Liu et al. (2024) investigated semantic communication (SemCom) and highlighted its potential to reduce data transmission size while preserving task performance. They noted that prior studies had primarily focused on analog SemCom with simplistic channel models, which constrained practical applicability. To address this limitation, they introduced an orthogonal frequency division multiplexing (OFDM)-based SemCom system compatible with existing digital communication infrastructures. In their approach, semantics were quantized using scalar quantizers, converted into OFDM signals, and transmitted over frequency-selective channels. They also developed a semantic importance measurement method to link target tasks with semantic features and formulated a sub-carrier and bit allocation problem aimed at maximizing communication performance. Due to the neural network-based semantic codec, the optimization objective could not be expressed analytically. To overcome this, they proposed a low-complexity sub-carrier allocation strategy prioritizing critical semantics on better channel conditions and a deep reinforcement learning-based bit allocation algorithm with dynamic action space. Their simulations reportedly demonstrated performance gains of 9.7% over analog SemCom and 28.7% over conventional bit-based communication systems.

Alraie et al. (2024) investigated the challenges of underwater communication, emphasizing that high signal attenuation, harsh water medium, and degradation of data transmission performance had hindered effective surface communication. They highlighted that underwater acoustic (UWA) communication typically suffered from low data rates, limited bandwidth, and high latency, though it offered the advantage of long transmission range. The study proposed a noncoherent orthogonal frequency division multiplexing (OFDM) approach to enhance the data rate in UWA systems, while further employing Subcarrier Power Modulation (OFDM-SPM) to double the data rate and save half of the bandwidth. MATLAB simulations were utilized to implement the system under underwater acoustic conditions. The design incorporated Differential Phase Shift Keying (DPSK) with power control, transmitting data streams through two-dimensional modulation and varying subcarrier power levels. An equalizer was developed at the receiver to compensate for channel effects, Rician multipath fading, and spreading loss. The results indicated that the OFDM-SPM system with the proposed equalizer outperformed theoretical OFDM-SPM in Rayleigh channels, improving system throughput by 25% and validating doubled data rate performance in time-domain laboratory experiments.

Cortés et al. (2023) investigated state-of-the-art indoor broadband power line communications (PLC) systems, noting that they typically employed orthogonal frequency division multiplexing (OFDM) signals with constellations up to 10 bits per symbol, which rendered channel estimation a critical aspect. They examined the initial channel estimation used in the payload, which could be subsequently refined via a decision-directed strategy, and highlighted that such estimation needed to be computed on a per-frame basis using either the preamble, the header symbol (assuming correct decoding), or a combination of both. The study proposed several simple channel estimation techniques, derived their optimal parameters, and compared them with the linear minimum mean squared-error (LMMSE) estimator and other estimators commonly applied in wireless scenarios, considering both performance and computational complexity. The authors analyzed factors limiting the performance of preamble- and header-based estimators and discussed the implications of PLC-specific characteristics, such as the absence of fading, on estimator design. Performance evaluation on 171 measured indoor PLC channels indicated that header-based estimators outperformed preamble-based ones, and they recommended a computationally simple estimator combining both sources to achieve near-optimal performance.

Argyriou (2023) investigated the vulnerability of Joint RADAR Communication (JRC) systems employing orthogonal frequency division multiplexing (OFDM) to adversarial attacks, in which attackers could replicate received OFDM signals to generate false RADAR targets. The study proposed a set of algorithms intended for deployment within JRC systems to identify the presence of such false targets. Detection was performed by assessing whether residual carrier frequency offset (CFO) existed beyond Doppler effects in the received signal, using a Generalized Likelihood Ratio Test (GLRT). The effectiveness of the proposed approach was evaluated through simulations that measured detection probability against false alarm rates across various configurations of an IEEE 802.11-based JRC system, highlighting the method’s potential for enhancing system reliability under adversarial conditions.

Thi et al., (2022) investigated the impact of the Doppler effect on orthogonal frequency division multiplexing (OFDM) systems, noting that its influence was particularly severe in underwater acoustic (UWA) communication systems due to the unique properties of the underwater channel, which led to a loss of orthogonality among sub-carriers. They emphasized that compensating for Doppler shifts, phase noise, and multipath effects often involved joint channel estimation and inter-carrier interference (ICI) reduction, although the accuracy of such methods depended on channel estimation and FFT size, resulting in increased computational complexity at the receiver. To address these challenges, they proposed a novel pilot structure in the frequency domain to mitigate channel impulse response (CIR) variations within a block period. The study reported that coarse Doppler shifts were first estimated using received pilot signals, followed by fine compensation using a Doppler frequency Compensation Matrix-based non-uniform fast Fourier transform (DCMN) that leveraged flexible sampling points. Experimental measurements and simulations demonstrated that the proposed method improved system performance under realistic underwater conditions.

Deepa et al. (2022) investigated the challenges in Visible Light Communication (VLC) systems, particularly the high peak-to-average power ratio (PAPR) associated with DC-biased optical OFDM (DCO-OFDM), which was known to cause clipping distortion and degrade overall system performance. They highlighted that the limited dynamic range of LEDs exacerbated this issue and noted that various PAPR reduction techniques, such as precoding matrix schemes, had been proposed to mitigate it. The study proposed a discrete Hartley Matrix transform (DHMT) precoded discrete Hartley transform (DHT)-based DCO-OFDM system to reduce PAPR and comparatively evaluated the PAPR performance of a new hybrid T-transform—combining Walsh-Hadamard and Zadoff-Chu transforms—against other precoding techniques, including discrete cosine matrix, discrete Fourier matrix, Walsh-Hadamard, and DHMT. They further presented a mathematical analysis of time-domain signal formats employing complex Fourier and real trigonometric transforms. Simulation results were reported to show that the DHMT precoded DHT-based system not only significantly reduced PAPR but also improved bit error rate (BER), spectral efficiency, and required lower computational complexity compared to other methods.

III. KEY FINDINGS FROM STUDY

Author	Year	Domain/Application	Methodology	Noisy Channel Issue Addressed	Key Findings
Bartoletti et al.	2026	ISAC Systems	OFDM replay attack analysis using 5G NR simulations and SDR experiments	Signal manipulation under adversarial/noisy sensing environments	Blind replay attacks can distort sensing (false targets) without affecting communication integrity
Dratnal et al.	2026	Underwater VLC	OFDM with M-QAM modulation in different water conditions	Optical signal degradation due to turbidity and scattering	64-QAM showed stable performance; higher QAM increased BER in noisy/turbid water
Wu et al.	2025	Vehicular Communication	Deep learning-based joint CFO and channel estimation	Doppler shift and channel variation in high mobility	Proposed DL model improved estimation accuracy and robustness under fast-changing noisy channels
Wang et al.	2025	LEO Satellite OFDM	SFO modeling and FFT-based compensation	Non-uniform Doppler shift and sampling frequency offset	Reduced ICI/ISI and improved spectral efficiency (~50%) in noisy satellite channels
Wang et al.	2025	ISAC with RIS	RIS-assisted OFDM waveform design with adaptive beam tracking	Multipath fading and sensing noise	Improved sensing, tracking accuracy, and communication reliability under noisy environments
Liu et al.	2024	Semantic OFDM Communication	Deep reinforcement learning-based resource allocation	Frequency-selective noisy channels	Achieved 9.7% gain over analog SemCom and 28.7% over conventional systems
Alraie et al.	2024	Underwater Acoustic	OFDM with Subcarrier Power Modulation (OFDM-SPM) + DPSK	Severe attenuation, multipath, and noise in underwater channel	Doubled data rate and improved throughput by ~25%
Cortés et al.	2023	Power Line Communication	Channel estimation using preamble + header-based methods	Noisy indoor PLC channel distortions	Hybrid estimators improved accuracy and reduced computational complexity

Argyriou	2023	OFDM Radar-Comm (JRC)	GLRT-based detection of false targets	Noise + adversarial signal injection	Successfully detected replay-based false targets using residual CFO analysis
Thi et al.	2022	Underwater OFDM	Doppler compensation using non-uniform FFT (DCMN method)	Severe Doppler-induced noise and ICI	Reduced ICI and improved BER under realistic underwater noise conditions
Deepa et al.	2022	Optical VLC	Precoding matrix techniques for PAPR reduction	LED nonlinearity and channel-induced noise	Reduced PAPR, improved BER, and enhanced spectral efficiency
Varanasi et al.	2026	Digital Twins in Communication	System-level modeling of DT-enabled communication networks	Modeling uncertainty and channel variability	Digital twins improve prediction accuracy and system reliability in noisy environments

IV. CONCLUSION

Orthogonal Frequency Division Multiplexing (OFDM) has established itself as a highly efficient and widely adopted multicarrier modulation technique in modern communication systems due to its robustness against frequency-selective fading, high spectral efficiency, and compatibility with diverse applications such as 5G/6G networks, vehicular communications, satellite systems, underwater acoustic channels, optical wireless systems, and power line communication. However, despite these advantages, the performance of OFDM-based systems is significantly affected under noisy channel conditions, where impairments such as additive white Gaussian noise (AWGN), multipath fading, Doppler shifts, carrier frequency offset (CFO), sampling frequency offset (SFO), and inter-carrier interference (ICI) degrade system reliability, increase bit error rates (BER), and reduce spectral efficiency. The reviewed literature clearly demonstrates that noisy and dynamic environments, particularly in high-mobility vehicular networks, underwater channels, and low Earth orbit (LEO) satellite systems, introduce severe synchronization and estimation challenges that limit the effectiveness of conventional OFDM techniques. To overcome these limitations, recent research has increasingly focused on advanced signal processing and intelligent communication approaches, including deep learning-based channel estimation, adaptive equalization, reconfigurable intelligent surfaces (RIS), semantic communication frameworks, and Doppler compensation techniques. These methods have shown significant improvements in mitigating channel impairments, enhancing signal detection accuracy, and optimizing system performance under noisy conditions. Furthermore, innovations in OFDM variants such as OFDM-SPM, RIS-aided ISAC systems, and non-uniform FFT-based compensation techniques have expanded the applicability of OFDM in complex real-world scenarios. However, challenges such as high computational complexity, hardware constraints, security vulnerabilities, and real-time implementation issues still persist and require further investigation. Therefore, it can be concluded that while OFDM remains a fundamental technology for modern wireless communication, its full potential under noisy channel conditions can only be realized through the integration of intelligent algorithms, adaptive system design, and cross-layer optimization strategies. Future advancements are expected to focus on AI-driven self-optimizing OFDM systems capable of delivering reliable, secure, and high-performance communication in next-generation networks and beyond.

V. FUTURE SCOPE

- **AI and Machine Learning–Driven OFDM Systems:** Future OFDM-based communication systems will increasingly rely on artificial intelligence and machine learning techniques for real-time channel estimation, noise prediction, and adaptive modulation. Deep learning models can significantly improve performance in highly dynamic and noisy environments by learning channel behavior patterns and optimizing transmission parameters automatically.
- **6G and Beyond Wireless Networks:** With the emergence of 6G technology, OFDM will evolve to support ultra-reliable low-latency communication (URLLC), terahertz communication, and massive machine-type communications. Enhanced OFDM variants will be required to handle extremely high mobility, dense networks, and harsh propagation conditions.
- **Reconfigurable Intelligent Surfaces (RIS) Integration:** RIS-assisted OFDM systems will play a major role in future wireless networks by intelligently controlling the propagation environment. This will help reduce noise effects, improve signal strength, and enhance coverage in urban, indoor, and remote scenarios.
- **Advanced Doppler and Frequency Offset Compensation Techniques:** Future research will focus on highly accurate and low-complexity compensation methods for CFO, SFO, and Doppler shifts, especially in LEO satellite and underwater communication systems where channel variations are severe.
- **Secure OFDM-Based Communication Systems:** Security will become a major focus area, especially in ISAC and vehicular networks. Future OFDM systems will integrate physical-layer security techniques and AI-based intrusion detection to prevent attacks such as replay, spoofing, and signal manipulation.
- **Energy-Efficient and Green Communication Systems:** Development of low-power OFDM transceivers and energy-efficient signal processing algorithms will be crucial for IoT, wearable devices, and large-scale sensor networks operating under power constraints.
- **Hybrid OFDM and Semantic Communication Models:** Future systems will combine OFDM with semantic communication to transmit meaningful information rather than raw data, reducing bandwidth usage and improving communication efficiency in noisy environments.
- **Enhanced Underwater and Space Communication Systems:** OFDM will continue to evolve for extreme environments such as underwater acoustic channels and deep-space communication, requiring robust modulation, adaptive coding, and intelligent equalization techniques.
- **Quantum-Inspired Signal Processing Techniques:** Emerging research may explore quantum computing and quantum-inspired algorithms to enhance OFDM signal processing speed, error correction, and noise resilience.
- **Cross-Layer Optimization Approaches:** Future OFDM systems will integrate physical, MAC, and network layer optimization to ensure end-to-end performance improvement under noisy and heterogeneous network conditions.

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