International Journal of Multiphysics
Volume 18, No. 3, 2024
ISSN: 1750-9548

Enhancing 5G Cellular Communications: A Comparative Analysis of OTFS and GFDM Multiple Access Schemes

T. Sairam Vamsi[1], Harish Chandra Mohanta[2], Sudheer Kumar Terlapu[3] and M. Vamshi Krishna[4]

[1]Research Scholar, Centurion University of Technology and Management, Odisha; vamsi.0438@gmail.com

[2]Department of Electronics and Communication Engineering, Centurion University of Technology and Management, Bhubaneswar

[3]Shri Vishnu Engineering College for Women, Bhimavaram; profsudheer@ieee.org

[4]Dhanekula Institute of Engineering and Technology, Vijayawada; vamshi51@yahoo.co.in

Abstract: The primary goal of 5G cellular communications is to facilitate high-speed data transmission, increased channel capacity, and superior quality of service. Achieving these objectives hinges on the selection of appropriate multiplexing techniques. Among the various options available, Orthogonal Time Frequency Space (OTFS) and Generalized Frequency Division Multiplexing (GFDM) stand out as prominent choices. OTFS modulation employs a unique two-dimensional approach, utilizing delay-Doppler techniques for information symbol multiplexing. Compared to conventional methods, OTFS and GFDM offer improved performance in terms of Bit Error Rate (BER) and Peak to Average Power Ratio (PAPR), owing to pre and post-processing operations in OTFS and Pulse Shaping Filters in GFDM. This paper conducts a comparative analysis between existing multiple access schemes such as UFMC and FBMC, and proposed techniques like GFDM and OTFS. It evaluates various criteria including power spectral density, spectral efficiency, and BER and PAPR performance. A key highlight of this study is the PAPR analysis of OTFS, along with the utilization of the Modified Bartlett Hanning Filter (MBHF) as the Pulse Shaping Filter in GFDM analysis.

Keywords: GFDM, OTFS, BER, PAPR, Spectral Efficiency

1 Introduction:

The world has got a lot of changes in the entire of communication. In the initial stages of cellular communications, the mobile phones hardly used to connect a call but now much more activities are carried out along with call connection at the same time just due to technology advancements along with generations [1]. Cellular networks have evolved through various generations from 1G to 5G technology. As the number of mobile users increases rapidly, there is a hues requirement in speed and bandwidth. As per statistics data rate required to serve these hues number of customers is greater than 1Gbps with bandwidth of 3 to 30GHz. To achieve these values in cellular communication systems, multiplexing techniques plays a vital role [2]. By doing deep analysis, comes to know that OTFS (Orthogonal Time Frequency Space) and GFDM (Generalized Frequency Division Multiplexing) will produce good results in 5G Cellular systems.

The advent of 5G cellular communications marks a significant leap forward in wireless technology, promising unprecedented data rates, ultra-low latency, and massive connectivity to support the diverse needs of modern digital ecosystems [3]. To achieve these ambitious goals, 5G networks must adopt advanced modulation and multiple access schemes that can efficiently handle the increasing demands on spectrum and resources. Among the various candidates, Orthogonal Time Frequency Space (OTFS) and Generalized Frequency Division

Multiplexing (GFDM) have emerged as two innovative approaches that offer distinct advantages in different 5G scenarios [4].

OTFS, a novel modulation scheme that operates in the delay-Doppler domain, is designed to provide robust performance in highly dynamic environments such as high-mobility scenarios, where traditional methods like Orthogonal Frequency Division Multiplexing (OFDM) struggle [5]. Its resilience to Doppler shifts and time-variant channels makes OTFS particularly suitable for applications requiring high reliability and consistency, such as vehicular communications and high-speed trains [6].

On the other hand, GFDM is a flexible and generalized multicarrier scheme that extends the capabilities of OFDM by incorporating subcarrier filtering, which reduces out-of-band emissions and improves spectral efficiency [7]. GFDM's adaptability makes it a strong contender for diverse 5G applications, including those requiring efficient use of fragmented spectrum, such as Internet of Things (IoT) networks and machine-type communications [8].

This paper presents a comparative analysis of OTFS and GFDM, focusing on their performance in 5G cellular communications. By examining key metrics such as spectral efficiency, robustness to interference, computational complexity, and suitability for various 5G use cases, this study aims to provide insights into the strengths and limitations of each scheme [9]. The findings from this analysis will contribute to the ongoing efforts to enhance 5G networks and guide the selection of appropriate multiple access schemes for different deployment scenarios, ultimately supporting the diverse and evolving demands of future wireless communication systems.

OTFS is the Two-Dimensional modulation technique, which uses Pre and Post processing operations on Conventional multicarrier modulations [10]. Due to this OTFS will produce better Bit Error Rate values compared to remaining multiple access schemes. In other side, GFDM is another flexible multicarrier modulation scheme, in which modulation is performed on independent blocks, each block consists of group of subcarriers and each subcarrier can carry group of sub symbols. The GFDM employs prototype filtering to all the subcarriers by shifting circularly in both frequency and time domain, which results in reducing Out of Band (OOB) emission, Inter Symbol (ISI) and Inter carrier (ICI) interferences [11]. Recently, there are some researchers working on these latest multiplexing techniques to serve 5G.

The authors Davide Mattera, Mario Tanda, discussed another multiplexing technique such as FBMC (Filter Bank Multi Carrier) with OQAM (Orthogonal QAM) modulation technique. This FBMC operates with smaller number of sub carriers that that required for other multicarrier systems and having the limitation of more receiver complexity [12].

The authors Evren Catak, Arild Moldsvor, Mohammad Derawi, discussed performance analysis of GFDM and uses Hexagonal Time -Frequency Allocation by Polyphase decomposition for analysing BER performance. Due to usage of polyphase decomposition PAPR value increases which cannot be tolerated.

The authors G. D. Surabhi, Rose Mary Augustine, and Ananth Narayanan Chockalingam, discussed OTFS multiplexing technique which uses Pre and Post processing operations on the information symbol to improvise BER, but the PAPR of OTFS signal is high which will be considered as its limitation.

After doing peer literature survey, there is a gap identified in PAPR analysis of OTFS, which was fulfilled in this paper and also a novel pulse shaping filter named as Modified Bartlett Hanning Filter (MBHF) is introduced for analysis of GFDM.

2. Literature survey

Guen et al. [13] investigated the various OFDM waveforms that have been suggested for 5G. The results demonstrated that F-OFDM outperformed CP-OFDM and W-OFDM in the high SNR domain in terms of spectral efficiency and robustness. As the inter-numerology out-of-band interference becomes stronger, these variables become more important. Therefore, F-OFDM (guard band removed entirely) can obtain the optimal spectrum utilisation.

An efficient CE-OFDM-CDMA type modulation method for 5G communication was proposed by Jamal Mes oui et al. [14]. This scheme exhibits strong energy efficiency and good spectral efficiency, which are modulation index dependent.

An FBMC method was suggested for future wireless communications by Ronald Nissel et al. [15]. The results show that both channel estimation and multi-antenna solutions benefit from the FBMC-based scheme. An FFT core-based feedback loop is employed in the design of a low-power FBMC transceiver architecture in to accommodate varying numbers of subscribers or multi-users. As compared to the standard approach, the suggested solution uses 15% less resources.

Many authors, such Jae Hoon Park et al. [16], have put forward ideas that utilise the OQAM-FBMC version to create a communication-effective WOLA structured transceiver. The developed transceiver outperforms the competition in BER.

Farhang-Boroujeny et al. (2011) [17] Traditional multiple access techniques like OFDM (Orthogonal Frequency Division Multiplexing), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access) have been widely used in previous generations of mobile networks. However, their limitations, such as sensitivity to Doppler shifts and high out-of-band emissions, have necessitated the exploration of new multiple access schemes. OTFS (Orthogonal Time Frequency Space) and GFDM (Generalized Frequency Division Multiplexing) have emerged as potential candidates for 5G and beyond, offering solutions to the challenges posed by high-mobility environments and diverse application requirements.

In response to 5G system situations like low latency, low Peak-to-average power ratio, and low emission off bandaged, Meryem Maraş et al. [18] suggested the LWT-GFDM approach. To enhance the spectral efficiency of GFDM systems in nonlinear channels with memory, Alexander Hilario-Tacuri et al. introduced closed-form analytical formulations.

Reference	focus	Key points
Andrews, J. G., et al. (2014).	Overview of 5G and key technologies	- Overview of 5G objectives (high data rates, low latency, massive connectivity) - Key technologies: MIMO, mmWave, advanced multiple access schemes
Goldsmith, A. (2005)	Traditional and emerging multiple access schemes	- Limitations of traditional schemes (OFDM, TDMA, CDMA) in 5G - Introduction to OTFS and GFDM as potential 5G multiple access schemes
Hadani, R., et al. (2017).	Theory and advantages of OTFS	- OTFS in delay-Doppler domain - Resilience to Doppler shifts and time-variant channels - Advantages in high-mobility environments
Fettweis, G., et al. (2009).	Concept and benefits of GFDM	- Flexible subcarrier filtering - Reduced PAPR and out-of-band emissions - Adaptability to different channel conditions

Table 1: literature survey summary.

3. Methodology

3.1 FBMC and UFMC (Existing Schemes)

Filtered Bank Multi Carrier (FBMC) is an extension of OFDM which is a multiple access scheme of 4G communications and it is more flexible because of negligible Out of Band (OOB) emission. It also offers good spectral efficiency compared to OFDM and other schemes in 5G even offers better than proposed schemes GFDM and OTFS because of two reasons

i) Not adding Cyclic Prefix (CP) to original information during transmission, which will reduce interreference caused in symbols.

ii) Due to usage of Synthesis Filter Bank (SFB) which involves overlapping of sub symbols during transmission.

For a system with K sub carriers with overlapping factor N, then the length of filter L= KN-1. The impulse response $h(t)$ of the filter (SFB) in time domain can be represented as

$$h(t) = 1 + 2\sum_{n=-(N-1)}^{(N-1)} H_n^2 \cos\left(2\pi \frac{nt}{NT}\right) \quad (1)$$

the corresponding frequency domain expression of the SFB can be represented as

$$H(f) = \sum_{n=-(N-1)}^{(N-1)} H_n^2 \frac{\sin\left(\pi\left(f-\frac{n}{KN}\right)KN\right)}{KN \sin\left(\pi\left(f-\frac{n}{KN}\right)\right)} \quad (2)$$

The frequency spectrum of FBMC majorly effected by overlapping factor N, the side lobe power is gradually decreases by increasing value of N, which gives effective utilization of bandwidth and hence increases spectral efficiency [19].

Universal Filtered Multicarrier (UFMC) is yet another multiple access scheme for 5G having similar advantages compared to FBMC. The filtering process is quite different in UFMC, here total available bandwidth is divided into number of sub bands and each sub band is allocated with set of data bits for transmission [20]. This UFMC also offers better spectral efficiency by covering all the sub carriers with in the bandwidth of the filter [21]. Let K represents number of sub carriers, the frequency domain impulse response of UFMC can be written as

$$H(f) = \frac{\cos\left\{K\,cos^{-1}\left[\alpha \cos\left(\frac{\pi n}{K}\right)\right]\right\}}{\cos[K\ \cos h^{-1}\,(\alpha)]} \quad (3)$$

Where n = 0,1,2, _ _ _ K-1 and α represents reduction of adjacent lobes.

3.2 System models of OTFS and GFDM

The figure 1 shows the System model for OTFS modulation. Compared to conventional techniques OTFS gives enhanced Bit Error rate (BER) performance because of using Pre and Post processing operations on the information symbols [22]. In OTFS, channel shows very minute differences in delay-Doppler domain due to rapid variation of multipath channel with respect to time [23]. The channel in OTFS becomes time-invariant for a longer period because of delay-Doppler representation, this makes channel estimation happens less frequent [24]. Which ultimately reduces estimation overhead.

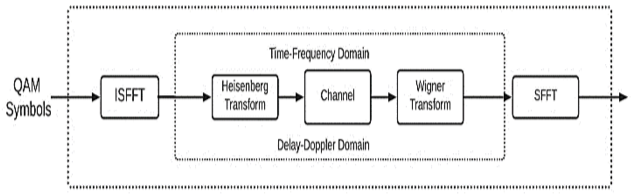

Fig.1 System model of OTFS

The transmitter section of OTFS uses 2D Inverse Symplectic Finite Fourier transform (ISFFT) to map QAM symbols with 2D delay-Doppler grids in time-frequency plane. It uses Heisenberg transform to convert obtained time-frequency signal into time domain and then transmits through channel [25].

Let consider the OTFS waveform with PQ information symbols, where P represents No. of Delay bits and Q denotes No. of Doppler bits. The Heisenberg transform of the information symbols are indicated as

$$s(t) = \sum_{p=0}^{P-1}\sum_{q=0}^{Q-1} X(p,q)\, g_{tx}(t-qT)e^{j2\pi m\Delta f(t-qT)} \quad (4)$$

where g_{tx} represents transmit periodic pulse shape signal with time duration of PT.

The signal s(t) is transmitted over the channel and received signal after channel can be represented as

$$r(t) = \int H(t,f)\, S(f)\, e^{j2\pi ft}\, df \quad (5)$$

Where $H(t,f)$ and $S(f)$ represents Heisenberg transform in time-frequency domain and transmitted signal in frequency domain. The receiver of OTFS uses Wigner transform (W) and Symplectic Finite Fourier transform (SFFT), the Winger transform used to convert received signal in time domain to time-frequency domain and SFFT used to map these time-frequency symbols into delay-Doppler grid.

$$W(t,f) = A_{g_{rx,r(t,f)}} = \int g_{rx}^{*}(t-T)\, r(t) e^{-j2\pi f(t-qT)} dt \qquad (6)$$

The figure 2 shows the transceiver of GFDM, the input signal is modulated using GFDM modulator the data obtained after modulation is parallel and it is converted to serial data by parallel to serial conversion and then cyclic prefix is added. It is used to protect the signal from inter-symbol interference and the signal passes through the channel and AWGN (additive white Gaussian noise) is added to the output signal of the channel and then these two signals are added. Then the signal passes through cyclic prefix removal. The data obtained after cyclic prefix removal is in serial and it is converted to parallel data by serial to parallel conversion. The signal is demodulated at the GFDM demodulator then the received signal is obtained after the demodulation process.

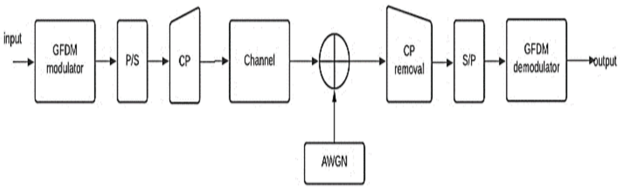

Fig. 2 System model of GFDM

The transmission in GFDM is done for each block, where each block contains K subcarriers in which each subcarrier transmits M sub symbols. Hence for each block of GFDM transmits a total of D=KM Symbols every time, Where D is the number of symbols transmitted.

3.3 Modified Bartlett Hanning Filter for GFDM

The Pulse Shaping Filters [PSF] plays a vital role in GFDM, which minimises Inter Symbol Interference (ISI) by modifying the characteristics of transmitted signal in according to channel features like minimizing bandwidth, changing amplitudes and shapes. There are many PSFs are developed to serve GFDM like Raised Cosine (RC), Root Raised Cosine (RRC), Better than Root Raised Cosine (BRCF) which are having only one control variable to change characteristics of signal, but MBHF having two control variables to control shaping of filter which leads to less ISI and less BER values are obtained.

$$P_{MBHF} = sinc\left(\frac{\tau}{T}\right)\left[\left(\frac{2\,(1-\gamma)\sin\left(\frac{\pi\alpha\tau}{T}\right)}{1-\left(\frac{2\alpha\tau}{T}\right)^{2}}\right) - \left(\frac{(1-2\gamma)\cos\left(\frac{\pi\alpha\tau}{T}\right)}{\left(\frac{\alpha\pi\tau}{T}\right)}\right)\right] \qquad (7)$$

The above is the major expression used to implement MBHF filter, where α as the rolling factor and γ is the windowing factor. Generally, the value of α is lies between 0 to 1 and the value of γ lice between 0.5 to 1.88 for obtaining accurate transmission of information with GFDM.

3.4. BER and PAPR

In general, performance of any multiplexing technique can be estimated with the help of BER and PAPR. The definitions and formulas used for calculation of these parameters as follows

PAPR is the square of peak amplitude divided by square of RMS value. Generally, PAPR value is affected when the sub-carriers in the multicarrier system are out of phase with each other. At any instant, the PAPR values are different with respect to each other for different phase values. Generally, high PAPR is not recommended and it can be expressed as,

$$PAPR = {\mathrm{x}_{\mathrm{peak}}}^{2} / {\mathrm{x}_{\mathrm{rms}}}^{2} \qquad (8)$$

Where $\mathrm{x}_{\mathrm{peak}}$ and $\mathrm{x}_{\mathrm{rms}}$ are the peak value and rms values of transmitted signal. PAPR value in dB can be expressed in equation 8.

$$\mathrm{PAPR} = 10\log\left({\mathrm{x}_{\mathrm{peak}}}^2 / {\mathrm{x}_{\mathrm{rms}}}^2 \right) \quad (9)$$

In particular, the PAPR of OTFS signal can be estimated with the help of

$$PAPR = \frac{max_{r,y}\{ |〚s(r+xP)| 〛^2\}}{X_{avg}} \quad (10)$$

Where

$$X_{avg}=\frac{1}{PQ}\sum_{r=0}^{P-1}\sum_{y=0}^{Q-1}\sum〚E\,\{|s(r+xP)|〛^2\} \quad (11)$$

and

$$max_{r,y}|s(r+xP)|^2 = P^2 max_{r,y}|\sum_{n=0}^{P-1}\overline{x_r}[n]g_{tx}([r+xP-nQ]_{PQ})\text{\^{}}2 \quad (12)$$

In General, OTFS and GFDM techniques the PAPR can also be calculated with the help of Complementary Cumulative Distribution Function (CCDF), it can be expressed as

$$\mathrm{CCDF}(\delta) = P_{papr}\,(\mathrm{PAPR}\,(y\,[n]) > \delta) = 1-(1-e^{-\delta}) \quad (13)$$

Where δ is the average threshold value.

BER is ratio of number of bit error occurs to the number of bits transmitted and it is expressed as,

$$BER = \frac{\text{N Errors}}{\text{N Bits}} \quad (14)$$

At the receiver side of communication system, the values of BER are affected due to many parameters such as synchronization of information bits, signal distortion, channel noise and multipath fading, etc… The performance of BER can be improved by choosing strong signal strength at the transmitter and also Multiplexing and modulation technique. This BER can be calculated with respect to SNR and it is defined as,

SNR $=\frac{\mathrm{p}_{\mathrm{out}}}{\mathrm{p}_{\mathrm{z}}}$, Where p_{z} is the noise power and $\mathrm{p}_{\mathrm{out}}$ is the high-power amplifier average output power.

4. Results and Discussion

With the help of mathematical analysis discussed above and by taking simulation environment mentioned in table1, the calculation and analyzation of BER, PAPR and PSDs are explained bellow

Table 1 Definition of Parameters

	Preferred Value			
Parameter	**OTFS**	**GFDM**	**FBMC**	**UHMC**
No. of Symbols	8	8	100	5
No. of Samples per Symbol	512	512	512	512
No. of Sub symbols	14	14	14	14
No. of allocated Sub carriers	1200	1200	1200	1200
Sub band Offset	-	-	212	156
No. of Doppler taps	4	-	-	-
No. of Delay taps	4	-	-	-
Modulation technique	QAM	QAM	QAM	QAM
Pulse Shaping filter	-	MBHF	-	-
Roll off factor	-	0.1		

SNR (in dB)	0,2,4 _ _ _ _20

The Table1 shows the different parameters taken for simulation of OTFS, GFDM, FBMC and UFMC. The Power Spectral Density (PSDs) four multiple access schemes are shown in Figure 3, Figure 4, Figure 5 and Figure 6 respectively.

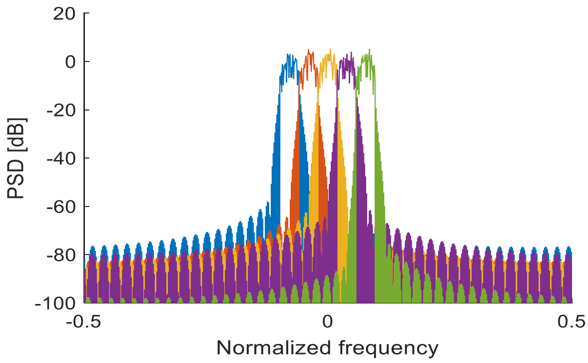

Fig. 3 Normalized frequency vs PSD (dB) of UFMC

On comparing PSDs of four multiplexing techniques like Existing technique like UFMC and FBMC, Proposed technique like OTFS and GFDM are shown in Table 2. For analysis UFMC and FBMC are taken with respect to Normalized frequency because of using multiple filter banks, GFDM and OTFS are analysed with respect to frequency (Hz). Based on definition of Normalized frequency all four techniques analysis are performed at same values. On comparison the FBMC having very less side lobe power i.e -170dB, this shows efficient utilization of frequency spectrum by FBMC which leads to increase of spectral efficiency. This will be considered as limitation in proposed techniques because of Non orthogonality behaviour in GFDM and complex transforms, filters used in OTFS. But due to same features these techniques will gives excellent performance in BER and PAPR analysis.

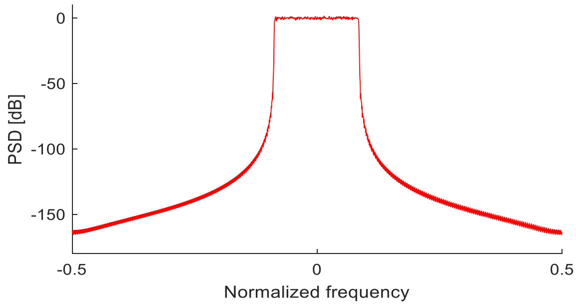

Fig. 4 Normalized frequency vs PSD (dB) of FBMC with N=4

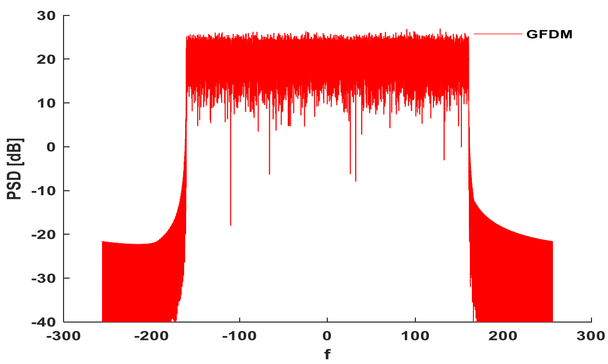

Fig. 5 frequency vs PSD (dB) of GFDM

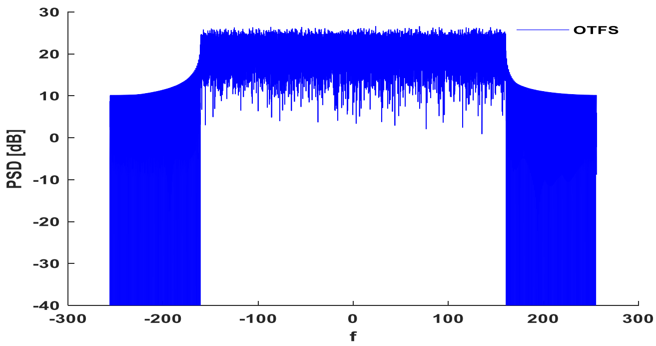

Fig. 6 frequency vs PSD (dB) of OTFS

Table 2 PSD values at sidelobes

Multiple Access Scheme	Normalized frequency/ frequency (Hz)	PSD (dB) value
UFMC	-0.5	-80
FBMC	-0.5	-170
GFDM	-250	-20
OTFS	-250	10

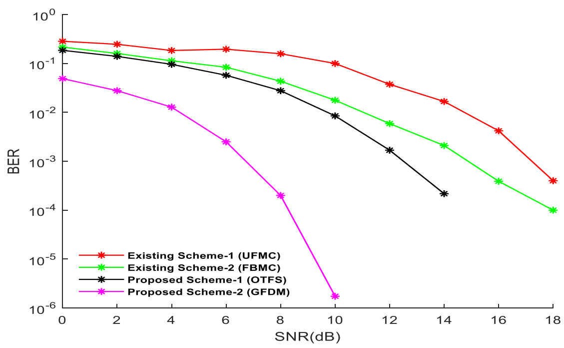

Fig. 7 BER vs SNR of GFDM and OTFS

The Figure 7 shows Bit Error Rate (BER) vs Signal to Noise Ratio (SNR) plot for existing and proposed multiple access schemes. In general, BER should be as low as possible to achieve low latency with high speed for the signal at the receiver end. By observing above Figure 7, the BER curves of proposed schemes are far better compared to existing schemes. The obtained BER values are very less because of using novel pulse shaping filter named as MBHF in GFDM and because of using Heisenberg, Wigner transform in OTFS. The linearity of curves also another added advantage in proposed techniques.

Table 3 PAPR analysis of four Multiple access schemes

QAM Modulation	No of Bits per Sub carrier	PAPR values of four schemes			
		OTFS	GFDM	FBMC	UFMC
4 QAM	2	6.182	6.0286	9.6503	8.5357
16 QAM	4	5.956	5.1923	8.7711	7.3575
64 QAM	6	5.695	4.4367	8.1743	6.9765
256 QAM	8	5.66	4.1557	7.3	5.2901
1024 QAM	10	4.7	3.991	6.4	4.0215

The above Table 3 shows PAPR values for four multiplexing techniques for different values of N-QAM and by taking no. of bits per sub carrier as 2, 4, 6, 8 or 10. So, from the table noted that again GFDM and OTFS multiplexing schemes has less PAPR compared to UFMC and FBMC, because having too many sub carriers with separate filtered banks. Generally, PAPR value should be as low as possible to have the accurate signal at receiver end and to maintain high speed with low latency.

6. Conclusion and Future scope

In 4G cellular communications, data transmission employing Orthogonal Frequency Division Multiplexing (OFDM) often encounters challenges related to high Peak to Average Power Ratio (PAPR) and Bit Error Rate (BER), rendering it less suitable for high-speed data transmission in 5G networks. This paper focuses on the performance analysis of two advanced multiplexing techniques, namely Orthogonal Time Frequency Space (OTFS) and Generalized Frequency Division Multiplexing (GFDM), which are more suited for 5G networks. It is observed that the orthogonality in data transmission and the utilization of two-dimensional Delay Doppler techniques in GFDM and OTFS contribute to better performance in terms of BER and PAPR compared to existing techniques such as UFMC and FBMC. However, the reliance on similar methodologies in both techniques poses challenges in efficiently utilizing spectrum, which remains a key concern for researchers in the field of 5G communications.

References:

[1] R. Hadani et al., “Orthogonal time frequency space modulation,” in Proc. IEEE Wireless Commun. Netw. Conf. (WCNC), Mar. 2017, pp. 1–6.

[2] R. Datta, N. Michailow, M. Lentmaier, and G. Fettweis, “GFDM Interference Cancellation for Flexible Cognitive Radio PHY Design,” in Proceedings 76th IEEE Vehicular Technology Conference (VTC Fall’12), Québec City, Canada, Sep. 2012, pp. 1–5.

[3] D. Mattera and M. Tanda, "FBMC/OQAM Transceiver for Ultralarge Bandwidths," 2020 IEEE 5th International Symposium on Telecommunication Technologies (ISTT), 2020, pp. 111-116, doi: 10.1109/ISTT50966.2020.9279347.

[4] Catak, E.; Moldsvor, A.; Derawi, M. Transceiver Design for GFDM with Hexagonal Time–Frequency Allocation Using the Polyphase Decomposition. Electronics 2020, 9, 1862. https://doi.org/10.3390/electronics9111862.

[5] G. D. Surabhi, R. M. Augustine and A. Chockalingam, "Peak-to-Average Power Ratio of OTFS Modulation," in IEEE Communications Letters, vol. 23, no. 6, pp. 999-1002, June 2019, doi: 10.1109/LCOMM.2019.2914042.

[6] P. Raviteja, Y. Hong, E. Viterbo, and E. Biglieri, “Practical pulse-shaping waveforms for reduced-cyclic-prefix OTFS,” IEEE Trans. Veh. Tech., vol. 68, no. 1, pp. 957–961, Jan. 2019.

[7] K. R. Murali and A. Chockalingam, “On OTFS modulation for high Doppler fading channels,” in Proc. ITA, San Diego, CA, USA, Feb. 2018, pp. 1–10.

[8] M. Murad, I. A. Tasadduq and P. Otero, "Towards Multicarrier Waveforms Beyond OFDM: Performance Analysis of GFDM Modulation for Underwater Acoustic Channels," in IEEE Access, vol. 8, pp. 222782-222799, 2020, doi: 10.1109/ACCESS.2020.3043718.

[9] N. Michailow et al., “Generalized frequency division multiplexing for 5th generation cellular networks,” IEEE Trans. Commun., vol. 62, no. 9, pp. 3045–3061, Sep. 2014.

[10] Saxena R and Joshi HD, “Performance Improvement in OFDM system with MBH Combinational pulse shapes”, Published in Digital Signal Processing, 23(1), 314-321, 2013.

[11] Mara¸s, M.; Ayvaz, E.N.; Gömeç, M.; Sava¸scıhabe¸s, A.; Özen, A. A Novel GFDM Waveform Design Based on Cascaded WHT-LWT Transform for the Beyond 5G Wireless Communications. Sensors 2021, 21, 1831. https://doi.org/10.3390/ s21051831.

[12] Jinqiu Wu, Xuefei Ma, Xiaofei Qi, Zeeshan Babar, Wenting Zheng, "Influence of Pulse Shaping Filters on PAPR Performance of Underwater 5G Communication System Technique: GFDM", Wireless

Communications and Mobile Computing, vol. 2017, Article ID 4361589, 7 pages, 2017. https://doi.org/10.1155/2017/4361589.

[13] Guan, P., Wu, D., Tian, T., Zhou, J., Zhang, X., Gu, L., Benjebbour, A., Iwabuchi, M. and Kishiyama, Y. (2017) 5G Field Trials: OFDM-Based Waveforms and Mixed Numerologies. IEEE Journal on Selected Areas in Communications, 35, 1234-1243.

[14] Mestoui, J., Ghzaoui, M.E., Elaage, S., Hmamou, A. and Foshi, J. (2021) CE-OFDM-CDMA Phase Modulation for 5G System. International Journal of Mathematical, Engineering and Management Sciences, 6, 1100-1114. https://doi.org/10.33889/IJMEMS.2021.6.4.065

[15] 15.Nissel, R., Schwarz, S. and Rupp, M. (2017) Filter Bank Multicarrier Modulation Schemes for Future Mobile Communications. IEEE Journal on Selected Areas in Communications, 35, 1768-1782. https://doi.org/10.1109/JSAC.2017.2710022

[16] Park, J.H. and Lee, W.C. (2018) An Efficient WOLA Structured OQAM-FBMC Transceiver. 2018 Tenth International Conference on Ubiquitous and Future Networks (ICUFN), Prague, 3-6 July 2018, 782-784. https://doi.org/10.1109/ICUFN.2018.8437042

[17] Farhang-Boroujeny, B. (2011). "OFDM versus filter bank multicarrier." IEEE Signal Processing Magazine, 28(3), 92-112.

[18] Maraş, M., Ayvaz, E.N., Gömeç, M. and özen, A. (2019) Improving the Performance of GFDM Waveform Employing Lifting Wavelet Transform. 2019 27th Signal Processing and Communications Applications Conference (SIU), Sivas, 24-26 April 2019, 1-4.

[19] Divya, K. S., Swetha, G., Charyulu, G. M., Madhuri, P. S., Srividya, M., Mutar, M. L., & Saikumar, K. (2024, April). Implementing Blockchain Based DApp for Secure Sharing of Students' Credentials. In *2024 IEEE 9th International Conference for Convergence in Technology (I2CT)* (pp. 1-6). IEEE.

[20] Vadlamudi, M. N., Jayanthi, N., Swetha, G., Nishitha, P., Al-Salman, G. A., & Saikumar, K. (2024, April). IoT Empowered GNSS Tracking in Real-time via Cloud Infrastructure. In 2024 IEEE 9th International Conference for Convergence in Technology (I2CT) (pp. 1-6). IEEE.

[21] Rao, K. M., Kumar, P. S., Reddy, T. V., Nilima, D., Saikumar, K., & Khlaif, A. M. (2024, April). Ultra Low Power High Speed DFT Implementation For ASIC SoC. In *2024 IEEE 9th International Conference for Convergence in Technology (I2CT)* (pp. 1-6). IEEE.

[22] Reddy, T. V., Saikumar, K., Reddy, R. A., Chary, V. B., Srinija, P., & Reddy, T. H. V. (2024, April). Integrating Soil Sensing and Rainfall Modelling for Precision Crop Recommendation Systems. In *2024 IEEE 9th International Conference for Convergence in Technology (I2CT)* (pp. 1-6). IEEE.

[23] Revathi, R., Kumar, K. S., Hamid, H. A., & Ahammad, H. S. (2024, March). A real time homogeneous wireless sensor network functioning using semi-tier clustering protocol for energy efficiency routing. In *AIP Conference Proceedings* (Vol. 2919, No. 1). AIP Publishing.

[24] Bommagani, N. J., Venkataramana, A., Vemulapalli, R., Singasani, T. R., Pani, A. K., Challageri, M. B., & Kayam, S. (2024). Artificial Butterfly Optimizer Based Two-Layer Convolutional Neural Network with Polarized Attention Mechanism for Human Activity Recognition. *Mathematical Modelling of Engineering Problems*, *11*(3).

[25] Kumar, G. N. K., Reddy, M. S., Malleswari, D. N., Rao, K. M., & Saikumar, K. (2024). A Real-Time Hadoop Bigdata Maintenance Model using A Software-Defined and U-Net Deep Learning Mode. International Journal of Intelligent Systems and Applications in Engineering, 12(7s), 364-376.