

Pulse Based GFDM Modulation Technique for Future Generation Communication Systems

Shatrughna Prasad Yadav

Abstract — Future mobile communication systems are mainly focused on flexibility, reliability, scalability, spectral efficiency, and robustness. A higher data rate, increased capacity, higher mobility, lower latency, and improved quality are prime objectives that need to be improved in future communication systems. This paper investigates generalized frequency division multiplexing (GFDM), a suitable waveform candidate for future communication systems. It has low complexity compared to FBMC and is highly suitable for burst signal transmission. Due to the use of non-rectangular pulse shaping, out-of-band leakage is also less. This technique is more flexible in terms of frequency localization, scalability, and integration with MIMO. Its performance in terms of BER has been computed considering the number of subcarriers, number of sub-symbols, input power back-off, and roll-off factor as variable parameters. It has been observed that change in the BER is low when the number of subcarriers is changed but is more for change in the number of sub-symbols. Its performance degrades when the number of subcarriers, the value of the roll-off factor, and the power back-off are increased. But BER performance improves with an increase in the number of sub-symbols.

Keywords — 5G, Bit Error Rate, Generalized Frequency Division Multiplexing, Out-Of-Band Leakage, Spectrum Efficiency.

I. INTRODUCTION

Spectrum efficiency, energy efficiency, and power efficiency are the major thrust areas that need to be optimized in future-generation mobile communication systems. Spectrum efficiency is the rate of data transmission over a given bandwidth, whereas energy efficiency is the measure of energy consumption by the system that includes both hardware and software involved in data processing. On the other hand, power efficiency is the measure of power required for signal transmission [1]. Requirements for future mobile communication are focused on flexibility, reliability, scalability, spectral efficiency and robustness. In particular, low latency is required for tactile internet services, high data rate in terms of 10 Gbps transmission is required for enhanced broadband services, massive connectivity is required for low power machine type communication and last but not the least, and greater coverage is required for wireless regional area network (WRAN). Filter bank multi-carrier (FBMC) and generalized frequency division multiplexing (GFDM) based on pulse shaping technique are considered to be suitable waveform candidate for future communication systems [2]. There is low power loss as synchronized of data is not required as both of these techniques do not require orthogonality to be maintained. Due to the use of non-

rectangular pulse shaping, out-of-band leakage is also less. In the case of FBMC, filter banks are used for modulation and demodulation process that does not demand strict requirement of synchronization between subcarriers [3]. But in FBMC design of prototype filters are highly complex as it has to meet the specific frequency response [4]. Whereas, GFDM is a flexible technique having two-dimensional data structure in time as well as in the frequency domain. It has low complexity compared to FBMC and is highly suitable for burst signal transmission [5].

II. OFDM TECHNIC

In the orthogonal frequency division multiplexing (OFDM) technique, the signal is generated by the multiplication of data symbols with subcarriers [6]. Equation (1) represents the generation of such OFDM signal.

$$x_k = \sum_{n=0}^{N-1} X_i e^{\frac{j2\pi kn}{N}} \quad (1)$$

Here, the data symbol is represented by X_i for the n -th subcarrier. In order to reduce inter-carrier interference (ICI) and inter-symbol interference and to maintain orthogonality among of subcarriers cyclic prefix (CP) is added between each symbol [7]. Fig. 1 depicts the OFDM system used in 4G mobile communication systems [8]. OFDM is used for downlink transmission in the 4G system as a multi carrier communication system as it provides better spectrum utilization, less susceptible to interference and multipath fading apart from possessing high data rate transmission capability. OFDM uses cyclic prefix (CP) to reduce the inter symbol interference, and simple receiver that is based on fast Fourier transform [9]. But it has low spectrum efficiency due to CP being added with each symbol, large side lobe owing to use of rectangular pulses, high peak to average power ratio, apart from strict requirement of synchronization to maintain orthogonality among the subcarriers [10]. In the case of internet of things (IoT) and wireless sensor network (WSN) data generated from sensors cannot be guaranteed to be synchronous [11]. Hence, requirement of synchronization cannot be met for future mobile communication systems. Due to these shortcoming OFDM is not considered as a suitable waveform for 5G and beyond communication systems [12].

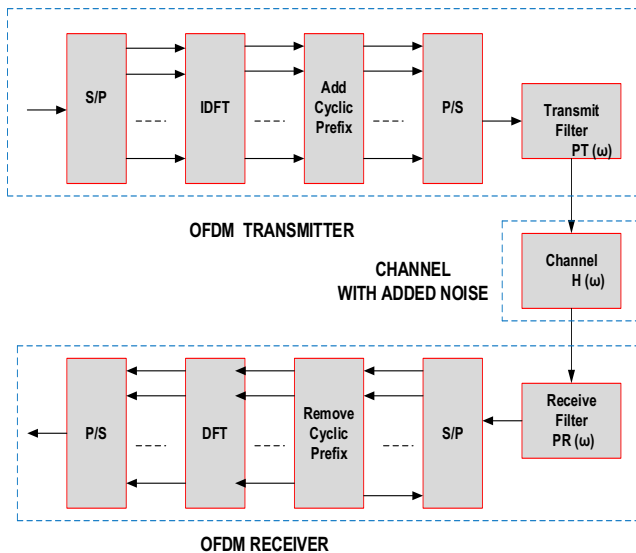


Fig. 1. Orthogonal Frequency Division Multiplexing System.

PAPR of the OFDM system is comparatively high due to fluctuations in the output and is represented in terms of complementary cumulative distribution function (CCDF) [13]. CCDF is a parameter to determine the probability of the PAPR being higher than a threshold value z as expressed by (2).

$$\tilde{F}_{z_{\max}}(z) = P(z_{\max} > z) = 1 - P(z_{\max} \leq z) = 1 - F_{z_{\max}}(z) = 1 - (1 - e^{-z^2})^N \quad (2)$$

Fig. 2 shows the PAPR of the OFDM communication system for different numbers of subcarriers, $N = 64, 128, 256, 512$, and 1024 with QPSK modulation. It is evident from the figure that PAPR increases with an increase in the number of subcarriers. High PAPR is undesirable as it causes the power amplifier to operate in the nonlinear region and produces distortion in its output [14].

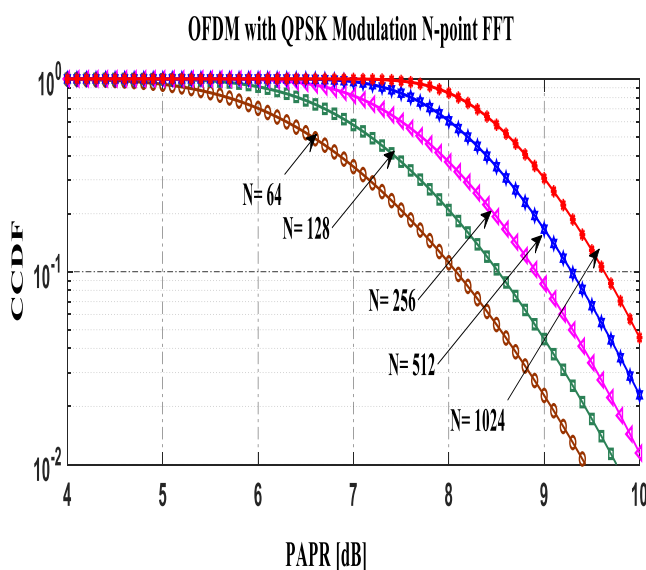


Fig. 2. PAPR of OFDM system with QPSK modulation.

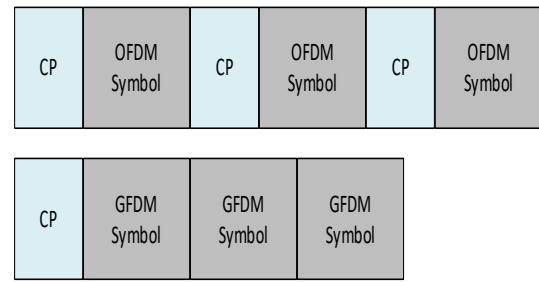


Fig. 3. OFDM and GFDM Symbol structure.

The data block structures of OFDM and GFDM are entirely different, even though both of them have many similarities. OFDM data block has one-dimensional data structure, whereas GFDM has a two-dimensional data structure [15]. Fig. 3 reflects the structural difference between OFDM and GFDM symbols.

III. GENERALIZED FREQUENCY DIVISION MULTIPLEXING

In the present paper, Generalized Frequency Division Multiplexing (GFDM) has been investigated that is based on pulse shaping novel orthogonal multiple accessing (OMA) technique and is used in 5G new radio (NR) networks [16]. GFDM does not require maintaining orthogonality among subcarriers, hence power loss can be minimized. By using nonrectangular pulse shaping, out of band leakage can also be reduced [17]. GFDM data block has two-dimensional structure in frequency and time domain, hence it has more flexible waveform, lower equalization complexity and is more suitable for burst signal transmission [18].

In OFDM system K number of subcarriers are divided only into the frequency domain whereas GFDM system divides the spectrum into K number of subcarriers in frequency domain as well as M number of sub symbols in time blocks. Fig. 4 shows the block structure of GFDM system [19].

GFDM systems are more flexible in terms of frequency localization, scalability and integration with MIMO [20]. Fig. 5 exhibits the block diagram of GFDM system. GFDM is equivalent to OFDM when number of sub block, $M = 1$, and rectangular pulse shaping is used [21].

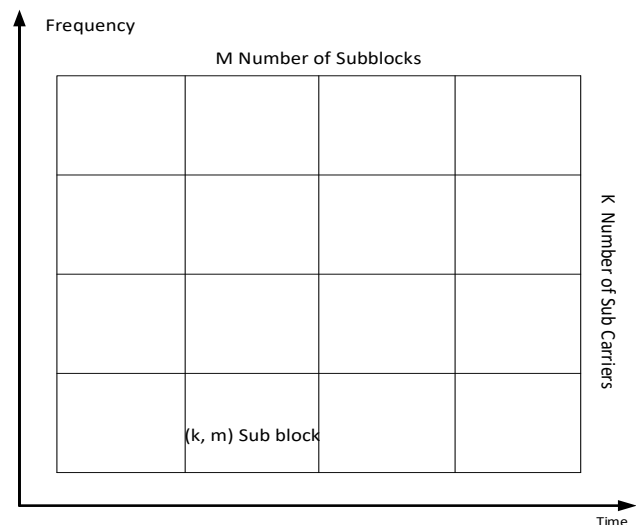


Fig. 4. Block Structure of GFDM.

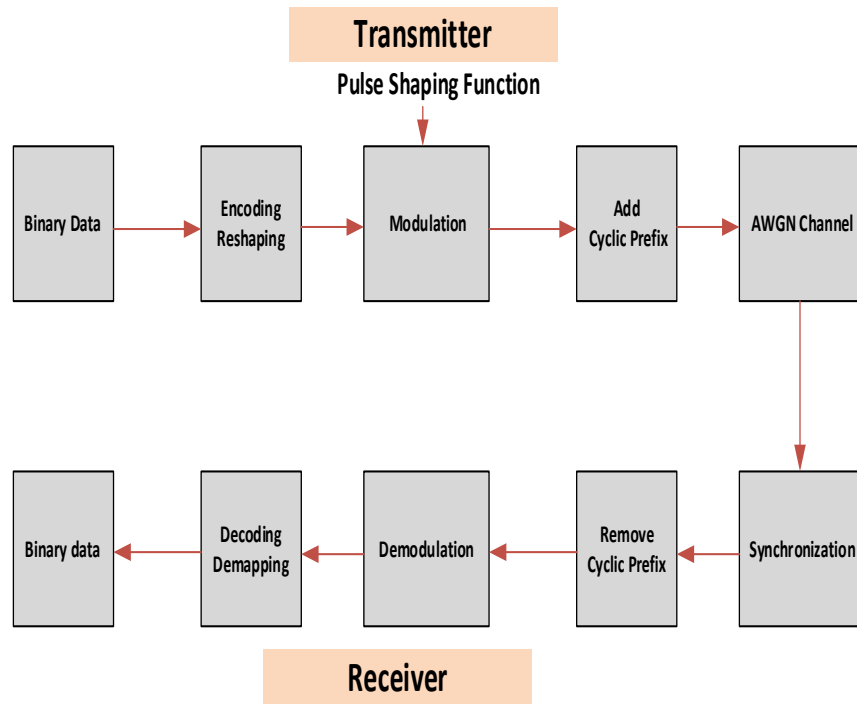


Fig. 5. GFDM Transceiver.

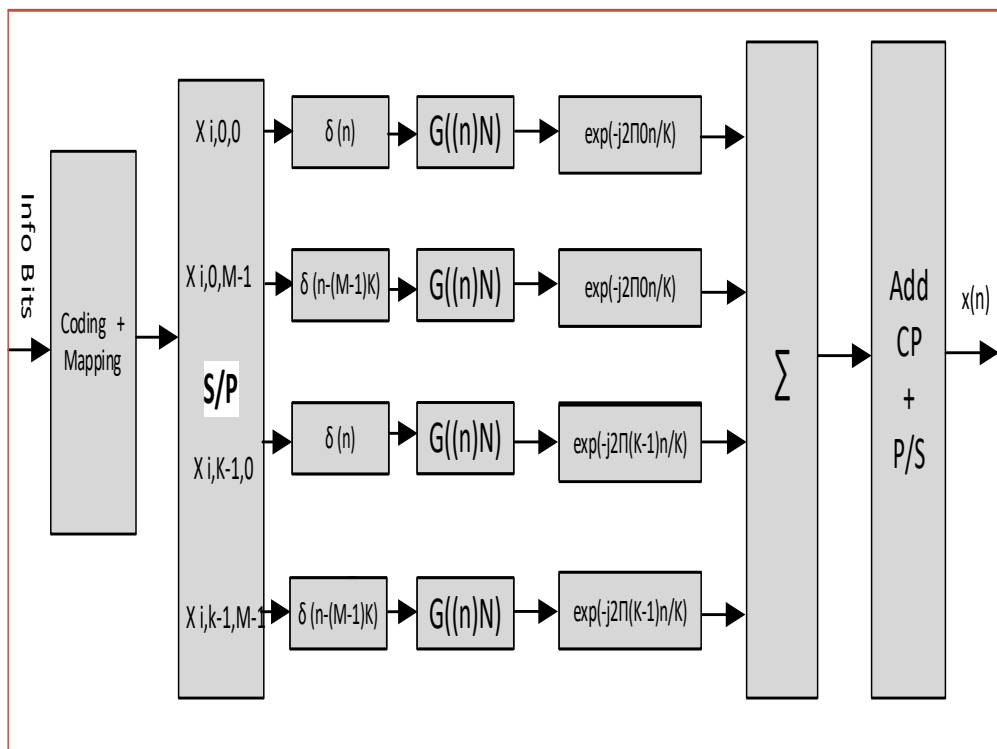


Fig. 6. GFDM Transmitter.

In order to maintain orthogonality in OFDM systems, a cyclic prefix is added to each block, whereas in GFDM, the cyclic prefix is added only once to every M -sub symbol reducing the overhead due to the cyclic prefix and improving spectrum efficiency [22].

In the transmitter of a GFDM system, a bit stream is initially modulated using either phase shift keying or quadrature phase shift keying [23]. It is further divided into KM symbols in the i th GFDM symbol denoted by $x_{i,k,m}$. Where each sequence,

x_i is denoted by (3) and $x_{i,m}$ given by (4) is spread onto K subcarriers in M time slots [24].

$$x_i = [x_{i,0}^T, x_{i,1}^T, x_{i,2}^T, \dots, x_{i,M-1}^T]^T \quad (3)$$

$$x_{i,m} = [x_{i,0,m}, x_{i,1,m}, x_{i,2,m}, \dots, x_{i,K-1,m}]^T \quad (4)$$

Equation (5) and (6) describes spreading of K sub carriers and M sub blocks.

$$m = 0, 1, 2, \dots, M-1 \quad (5)$$

$$k = 0, 1, 2, \dots, K-1 \quad (6)$$

Here, $x_{i,k,m}$ is the data transmitted for (m+1)th sub symbol and (k+1)th subcarrier of ith GFDM symbol. Each $x_{i,k,m}$ data is passed through a pulse shaping filter represented by (7).

$$s_{k,m}(n) = s((n - mK)_N) e^{\frac{-j2\pi kn}{N}} \quad (7)$$

Here, n is the signal sample index denoted by (8) and N= KM.

$$n = 0, 1, 2, \dots, N-1 \quad (8)$$

$s(n)$ is a prototype filter whose time and frequency shifted version is denoted by $s_{k,m}(n)$ and $(.)_N$ is the modulo of N. The GFDM signal obtained by superposing $x_{i,k,m}$ data that has been filtered by the prototype filter $s_{k,m}(n)$ is represented by (9).

$$f_i(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} x_{i,k,m} \cdot s_{k,m}(n) \quad (9)$$

Fig. 6 represents the block diagram of the GFDM transmitter through which (9) is implemented [25].

IV. PERFORMANCE EVALUATION

Linear receivers such as Matched Filter (MF), Zero Forcing (ZF), Minimum mean square error (MMSE) receiver, etc. are being used to improve the system performance [26]. When compared, each of them has some merits and demerits over the other. Such as MF receivers cannot remove intrinsic self-interference, and MMSE has high computational complexity [27]. In the following paragraph, these receivers are introduced briefly.

A. Matched Filter Receiver

Matched Filter (MF) receiver is used to detect the optimum signal-to-noise ratio (SNR) or BER even in the presence of AWGN using a correlation process. Its response is expressed by (10). The main demerit of MF receiver is that it cannot remove intrinsic self-interference, ZF amplifies noise causing [28].

$$g = B^H \cdot f_e \quad (10)$$

B. Zero Forcing Receive

Zero forcing (ZF) receiver is used with transmit correlation in a flat fading channel to recover the transmitted data corrupted with AWGN. The response of the ZF receiver is expressed by equation (11). A major drawback of ZF receiver is that it amplifies noise also which degrades BER performance [29].

$$g = B^+ \cdot f_e \quad (11)$$

where B^+ is given by (12).

$$B^+ = (B^H B)^{-1} \cdot B^H \quad (12)$$

C. Minimum Mean Square Error Receiver

Minimum mean square error (MMSE) receiver uses transformation matrix such that it minimizes the mean square error distance between the transformed vector and the transmitted signal vector. It resolves the problem of noise enhancement that cannot be obtained in the ZF receiver. Its performance in terms of BER is better than MF and ZF receivers at the cost of high computational complexity. Its response is expressed by (13) and (14).

$$g = B^t \cdot f_e \quad (13)$$

where,

$$B^t = \left(\frac{\sigma_n^2}{\sigma_d^2} I + B^H B \right)^{-1} \cdot B^H \quad (14)$$

V. COMPUTATION OF BIT ERROR RATE

In the present work, a matched filter as shown in Fig. 7 has been used for evaluation of its performance in terms of bit error rate (BER) for different values of sub-carrier, sub-symbol, input power back off and roll-off factor. The output of the GFDM system expressed by (9) can also be expressed in matrix form as represented by (15).

$$f = B \cdot g \quad (15)$$

where B and g are represented by (16) and (17).

$$B = [x_{0,0}(n) \dots x_{K-1,0}(n) \ x_{0,1}(n) \dots x_{K-1,M-1}(n)] \quad (16)$$

$$g = [g_{0,0} \dots g_{K-1,0} \ xg_{0,1} \dots g_{K-1,M-1}]^T \quad (17)$$

The received signal after removing the cyclic prefix is represented by (18).

$$f = Hx + n \quad (18)$$

Here n is additive white Gaussian noise (AWGN), h is the channel impulse response and H is circulant matrix of h. h is expressed by (19).

$$h = h_0 \ h_1 \ \dots \ h_{L-1} \quad (19)$$

After applying equalization, the received signal is represented in frequency domain by (20).

$$f_e = F^{-1} \left\{ \frac{F(f)}{F(h)} \right\} \quad (20)$$

Here F is the fast Fourier transform (FFT) and F^{-1} is the inverse fast Fourier transform (IFFT).

Fig. 8 depicts BER of the GFDM system corrupted with additive white Gaussian noise for different number of subcarriers, $N=8, 16$ and 32 when number of sub symbols,

$M=7$ input power back-off, $IBO=6$ and roll-off factor $\beta=0.8$. It can be observed from the figure that change in the BER performance is very low when number of sub carriers are changed.

But the change in the number of sub symbol has larger effect in the BER performance of the GFDM system. Fig. 9 illustrates BER of GFDM system for number of sub symbols $M=3, 5$ and 7 when number of subcarriers, $N=8$ input power back-off, $IBO=6$ and roll-off factor $\beta=0.8$ are kept constant. It is observed that BER performance degrades with increase in a number of sub-symbols.

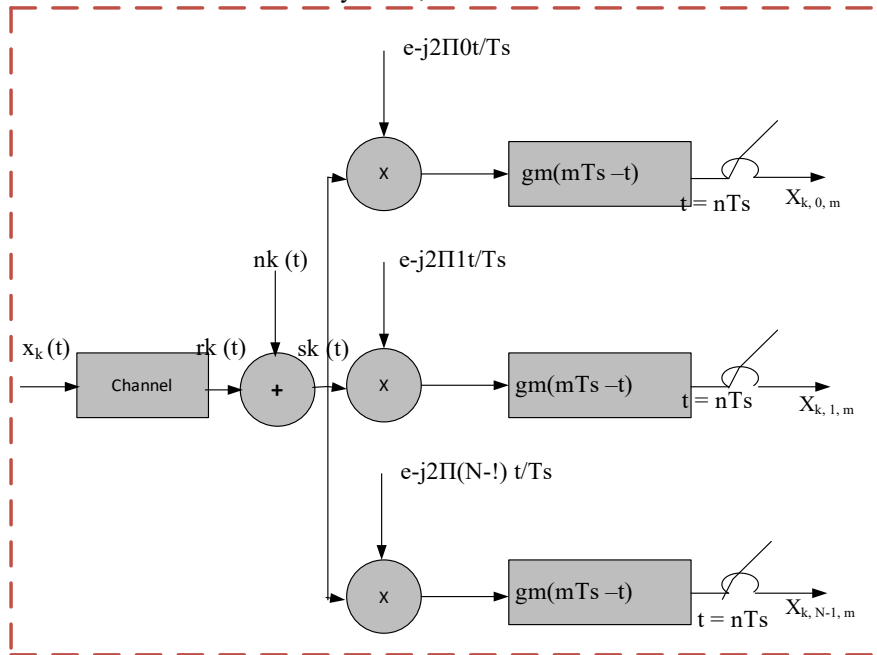


Fig. 7. Block Diagram of GFDM Receiver with Matched Filter.

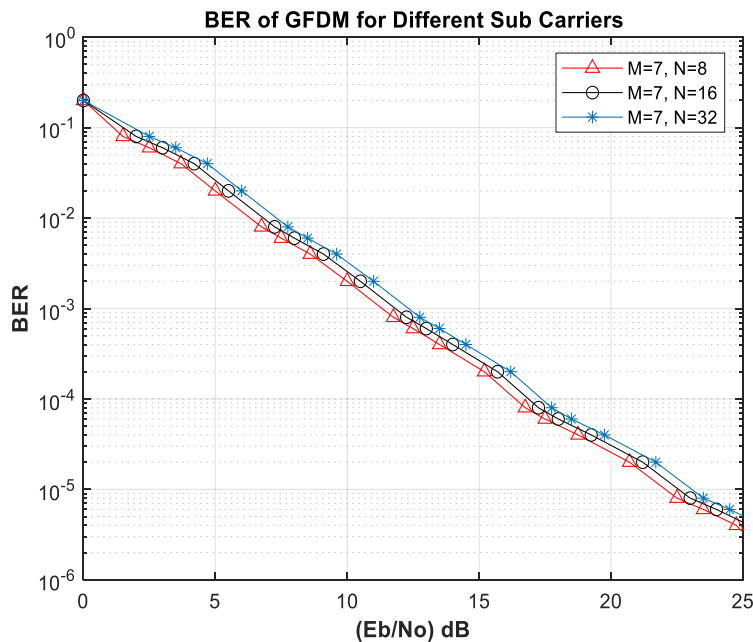


Fig. 8. BER of GFDM for Different Number of Subcarriers.

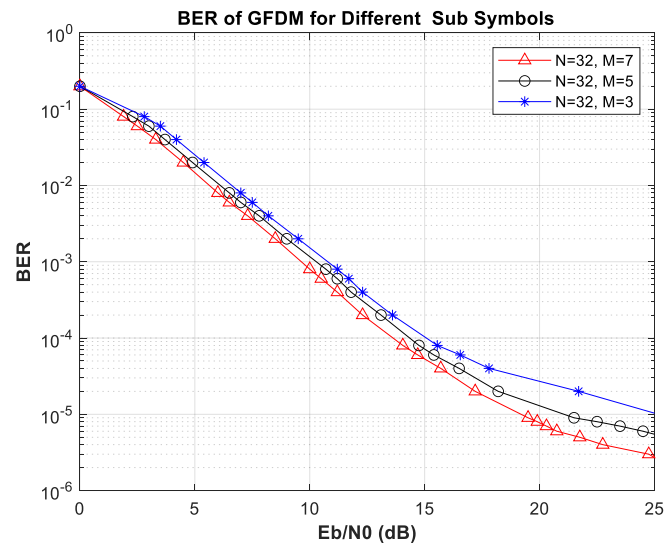


Fig. 9. BER of GFDM for Different Number of Sub symbols.

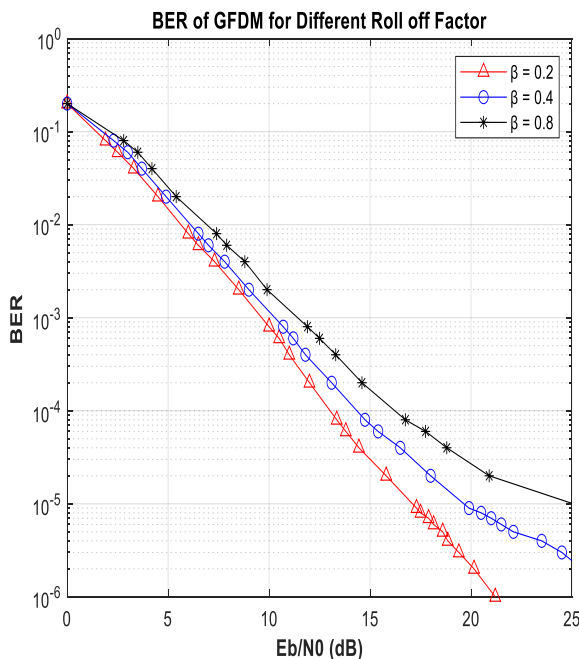


Fig. 10. BER of GFDM for Different Value of Roll-off Factor.

Fig. 10 depicts the BER of the GFDM system with the change in roll-off factor $\beta = 0.2, 0.4$ and 0.8 when number of subcarriers, $N = 32$, number of sub symbols, $M = 7$ input power back-off, $IBO = 6$ are kept constant. The value of β lies between 0 and 1, i.e. $0 \leq \beta \leq 1$ and it is used to reduce out-of-band energy leakage at the cost of excess bandwidth requirement for a Nyquist inter symbol interference (ISI) free pulse. A raised cosine pulse has been used for shaping the waveform of the GFDM system that is expressed by (21).

$$S(f) = \begin{cases} T; & 0 \leq f < B(1 - \beta) \\ \frac{T}{2} \{1 + \cos\left(\frac{\pi}{2B\beta}(f - B(1 - \beta))\right)\}; & B(1 - \beta) \leq f \leq B(1 + \beta) \\ 0; & B(1 + \beta) < f \end{cases} \quad (21)$$

It can be observed from Fig. 10 that BER performance degrades for larger value of β .

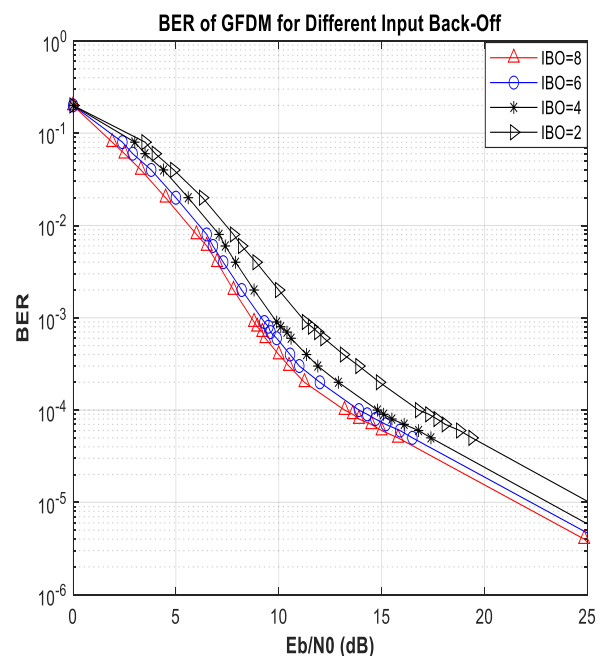


Fig. 11. BER of GFDM for Different Value of Input Power Back off.

Due to the fluctuations in the output of GFDM system, its peak-to-average power ratio (PAPR) is high. High PAPR drives power amplifiers into the saturation region and forces it to operate in a nonlinear region. These nonlinear characteristics of the power amplifier bring forth many undesirable characteristics in the system such as gain compression, phase distortion, harmonic distortion, adjacent channel distortion, and intermodulation distortion, etc. Linearization techniques are used to maintain high efficiency with improved linearity of the power amplifier. There are several techniques to improve the linearity of power amplifiers that includes, feedback, feedforward and pre-distortion techniques. At the cost of slight loss in efficiency and an increase in the size of the amplifier, linearity of power amplifiers can also be improved by operating it in the power back-off mode. In order to keep the power amplifier operates in the linear region its input signal is attenuated and is said to be in the power back-off mode. It can be operated either in

input power back-off (IBO) or in output power back-off (OBO) mode as expressed by (22) and (23).

$$IBO = 10 \log_{10} \frac{P_{i,sat}}{P_i} \quad (22)$$

$$OBO = 10 \log_{10} \frac{P_{o,sat}}{P_o} \quad (23)$$

where P_i and P_o are the average power of input and output signals. Similarly, $P_{i,sat}$ and $P_{o,sat}$ input and output saturation power. In the present work, BER performance of the GFDM system has been obtained for different values of input power back-off, IBO=2, 4, 6, and 8 keeping the number of sub-block, $M = 7$ number of subcarriers, $N = 8$ input and roll-off factor $\beta=0.8$ constant. It is evident from Fig. 11 that BER performance decreases with an increase in the value of IBO.

VI. RESULTS AND DISCUSSIONS

It has been observed that the PAPR of the OFDM system is comparatively high due to fluctuations in the output. Further, it has been found that PAPR increases with an increase in the number of subcarriers. High PAPR is undesirable for the communication system as it causes the power amplifier to operate in the nonlinear region and produces distortion in the output. BER of the GFDM system corrupted with additive white Gaussian noise has been computed for a different number of subcarriers when a number of sub-symbols, input power back-off, and roll-off factor have been kept constant. It has been observed that change in the BER is very low when the number of subcarriers are changed. But the change in the number of sub-symbols has a larger effect in the BER performance. It suggests that BER performance degrades with an increase in the number of sub-symbols.

BER with different values of roll-off factor keeping the number of subcarriers, number of sub symbols, and input power back-off constant reveal that BER performance decreases with an increase in the value of the roll-off factor. BER has also been computed for different values of input power back-off, keeping other parameters constant. It is evident from the result that BER performance decreases with an increase in the value of power back-off.

VII. CONCLUSIONS

Generalized frequency division multiplexing (GFDM) is a pulse-shaping-based modulation technique considered to be suitable for future communication systems. Due to the use of non-rectangular pulse shaping, it has low out-of-band leakage. Its performance in terms of BER has been computed considering a number of subcarriers, number of sub-symbols, input power back-off, and roll-off factor as a variable parameter. It has been observed that change in the BER is low when a number of sub-carriers are changed but is more for change in the number of sub-symbols. Its performance degrades when the number of sub-carriers, the value of the roll-off factor and power back-off are increased. But BER performance improves with an increase in the number of sub-

symbols. It has low complexity and better performance and is highly suitable for burst signal transmission. This technique is more flexible in terms of frequency localization, scalability and integration with MIMO.

REFERENCES

- [1] Hilario-Tacuri A, Fortes JMP, Sampaio-Neto R, Soncco L, Donaires D, Borja J. Performance Evaluation of Generalized Frequency Division Multiplexing Systems over Non-Linearities With Memory, *IEEE Access*, 2019; 7: 119131-119139.
- [2] Prasad YS. Filter Bank Multicarrier Modulation Techniques for 5G and Beyond Wireless Communication Systems, *European Journal of Electrical Engineering and Computer Science*, 2022; 6(2): 8-24.
- [3] Murad M, Tasadduq IA, Otero P. Towards Multicarrier Waveforms Beyond OFDM: Performance Analysis of GFDM Modulation for Underwater Acoustic Channels, *IEEE Access*, 2020; 8: 222782-222799.
- [4] Na Z, Zhang M, Xiong M, Xia J, Liu X, Lu W. Pseudo-Noise Sequence Based Synchronization for Generalized Frequency Division Multiplexing in 5G Communication System, *IEEE Access*, 2018; 6:14812-14819.
- [5] Prasad YS, Chandra BS. PAPR Reduction for Improved Efficiency of OFDM Modulation for Next Generation Communication Systems, *International Journal of Electrical and Computer Engineering*, 2016; 6(5): 2310-2321.
- [6] Zhenyu Na, Jiaqi Lv, Fan Jiang, Mudi Xiong, and Nan Zhao, Joint Subcarrier and Subsymbol Allocation-Based Simultaneous Wireless Information and Power Transfer for Multiuser GFDM in IoT, *IEEE Internet of Things Journal*, 2019; 6(4): 5999-6006.
- [7] Prasad Y, Bera, Chandra S. Investigations on PAPR Reduction using PTS Technique for OFDM Communication Systems. *Journal of Communication Engineering & Systems*, 2015; 5(3):19-26.
- [8] Osaki S, Sugiura S. Impact of Inter-Frame Interference on Eigen decomposition-precoded Non-Orthogonal Frequency-Division Multiplexing, *IEEE Wireless Communications Letters*, 2021; 10(7): 1567-1571.
- [9] Han S, Sung Y, Lee YH. Filter Design for Generalized Frequency-Division Multiplexing, *IEEE Transactions on Signal Processing*, 2017; 65(7): 1644-1659.
- [10] Prasad YS, Chandra BS. PAPR Reduction using Selective Mapping Method for OFDM Communication Systems, *Journal of Communication Engineering & Systems*, 2015; 5(3): 50-57.
- [11] Wei P, Xiao Y, Dan L, Ge L, Xiang W. N-Continuous Signaling for GFDM, *IEEE Transactions on Communications*, 2020; 68(2): 947-958.
- [12] Li F, Zheng K, Zhao L, Zhao H, Li Y. Design and Performance of a Novel Interference-Free GFDM Transceiver with Dual Filter, *IEEE Transactions on Vehicular Technology*, 2019; 68 (5): 4695-6706.
- [13] Towliat M, Tabatabaei SMJA. GFDM Interference Mitigation Without Noise Enhancement, *IEEE Communications Letters*, 2018; 22(5): 1042-1045.
- [14] Yan Li, Kai Niu, and Chao Dong, *Polar-Coded GFDM Systems*, *IEEE Access*, 2019; 7:149299-149307.
- [15] Prasad YS, Chandra BS. Reduction of PAPR in SC-FDMA System using Pulse Shaping Technique. *International Journal of Applied Engineering Research*, 2015; 10 (23): 43509-43513.
- [16] Li F, Zhao L, Zheng K, Wang J. A interference-free transmission scheme for GFDM system, in *Proc. IEEE Globecom Workshops*, 2016; 1-6.
- [17] Wollschlaeger M, Sauter T, Jasperneite J. The future of industrial communication: Automation networks in the era of the Internet of Things and industry 4.0, *IEEE Ind. Electron. Mag*, 2017; 11 (1):17-27.
- [18] Bingham JAC. Multicarrier modulation for data transmission: An idea whose time has come, *IEEE Commun. Mag*, 1990; 28(5): 5-14.
- [19] Chen S, Zhao J. The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication, *IEEE Commun. Mag*, 2014; 52(5), 36-43.
- [20] Mirahmadi M, Al-Dweik A, Shami A. BER reduction of OFDM based broadband communication systems over multipath channels with impulsive noise. *IEEE Trans. Commun*, 2013; 61(11): 4602-4615.
- [21] Fechtel SA, Blaukner A. Efficient FFT and equalizer implementation for OFDM receivers, *IEEE Trans. Consum. Electron*, 1999; 45(4): 1104-1107.
- [22] Haykin S. Cognitive radio: Brain-empowered wireless communications, *IEEE J. Sel. Areas Commun*, 2005; 23 (2): 201-220.
- [23] Banelli P, Buzzi S, Colavolpe G, Modenini A, Rusek F, Ugolini A. Modulation formats and waveforms for 5G networks: Who will be the heir of OFDM?: An overview of alternative modulation schemes for

- improved spectral efficiency, *IEEE Signal Process. Mag.*, 2014; 31 (6): 80–93.
- [24] Fettweis GP. The tactile Internet: Applications and challenges, *IEEE Veh. Technol. Mag.*, 2014; 9(1): 64–70.
- [25] Wunder G, Jung P, Kasparick M, Wild T, Schaich F, Chen Y, ten Brink S, *et al.* 5G New: Non-orthogonal, asynchronous waveforms for future mobile applications, *IEEE Communications Magazine*, 2014; 52(2): 97–105.
- [26] Matth M, Michailow N, Gaspar I, Fettweis G. Influence of pulse shaping on bit error rate performance and out of band radiation of generalized frequency division multiplexing, in *Proc. IEEE Int. Conf. Commun. Workshops*, 2014; 43–48.
- [27] Shariatmadari H, Ratasuk R, Iraj S, Laya A, Taleb T, Jäntti R, Ghosh A. Machine-type communications: Current status and future perspectives toward 5G systems, *IEEE Commun. Mag.*, 2015; 53(9):10–17.
- [28] Prasad YS. Orthogonal Versus Novel Orthogonal Pulse Shaped Waveforms for Future Generation Wireless Communication Systems, *IEEE R10 HTC 2022 Conference*, Hyderabad, 2022.
- [29] Campolo C, Molinaro A, Iera A, Menichella F. 5G network slicing for vehicle-to-everything services, *IEEE Wireless Commun.*, 2017; 24 (6): 38–45.



Shatrughna Prasad Yadav received B. Tech. degree in electronics and communication engineering from the Institution of Engineers (India) in 1992, MBA in marketing management from Indira Gandhi National Open University, New Delhi in 1998, M. Tech. in digital systems from Motilal Nehru National Institute of Technology, Allahabad in 2002 and Ph.D. in Electronics and Communication Engineering from Gujarat Technological University, Ahmedabad in 2017.

From 1986 to 2006, he worked with the Indian Air force. From 2006 to 2007, he worked as a senior lecturer in the electronics and communication engineering department at the Institute of Technology, Nirma University, Ahmedabad. From 2007 to 2018, he worked with Indus University, Ahmedabad as head of the Electrical and Electronics Engineering department. From 2018 to 2019 he worked as an associate professor and Dean of Students Welfare at Symbiosis University of applied sciences, Indore. From 2019 onwards he is working with Guru Nanak Institutions, Hyderabad. His research interest includes digital communication systems, IoT, electromagnetics, and digital signal processing.