Comparative Analysis of OFDM Characteristics Across 5G NR, Wi-Fi 6 and DVB-T2

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Abstract. Orthogonal Frequency Division Multiplexing (OFDM) serves as the backbone of modern wireless systems, including 5G NR, Wi-Fi 6, and DVB-T2, due to its robustness against multipath interference and high spectral efficiency. This paper presents a comparative analysis of OFDM's adaptive implementations across these three standards, focusing on their unique optimizations for spectral efficiency, multipath resistance, and power efficiency. In 5G NR, dynamic numerology (15–120 kHz SCS) and massive Multiple Input Multiple Output (MIMO) enhance mobility and capacity, while Wi-Fi 6 leverages OFDMA and 1024-QAM for dense indoor deployments. Digital video broadcasting (DVB-T2) prioritizes reliability through long symbol durations (448 μs) and tone reservation for broadcast resilience. Despite its advantages, OFDM faces persistent challenges such as high peak-to-average power ratio (PAPR), synchronization sensitivity, and hardware complexity. Emerging solutions like AI-driven PAPR reduction and integrated sensing-communication (ISAC) systems are explored as future directions. The study underscores OFDM's critical role in current and next-generation networks, emphasizing the need for innovative approaches to address its limitations while harnessing its adaptability for 6G and IoT applications.

INTRODUCTION

OFDM has emerged as a cornerstone of modern digital communication systems due to its robustness against multipath interference and high spectral efficiency. Originally proposed in the 1960s, OFDM gained prominence with the advent of fast Fourier transform (FFT)-based implementations and cyclic prefix (CP) techniques [1-3]. Today, it underpins key wireless standards, including 5G New Radio (NR), Wi-Fi 6 (802.11ax), and DVB-T2. The technology's ability to convert wideband frequency-selective channels into parallel narrowband subchannels has made it indispensable for high-speed data transmission. However, challenges such as peak-to-average power ratio (PAPR), synchronization, and inter-carrier interference (ICI) persist, driving ongoing research into advanced OFDM variants.

This paper provides a comprehensive analysis of OFDM's principles, implementation, and applications across three major communication scenarios: 5G NR (mobile networks), Wi-Fi 6 (indoor high-density networks), and DVB-T2 (broadcast systems). First, we examine the mathematical foundations of OFDM, including time-domain signal representation, orthogonality conditions, and DFT/IDFT implementation. Next, we explore how OFDM's key features—spectral efficiency, multipath resistance, and power efficiency—are optimized differently in each scenario. For instance, 5G NR employs dynamic numerology to adapt subcarrier spacing, while Wi-Fi 6 leverages OFDMA for dense user environments. DVB-T2, on the other hand, prioritizes long symbol durations for robust broadcast coverage. Finally, this paper discusses current challenges (e.g., PAPR, synchronization, and hardware complexity) and future research directions, such as AI-driven OFDM optimization and integrated sensing-communication systems.

This study highlights OFDM's critical role in modern communications, offering insights into its adaptive implementations and future evolution. Understanding these principles is essential for engineers and researchers working on next-generation wireless systems.

THE PRINCIPLES OF OFDM

Definitions of OFDM

OFDM is a multi-carrier modulation technique that enhances spectral efficiency by transmitting data through multiple orthogonal subcarriers.

The fundamental principle relies on maintaining orthogonality through precise frequency spacing $\Delta f = \frac{1}{T_{sym}}$, as established by Chang. The transmitter converts serial data into parallel streams, modulates each subcarrier using schemes such as QAM, and transforms the signals into the time domain via IFFT [4]. To combat multipath effects, a cyclic prefix is appended to each symbol (Peled & Ruiz, 1980). The receiver performs inverse operations, including CP removal and FFT-based demodulation [5]. OFDM's key strengths include inherent resistance to frequency-selective fading and efficient spectrum utilization through overlapping yet orthogonal subcarriers [6]. This combination of features makes OFDM particularly suitable for high-speed wireless communications, as evidenced by its widespread adoption in modern standards like LTE and 5G NR. The technique's robustness stems from its ability to convert wideband frequency-selective channels into multiple flat-fading narrowband subchannels, significantly simplifying equalization requirements while maintaining high data rates.

Basic math representations

Time-domain OFDM signal representation

The time-domain OFDM representation is shown in equation (1)

$$x(t)=\sum_{k=0}^{N-1} X_k \cdot e^{j2\pi f_k t},\ 0 \le t \le T_{sym} \quad (1)$$

In equation (1), x(t) is the Time-domain signal of the OFDM symbol. And it is a baseband representation; X_k is a modulation symbol which transmitted on the kth subcarrier, for example, the signal of QAM or PSK; f_k is the k-th frequency of the subcarrier and as the interval of the subcarrier; N is the total counting of subcarrier; t is the duration of OFDM signal, which excluded the CP prefix.

Relation between critical arguments

The relation representation is shown in equation (2)

$$\Delta f = \frac{1}{T_{sym}} \quad (2)$$

In equation (2), the frequency of the signal is represented as Δf, and the subcarrier interval to be T_{sym}. Moreover, the interval is the inverse of the duration t to ensure the orthogonality, namely, the inner product is equal to zero. Orthogonality allows subcarrier spectra to overlap but not interfere with each other.

The implementation of DFT

The implementation of DFT representation is shown in equation (3)

$$x[n] = \sum_{k=0}^{N-1} X_k \cdot e^{j\frac{2\pi kn}{N}}, n = 0,1, \dots, N-1 \quad (3)$$

In equation (3), X[n] is the IFFT output, and X_k is the IFFT output. N is an integer to indicate the length of the DFT. X_k is a complex number, namely, a frequency-domain coefficient. K is an index to represent the frequency components of the DFT. N is an index to represent the time-domain samples of the signal x[n].

Key feature analysis

OFDM demonstrates remarkable adaptability across three major communication scenarios, 5G mobile networks (NR), Wi-Fi 6 (802.11ax), and DVB-T2 broadcasting, through three fundamental characteristics: spectral efficiency, multipath resistance, and power efficiency. Each scenario optimizes these features differently to address specific operational requirements.

Firstly, about the spectral Efficiency Optimization. In 5G NR, dynamic numerology enables flexible subcarrier spacing (15-120 kHz), improving spectral efficiency by 18-22% over LTE through adaptive matching to channel conditions [7]. Then Wi-Fi 6 achieves high-density connectivity via OFDMA's resource unit allocation and 1024-QAM modulation, quadrupling capacity in indoor environments but requiring SNR >35 dB [8]. DVB-T2 employs fixed 16k/32k FFT modes with static pilots (6-7% overhead) to ensure reliable broadcast coverage at the cost of reduced flexibility [9].

Then another feature is the multipath Resistance Mechanisms. 5G NR utilizes configurable cyclic prefixes (4.7-33.3 μs) and massive MIMO beamforming to combat urban interference while supporting 500 km/h mobility [10]. Wi-Fi 6 relies on fixed CP durations (0.8-3.2 μs) combined with MU-MIMO beam tracking to maintain 75% lower packet errors in crowded indoor spaces [11]. DVB-T2's long symbols (448 μs) and 250 ms interleaving provide exceptional resilience against 280 μs echoes in terrestrial broadcast environments [12].

And the Power Efficiency Solutions. For power efficiency, 5G NR adopts DFT-s-OFDM for 3-4 dB PAPR reduction in uplink, while accepting 15-20% higher power draw from massive MIMO processing [13]. Wi-Fi 6 prioritizes client-side efficiency through Target Wake Time, cutting IoT device energy by 73% via scheduled sleep intervals [14]. DVB-T2's tone reservation enables 10 kW transmitters to operate with just 2 dB backoff through intelligent subcarrier reservation, achieving >70% PA efficiency [15].

OFDM IMPLEMENTATION ACROSS DIVERSE COMMUNICATION SCENARIOS

Mobile Communication Scenario: 5G NR

In the respect of the Dynamic Numerology and Spectral Efficiency. In 5G New Radio (NR), OFDM serves as the foundational waveform, optimized through dynamic numerology to address the heterogeneous demands of mobile networks. The 3GPP TS 38.211 standard (2021) defines a flexible framework where subcarrier spacing (SCS) can be dynamically adjusted between 15 kHz, 30 kHz, 60 kHz, and 120 kHz, enabling tailored performance for different frequency bands and use cases [7]. For example, 30 kHz SCS in sub-6 GHz bands balances coverage and capacity, while 120 kHz SCS in millimeter-wave (mmWave) bands mitigates phase noise and supports shorter symbol durations for low-latency applications.

Andrews et al. in IEEE Communications Magazine validate that 5G's dynamic SCS improves spectral efficiency by 18–22% over LTE's static configurations, achieved by matching subcarrier spacing to channel density (e.g., urban vs. rural) [16]. This adaptability allows 5G to pack more data in dense urban environments using smaller SCS while reducing overhead in rural areas. However, dynamic numerology introduces 15–20% signaling overhead for transmitting parameter sets, as noted in 3GPP specifications.

Then, in the feature of the multipath Resistance and High Mobility. 5G NR employs configurable cyclic prefix (CP) lengths ,from 4.7 to 33.3 μs to combat multipath fading, with longer CPs (e.g., 33.3 μs for 15 kHz SCS) suitable for urban environments with delay spreads up to 33 μs. Björnson et al. in IEEE Transactions on Wireless Communications demonstrate that massive MIMO, ranging from 64 to 256 antennas, suppresses interference via spatial filtering, reducing error rates by 90% in factory automation scenarios with complex multipath [10].

However, high-mobility scenarios (e.g., 500 km/h) require advanced Doppler compensation. The 3GPP TR 38.824 report highlights adaptive equalization techniques to mitigate frequency shifts, though they increase baseband complexity by 20–30% [17].

Finally, the Power Efficiency and Implementation Trade-offs. Power efficiency in 5G NR is optimized through DFT-s-OFDM for uplink transmissions, which reduces peak-to-average power ratio (PAPR) by 3–4 dB compared to CP-OFDM, extending UE battery life. Zhang et al. in IEEE Journal on Selected Areas in Communications show that adaptive power amplifier (PA) backoff (2–6 dB) and active antenna units (AAUs) with >50% PA efficiency minimize base station energy consumption during high-throughput tasks [18].

Yet, UE power management remains challenging: massive MIMO processing increases power draw by 15–20%. Wang in IEEE Transactions on Wireless Communications emphasizes that while DFT-s-OFDM improves uplink efficiency, downlink CP-OFDM with 256-QAM requires PAPR mitigation to avoid PA saturation [19].

Indoor High-Density Scenario: Wi-Fi 6 (IEEE 802.11ax)

Firstly, OFDMA and Spectral Efficiency in Dense Networks. Wi-Fi 6 revolutionizes indoor wireless through Orthogonal Frequency Division Multiple Access (OFDMA), which partitions 20/40/80 MHz channels into smaller Resource Units (RUs). The IEEE 802.11ax-2021 standard specifies dynamic RU allocation, enabling a 20 MHz channel to support nine 26-tone RUs for parallel transmissions [20]. Khorov et al. in IEEE Transactions on Communications validate a 4× capacity increase in dense offices compared to 802.11ac [8].

Higher spectral efficiency is further enabled by 1024-QAM modulation, which boosts peak rates by 25% but requires SNR >35 dB. Zhang et al. in IEEE Wireless Communications show that 1024-QAM operates reliably within 5 meters in clutter-free environments but degrades rapidly beyond due to path loss [21].

Wi-Fi 6 employs fixed CP durations (0.8 μs short CP, 3.2 μs long CP) tailored to indoor delay spreads (<0.3 μs RMS). Wang et al. in IEEE Transactions on Vehicular Technology demonstrate that 8×8 MU-MIMO beam tracking reduces packet errors by 75% in crowded spaces by dynamically rerouting signals around obstacles. However, performance drops beyond 5 meters due to co-channel interference [22].

Power Efficiency for IoT Devices. The Target Wake Time (TWT) mechanism reduces IoT device energy consumption by 73%, as shown by Kosek-Szott et al. in IEEE Access [14]. Broadcast TWT modes balance 65% energy savings with sub-10 ms latency for 95% of packets, benefiting battery-powered sensors. While client PAs have lower efficiency (30–40%), TWT's scheduled sleep intervals compensate for limited battery capacity.

Broadcast Transmission Scenario: DVB-T2

Static Numerology and Robust Channel Estimation. DVB-T2 prioritizes reliability through fixed OFDM numerology (16k/32k FFT) and static pilot patterns (8% of subcarriers). ETSI EN 302 755 specifies scattered pilots (1/12 active carriers) for channel estimation, ensuring reception at C/N ≥10 dB in fading channels [9]. Alagha et al. (2014) in EURASIP Journal on Wireless Communications note that while this design simplifies receivers, its 6–7% pilot overhead limits spectral efficiency compared to adaptive systems [23].

Multipath Resilience and Interleaving. DVB-T2's long symbol duration (448 μs for 16k FFT) and 1/16 CP tolerate echo delays up to 280 μs, outperforming DVB-T by 5–7 dB in multipath environments, as shown by Zhang et al. in IEEE Transactions on Broadcasting [24]. Two-layer time interleaving (250 ms) further mitigates impulse noise, though it introduces 150–200 ms channel switching delays.

Tone reservation (TR) reduces PAPR by 4–5 dB for 10 kW transmitters, enabling 2 dB output backoff versus DVB-T's 6–8 dB. Chen et al. in IEEE Transactions on Broadcasting demonstrate that reserving 1% of subcarriers for peak cancellation achieves this with <5% computational overhead [25]. High-efficiency PAs (>70%) further optimize power usage, though subcarrier reservation slightly reduces capacity.

CHALLENGES AND FUTURE PERSPECTIVES

Despite its widespread adoption in modern communication systems, OFDM technology still faces several critical challenges that hinder its optimal performance. One of the most significant issues is the high peak-to-average power ratio (PAPR), which forces power amplifiers to operate inefficiently with large back-offs, particularly in high-bandwidth applications like 5G and Wi-Fi 6. This not only increases energy consumption but also raises hardware costs. Additionally, OFDM systems are highly sensitive to synchronization errors, where even minor carrier frequency offsets (CFO) or timing misalignments can severely degrade signal quality, especially in high-mobility environments. The Doppler effect further exacerbates these problems by introducing ICI, which disrupts the orthogonality between subcarriers and reduces system reliability.

Looking ahead, the future of OFDM lies in addressing these limitations while exploring new opportunities for enhancement. Advanced signal processing techniques, such as machine learning-based PAPR reduction and AI-driven synchronization algorithms, show great promise in mitigating current drawbacks. The integration of OFDM with emerging technologies like integrated sensing and communication (ISAC) could unlock new applications in 6G networks, enabling ultra-reliable low-latency communications combined with high-precision sensing capabilities. Furthermore, the development of energy-efficient OFDM variants, such as those utilizing approximate computing or hybrid waveform designs, could make the technology more sustainable for next-generation IoT and mobile devices. As wireless systems continue to evolve, OFDM's adaptability and proven performance ensure its continued relevance, provided these challenges are met with innovative solutions.

CONCLUSION

This paper has provided a comprehensive examination of OFDM technology, from its fundamental principles to its diverse implementations in 5G NR, Wi-Fi 6, and DVB-T2 systems. The analysis underscores OFDM's unparalleled ability to balance spectral efficiency, multipath resistance, and adaptability across different communication scenarios. However, the discussion also highlights persistent challenges, including PAPR, synchronization sensitivity, and energy consumption, which must be addressed to fully realize OFDM's potential in future wireless systems.

The insights presented here emphasize that OFDM remains a cornerstone of modern communications, but its continued success depends on overcoming existing limitations through innovation. Researchers and engineers must focus on developing advanced techniques—such as AI-enhanced signal processing, hybrid waveforms, and energy-efficient architectures—to ensure OFDM can meet the demands of emerging technologies like 6G and IoT. By building on its strengths while addressing its weaknesses, OFDM will remain a vital enabler of high-speed, reliable, and scalable wireless communication in the years to come.

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