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COMPARATIVE PERFORMANCE EVALUATION OF 5G WAVEFORM CANDIDATES UNDER REALISTIC CHANNEL CONDITIONS

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Abstract: *The development of 5G wireless networks necessitates the adoption of advanced waveform techniques that meet stringent performance requirements in terms of spectral efficiency, robustness, and power optimization. This paper presents a comparative performance evaluation of several prominent waveform candidates for 5G systems, including Orthogonal Frequency Division Multiplexing (OFDM), Filtered-OFDM (F-OFDM), Filter Bank Multicarrier (FBMC), Universal Filtered Multicarrier (UFMC), and Weighted Overlap and Add (WOLA). The assessment is based on key performance indicators (KPIs) such as Peak-to-Average Power Ratio (PAPR), Power Spectral Density (PSD), Bit Error Rate (BER), and throughput. Simulation results under various channel conditions demonstrate that FBMC offers superior spectral efficiency and throughput, particularly in uncoded scenarios, while WOLA and F-OFDM exhibit notable improvements in sidelobe suppression and BER under channel coding. The findings highlight the trade-offs between complexity, performance, and implementation feasibility, supporting the selection of optimized waveforms for diverse 5G use cases.*

Keywords: *Waveform, 5G, OFDM, F-OFDM, FBMC, UFMC, WOLA, KPI*

1. INTRODUCTION

The evolution of wireless communication has been marked by continuous advancements in data rate, capacity, and spectral efficiency, driven by changing user needs and technological innovation. With each generation, from 2G to 4G, mobile systems have grown more complex, enabling increasingly diverse applications. Now, with the emergence of the fifth generation (5G), the focus has shifted toward enabling enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC), thereby laying the foundation for a vast IoT ecosystem connecting billions of devices [1].

To meet these ambitious requirements, 5G networks must be highly efficient, robust, and flexible. One of the critical components of this evolution is the choice of waveform modulation techniques, which influence the system's performance in terms of interference management, spectral efficiency, and energy consumption [2]. Multi-carrier modulation schemes have proven effective in handling both intra-cell and inter-cell interference, optimizing spectral use, and reducing transmission delays. In addition, they offer enhanced energy efficiency by enabling adaptive power control based on channel conditions.

Among these, Orthogonal Frequency Division Multiplexing (OFDM) was the core waveform in 4G systems due to its robustness and ease of implementation via the Fast Fourier Transform (FFT). Despite its strengths, OFDM suffers from high Peak-to-Average Power Ratio (PAPR) and significant out-of-band emissions, which limit its ability to fulfill the stringent requirements of 5G networks [3].

As a result, several alternative waveform techniques have been proposed for 5G, including Filtered-OFDM (F-OFDM), Universal Filtered Multicarrier (UFMC), Filter Bank Multicarrier (FBMC), and windowing-based methods like Weighted Overlap and Add (WOLA). Each of these candidates has been investigated in terms of their respective advantages, limitations, and performance characteristics. For example, FBMC has shown significantly lower sidelobe emissions and reduced intercarrier interference compared to OFDM, making it a promising alternative [4]. However, despite its potential, FBMC remains an area of active research and development [5].

Recent research has further enriched the discussion on multicarrier waveform design. Debnath *et al.* [6] provided a detailed comparison of OFDM, FBMC, and UFMC in terms of BER and PAPR, highlighting the trade-offs in 5G environments. Yahya *et al.* [7] extended this line of work by proposing hybrid FBMC/UFMC designs tailored for 6G wireless networks, demonstrating improved coexistence and flexibility. At the same time, Akbar *et al.* [8] discussed broader challenges for sixth-generation (6G) systems, underlining the need for new waveform paradigms that balance spectral efficiency, robustness, and implementation complexity. These studies emphasize that waveform selection will remain a central issue as networks evolve from 5G to 6G.

This paper aims to evaluate and compare these waveform candidates based on critical performance metrics including PAPR, PSD, BER, and throughput under different channel models. The remainder of this paper is organized as follows: Section II introduces the concept of waveform design and presents the major 5G waveform candidates. Section III outlines the simulation parameters and performance indicators. Section IV discusses the simulation results and comparative analysis. Finally, Section V concludes with key findings and insights into the suitability of each waveform for 5G applications.

2. Waveform technique in 5G network.

The fifth generation (5G) of mobile networks aims to meet unprecedented performance demands, including significantly higher data rates, enhanced spectral efficiency, ultra-low latency, and support for massive connectivity and high mobility [3]. Achieving these targets requires fundamental changes at the physical layer particularly in waveform design.

Waveforms are central to modulation schemes, defining how information is transmitted over the air. In 5G, selecting an appropriate waveform is critical to fulfilling the system's diverse requirements. A well-designed waveform must provide robustness against interference, efficient spectrum utilization, low out-of-band emissions, and support for asynchronous and fragmented transmissions.

This section introduces the concept of waveforms from both theoretical and practical perspectives and outlines the primary waveform candidates proposed for 5G. Their key features, advantages, and limitations are discussed to highlight their suitability for different 5G scenarios.

2.1. Definition and Principles of Waveforms

The concept of waveform in communication systems dates back to Shannon’s foundational work, which describes communication through mappings between a message space and a signal space. In this context, the waveform represents the physical structure of the modulated signal that conveys information through the channel.

Formally, a waveform comprises three core components: the symbol (representing the data), the pulse shape (defining temporal characteristics), and the lattice (determining time–frequency positioning) [5]. While the symbol component is random, both the pulse shape and lattice are deterministic. Figure 1 illustrates this conceptual model [9].

Waveform design aims to optimize signal generation and detection under practical constraints. Key design criteria include spectral containment, time-domain localization, resistance to multipath effects, and compatibility with advanced technologies such as Massive MIMO and carrier aggregation. The evolution of waveform techniques has mirrored the shift in performance expectations from earlier generations (2G–4G) to 5G and beyond. OFDM, the backbone of 4G LTE, is no longer sufficient due to its high PAPR and spectral leakage. These limitations have prompted the development of more efficient alternatives like UFMC and FBMC.

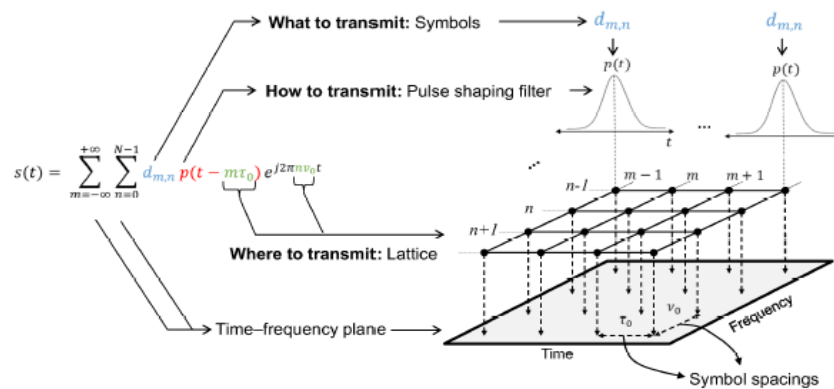


Figure 1. Waveform definition [9].

2.2. MAJOR WAVEFORM CANDIDATES FOR 5G

Waveforms are generally classified into two main categories: single-carrier and multi-carrier waveforms. The key distinction lies in how the signal bandwidth is utilized. In multi-carrier systems, a wideband channel is divided into multiple narrowband subcarriers. This subdivision enhances transmission

efficiency by mitigating delay spread and inter-symbol interference, making these schemes highly suitable for modern wireless communications. As such, multi-carrier techniques have become central to the design of 5G wireless systems due to their ability to enable dynamic spectrum access, facilitate resource allocation, improve spectral coexistence, and support advanced features such as Massive MIMO.

Among these techniques, the most prominent and widely adopted multi-carrier modulation scheme is Orthogonal Frequency Division Multiplexing (OFDM) [10]. OFDM is a specialized form of Frequency Division Multiplexing (FDM). To better understand OFDM, it is helpful to first examine the principles of conventional FDM.

FDM allows multiple users to share a single communication link by dividing the total available bandwidth into several non-overlapping sub-channels. Each sub-channel is separated by a guard band to prevent interference, allowing simultaneous but independent transmission. The transmitted FDM signal can be mathematically expressed as:

$$s(t) = \sum_{n=0}^N X_n e^{j\omega_n t}$$

Where X_n denotes the symbol transmitted on the n -th subcarrier and ω_n is its angular frequency.

Figure 2 illustrates the structured methodology adopted for the comparative performance evaluation of the selected waveform candidates under realistic channel conditions.

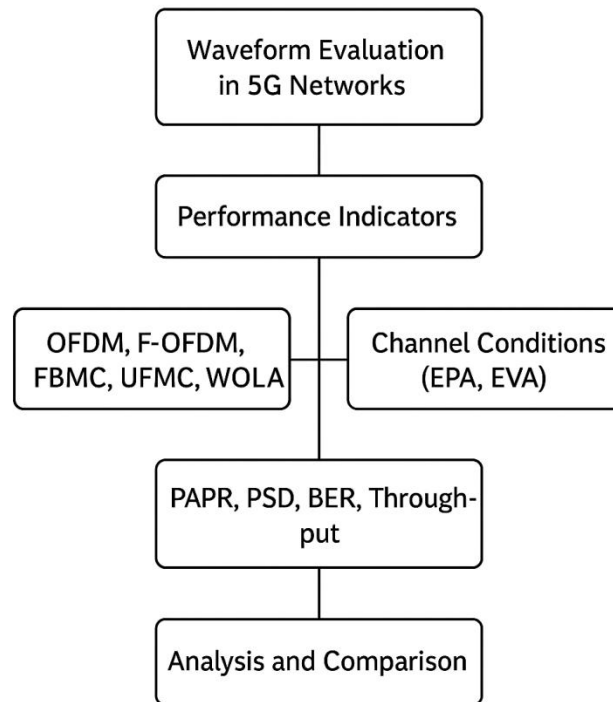


Figure 2. Proposed methodology for the comparative evaluation of waveform candidates in 5G networks.

This flowchart presents the step-by-step methodology used to evaluate waveform candidates for 5G communication systems. The process begins with selecting waveform types (OFDM, F-OFDM, FBMC, UFMC, WOLA), followed by identifying key performance indicators (PAPR, PSD, BER, Throughput). The evaluation is conducted under two realistic channel models (EPA and EVA), and results are analyzed to compare performance across different waveforms.

The simulation methodology presented in Figure 2 forms the foundation for the performance comparison discussed in the next section.

2.2.1. OFDM (Orthogonal Frequency Division Multiplexing)

Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique widely used in modern wireless communication systems, such as LTE (4G) and IEEE 802.11 (Wi-Fi) networks [11]. OFDM is a special case of Frequency Division Multiplexing (FDM) where a single frequency band is divided into multiple sub-channels. Unlike traditional FDM, these subcarriers in OFDM are designed to be orthogonal to each other. Orthogonality ensures that the signals can overlap in frequency without causing interference, meaning that the peak of one subcarrier aligns with the nulls of the neighboring subcarriers.

The orthogonality can be mathematically expressed as:

$$\int_0^T s(t+T) \cdot s(t) dt = 0$$

Where $s(t)$ represents the time-domain signal for each subcarrier, and T is the symbol period. The Inverse Fast Fourier Transform (IFFT) is used at the transmitter side to convert data into the time domain for transmission, while the Fast Fourier Transform (FFT) is applied at the receiver side to retrieve the individual subcarriers [12].

OFDM is highly praised for its spectral efficiency, as it divides the available spectrum into many orthogonal sub-bands, making it possible to use the spectrum efficiently without interference. Moreover, OFDM offers robustness against multipath fading and channel delay, which are significant issues in high-speed communication systems.

However, the high Peak-to-Average Power Ratio (PAPR) remains a major disadvantage of OFDM. This arises due to the superposition of the multiple subcarriers, causing large peaks in the transmitted signal. Mathematically, the PAPR can be expressed as:

$$PAPR = \frac{\text{Peak Power}}{\text{Average Power}}$$

Another drawback is the high Bit Error Rate (BER) in poor channel conditions, as well as the high out-of-band emissions (OOBE) resulting from the rectangular pulse shaping of the OFDM symbols.

2.2.2. F-OFDM (Filtered Orthogonal Frequency Division Multiplexing)

Filtered Orthogonal Frequency Division Multiplexing (F-OFDM) is an enhancement of OFDM, where filtering is applied to the frequency domain to improve spectral efficiency and reduce out-of-band emissions. In F-OFDM, the available bandwidth is divided into multiple sub-bands, each of which is filtered using a prototype filter. The filtering process confines the transmitted signal to a specific frequency band, thus minimizing interference between sub-bands [13].

The filtering operation can be represented as:

$$h(t) * x(t) = y(t)$$

Where $x(t)$ is the input signal, $h(t)$ is the filter impulse response, and $*$ denotes convolution. This process ensures that the transmitted signal is more confined, reducing spectral leakage.

F-OFDM provides better resilience to channel impairments and enhanced coexistence with other systems like OFDM and U-FMC. However, the main limitation is the filter length. A longer filter reduces the effective bandwidth of the system, while a shorter filter leads to increased out-of-band emissions. Additionally, the dynamic construction of filters based on tone allocation adds significant complexity to F-OFDM systems.

2.2.3. FBMC (Filter Bank Multicarrier)

FBMC (Filtered-OFDM) is a modulation technique that has been considered as a potential candidate and that was initially investigated by researchers in order to make it more suitable for the requirement of 5G networks [14]. FBMC is another evolved form of OFDM and MC modulation scheme, where each OFDM signal sub-carrier is filtered individually to effectively improve out-of-band (OOB) interference and significantly enhance spectral efficiency.

Actually, there are diverse methodologies for implementing Filter Bank Multicarrier (FBMC), including Filtered Multitone (FMT), Cosine Modulated Multitone (CMT), and Staggered Modulated Multitone (SMT), the latter being commonly referred to as Offset Quadrature Amplitude Modulation (OQAM-FBMC) and it is the focus case considered of 5G waveform due to its ability to reduce Inter Carrier Interference (ICI) [5],[15].

In this approach, the OQAM technique is based on the transmits of the imaginary and real portions of complex symbols separately in isolation with a time delay equaling half a symbol, while the signals are combined and modulated by a specific subcarrier frequency. Furthermore, OQAM ensures orthogonality between neighboring subcarriers. Consequently, equalization is simplified without the need for CP, and the well-localized subcarriers in OQAM-FBMC make it suitable for high mobility applications, as it is more immune to Doppler effects.

Despite all the potential benefits that FBMC has shown, it has not been widely adopted as the primary modulation scheme in 5G because it poses certain challenges, such as increased complexity in the implementation especially the integration between the MIMO and OQAM-FBMC design, moreover its potential sensitivity to carrier frequency offsets. Nevertheless, FBMS is still an area of ongoing research and development

2.2.4. UFMC (Universal filtered multicarrier)

Universal Filtered Multicarrier (UFMC) is another advanced modulation scheme considered for 5G networks. UFMC differs from FBMC by filtering blocks of subcarriers rather than each individual subcarrier. This filtering approach reduces both intra-symbol and inter-symbol interference, improving the overall spectral containment. In UFMC, the filtering operation is applied to blocks of subcarriers as follows:

$$y(t) = \sum_n x_n(t) * h_n(t)$$

Where $x_n(t)$ represents the n-th block of subcarriers, and $h_n(t)$ is the filter applied to each block.

UFMC offers flexibility in the design of filters, making it adaptable for different network requirements. It significantly improves spectral containment and reduces out-of-band emissions, but it requires higher synchronization with user mobility, and the computational complexity increases as more sub-bands are used [13]. The following figure summarizes and illustrates the differences between filtering methods of the various candidates for 5G (OFDM, FBMC, UFMC, and F-OFDM) [16][17].

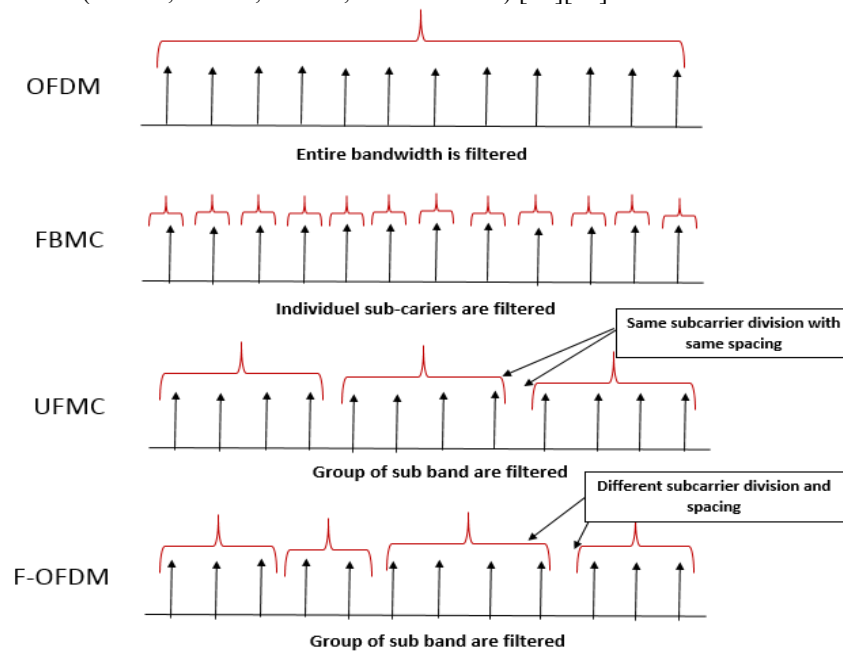


Figure 3. Comparison of filtering techniques used in 5G waveform candidates.

2.2.5. WOLA (Weighted Overlap and Add)

WOLA (Weighted Overlap and Add) is a time-frequency analysis technique highly recommended for 5G systems, particularly when combined with MIMO (Multiple Input Multiple Output) and OFDM (Orthogonal Frequency Division Multiplexing) technologies. This approach enhances side-lobe suppression, reduces out-of-band emissions (OOBE), and mitigates interference, making it an appealing candidate for 5G communication systems [18]

WOLA operates as an oversampled filter bank, based on time-frequency analysis, using the weighted overlap-add method. This technique involves applying a windowing function to each OFDM symbol before transmission. The windowing function smoothly tapers the edges of the symbols, thus reducing side lobes and improving spectral containment. Furthermore, WOLA introduces an overlap between consecutive OFDM symbols, where portions of each symbol overlap with both preceding and subsequent symbols. These overlapping segments are then combined using the overlap-add method to reconstruct the signal [19].

The use of oversampling in WOLA enhances the time-frequency resolution, providing a more detailed insight into the signal's characteristics, and improving its efficiency in managing spectral resources.

WOLA is an optional technique that can be integrated with OFDM in 5G, providing additional flexibility in waveform design to meet specific performance objectives and regulatory constraints. However, the advantages of WOLA are contingent upon the deployment environment, spectrum allocation, and regulatory framework. These factors significantly influence the technique's effectiveness in fulfilling the required standards for 5G communication systems.

3. RESULTS AND DISCUSSION

Various waveform candidates are being suggested to replace OFDM, which was the primary waveform in the 4G network. Hence, our objective for this research is to compare the different multicarrier recommendation techniques for 5G network, to give an insight into which technologies will best suit 5G.

In this section, we will elucidate the distinct parameters of waveforms employed, then present and discuss the simulation results using the probability of error, PAPR, and PSD to examine the performance of each waveform.

Table 1 presents some of the key simulation parameters to provide a clear understanding of the simulated environment.

Table 1: system parameters.

Parameter	Value
Waveforms	OFDM, F-OFDM, FBMC, UPMC, WOLA
Filter length/type	F-OFDM: Windowed-sinc FIR (33–64 taps); UPMC: Dolph–Chebyshev (40 dB); FBMC: PHYDYAS OQAM (K=4); WOLA: Raised-cosine window (50% overlap)
CP length	Normal CP: 4.7–5.2 μ s @ 15 kHz; 2.3–2.6 μ s @ 30 kHz
Subcarriers per sub-band	24 (OFDM, F-OFDM, WOLA), 12 (FBMC, UPMC)
Subcarrier spacing	30 kHz (User 1), 15 kHz (User 2)
Used subcarriers per BS	72 (BS1), 72 (BS2)
Symbols per frame	30 (BS1), 15 (BS2)
Modulation/coding	16-QAM / Turbo Code
Channel models	EPA (slow fading), EVA (fast fading)
Tx Power	30 dBm
Doppler	Jakes model, 50 paths
Bandwidth	0.36 MHz (<i>sub-band equivalent; corresponds to 24×15 kHz</i>)

The 0.36 MHz corresponds to a simulated sub-band (24 subcarriers \times 15 kHz). For larger bandwidths (≥ 5 MHz), the relative performance trends remain consistent.

To examine the performance of each chosen waveform, the following section presents a comprehensive comparison of simulation results based on several criteria.

Figure 4 shows the power spectral density as a function of the frequency of the different waveforms, we can clearly see that the FBMC has the lowest power spectral density compared to the other waveforms, due to its very low OOB radiation. On the other hand, the F-OFDM also shows a good performance almost close to the FBMC. Meanwhile, the UPMC and WOLA are somehow close to one another but the UPMC system performance is better than WOLA, while it's evident that the OFDM suffers from severe performance degradation. It can be concluded that the FBMC has the most optimal PSD in the 5G network.

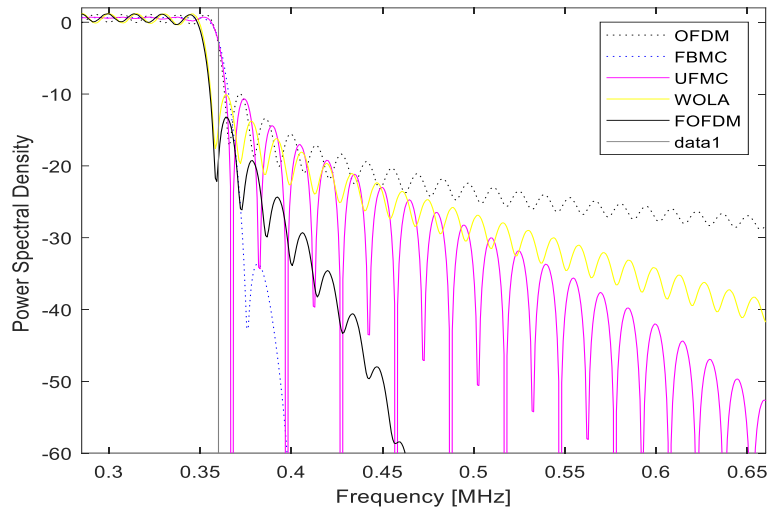


Figure 4. Performance comparison of 5G's waveform candidates in terms of PSD.

The second essential factor to consider is the complementary cumulative distribution function (CCDF) of the peak-to-average power ratio (PAPR). The comparison depicted in Figure 5 indicates that FBMC and WOLA exhibit nearly identical PAPR and outperform other contenders. Following closely are F-OFDM and OFDM, which demonstrate superior performance compared to UFMC, which had a higher PAPR compared to other candidates.

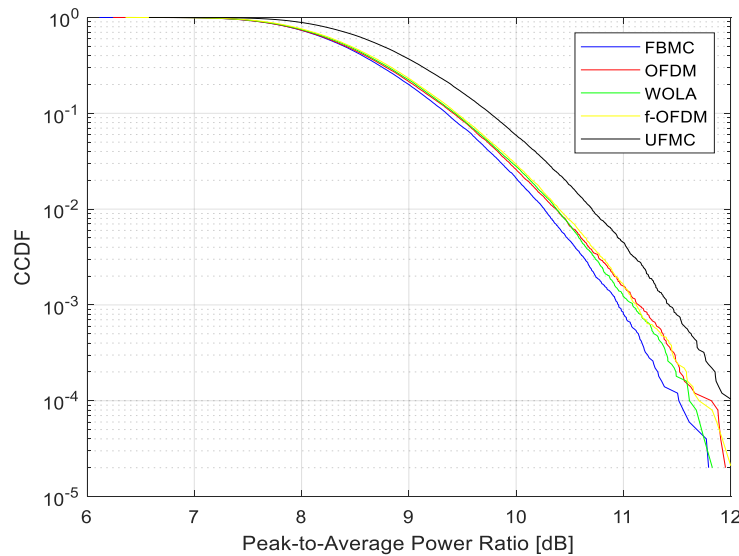


Figure 5. Performance comparison of 5G's waveform candidates in terms of PAPR.

Another important factor that we relied on in our analytical study is the Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) over two model channels in particular the EPA (Extended Pedestrian A) which is a slow fading channel and EVA (Extended Vehicular A) which is the fast fading channel due to their important characteristics which correspond exactly to the exigencies of the 5G systems [1]. Additionally, the different waveforms were simulated with and without channel coding choosing Turbo code.

Figure 6(a) shows that, under the EPA channel with Turbo coding (rate $\approx 1/3$, 16-QAM modulation), the BER curves of UFMC, F-OFDM, WOLA, and OFDM are almost identical, with UFMC achieving a slight advantage and OFDM performing the worst. In contrast, Figure 6(b) (uncoded transmission) indicates that FBMC outperforms all other waveforms, highlighting its strength in the absence of channel coding.

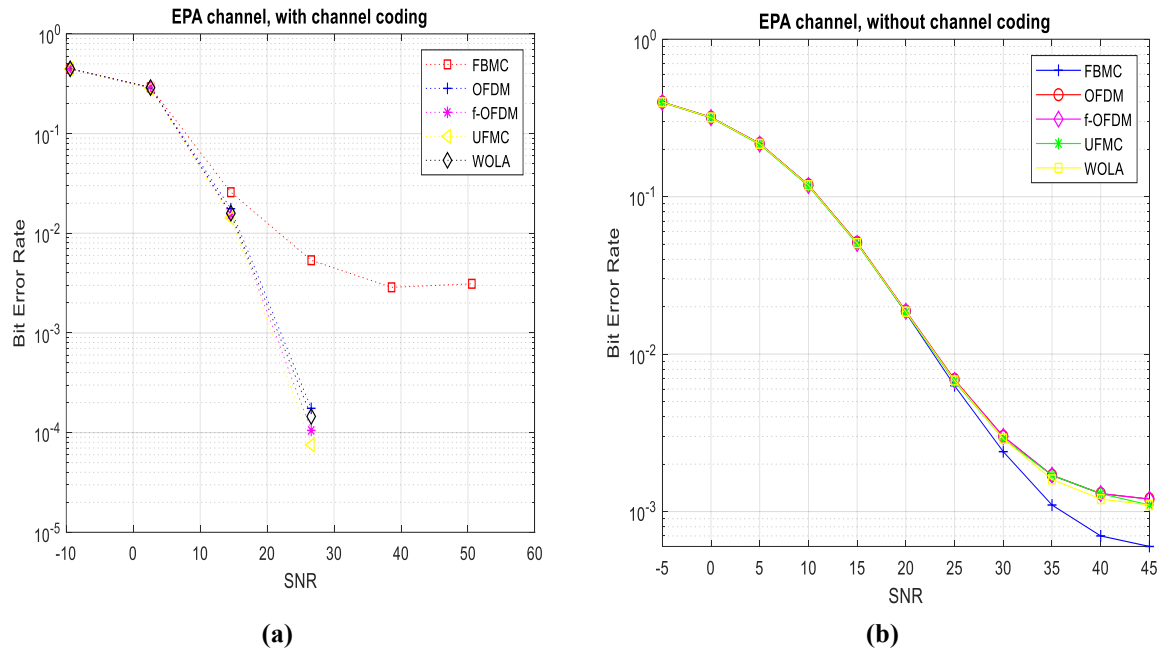


Figure 6. Performance comparison of 5G's waveform candidates in terms of BER over EPA channel and (a) with channel coding and (b) without channel coding.

Figure 7(a) illustrates the BER results under the EVA channel with Turbo coding. In this scenario, WOLA achieves the best performance among the candidate waveforms, while FBMC shows the weakest results. By contrast, Figure 7(b) presents the uncoded case, where FBMC provides the best BER performance, whereas F-OFDM deteriorates significantly and becomes the least competitive.

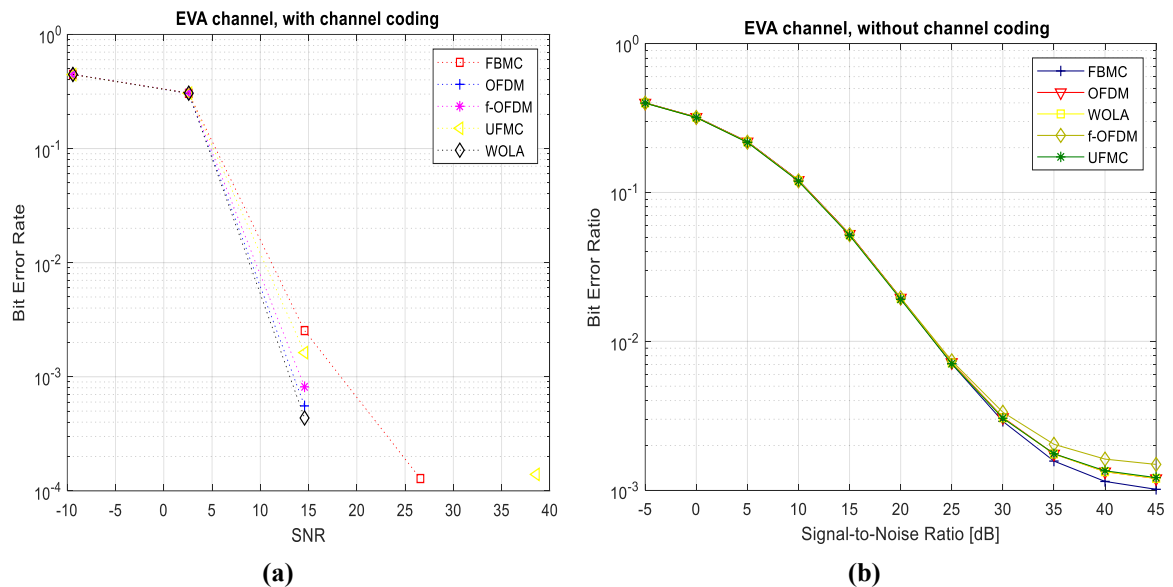


Figure 7. Performance comparison of 5G's waveform candidates in terms of BER over EVA channel and (a) with channel coding and (b) without channel coding.

From Figures 6 and 7, it is evident that FBMC's BER performance is the most affected by the application of channel coding compared to the other studied waveforms. This finding highlights that reliable performance in 5G systems depends not only on the selected waveform but also on the coding strategy, underscoring the importance of jointly considering both aspects in system design.

Another important aspect is the complexity–performance trade-off. While FBMC provides excellent spectral localization, it requires longer prototype filters and OQAM processing, which increase both

implementation cost and latency. Table 2 provides a simple comparison of computational costs among candidate waveforms in terms of filter length and approximate FLOPs per symbol, following [20]. This comparison confirms that FBMC incurs the highest complexity, whereas OFDM remains the simplest to implement.

Table 2. Complexity–Performance Trade-off of 5G Waveform Candidates.

Waveform	Filter length / window	Complexity (relative FLOPs)	BER performance (uncoded)	BER performance (coded)
OFDM	CP only	1.0×	Weak	Moderate
F-OFDM	33–64 taps FIR	1.3×	Good	Good
UFMC	43-tap Chebyshev	1.5×	Good	Best (coded)
WOLA	RC window (50% overlap)	1.2×	Good	Very good
FBMC	OQAM, K=4 overlap	2.0×	Best (uncoded)	Weakest (coded)

Figure 8, illustrate throughput (Mbit/s) as a function of SNR for 5G systeme using two users over EPA and EVA, channels with turbo channel coding.

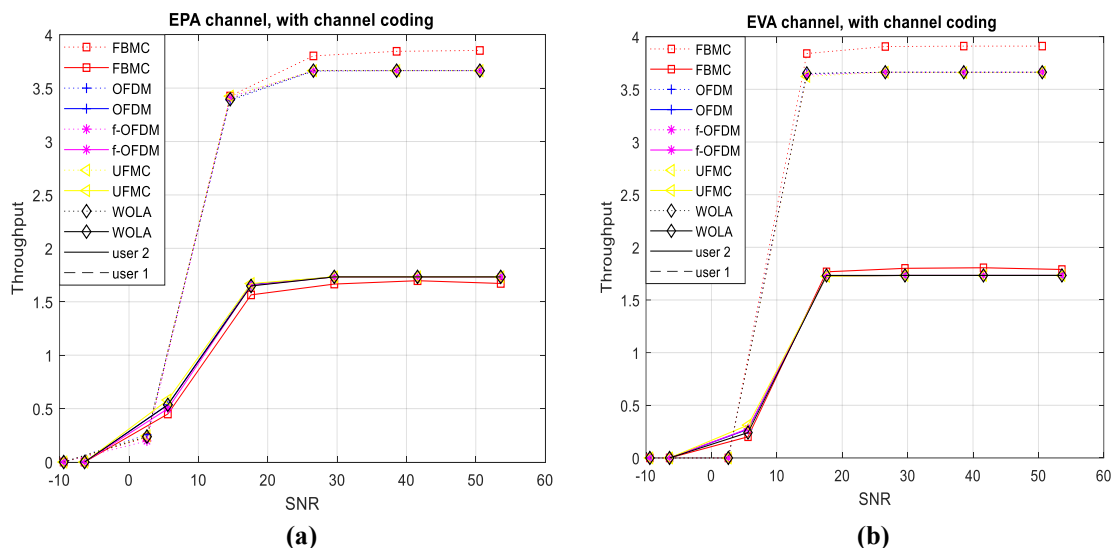


Figure 8. Performance comparison of 5G's waveform candidates in terms of Throughput (Mbit/s) of two users with turbo coding (a) over EPA channel (b) over EVA channel.

According to figure 8, we notice that the FBMC technique provides higher throughput compared with other techniques over EPA and EVA channels.

Based on the simulation results, the table 3 below summarizes the performance comparison of the different waveforms candidates.

Table 3. Summary for different performance comparison waveforms.

Variable	OFDM	F-OFDM	FBMC	UFMC	WOLA
PSD (dB)	Higher	Moderate	Low	Moderate	high
PAPR (dB)	Moderate	Moderate	Low	Higher	Low
BER with coding over EPA channel	Moderate	Moderate	Poor	Excellent	Moderate
BER without coding over EPA channel	Moderate	Moderate	Excellent	moderate	Moderate

BER with coding over EVA channel	Moderate	Moderate	Poor	Moderate	Excellent
BER without coding over EVA channel	Moderate	Poor	Excellent	Moderate	Moderate
Throughput with coding over EVA channel	Moderate	Moderate	Excellent	Moderate	Moderate
Throughput with coding over EPA channel	Moderate	Moderate	Excellent	Moderate	Moderate

Overall, FBMC emerges as the strongest candidate in uncoded scenarios; however, it shows sensitivity to channel coding and higher implementation complexity, particularly with MIMO.

3. CONCLUSION

This study presented a comparative evaluation of five major waveform candidates for 5G wireless communication systems: OFDM, F-OFDM, FBMC, UFMC, and WOLA. Each waveform was analyzed based on key performance indicators (KPIs) such as Peak-to-Average Power Ratio (PAPR), Power Spectral Density (PSD), Bit Error Rate (BER), and throughput under realistic channel conditions (EPA and EVA), with and without channel coding.

The simulation results revealed that FBMC consistently achieved superior performance in terms of spectral containment and throughput, particularly in uncoded scenarios, due to its excellent out-of-band suppression and efficient use of subcarriers. However, it demonstrated sensitivity to channel coding and higher implementation complexity, particularly in MIMO environments. WOLA showed strong potential in coded environments, benefiting from its windowing mechanism that reduces sidelobes and improves signal integrity. F-OFDM provided a good compromise between compatibility with OFDM-based systems and enhanced spectral efficiency, though at the cost of increased filter complexity.

While no single waveform satisfies all 5G requirements simultaneously, the results suggest that FBMC and WOLA are strong candidates for specific 5G use cases, such as enhanced mobile broadband (eMBB) and asynchronous transmissions. Moreover, the choice of waveform should be context-aware, considering channel conditions, deployment architecture, and service type.

Future work may extend this analysis by incorporating massive MIMO, millimeter-wave frequencies, and hybrid waveform strategies to evaluate their combined impact on system performance. Additionally, practical implementation challenges such as computational complexity, energy efficiency, and hardware constraints should be addressed to guide real-world deployment.

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