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Comparative Analysis of UFMC and GFDM Modulation Techniques in 5G New Radio

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ABSTRACT

In the evolving landscape of Fifth Generation (5G) New Radio (NR), waveform design plays a crucial role in meeting the diverse requirements of enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC). Among the contenders proposed as alternatives to conventional Orthogonal Frequency Division Multiplexing (OFDM), Universal Filtered Multi-Carrier (UFMC) and Generalized Frequency Division Multiplexing (GFDM) have gained significant attention in 5G due to their superior spectral containment and flexibility. This paper presents a comparative analysis of UFMC and GFDM modulation techniques with a focus on Bit Error Rate (BER) and Power Spectral Density (PSD) performance. The BER performance of both waveforms is evaluated across varying signal-to-noise ratio (SNR) levels. Additionally, the spectral characteristics of UFMC and GFDM are analysed to quantify their out-of-band (OOB) emissions. Results demonstrate that while UFMC offers improved spectral localization with significantly lower OOB leakage, GFDM achieves better BER performance in moderate to high SNR regimes due to its flexibility in pulse shaping and time-frequency localization. The results provide insights that can be used for waveform selection in 6G networks, where UFMC's spectral efficiency supports high-frequency bands, while GFDM's flexibility and low-latency traits align with ultra-reliable, real-time applications.

Keywords: New Radio (NR), UFMC, GFDM, BER, PSD

1. INTRODUCTION

Since the inception of first-generation mobile networks, the telecommunications sector has encountered several obstacles regarding technology, effective spectrum usage, and, most critically, user security. To endure in a rapidly evolving world characterized by constant technological advancement, we introduce fifth-generation technology: 5G. In the future, beyond 4G, key aims to achieve include enhanced capacity, elevated data rates, reduced latency, and superior quality of service. A substantial enhancement in the cellular architecture of 5G is necessary to fulfil these requirements [1]. These challenges have led to investigating some new modulation techniques that can better align with the requirements of 5G and future communication standards. 5G delivers services categorized into three categories:

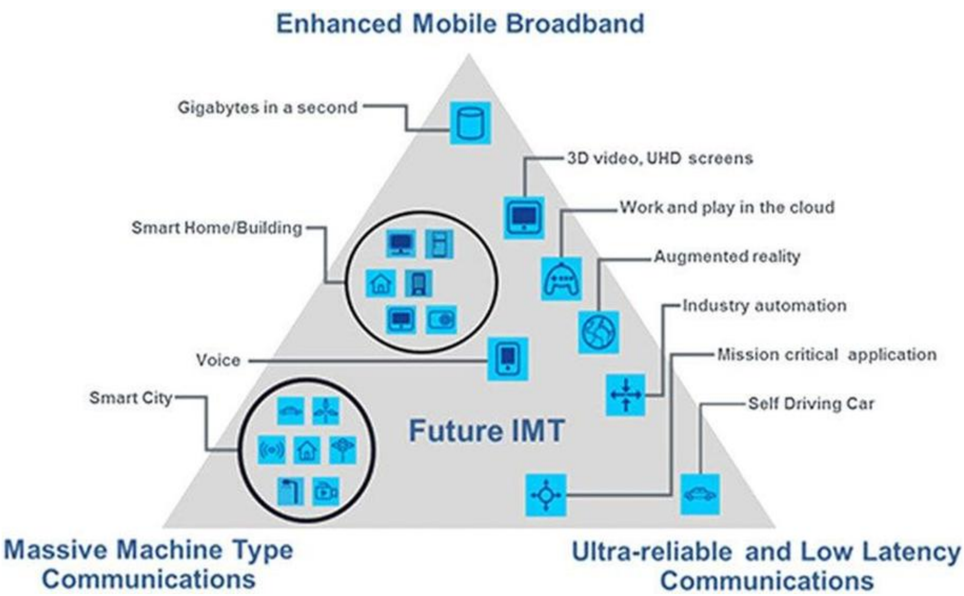


Fig.1: Usage scenarios of IMT-2020 and beyond

Universal Filtered Multi-Carrier (UFMC) and Generalized Frequency Division Multiplexing (GFDM) have emerged as promising waveform candidates to address these shortcomings. UFMC enhances spectral containment by applying sub-band filtering, thus reducing OOB emissions without the need for a cyclic prefix (CP) [2]. GFDM, on the other hand, offers greater flexibility in time-frequency resource allocation and supports low-latency communication through block-based transmission, making it suitable for ultra-reliable low-latency communication (URLLC) scenarios [3].

This paper presents a comparative study of UFMC and GFDM modulation techniques with a focus on their performance in terms of Bit Error Rate (BER), Power Spectral Density (PSD), and other critical physical layer parameters under 5G New Radio conditions. Through MATLAB-based simulations, we evaluate the waveforms under AWGN and Rayleigh fading channels to provide a practical assessment of their suitability for different 5G applications.

The rest of the paper is organized as follows: Section 3 provides a review of related work and a brief theoretical background of the waveforms. Section 4 describes the system model and simulation parameters. Section 5 presents and discusses the simulation results, including BER and PSD comparisons. Section 6 highlights the practical implications and possible applications in 5G and beyond. Finally, Section 7 concludes the paper with key findings and suggestions for future research.

2. BACKGROUND AND RELATED WORK

The 5G wireless communication systems demand waveforms that can efficiently support diverse scenarios, eMBB, URLLC, and mMTC. Conventional OFDM has been the baseline waveform in 4G and initial 5G deployments due to its simplicity and robustness against multipath fading. However, its high peak-to-average power ratio (PAPR) and significant OOB emissions limit its suitability in scenarios requiring stringent spectral efficiency and asynchronous transmissions [4-5]. In 5G, multicarrier waveforms are categorized into sub-band-wise filtered or sub-carrier-wise filtered waveforms. In subcarrier-filtered Waveforms filtered waveforms, each subcarrier is filtered or shaped independently with a dedicated pulse shaping filter. In Sub-Band-Filtered Waveforms, instead of filtering each subcarrier separately, groups of subcarriers (sub-band or blocks) are filtered together using a single filter per sub-band. Longer filter lengths lead to higher latency and computational complexity [6]. In subcarrier-filtered Waveforms, the major drawbacks are that longer filter lengths lead to higher latency and computational complexity. Also, they have difficulties in supporting MIMO and channel estimation because of the intrinsic interference between adjacent subcarriers. While sub-band filtered waveforms balance spectral containment and computational complexity. Shorter filter lengths can be used to reduce latency compared to subcarrier filtering and are better suited for fragmented spectrum and dynamic spectrum access [7].

UFMC implements filtering on sub-bands rather than individual subcarriers. This results in reduced OOB emissions with shorter filter lengths and without the need for a cyclic prefix, improving spectral efficiency and reducing latency. GFDM extends traditional multicarrier schemes by employing flexible pulse shaping per subcarrier and symbol. GFDM’s block-based transmission structure provides high flexibility in time-frequency resource allocation and reduces latency, making it suitable for the low-latency requirements of 5G URLLC applications.

This paper compares GFDM, a flexible subcarrier-filtered multicarrier waveform offering low latency and fine-grained time-frequency control, with UFMC, a sub-band-filtered technique that balances spectral containment and complexity for efficient 5G communication.

2.1 Related Comparative Studies on UFMC and GFDM

Several studies have explored the performance of UFMC and GFDM as candidates for next-generation wireless systems. Comparative studies, such as the work by Gao et al. [8], have evaluated UFMC and GFDM in terms of BER performance, spectral containment, and implementation complexity. Their results indicate that while UFMC excels in spectral localization, GFDM offers superior flexibility and latency performance under certain channel conditions. In Gaspar et al. [9], GFDM is shown to provide good performance in asynchronous and cognitive radio scenarios. It concludes that, compared to UFMC, GFDM has higher complexity but supports dynamic bandwidth allocation. Chen et al. [10] compare the PAPR and spectral efficiency of UFMC and GFDM under power amplifier non-linearities, proving that GFDM achieves better spectral efficiency and UFMC performs better in terms of PAPR. Zhang et al. [11] compare OFDM, UFMC, and GFDM based on implementation complexity, robustness, and flexibility. Key results show that UFMC is less complex and more robust to synchronization errors; GFDM is highly flexible but computationally demanding. However, these studies often focus on limited parameter sets or specific simulation conditions, leaving a comprehensive comparative analysis in realistic 5G New Radio (NR) environments underexplored.

2.2 Research Gap

Despite promising individual evaluations, there remains a lack of thorough, side-by-side comparative analyses of UFMC and GFDM covering critical performance metrics, such as BER, PAPR, spectral efficiency, and computational complexity, under both AWGN and multipath fading channels representative of 5G NR. Moreover, the practical trade-offs involved in selecting either waveform for different 5G use cases (eMBB, URLLC, mMTC) have not been systematically addressed. This paper aims to fill this gap by providing a detailed simulation-based comparison of UFMC and GFDM in a consistent framework, thereby guiding waveform selection for future wireless networks.

3. SYSTEM MODEL

3.1 Overview of UFMC

The Universal Filtered Multi-Carrier (UFMC) system is designed to enhance spectral containment by applying sub-band-wise filtering. The system consists of a channel coding block followed by a UFMC transmitter. The overall process can be divided into the following stages: Serial-to-parallel conversion, QAM Modulation, Sub-band allocation, IFFT on each sub-band, and Sub-band-wise filtering (e.g., Dolph–Chebyshev) [12]. Fig. 2 presents the detailed block diagram for the transceiver section of the UFMC waveform.

3.1.1 Transmitter and receiver design

In a UFMC transmitter, the input bitstream is first modulated using digital modulation schemes such as QPSK or QAM. The modulated data is then divided into sub-bands, with each sub-band containing a group of contiguous subcarriers. For each sub-band, an Inverse Fast Fourier Transform (IFFT) is applied to generate time-domain symbols. Unlike OFDM, UFMC applies filtering at the sub-band level rather than on the entire bandwidth or individual subcarriers. This is typically achieved using well-shaped finite impulse response (FIR) filters such as the Dolph-Chebyshev filter.

3.1.2 Mathematical model for UFMC

1. Channel Coding and Interleaving

Let b = [b1, b2, ...,b_A] denote the input binary data stream of length A. In channel Coding, the bitstream is encoded using a forward error correction scheme such as convolutional coding, LDPC, or polar coding, producing:

$$c = \text{Encode}(b) \tag{1}$$

After that, channel Interleaving is implemented where the coded bits are permuted to minimize the impact of burst errors:

$$C' = \text{Interleave}(c) \tag{2}$$

The interleaved bitstream is segmented into B sub-bands. Each sub-band undergoes QAM Modulation. Each sub-band i∈{1, 2, …B} maps the incoming bits to QAM symbols:

$$X_{i,k} = \text{QAMMod}(c'_{I,k}),\ k=0, 1, \ldots, N-1 \tag{3}$$

where N is the number of subcarriers per sub-band.

The QAM symbols of each sub-band are transformed into the time domain using an N-point IFFT:

$$X_i[n] = \frac{1}{N}\sum_{k=0}^{N-1} e^{\frac{j2\pi kn}{N}},\quad n=0,1\ldots\ldots, N-1. \tag{4}$$

A sub-band-specific finite impulse response (FIR) filter h[n] of length L is applied to each time-domain sub-band signal:

$$r_i[n] = x_i[n] * h[n] = \sum_{l=0}^{L-1} x_i[n-l]h[l] \tag{5}$$

The filtered sub-band signals are aligned and summed to form the composite UFMC transmit signal:

$$s[n] = \sum_{i=1}^{B} r_i[n-\Delta_i] \tag{6}$$

where Δ_i is a sub-band-specific delay to align the sub-band appropriately in the frequency domain. The baseband signal s[n] is converted to the RF domain and transmitted using a MIMO antenna array:

$$S_{RF} = \sum_{n=0}^{N_s-1} s[n].p(t-nT_s) \tag{7}$$

where p(t) is a pulse shaping function and Ts is the symbol duration.
The receiver architecture of the UFMC system performs the inverse operations of the transmitter. The received signal undergoes baseband conversion, filtering, FFT, equalization, and QAM demapping before decoding [13].
Let the signal received at the receiver antenna array be modeled as:

$$Y = H \cdot X + \eta \quad (8)$$

Where Y is the received signal matrix, H is channel matrix, X is the transmitted signal matrix η is the complex Gaussian noise. The received RF signal from each antenna is downconverted to baseband and digitized:

$$\hat{x}_{RF}(t) = \text{RF to Baseband } \hat{x}_{ZF\,[n]} \quad (9)$$

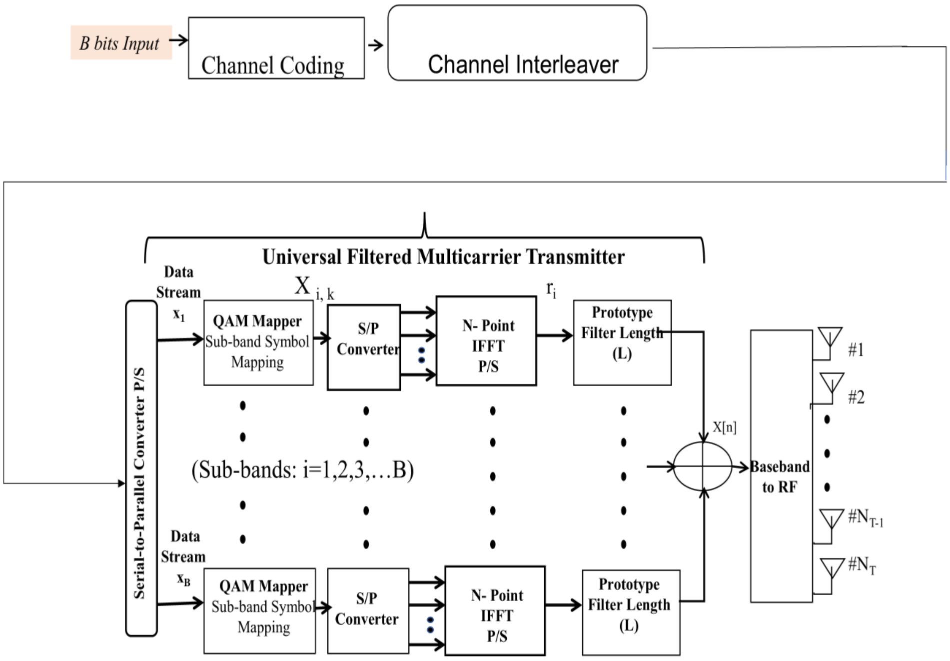


Fig. 2. Transceiver block for UFMC

A Zero Forcing (ZF) detector is used to suppress inter-stream interference from the MIMO channel:

$$\hat{X} = (H^H H)^{-1} H^H Y \quad (10)$$

This operation isolates the signal streams transmitted from each antenna. The ZF output signals are prepared for UFMC demodulation by applying appropriate buffering and alignment. Zero padding may be included for symmetry before FFT:

$$\hat{X}'_{ZF}[n] = \text{ZeroPad}(\hat{x}_{ZF}[n]) \quad (11)$$

Each received subband signal is converted back to the frequency domain using a 2N-point FFT:

$$\hat{X}_{I,k} = \sum_{n=0}^{2N-1} \hat{x}_i[n]\, e^{-j\frac{2\pi}{2N}} \quad , \quad k=0,1,\ldots\ldots N-1 \quad (12)$$

This operation recovers the subcarrier symbols across all subbands. Each subcarrier is equalized using the channel estimate $\hat{H}_{i,k}$ to mitigate frequency-selective fading:

$$\hat{X}_{i,k}^{eq} = \frac{\hat{X}_{i,k}}{\hat{H}_{i,k}} \quad \forall\, i_k \quad (13)$$

The equalized symbols $\hat{X}_{i,k}^{eq}$ are demapped back to bits using QAM demodulation:

$$\hat{b}_{I,k} = \text{QAMDemod}\,(\hat{X}_{i,k}^{eq}) \quad (14)$$

The recovered bits are passed through a decoder corresponding to the encoder used at the transmitter to retrieve the original data stream.

3.2 Overview of GFDM

GFDM uses block-based modulation and transmits a block of K×MK, where M QAM symbols, K is the number of subcarriers, and M is the number of sub-symbols (time slots). The GFDM symbol is composed of M QAM symbols for each of the N sub-carriers, resulting in transmission of K = NM complex modulated data [14]. After mapping, up-sampling of the data is implemented so that pulse-shaping circular filter g[n] can be applied through a convolution process [15].

3.2.1 Transmitter and receiver design

The complete GFDM transmitter is presented in Fig. 3. GFDM transmits data in blocks, each consisting of multiple sub-symbols and subcarriers. The input bit stream is first modulated using schemes such as QAM or PSK. These symbols are then arranged into a two-dimensional grid of K subcarriers and M sub-symbols. Each subcarrier is pulse-shaped using a prototype filter, typically a circularly shifted version of a root raised cosine filter, allowing filtering at the subcarrier level.

This filtering is applied using circular convolution, which enables the use of a single cyclic prefix for the entire block rather than per symbol, improving spectral efficiency. The filtered subcarrier signals are then summed to form the complete GFDM signal.

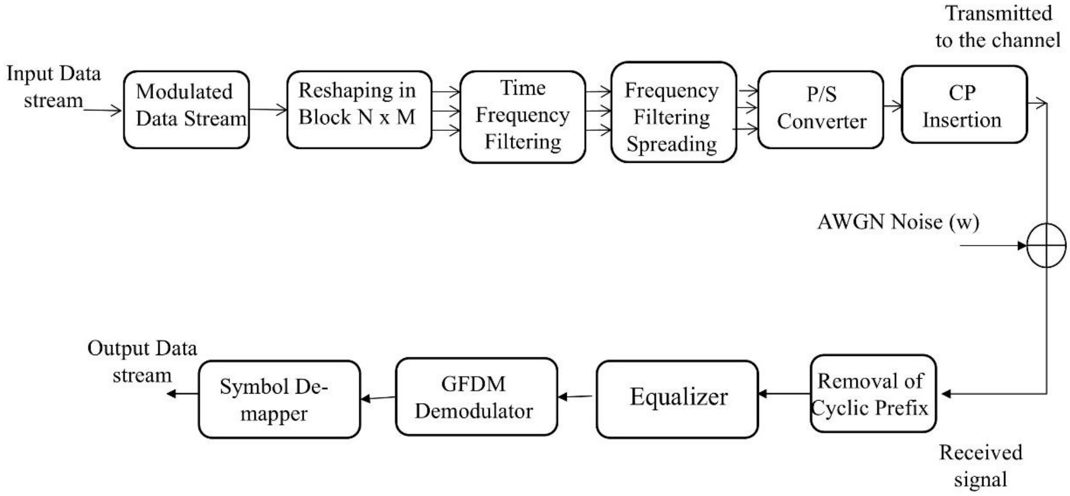


Fig. 3. Transceiver block for GFDM 5G NR waveform

3.2.2 Mathematical model for GFDM

GFDM is a block-based multicarrier modulation technique, where each block consists of K subcarriers and M symbols. The transmitted GFDM signal x[n] is given by:

$$X[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} d_{k,m} . g[(n-mK) mod\ N] .\ e^{j2\pi \frac{k}{K} n} \tag{15}$$

Where $d_{k,m}$ is the data symbol transmitted on the k^{th} subcarrier and m^{th} subsymbol, g[n] is the RRC filter (pulse shaping filter), K is the Total number of subcarriers, M is the Number of time slots (sub symbols), N=KM is total number of samples in a GFDM block, $e^{j2\pi \frac{k}{K} n}$ is Subcarrier modulation.

The received signal can be expressed as:

$$Y=Ad+n \tag{16}$$

Where:

Y is the received signal vector, A is the GFDM modulation matrix, d is the transmitted data vector, and n is the Additive white Gaussian noise.

At the receiver, the transmitted data is estimated using a linear equalizer. Here we have implemented, Zero Forcing (ZF) detector:

$$D = (A^H A)^{-1} A^H y \tag{17}$$

Finally, the estimated vector d is demapped and decoded to recover the transmitted bits.

4. SIMULATION AND RESULTS

The performance comparison of UFMC and GFDM modulation techniques is conducted using a custom-built simulation framework in MATLAB R2022a. The simulation environment is designed to emulate a downlink wireless transmission scenario typical of 5G NR systems. To evaluate the robustness of the modulation schemes under the Additive White Gaussian Noise (AWGN) channel model. Table 1. Represents the simulation parameters used.

Table 1. Simulation Parameters

Waveform Technique	Simulation Parameter	Value
GFDM	Block length	32
	Number of Subcarriers	128
	RRC filter roll-off	0.15
	Type of filter	RRC
UFMC	Number of Sub-bands	10
	Sub-band Size	20
	FFT size	512

	Filter	Dolph-Chebyshev
	Sideband filter attenuation	40 dB

The filters used in system design are the Dolph-Chebyshev for UFMC and the RRC filter for GFDM. The Filter characteristics are shown in Fig. 4.

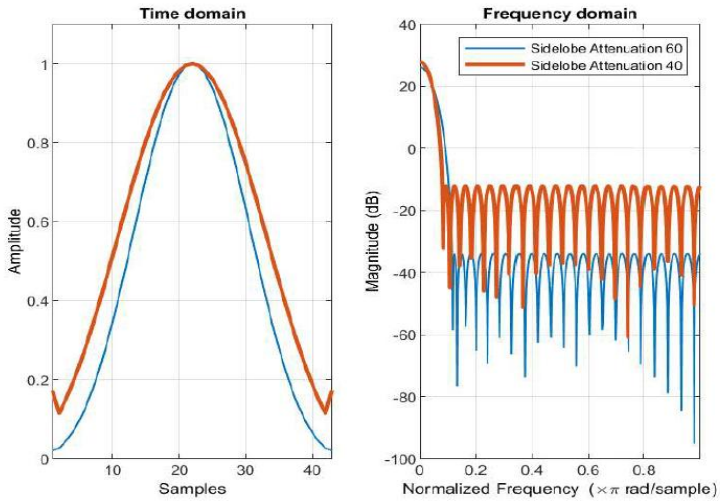


Fig. 4. Dolph Chebyshev filter for UFMC with filter length 43.

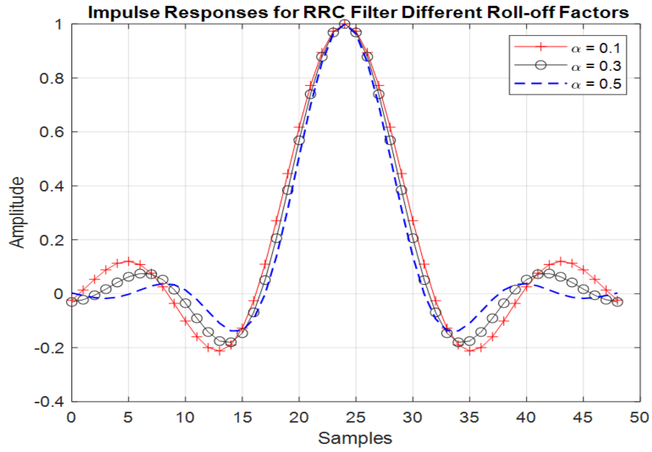
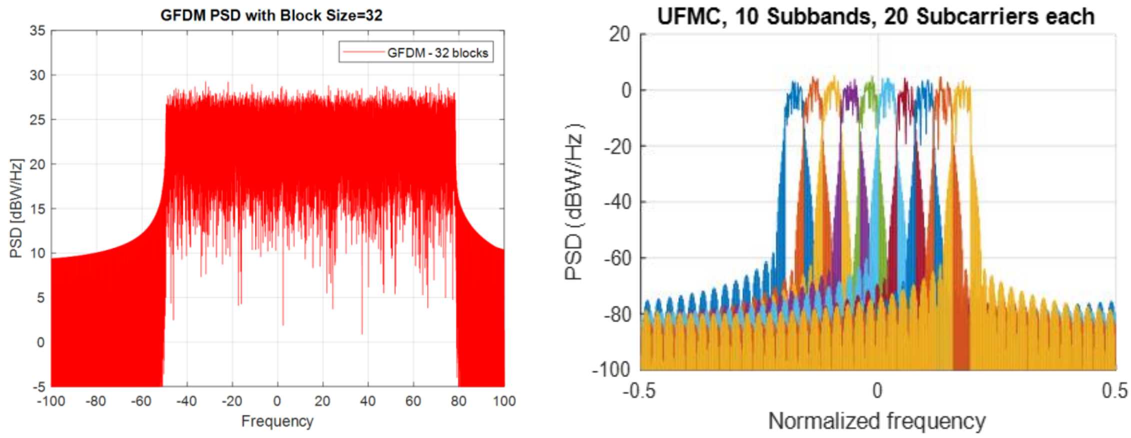


Fig. 5 RRC filter for GFDM with variable roll-off factor

4.1 Performance Evaluation and Results

Firstly, the spectra for UFMC and GFDM waveforms are illustrated in terms of the PSD. In Fig. 6 (a), the GFDM PSD graph is shown. Fig. 6 (b) shows the normalized spectrum of the UFMC system with 20 subcarriers in each sub-band. It is concluded from Fig. 7 that UFMC is a spectrally efficient waveform with minimum OOBE as compared to GFDM.



(a) (b)

Fig. 6 (a) PSD of GFDM for 32 block size (b) PSD of UFMC for 200 sub-carriers

From Fig. 5, it is observed that UFMC exhibits significantly better spectral confinement and sharp decay in power beyond its bandwidth, indicating excellent out-of-band (OOB) emission performance. Characteristic ripples are due to filtering, but the side lobes are attenuated rapidly. On the other hand, GFDM shows higher and relatively flat side lobes, implying poor spectral containment. Power decays slowly beyond the band, leading to more interference with adjacent channels.

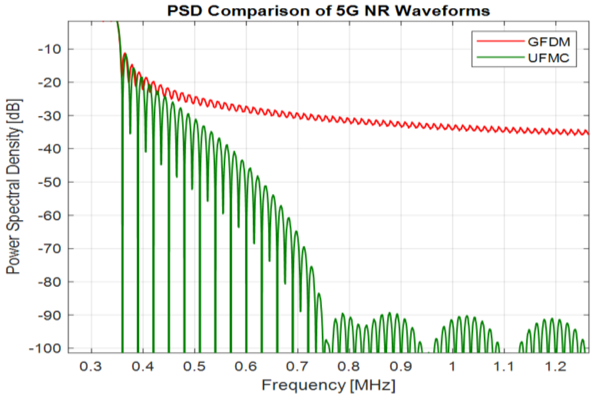


Fig. 7 PSD comparison of UFMC and GFDM

Fig. 8 shows the BER Vs SNR curve for GFDM systems for 8QAM modulation. The modulation used is 8-QAM; the channel is AWGN. A raised cosine filter is used at the transmitter side with a roll-off factor of 0.15. System Bandwidth is 10 MHz. BER continues to decline smoothly, reaching values around 10^{-3}. This is indicative of the effective noise suppression and signal recovery capability of GFDM in moderate SNR regimes. The BER curve flattens out, showing a BER floor around $10^{-2.5}$-10^{-2}. This suggests the error rate does not improve further with increasing SNR, possibly due to system impairments (e.g., non-ideal channel estimation, synchronization issues) and inherent limitations of GFDM (e.g., inter-symbol or inter-carrier interference). Fig. 9 shows the Throughput Vs SNR curve for GFDM systems using the same system parameters. GFDM performs efficiently in terms of throughput, achieving near-maximum capacity beyond moderate SNR levels. The throughput saturation around 15 dB suggests that GFDM can achieve high performance with relatively low SNR, a valuable trait for energy- and bandwidth-efficient 5G systems.

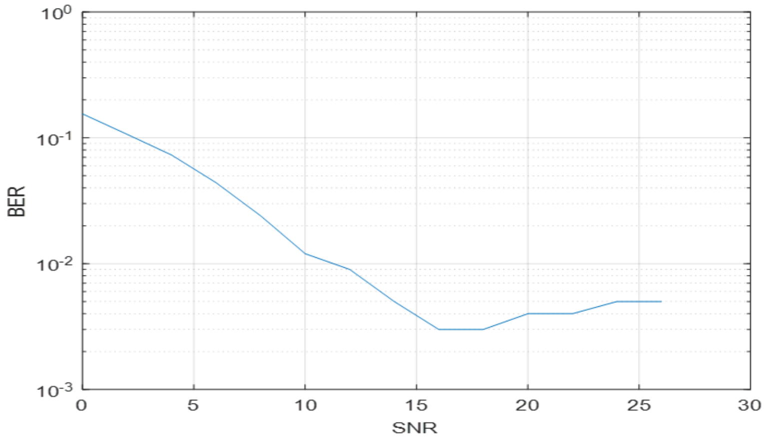


Fig. 8 BER Vs SNR for GFDM system

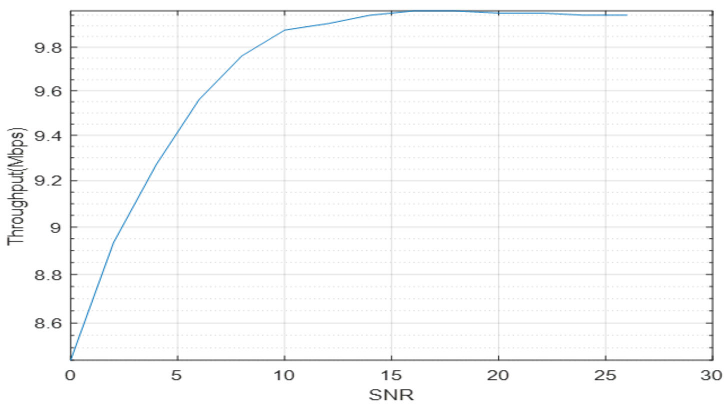


Fig: 9 Throughput Vs SNR for GFDM

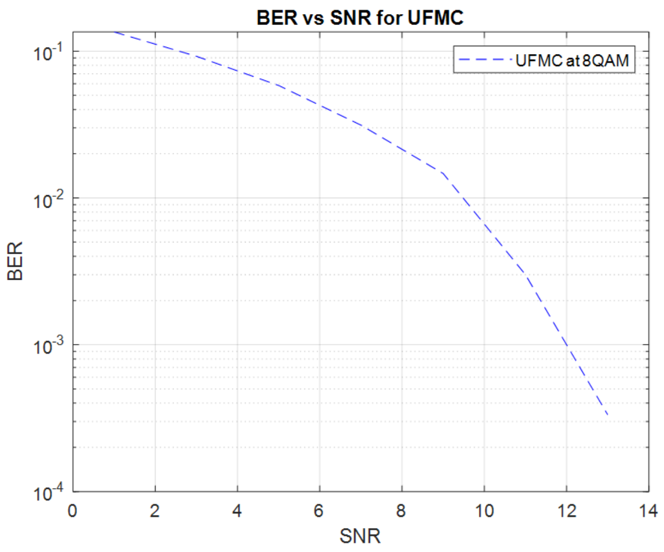


Fig. 10. BER Vs SNR for UFMC

From Fig. 10 BER versus SNR curve of UFMC shows that BER decreases exponentially with increasing SNR. Around 9–12 db, BER rapidly drops below 10^{-2}, reaching around $10^{-3.5}$ at 13–14 db.

Table 2: Comparison of the GFDM and UFMC 5G waveforms [16-19]

S. No.	Metrics for comparison of waveforms	Performance report
1	Backward Compatibility (4G LTE)	UFMC is compatible with LTE, but GFDM does not support backward compatibility
2	Latency	UFMC is used for low-latency applications
3	Standardization/Use	UFMC is considered for 5G NR and beyond. On the other hand, GFDM is experimentally studied in academia, but has not been standardized yet
4	Flexible, adapting to different scenarios	UFMC is the most flexible with various numerology
5	Compatibility for Short burst traffic	UFMC and GFDM are most suitable for short burst traffic
6	Complexity	GFDM has higher complexity due to block processing and filter design
7	Suitability for 6G Use Cases	UFMC is good for low-latency, high-reliability links, while GFDM is suitable for flexible Internet of Things (IoT) and asynchronous access scenarios

5. CONCLUSION

In this study, a comparison between GFDM and UFMC modulation techniques has been presented in the context of 5G New Radio. The evaluation was primarily focused on two key performance indicators: Power Spectral Density (PSD) and Bit Error Rate (BER) under varying channel conditions and SNR levels.

The PSD analysis revealed that UFMC offers better spectral confinement due to its sub-band filtering approach. This leads to reduced out-of-band emissions compared to GFDM, making UFMC more suitable for asynchronous transmission scenarios and spectrum-sharing environments. On the other hand, GFDM, which uses circular filtering, shows higher sidelobe levels but provides better flexibility in resource allocation and time-frequency localization.

UFMC outperforms GFDM in terms of spectral efficiency and OOB emission, making it a stronger candidate for environments requiring tight spectral masks and coexistence. UFMC outperforms GFDM in terms of BER, especially in higher SNR ranges. It achieves lower BER at lower SNR, showing better noise tolerance and more efficient symbol detection. Filtering in UFMC helps reduce out-of-band interference and maintains good symbol recovery under noise. Overall, both modulation schemes exhibit promising attributes for future 5G systems. The choice between UFMC and

GFDM should be application-specific, considering trade-offs in spectral containment, error resilience, and computational complexity.

REFERENCES

[1] Khushneet Kour and Kausar Al, “A Review Paper on 5G Wireless Networks”, International Journal of Engineering Research & Technology (IJERT), 2016, Volume 4, Issue 32, ISSN: 2278-0181.

[2] V. Vakilian et al., “Universal-filtered multi-carrier technique for wireless systems beyond LTE,” in *Proc. IEEE Globecom Workshops*, 2013, pp. 223–228.

[3] N. Michailow et al., “Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks,” *IEEE Trans. Commun.*, vol. 62, no. 9, pp. 3045–3061, Sept. 2014.

[4] S. H. Han and J. H. Lee, “An overview of peak-to-average power ratio reduction techniques for multicarrier transmission,” IEEE Wireless Commun., vol. 12, no. 2, pp. 56–65, Apr. 2005.

[5] B. Farhang-Boroujeny, “OFDM versus filter bank multicarrier,” IEEE Signal Process. Mag., vol. 28, no. 3, pp. 92–112, May 2011.

[6] Asia Hazareena, B. Aziz Musthafa “UFMC System Performance Analysis for 5G Cellular Networks” Turkish Journal of Computer and Mathematics Education Vol.12 No.10 (2021), 162-167.

[7] A. S. Ahmed, H. Al-amaireh, and Z. Kollar, “Multicarrier Modulation Schemes for 5G Wireless Access”, ECTI-CIT Transactions, vol. 16, no. 4, pp. 378–392, Sep. 2022.

[8] X. Gao, J. Zhang, L. Dai, and Z. Wang, "Low-Complexity GFDM Receiver Based on Successive Interference Cancellation," IEEE Transactions on Vehicular Technology, vol. 66, no. 2, pp. 1447–1451, Feb. 2017.DOI: 10.1109/TVT.2016.2554565

[9] D. Gaspar et al., “GFDM – A Flexible Multi-Carrier Modulation Scheme for 5th Generation Cellular Networks,” Proc. Eur. Wireless Conf., 2013.

[10] Y. Chen, Z. Liu, and Y. Li, “Performance analysis of 5G candidate waveforms under non-linear power amplifier,” IEEE Access, vol. 5, pp. 10352–10360, 2017.

[11] DOI: 10.1109/ACCESS.2017.2706621

[12] X. Zhang et al., “Comparison of candidate waveforms for 5G,” Proc. IEEE ICC Workshops, 2017. DOI: 10.1109/ICCW.2017.7962766

[13] F. Schaich and T. Wild, "Waveform contenders for 5G-OFDM vs. FBMC vs. UFMC," 2014 6th International Symposium on Communications, Control and Signal Processing (ISCCSP), Athens, Greece, 2014, pp. 457-460, doi: 10.1109/ISCCSP.2014.6877912.

[14] Nilofer, Shaik & Malik, Praveen. (2021). 5G Multi-Carrier Modulation Techniques: Prototype Filters, Power Spectral Density, and Bit Error Rate Performance. 10.21203/rs.3.rs-345216/v1.

[15] G Fettweis, M Krondorf, S Bittner, in Proc. IEEE 69th Vehicular Technology Conference (VTC). GFDM—generalized frequency division multiplexing, (2009), pp. 1–4. doi:10.1109/VETECS.2009.5073571

[16] R. Datta, N. Michailow, M. Lentmaier and G. Fettweis, “GFDM Interference Cancellation for Flexible Cognitive Radio PHY Design,” IEEE Vehicular Technology Conference (VTC Fall), Quebec City, QC, pp. 1-5. Sep.2012.

[17] A. Hazareena and B. A. Mustafa, "A Survey: On the Waveforms for 5G," 2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, India, 2018, pp. 64-67, doi: 10.1109/ICECA.2018.8474641.

[18] S. K. Sharma, T. E. Bogale, S. Chatzinotas, X. Wang, and B. Ottersten, “Waveform design for 5G and beyond: A survey,” IEEE Communications Surveys & Tutorials, vol. 23, no. 1, pp. 127–158, Firstquarter 2021, doi: 10.1109/COMST.2020.3033950.

[19] R. B. Nair, S. K. Sharma, T. E. Bogale, and S. Chatzinotas, “A survey on 5G waveforms: Challenges and design considerations,” Physical Communication, vol. 52, 2022, Art. no. 101619, doi: 10.1016/j.phycom.2021.101619.

[20] R. Anil Kumar, Kodati Satya Prasad. (2020). Comparative Analysis of OFDM, FBMC, UFMC & GFDM for 5G Wireless Communications. International Journal of Advanced Science and Technology, 29(05), 2097 - 2108. Retrieved from http://sersc.org/journals/index.php/IJAST/article/view/10903