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Improving Spectrum Efficicency of 5G Network

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Abstract—High peak-to-average power ratio (PAPR) is a major limitation of orthogonal frequency division multiplexing (OFDM), making it less suitable for achieving high spectrum efficiency in 5G networks. The impact of PAPR on spectrum efficiency and bit error rate (BER) is particularly critical. To address this challenge and enhance 5G performance, a spectrum-efficient cosine-modulated filter bank with tone companding method (CM-FBMC TCM) was developed and evaluated. Simulations were carried out in the MATLAB 2021 environment, with the CM-FBMC TCM model tested across three iterations. The baseline CM-FBMC exhibited a PAPR value of 16.9 dB, while the proposed CM-FBMC TCM achieved significant reductions: 7.3 dB in iteration 1, 3.8 dB in iteration 2, and 2.9 dB in iteration 3. In terms of error performance, CM-FBMC TCM reduced BER by approximately 50% compared to the conventional CM-FBMC. However, BER performance in iteration 3 deteriorated relative to iterations 1 and 2. Overall, the results indicate that CM-FBMC TCM IT3 achieved the lowest PAPR, approaching the ideal 3 dB range for multi-carrier signals in 5G systems. Nonetheless, this improvement in PAPR came at the cost of increased BER compared with earlier iterations, highlighting a trade-off between PAPR reduction and BER performance.

Keywords: Peak to Average Power Ratio, Constant envelop filtered orthogonal frequency division multiple access, Orthogonal Frequency Division Multiplexing, Complementary Cumulative Distribution Function, Cosine Modulated Filter Bank Multi Carrier.

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1. Introduction

Fifth generation technology require high spectral efficiency, low out of band radiation and low peak average to power ratio in order to meet the growing demand of mobile technology [1]. One of the ways of improving spectrum efficiency in 5G network is through digital modulation techniques. OFDM is a multi-carrier modulation scheme for 5G technologies with enhanced spectrum robustness but its shortcomings in terms of high peak to average power and in and out-band radiation effects [2]–[6] render it unfit for 5G spectrum efficiency. Also, Orthogonal Frequency Division Multiple Access (OFDMA) is a variant of OFDM with multiple access features for time division multiple access (TDMA) and frequency division multiple access (FDMA). Its high PAPR values are a deficit which puts the spectral in perspective [7].

Apart from the two major frequency divisions aforementioned, proposition from various scholars emerged on how to curb the PAPR affects in 5G technologies. Among these propositions were Constant envelope OFDM (CE-OFDM) and its variants. CE-OFDM was proposed to optimize the performance of 5G technology [3], [8]–[11] and to mitigate the effects of PAPR. Although spectral efficiency was attained, frequency modulation (FM) threshold was disadvantaged with resultant effect on signal degradation. Single carrier OFDM (SC-OFDM) and multi-users access referred to as SC-FDMA was proposed [11] for 5G technology but its high PAPR values render it unfit for 5G technology although its PAPR value was not as high as OFDM PAPR.

[12]–[14] proposed constant envelop single carrier FDMA (CE-SC FDMA) with improved robustness against noise but there was a decrease of half spectral efficiency. [14]–[16] developed

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OFDM index modulation (IM) modulation scheme for 5G technology with higher spectral and energy efficiency but with lower trans-receiver complexity. [3], [17] proposed CE-OFDM-aided MIMO STSK to achieve system performance and better spatial diversity. The performance of the system was influenced by additive white Gaussian noise (AWGN) in which there is no channel. [14] Incorporated spectral pre-coding into CE-OFDM channel in order to reduce side-lobe power spectral.

Having seen variants of OFDM, one can infer that PAPR values for OFDM technologies are good for spectral management in 5G signal but disadvantaged with high PAPR values. An alternative method to resolve PAPR in 5G spectrum efficiency is to use filter based multi-carrier technology [5], [6], [18], [19]. Filter bank waveform can be categorized into three types, namely: sub-carrier, sub band and full time filter. Filter bank multi carrier (FBMC) is a special type of sub-carrier filtering [20]–[22]. Despite its optimum performance in overcoming PAPR, performance degradation and inter symbol interference (ISI) characterize the non-orthogonal frequency division filter [22]. The sub-band filtering waveform is also known as universal filtered multi-carrier waveform (UFMC) [23], [24]. The system offered several advantages such as spectrum efficiency, less complexity and lower power back off than OFDM.

The full band filter employed by Filtered OFDM (F-OFDM) reduced the input back off power (IBO) [25], [26]. Generalized frequency division multiplexing (GFDM) is based on modulation of independent blocks, where each block consists of number of sub carriers and sub-symbols [26], [27]. The sub-carriers are filtered using prototype filter circularly shifted in time and frequency domain. This feature reduces out of band (OOB) effets on OFDM but it still suffers from ISI and Inter Carrier Interference (ICI) due to its non-orthogonal nature [28]. However, this can be resolved by using matched filter receiver with iterative interference cancellation. Despite this intrigue feature of GFDM, high complexity affects its performance for 5G design. It was seen that FBMC can proffer solution to high PAPR values seen in 5G technology with better spectral efficiency but there is problem with out of band radiation from the effect of ISI and ICI.

In order to resolve the interference, FBMC waveform with orthogonal features will be a good contender for 5G waveform. Conventional method of lowering PAPR using clipping and filtering, tone reservation, tone injection and companding technique can also be introduced into the orthogonal FBMC in order to reduce the effects of PAPR values to the barest minimum in 5G technology. Clipping and filtering technique limit the input signal amplitude to a pre-determined level. However, degradation in terms of bit error rate, out of band radiation and peak regrowth of filtered clipped signals reduced the efficiency of the technique.

Tone reservation method [29]–[32] subdivides N-sub-carrier into data tones and peak reduction tone. Symbols in PRTs were chosen such that signal in time domain has a lower PAPR but high data rate loss and high power rate are the shortcomings of this method. Tone injection method [33]–[35] reduces PAPR without reducing the data rate by allowing PRTs to be overlapped with data tones. The principle of this technique is to increase the constellation size so that each point in the constellation can be mapped onto several equivalents to reduce PAPR performance. This method incurs no data rate loss or distortion but there is power increase. The compounding technique [36]–[44] enlarges the small signal while the large signal is compressed to take care of small signal immunity from noise. The compression is carried out at the transmitter end after the output is taken from Inverse Fast Fourier Transform (IFFT) block. The method incurs no data loss or distortion but there is power overload.

The outline of this paper is as follows: Section 2 explained the methodology employed. Results and Conclusion were discussed in Section 3 and Section 4 respectively.

2. Method

Figure 1 shows the block diagram of the transmitter used for the simulation implementation. An input signal was firstly quadrature amplitude (QAM) modulated. The complex input QAM signals were converted from serial to parallel data streams. The parallel data stream was given to offset quadrature amplitude modulation (OQAM) pre-processing block. Complex input signals generated were cosine modulated using cosine modulated filter block, which orthogonally spreads each data into 2K-1 sub-carriers and filter input data elements. The parallel input was given to IFFT block and the output was converted from parallel to serial converter to get CM-FBMC signals. The size of IFFT block is KN where K is the oversampling factor and N is the number of sub channels.

CM-FBMC signals were processed further to reduce the PAPR to barest minimum. Tone injection (T1), companding techniques and tone companding method (TCM), which is a combination of tone injection and companding techniques, were applied to the output of CM-FBMC signal. Companding technique was introduced to expand low amplitude signal and compress high amplitude signal while the injection was added to the input signal. 104 randomly generated complex input samples were used.

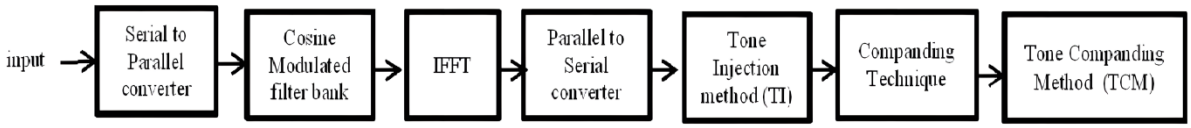


Figure 1. Cosine Modulated Filter Bank Multicarrier transmitter for Peak Average Power Reduction Technique

2.1 Mathematical derivation of Cosine Modulated Filter Bank Multicarrier (CM-FBMC)

This section describes the mathematical theory used for solving PAPR problems. The method used is known as cosine modulated filter bank multicarrier (CM-FBMC).

CM-FBMC is an attractive choice for the design and implementation of modulated orthogonal filter banks with a large number of sub-bands [1,45, 46]. The main features of the cosine modulated filter bank are:

- Simple design approach for generating the low-pass prototype when perfect reconstructions must be achieved.
- Low implementation cost

The linear phase prototype low-pass filter, $H(z)$ of order N, has a pass-band edge of $\omega_p = \left[\frac{\pi}{2M} + \rho\right]$, and stop-band edge, $\omega_s = \left[\frac{\pi}{2M} - \rho\right]$, and 2ρ is the width of the transition band. For even multiples of number, M of sub-bands, the length is $2N + 1$, that is, $N = 2(LM + 1)$.

Given the prototype filter, the cosine modulated filter version of the analysis filter bank is given by Equation (1).

$$h_m(n) = 2h(n)cos \quad \left[(2m+1)\frac{\pi}{2M}\left(n - \frac{N}{2}\right) + (-1)^m\frac{\pi}{4}\right] \tag{1}$$

For n= 0,1,…….,N and m=0,1,…….,(M-1) with N=$(2LM + 1)$

The prototype filter can be decomposed into 2M poly-phase components as follows in Equation (2), where $S_j(z) = \sum_{i=0}^{L-1} h(2LM + j)z^{(-1)}$ are the components of the filter$H(z)$.

$$H(z) = \sum_{i=0}^{L-1} \sum_{j=0}^{2M-1} h(2LM + j) z^{-(2LM+1)}$$

$$= \sum_{j=0}^{2M-1} z^{-j} S_j(z^{2M}) \quad (2)$$

The analysis filter can be described as shown in Equation (3).

$$H_m(z) = \sum_{n=0}^{N} h_m z^{(-n)}$$

$$= \sum_{n=0}^{2LM-1} D_{m,n}\, h(n) z^{(-n)} \quad (3)$$

$$= \sum_{i=0}^{L-1} \sum_{j=0}^{2LM-1} D_{m,2LM+J} h(2LM + j) z^{(-2LM+j)}$$

Applying the cosine modulated algorithm as seen in Equation (4).

$$\cos\left\{(2m+1)\frac{\pi}{2M}\left[(N + 2kM) - \frac{N}{2} + \emptyset\right]\right\}$$

$$= (-1)^k \cos\left\{(2m+1)\frac{\pi}{2M}\left[(N + 2kM) - \frac{N}{2} + \emptyset\right]\right\} \quad (4)$$

$$H_m = D_{m,n+2kM}$$

$$= (-1)^k D_{m,n} \quad (5)$$

Substituting j for n, and l for k, Equation (5) becomes $D_{m,n+2LM} = (-1)^l D_{m,j}$. Rewriting Equation (3), the following Equation (6) is derived.

$$H_m(z) = \sum_{j=0}^{2LM-1} D_{m,J} z^{-j} \sum_{l=0}^{L-1} h(2LM + j) z^{(-2LM)}$$

$$= \sum_{j=0}^{2LM-1} D_{m,J} z^{-j}\, S_j(-z^{2M}) \quad (6)$$

Equation (6)are represented as given in Equation (7) , where D_1 and D_2 are $M \times N$ matrices, whose (m,j) elements are $D_{m,j}$ and $D_{m,j+m,}$ respectively for m=0,1,……,(m-1).

$$S(z) = \begin{bmatrix} H_0(z) \\ H_1(z) \\ \vdots \\ \vdots \\ H_{m-1}(z) \end{bmatrix} = [D_I \quad D_2] \begin{bmatrix} S_0(-z^{2m}) \\ z^{-1} S_1(-z^{2m}) \\ \vdots \\ \vdots \\ z^{(-2m-1)} S_{2m-1}(-z^{2m}) \end{bmatrix} \quad (7)$$

Representing $\delta(z)$ as shown in Equation (8)

$$\delta(z) = [1 \quad z^{-1} \cdots \quad z^{-M+1}]^T \quad (8)$$

The poly phase representation of the matrix can be represented as in Equation (10), where $\delta(z)$ is the poly phase matrix.

$$e(z) = [D_I \quad D_2] \begin{bmatrix} S_0(-z^{2m}) & & & 0 \\ & S_1(-z^{2m}) & & \\ & & \ddots & \\ & & \ddots & \\ 0 & & & S_{2m-1}(-z^{2m}) \end{bmatrix} \begin{bmatrix} \delta(z) \\ z^{-m}\delta(z) \end{bmatrix} \tag{9}$$

$$S(z^m)\ \delta(z) = \left\{ D_1 \begin{bmatrix} S_0(-z^{2m}) & & & 0 \\ & S_1(-z^{2m}) & & \\ & & \ddots & \\ & & \ddots & \\ 0 & & & S_{2m-1}(-z^{2m}) \end{bmatrix} + z^{-m} D_2 \begin{bmatrix} S_0(-z^{2m}) & & & 0 \\ & S_{M+1}(-z^{2m}) & & \\ & & \ddots & \\ & & \ddots & \\ 0 & & & S_{2m-1}(-z^{2m}) \end{bmatrix} \right\} \delta(z) \tag{10}$$

2.2 Simulation Analysis

Matlab 2021 was the simulation design environment of choice. The simulation was carried out using 16-QAM modulated input signals. The number of sub-channels used were N = 64 with an overlapping factor of K = 4 [36]. Clipping level A of 3 dB above average power level was chosen. For this simulation, a randomly generated complex input signal of 104 was taken. Three iterations (IT1, IT2, IT3) were observed for Tone Injection (TI), companding technique as well as for tone companding method (TCM). The performance metrics are: complementary cumulative distribution function (CCDF), PAPR, BER and SER.

3. Result and Discussion

The complementary cumulative distribution function (CCDF) is equivalent to PAPR distribution as shown in Figure 2. Figure 2 represents CCDF plots for CM-FBMC signal hybridized with either a companding or tone injections. Thus, the PAPR of CM-FBMC signal increases significantly compared to when CM-FBMC companding technique were used. PAPR values for CM-FBMC was 16.9dB while the PAPR values of three iterations for CM-FBMC TI IT1, CM-FBMC TI IT 2 and CM-FBMC Ti IT 3 were 13.7dB, 13.5dB and 11.6dB respectively and the PAPR values for CM-FBMC companding technique was 7.9dB.

The PAPR value for CM-FBMC TI was 19% while CM-FBMC companding technique was 53% lower than CM-FBMC. Figure 3 showed CCDR plot for original CM-FBMC signal and with hybridized scheme of Tone Companding Method (TCM). Thus, the PAPR of CM-FBMC signal was relatively higher compared to when CM-FBMC companding technique was used. PAPR values for CM-FBMC was 16.9dB while the PAPR values of CM-FBMC TCM IT1, CM-FBMC TCM IT2 and CM-FBMC TCM IT3 were 7.3dB, 3.8dB and 2.9dB respectively. The PAPR values for CM-FBMC TCM IT1, CM-FBMC TCM IT2 and CM-FBMC TCM IT3 were 57%, 78% and 83% and they are of lower values than PAPR values of CM-FBMC.

From the two Figures, there was drastic reduction in PAPR values when CM-FBMC TCM were used compared to when CM-FBMC TI ite and CM-FBMC. Figure 4 represents BER plot for original CM-FBMC signal as well as for CM-FBMC TCM IT1, CM-FBMC TCM IT2, and CM-FBMC TCM IT2. At 10 dB, the BER for CM-FMBC, CM-FBMC TCM IT1, CM-FBMC TCM IT2, and CM-FBMC TCM IT3 were 0.1, 0.2, 0.4 and 0.3. At 20 dB, the BER for CM-FMBC, CM-FBMC TCM IT1, CM-FBMC TCM IT2, and CM-FBMC TCM IT3 and CM-FBMC were 0.03, 0.01, 0.05, and 0.07. At

25 dB, the BER for CM-FBMC, CM-FBMC TCM IT1, CM-FBMC TCM IT2, and CM-FBMC TCM IT3 and CM-FBMC were 0.01, 0.0001, 0.001, and 0.05.

The BER performances for CM-FBMC-TCM were 50% lower than BER values of CM-FBMC. Thus, it can be concluded that there was high deterioration in the BER values for CM-FBMC signals compared to the other techniques used. As the PAPR values increase, so does the BER values increase. This shows that the higher the PAPR value, the higher the signal loss experienced by the modulation scheme. In conclusion, the CM-FBMC signal can be used to lower PAPR value when combined with tone companding method (TCM) with significant reduction in signal loss.

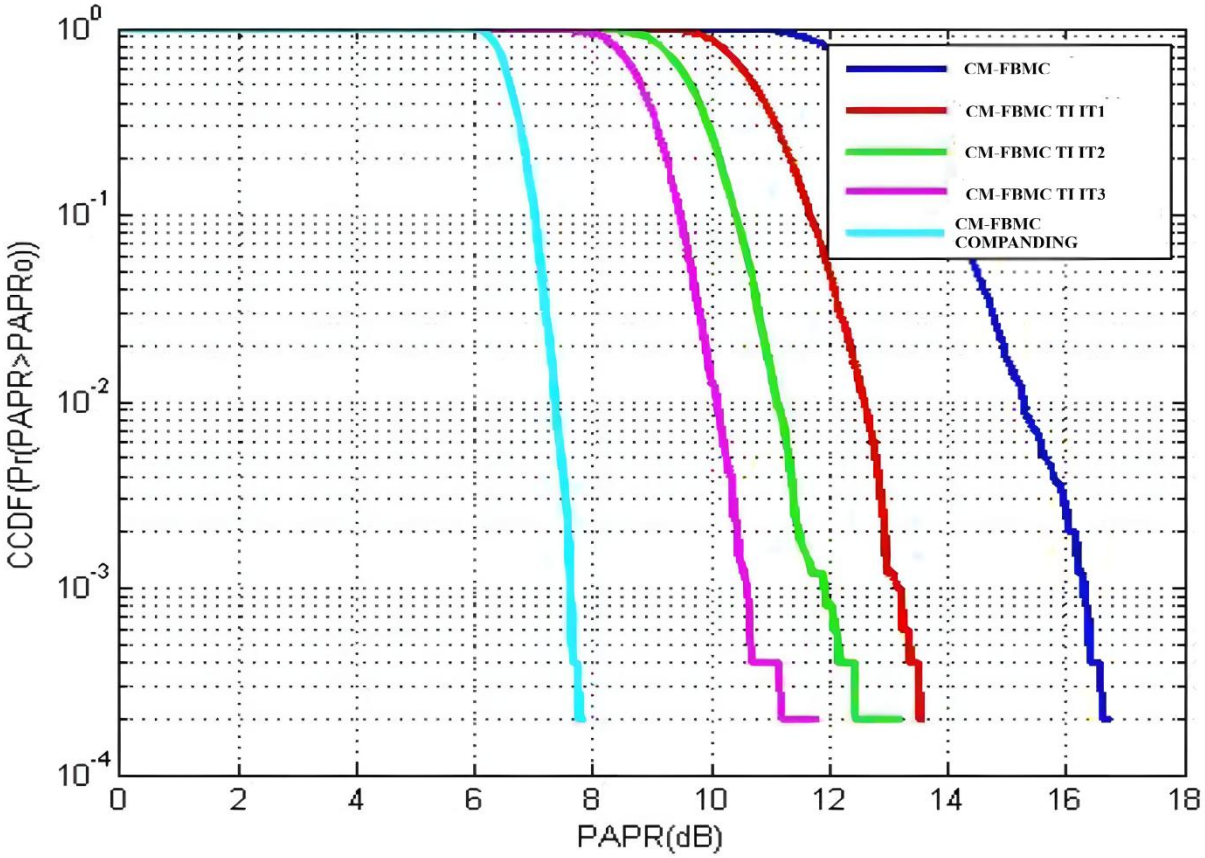


Figure 2. CCDF plot for original CM-FBMC, CM TI and CM Companding Techniques.

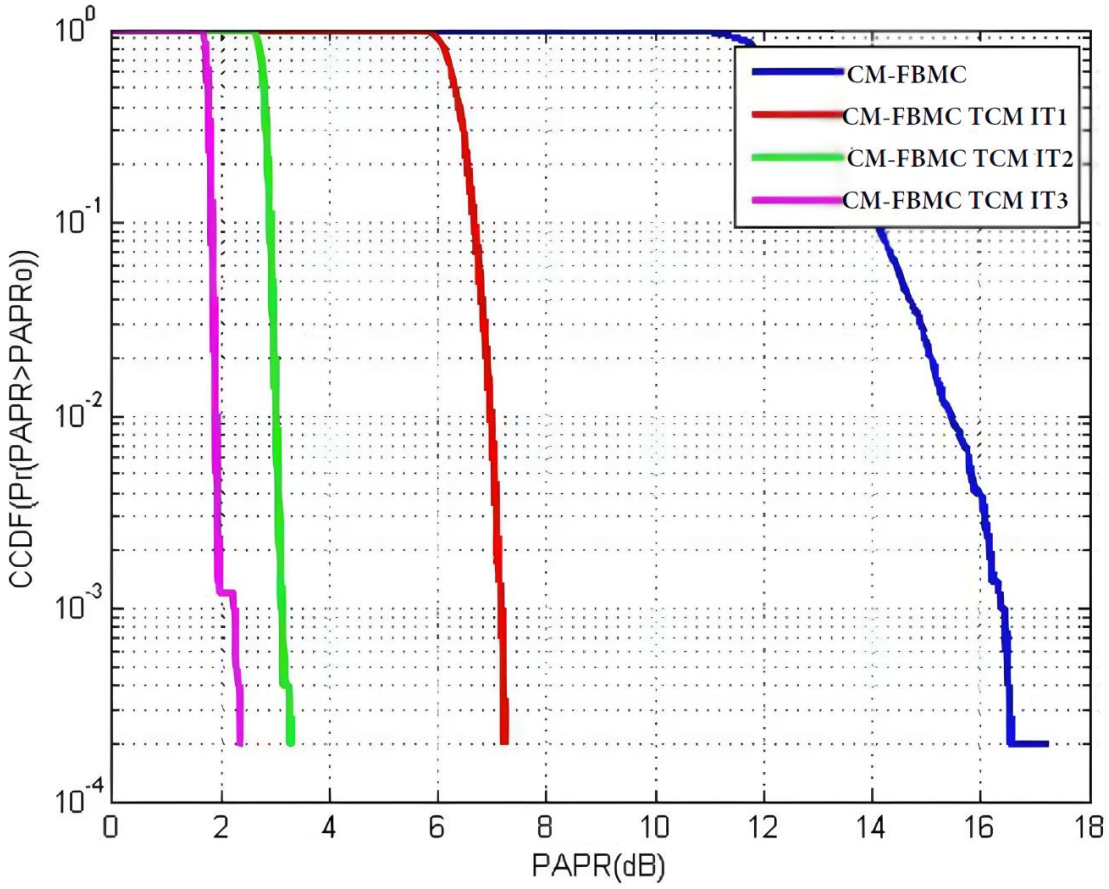


Figure 3. CCDF Plot for original CM-FBMC, CM-FBMC TCM IT1, CM-FBMC TCM IT2, and CM-FBMC TCM IT3.

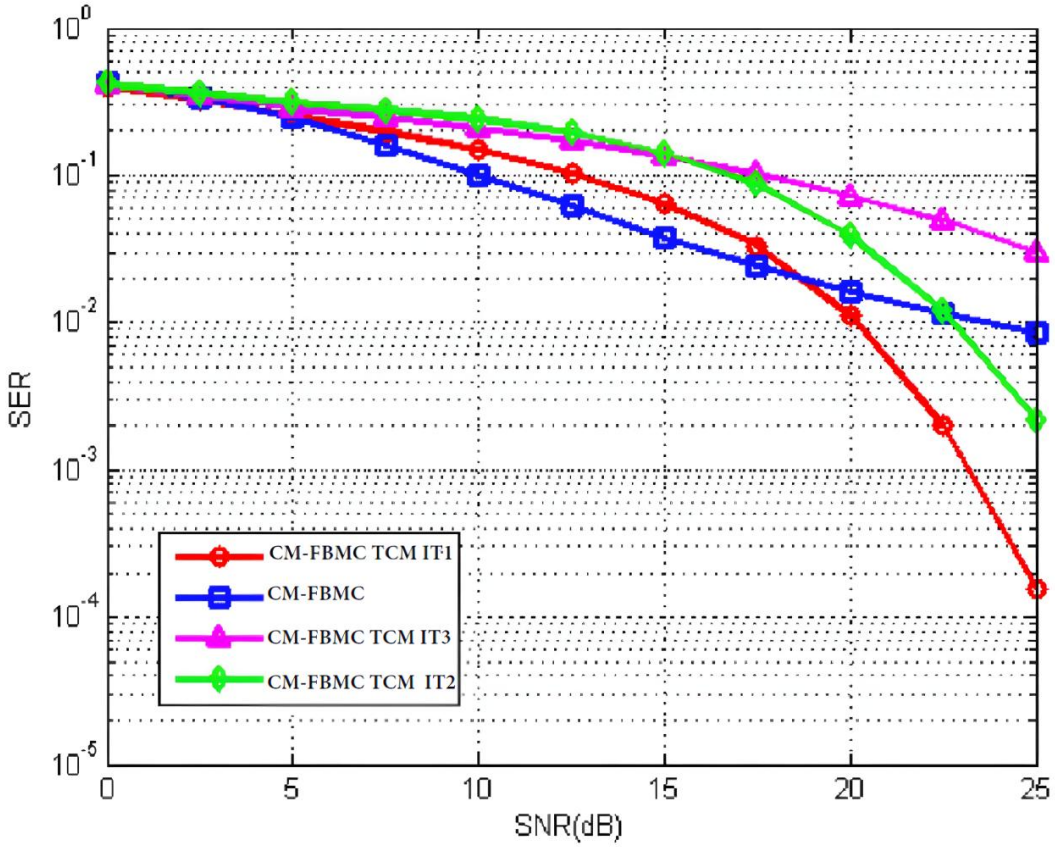


Figure 4. BER Versus EbNo for Cosine Modulated filter banks modulation in combination with Tone injection companding techniques after three iterations

4. Conclusion

CM-FBMC is a digital multi carrier filter bank with low implementation cost and simple design. It can reduce the PAPR values as well as BER values of 5G technology. Hybridizing CM-FBMC together with tone companding method (TCM) further reduces the PAPR values drastically. By performing the hybridized multi-carrier filter under three iterations further helps to lower the PAPR results and reduces the BER values to the ideal values. The PAPR values obtained for the hybridized filter bank was closer to 3dB which is the ideal for multi-carrier signal in 5G technology. This makes it a good candidate for improving the spectrum efficiency of 5G signals.

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References

[1] B. Farhang-Boroujeny and C. Yuen, "Cosine modulated and offset QAM filter bank multicarrier techniques: A continuous-time prospect," *EURASIP Journal on Advances in Signal Processing*, vol. 2010, pp. 1–16, 2010.

[2] Y. Liu, Z. Tan, H. Hu, L. J. Cimini, and G. Y. Li, "Channel estimation for OFDM," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1891–1908, 2014.

[3] C. K. Kajuna, *Design and Analysis of a Constant Envelope-Multicarrier Modulation Scheme for Multi-User System Based on mmWave MIMO for 5G Communication System*, Ph.D. dissertation, JKUAT, 2018.

[4] S. Gautam, S. Kumar, S. Chatzinotas, and B. Ottersten, "Experimental evaluation of RF waveform designs for wireless power transfer using software defined radio," *IEEE Access*, vol. 9, pp. 132609–132622, 2021.
[5] S. A. Khudhair and M. J. Singh, "Performance evaluation of the use of filter bank multi-carrier waveform in different mmWave frequency bands," *Journal of Communications*, vol. 16, no. 1, p. 36, 2021.
[6] B. J. El Ghzaoui Mohammed and A. Benbassou, "Peak to average power ratio reduction in OFDM system using constant envelope for transmission via PLC channel," *Progress in Electromagnetics Research*, vol. 1541, 2011.
[7] E. H. M. A. Emarah, M. El Tokhy, and H. Kasban, "Development of signal recovery algorithm for overcoming PAPR in OFDMA communication system," *Arab Journal of Nuclear Sciences and Applications*, vol. 55, no. 1, pp. 15–33, 2022.
[8] S. C. Thompson *et al.*, "Constant envelope OFDM," *IEEE Transactions on Communications*, vol. 56, no. 8, pp. 1300–1312, 2008.
[9] A. Deshmukh and S. Bodhe, "Performance evaluation of constant envelope OFDM working in 60 GHz band," *International Journal of Engineering and Technology*, 2012.
[10] E. Uludag, *Constant-Envelope OFDM and Constant-Envelope SC-FDMA*, Univ. of California, Irvine, 2016.
[11] C. Sacchi *et al.*, "Design and assessment of a CE-OFDM-based mm-wave 5G communication system," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, 2016, pp. 1–7.
[12] R. Mulinde, T. F. Rahman, and C. Sacchi, "Constant-envelope SC-FDMA for nonlinear satellite channels," in *Proc. IEEE Global Communications Conf. (GLOBECOM)*, 2013, pp. 2939–2944.
[13] T. F. Rahman *et al.*, "Constant-envelope multicarrier waveforms for millimeter wave 5G applications," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 10, pp. 9406–9420, 2018.
[14] C.-D. Chung, "Spectral precoding for constant-envelope OFDM," *IEEE Transactions on Communications*, vol. 58, no. 2, pp. 555–567, 2010.
[15] E. Basar, "On multiple-input multiple-output OFDM with index modulation for next generation wireless networks," *IEEE Transactions on Signal Processing*, vol. 64, no. 15, pp. 3868–3878, 2016.
[16] K.-H. Kim, "PAPR reduction in OFDM-IM using multilevel dither signals," *IEEE Communications Letters*, vol. 23, no. 2, pp. 258–261, 2019.
[17] S. Domouchtsidis *et al.*, "Constant envelope MIMO-OFDM precoding for low complexity large-scale antenna array systems," *IEEE Transactions on Wireless Communications*, vol. 19, no. 12, pp. 7973–7985, 2020.
[18] T. Kebede *et al.*, "Multi-carrier waveforms and multiple access strategies in wireless networks: Performance, applications, and challenges," *IEEE Access*, vol. 10, pp. 21120–21140, 2022.
[19] G. Wunder *et al.*, "5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97–105, 2014.
[20] A. J. Ramadhan, "Overview and comparison of candidate 5G waveforms: FBMC, UFMC and F-OFDM," *International Journal of Computer Network & Information Security*, vol. 14, no. 2, 2022.
[21] L. Zhang *et al.*, "FBMC system: An insight into doubly dispersive channel impact," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 3942–3956, 2016.
[22] D. Chen *et al.*, "Prototype filter optimization to minimize stopband energy with NPR constraint for filter bank multicarrier modulation systems," *IEEE Transactions on Signal Processing*, vol. 61, no. 1, pp. 159–169, 2012.
[23] V. Vakilian *et al.*, "Universal-filtered multi-carrier technique for wireless systems beyond LTE," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, 2013, pp. 223–228.
[24] X. Wang *et al.*, "Filter optimization for carrier-frequency-and timing-offset in universal filtered multi-carrier systems," in *Proc. IEEE Vehicular Technology Conf. (VTC Spring)*, 2015, pp. 1–6.
[25] L. Zhang *et al.*, "Filtered OFDM systems, algorithms, and performance analysis for 5G and beyond," *IEEE Transactions on Communications*, vol. 66, no. 3, pp. 1205–1218, 2017.

[26] J. Abdoli, M. Jia, and J. Ma, "Filtered OFDM: A new waveform for future wireless systems," in *Proc. IEEE Signal Processing Advances in Wireless Communications (SPAWC)*, 2015, pp. 66–70.
[27] N. Michailow *et al.*, "Generalized frequency division multiplexing for 5th generation cellular networks," *IEEE Transactions on Communications*, vol. 62, no. 9, pp. 3045–3061, 2014.
[28] R. Datta *et al.*, "GFDM interference cancellation for flexible cognitive radio PHY design," in *Proc. IEEE Vehicular Technology Conf. (VTC Fall)*, 2012, pp. 1–5.
[29] B. S. da Silva *et al.*, "A survey of PAPR techniques based on machine learning," *Sensors*, vol. 24, no. 6, p. 1918, 2024.
[30] Y.-P. Tu and C.-C. Chang, "A novel low complexity two-stage tone reservation scheme for PAPR reduction in OFDM systems," *Sensors*, vol. 23, no. 2, p. 950, 2023.
[31] S. Kiambi *et al.*, "Reducing PAPR of OFDM signals using a tone reservation method based on L-norm minimization," *Journal of Electrical Systems and Information Technology*, vol. 9, no. 1, p. 12, 2022.
[32] S. Elaage *et al.*, "PAPR reduction techniques optimization-based OFDM signal for wireless communication systems," *Telematics and Informatics Reports*, vol. 14, p. 100137, 2024.
[33] T. Wattanasuwakull and W. Benjapolakul, "PAPR reduction for OFDM transmission by using a method of tone reservation and tone injection," in *Proc. IEEE Information Communications & Signal Processing Conf.*, 2005, pp. 273–277.
[34] N. Jacklin and Z. Ding, "A linear programming based tone injection algorithm for PAPR reduction of OFDM and linearly precoded systems," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 7, pp. 1937–1945, 2013.
[35] A. Quirini *et al.*, "Pilot tones injection in Golay sequences for PAPR reduction in OFDM-based JRC systems," in *Proc. IEEE Int. Radar Symposium (IRS)*, 2024, pp. 188–193.
[36] B. Elmaroud *et al.*, "On the impact of prototype filter length on the PAPR reduction of FBMC signals," *International Journal of Engineering and Technology*, vol. 6, pp. 1951–1960, 2014.
[37] R. O'Neill and L. B. Lopes, "Envelope variations and spectral splatter in clipped multicarrier signals," in *Proc. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications*, vol. 1, 1995, pp. 71–75.
[38] X. Wang, T. T. Tjhung, and C. S. Ng, "Reduction of peak-to-average power ratio of OFDM system using a companding technique," *IEEE Transactions on Broadcasting*, vol. 45, no. 3, pp. 303–307, 1999.
[39] S.-S. Jeng and J.-M. Chen, "Efficient PAPR reduction in OFDM systems based on a companding technique with trapezium distribution," *IEEE Transactions on Broadcasting*, vol. 57, no. 2, pp. 291–298, 2011.
[40] A. Kumar, "A low complex PTS-SLM-companding technique for PAPR reduction in 5G NOMA waveform," *Multimedia Tools and Applications*, vol. 83, no. 15, pp. 45141–45162, 2024.
[41] T. G. Pratt *et al.*, "OFDM link performance with companding for PAPR reduction in the presence of non-linear amplification," *IEEE Transactions on Broadcasting*, vol. 52, no. 2, pp. 261–267, 2006.
[42] Z. Wang, "Combined DCT and companding for PAPR reduction in OFDM signals," *Journal of Signal and Information Processing*, vol. 2, no. 2, pp. 100–104, 2011.
[43] N. B. Ali *et al.*, "On companding techniques for PAPR reduction in DCT SC-FDMA system in the presence of CFOs," *Alexandria Engineering Journal*, vol. 79, pp. 34–43, 2023.
[44] S. Appalla *et al.*, "Testbed configuration for minimizing PAPR in GFDM systems through a novel companding approach," *IEEE Access*, 2025.
[45] A. P. Navarro, *Channelization for Multi-Standard Software-Defined Radio Base Stations*, Ph.D. dissertation, National Univ. of Ireland Maynooth, 2011.
[46] S. Kalathil and E. Elias, "Design of multiplier-less sharp non-uniform cosine modulated filter banks for efficient channelizers in software defined radio," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 147–160, 2016.