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Deep Learning Integration in PAPR Reduction in 5G Filter Bank Multicarrier Systems

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Abstract: High peak-to-average power ratio (PAPR) has been a major drawback of Filter bank Multicarrier (FBMC) in 5G system. This research aims to calculate the Peak to Average Power Ratio (PAPR) reduction associated with the FBMC system. This research uses four techniques to reduce PAPR. They are classical tone reservation (TR). It combines tone reservation with sliding window (SW-TR). It also combines them with active constellations extension (TRACE) and with deep learning (TR-Net). TR-net decreases the greatest PAPR reduction by around 8.6 dB compared to the original value. This work significantly advances PAPR reduction in FBMC systems by proposing three hybrid methods, emphasizing the deep learning-based TRNet technique as a groundbreaking solution for efficient, distortion-free signal processing.

Keywords: Filter Bank Multi-Carrier (FBMC), Peak-to-Average Power Ratio (PAPR), Sliding Window Tone Reservation (SW-TR), Trace Detection (TRACE), Tone Reservation Neural Network (TRNet).

1 Introduction

FILTER Bank Multi-Carrier (FBMC) systems, combined work Offset Quadrature Amplitude Modulation (OQAM), are becoming a strong contender for the primary radio waveform in the upcoming 5G Radio Access Technology (RAT) [1]. This advanced modulation scheme offers several advantages, including excellent frequency localization, very low side lobes in its Power Spectral Density (PSD), and robustness to phase noise and frequency offsets, making it more suitable than OFDM for 5G RAT [2]. The research interest of this work lies in OQAM/FBMC system, which is deemed as a potential technology for 5G owing its spectral efficiency and the ability to eliminate ICI and ISI. FBMC, on the other hand, employs pulse shaping filters as opposed to rectangular window filters, significantly reducing spectral leakage and enhancing spectral efficiency compared to Orthogonal Frequency Division Multiplexing (OFDM). But this improvement comes at the cost of added complexity to the system from filtering.

In figure 1 depicts the single-input single-output (SISO) transceiver structure of the FBMC/OQAM system based on the PHYDYAS implementation [13]. The structure includes a bank of filters—synthesis filter bank at the transmitter and analysis filter bank at the receiver. These filters handle overlapping symbols effectively while maintaining the same symbol duration, ensuring efficient spectral usage. The FBMC-OQAM system is particularly advantageous for high-mobility scenarios, making it a strong candidate for 5G networks. The system mitigates ISI and ICI through advanced filtering techniques and avoids the need for a cyclic prefix, unlike OFDM. Despite its complexity, FBMC's overlapping subcarrier structure, as shown in Figure 2, enables better utilization of available bandwidth. Additionally, the use of a prototype filter ensures proper reconstruction of signals, achieving perfect reconstruction (PR) conditions under ideal circumstances. This robust signal processing capability makes FBMC-OQAM a compelling approach for next-generation wireless systems [8].

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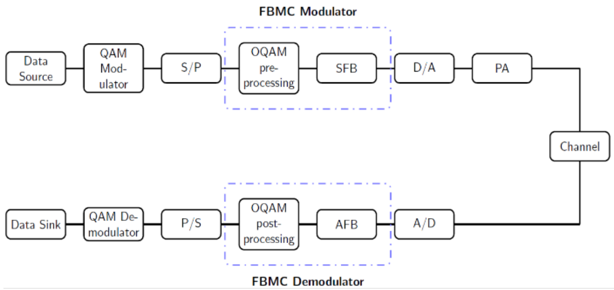


Fig. 1 FBMC/OQAM single-input single-output (SISO) transceiver structure.

However, the high peak-to-average power ratio (PAPR) in FBMC systems can cause the transmitted signal to enter the nonlinear region of the high-power amplifier (HPA), resulting in signal distortion. Previous research has proposed various methods to address the PAPR issue, with the tone reservation (TR) technique receiving considerable attention [3]. This technique involves reserving a minimal number of subcarriers to create a peak-canceling signal that reduces the PAPR of the transmitted signal. The peak reduction tones (PRT) can be directly removed at the receiver side; hence the TR method can reduce PAPR without causing any additional signal distortion. This paper proposes a joint algorithm based on classical tone reservation with sliding window, active constellations extensions, and deep learning respectively to reduce PAPR in FBMC/OQAM 5G candidate systems, where the hybrid of the previously mentioned techniques can compute better PAPR reduction results. towards the above background, the major contributions of this paper are as follows.

- Description of filter bank multi-carrier (FBMC) system. Furthermore, a comparison of FBMC and OFDM is discussed.
- High PAPR problem
- Description of Selected PAPR reduction technique and analysis of PAPR using CCDF.
- The results and simulations of using hybrid joint methods of tone reservation with Sliding Window, tone reservation with Active Constellations Extensions, and tone reservation with deep learning are displayed and analyzed.
- Conclusion and future of this work.

2 Filter Bank Multi-Carrier

FBMC is essentially an advanced version of OFDM that does not use a cyclic prefix, resulting in better performance and efficiency compared to OFDM [4]. Because of this, using FBMC increases the system's capacity and spectral efficiency. Each subcarrier of the multicarrier signals is filtered in FBMC, which lowers the frequency domain sidelobe levels. Figure 2 describes FBMC block diagram which is divided into "synthesis" filter bank at the transmitter and a "analysis" filter bank at the receiver, both of which carry out suitable subcarrier-level filtering operations.

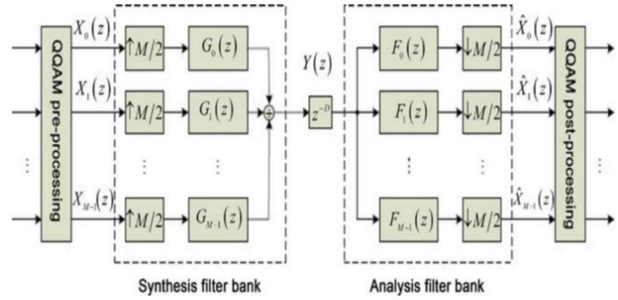


Fig. 2 TMUX configuration of filter bank multi-carrier.

2.1 Difference between FBMC and OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation scheme [21]. Data streams are carried by many orthogonal sub-carrier signals. In the last few decades, an increasing number of systems in the sector have adopted this scheme, including Long-Term Evolution (LTE) and Asymmetric Digital Subscriber Line (ADSL). Unfortunately. OFDM has two main drawbacks. The first is that it restricts the use of OFDM-based systems in dynamic spectrum environments. It requires a Cyclic Prefix (CP), which reduces spectral efficiency. This issue is exacerbated when the symbol length is very small. The second drawback is related to the high sidelobes in the OFDM signal, as presented in Figure 3. These sidelobes will then result in strong adjacent channel interference (ACI), but also a strong inter-carrier interference (ICI). In contrast, FBMC implements a sidelobe that is minimized and does not need a CP [13]. FBMC is an advancement of OFDM by accompanying the IFFT/FFT with a polyphase structure plus simple.

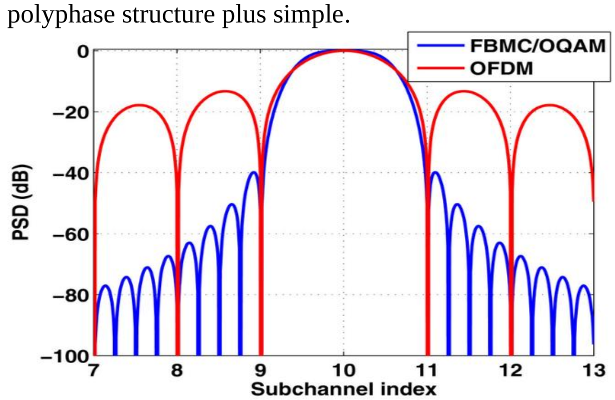


Fig. 3 Power spectral density of subcarrier in OFDM and FBMC/OQAM systems.

3 High PAPR Problem in FBMC Systems

The Peak-to-Average Power Ratio of s(t) signal is distinct as the ratio of the peak power of s(t) given signal to its average power [5]. Because of the high PAPR, the selection of power amplifiers and up-converters will be critical. The working range of the power amplifier and up converters is essential to avoid nonlinear distortion, which reduces the power efficiency of the power amplifier. As specified in the IEEE 802.11a standard, increasing the PAPR from 0dB to 17dB reduces the maximum power efficiency of a Class B power amplifier from 78.5% to 4.6% [20]. The PAPR of the complex envelope s(t) of a continuous baseband signal transmitting complex symbols with duration can be written as [6], [7]:

$$\mathrm{PAPR}\big(s(t)\big) = \frac{\max_{[0,T_o]}|s(t)|^2}{\frac{1}{T_o}\int_0^{T_o}|s(t)|^2\,dt} \tag{1}$$

The PAPR definition [8], of discrete time FBMC signal with N sub-carriers is:

$$\mathrm{PAPR}\ (s(n)) = \frac{\max_{0<n<N}|s[n]|^2}{E[|s[n]|^2]} \tag{1.1}$$

Where;

$$0 \le n \le \frac{(M-1)N}{2} + KN$$

Where;

M: number of symbols.

K: filter overlap factor.

N: subcarrier numbers.

$$\mathrm{CDF}\big[\mathrm{PAPR}\big(s(n)\big)\big] = \Pr\big(\mathrm{PAPR}\big(s(n)\big) > k\big) \tag{1.2}$$

Equation 1.2: This equation defines the Cumulative Distribution Function (CDF) of the PAPR. It represents the probability that the PAPR of the signal exceeds a certain threshold value **k**. The CDF is important for evaluating the occurrence of PAPR values above specific limits in communication systems [6-7].

$$\mathrm{CCDF}(\gamma) = \Pr\big(\mathrm{PAPR}\big(s(n)\big) < \gamma\big) = (1 - e^{-\gamma})^N \tag{1.3}$$

Equation 1.3 Provides the Cumulative Distribution Function (CDF) of the PAPR for FBMC signals under a threshold value γ It represents the probability that the PAPR is less than or equal to γ, calculated as $(1 - e^{-\gamma})^N$, where **N** represents the number of subcarriers [22].

$$\mathrm{CCDF}(\gamma) = \Pr\big(PAPR\big(s(n)\big) > \gamma\big) = 1 - (1 - e^{-\gamma})^N \tag{1.4}$$

4 PAPR Reduction Techniques

Several approaches have been proposed for PAPR reduction, with the tone reservation (TR) technique standing out for its simplicity and strong performance. Moreover, TR is distortion-free and does not require any side information [9]. TR method generates a peak-canceling signal by utilizing a small group of subcarriers known as peak reduction tones (PRTs). This signal has the potential to reduce the PAPR of a transmitted signal. The remaining subcarriers are used to transmit data.

Nevertheless, its performance is still insufficient. To achieve greater outcomes, we integrated tone reserve with other techniques.

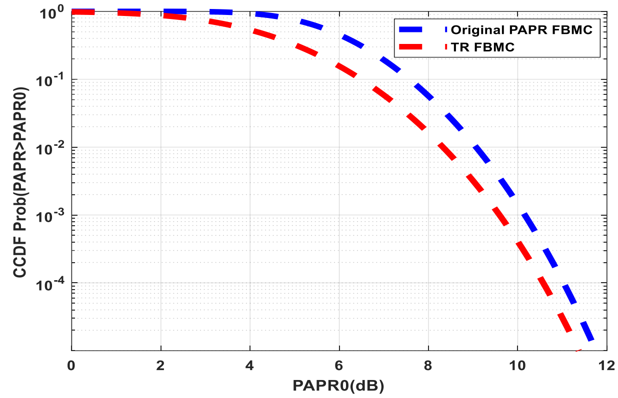


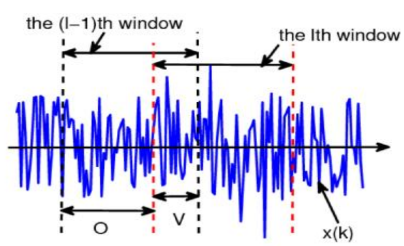
Fig. 4 PAPR Reduction Performance for tone reservation in FBMC 5G Systems.

In figure 4 shows the traditional method of tone reservation technique in FBMC which shows CCDF between the original and TR where the PAPR of TR is at 9.4 dB when has clipped at 0.001 [10].

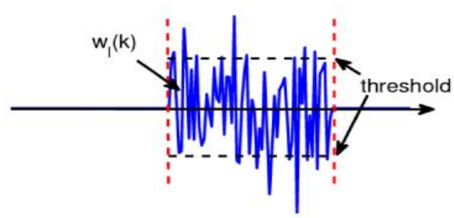
4.1 Hybrid Sliding Window with Tone Reservation Technique

A combination of two PAPR reduction strategies is used in that section: sliding window and tone reservation. The techniques are two methods presented for lowering the PAPR in FBMC/OQAM. Furthermore, to reduce the peak re-growth induced by undesirable signal clipping. As a result, we suggest the overlapping sliding window approach as it helps in PAPR reduction. The fundamental steps of the proposed SW-TR technique are as follows:

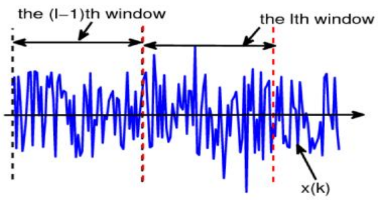
First, the PRTs of multiple consecutive data blocks are used to cancel the peaks of the FBMC-OQAM signal within a window. Second, the window slides once the peak threshold is reached or the maximum number of iterations is achieved.



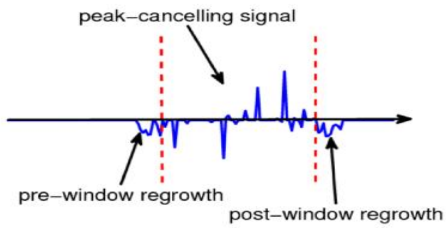
(a) x (k)



(b) wl (k)



(c) Out-of-window



(d) Overlapping window SW-TR

Fig. 5 Decomposition of SWTR hybrid technique

Figure 4 is illustrated in detail in the following steps:

Step 1: Once the $(l-1)^{th}$ window has been properly processed, extract the signal in the l^{th} window from x(k) shown in (Fig. 5(a)), and denoted the following sequence.

$$w_1(K) = \begin{cases} x(k), & (l-1)W \le k \le lW - 1 \\ 0, & \text{else} \end{cases} \tag{2}$$

Step 2: Clip the amplitude of the signal with a previously defined threshold B as shown in Fig. 5(b)

$$w_1^{`}(K) = \begin{cases} w_1(k), |w_1(k)| \le B \\ e^{j\angle w_1(k)}, |w_1(k)| > B \end{cases} \tag{3}$$

where $\angle w_1(k)$. represents the phase of $w_1(k)$. The threshold B influences the PAPR reduction performance and always determined through simulation results. The expected clipping signal shows in equation (3).

$$f_1(k) = \begin{cases} (B - |w_1(K)|)e^{j\angle w_1(k)}, |w_1(K)| \le B \\ 0, \qquad |w_1(K)| > B \end{cases} \tag{4}$$

Although $f_1(k)$ can reduce the signal`s peak to the previously defined threshold, it introduces interference to the data tones, degrading the system`s bit error rate performance. So, it is better to approximate the clipping signal $f_1(k)$ to $f_1^{`}$ [k], which only has nonzero signal on the reserved tones. Like the approach in [11], several iterations are needed CG(l), CG(l)+1, ...., CG(l)+P −1 that bring $f_1^{`}$ [k]. this iterative process is similar to that in the OFDM system [11], with the main difference being that the TR method of the FBMC-OQAM system uses reserved tones of several data blocks instead of just one. The iteration stops when the maximum number of iterations is reached or the threshold level B is achieved. Then, the signal after peak-cancelation is:

$$f_1^{`}(k) = \begin{cases} \sum_{m=G(l)}^{G(l)+P-1} C_m(k), (Gl-1)F \le k \le (G(l) + P - 1 + A)F \\ 0, \quad \text{otherwise} \end{cases} \tag{5}$$

where cm[k] is the time domain signal equivalent to Cm.

Step 3: replace x[k] with $x(k) \Leftarrow= x(k) + f_1^{`}$ (k).

Step 4: Slide the window, i.e., let l ⇐= l + 1, and got to Step 1. Simulated tests are run to determine how well the suggested SW-TR approach can reduce PAPR. 768 of the 1024 tons of the FBMC-OQAM systems are used for data transmission, leaving the remaining tones (PRTs) free for any additional uses. The SW-TR parameters are shown in table 1.

In Fig. 6 shows the PAPR performance of the Hybrid SW-TR technique with different thresholds. The curve "FBMCOQAM original PAPR" represents the performance of the FBMC-OQAM system without TR. Sliding window length is W = 3F, and the overlapping length is set as V = 0, F and 2F respectively.

Table 1 Parameter and Values used in Hybrid SW-TR

Parameter	Value
Modulation Technique	OQAM
Selected tone	768 tones
Reserved tone	256 tones
Iteration	1000
Length of prototype filter	64
A	4 sec
Over sampling Factor (F)	8

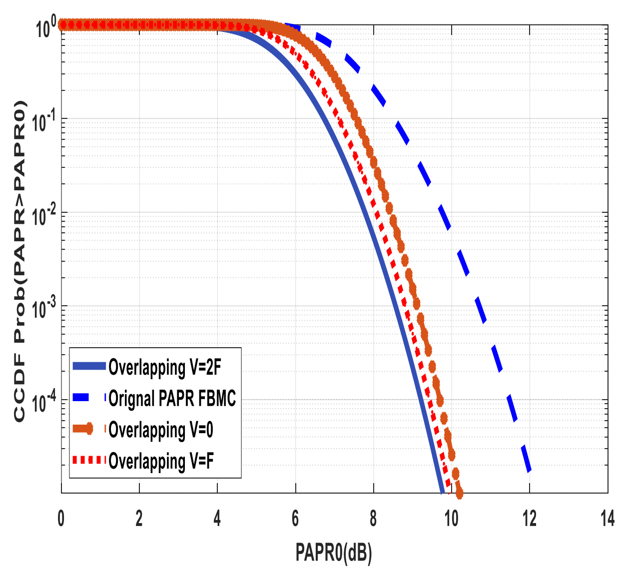


Fig. 6 PAPR performance of the SW-TR FBMC method with same window size W = 3F and different V.

The ability of the PAPR reduction of the proposed SW-TR technique is shown in Figure 7 using different window sizes. The overlapping part`s length is given by V = W − F. It is obvious that the best performance is achieved with the largest W, W = 4F and V = 3F among all simulated parameters. In Comparison with the PAPR performance of the traditional TR method, The SW-TR method outperforms it for FBMC/OQAM system with approximately 5.5 dB at CCDF = 0.001, W = 4F and V = 3F.

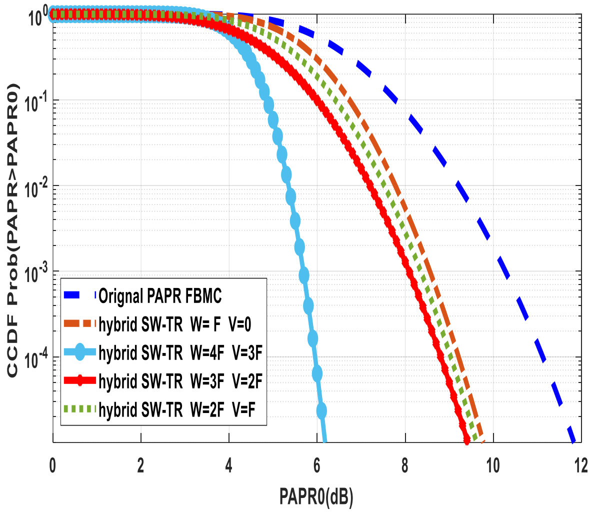


Fig. 7 PAPR performance of the Hybrid SW-TR FBMC method with different window size W &different Overlapping V.

4.2 Hybrid Active Constellations Extensionswith Tone Reservation technique

The hybrid TRACE technique combines Tone Reservation (TR) and Active Constellation Extension (ACE) to reduce PAPR. TR reserves non-data subcarriers [12] for adjustments, while ACE extends outer constellation points to lower PAPR. For 16-QAM modulation, ACE limits point extensions to four specific directions to avoid increasing BER [13]. Figure 8 illustrates the constellation patterns before and after applying TRACE hybrid technique for PAPR reduction. The original constellation diagram (Fig. 8a) exhibits a conventional 16 QAM modulation scheme with symbol points positioned at normalized coordinates on the complex plane. The constellation points are symmetrically distributed across the I-Q plane, maintaining equal Euclidean distances between adjacent symbols to ensure optimal decision boundaries. Fig. 8b demonstrates the effect of the TRACE hybrid technique, where the original constellation points undergo controlled extension and clustering. The TRACE hybrid methodology leverages the complementary advantages of both techniques. ACE facilitates the extension of outer constellation points, providing degrees of freedom for PAPR reduction while maintaining minimum distance properties. Simultaneously, TR utilizes reserved tones for optimization of the signal envelope, resulting in enhanced PAPR reduction capability compared to individual implementation of either method.

Figure 9 establishes the flow chart of Hybrid TR-ACE algorithm, which improves the outcomes over simple tone reservation and upgraded SW-TR algorithms.

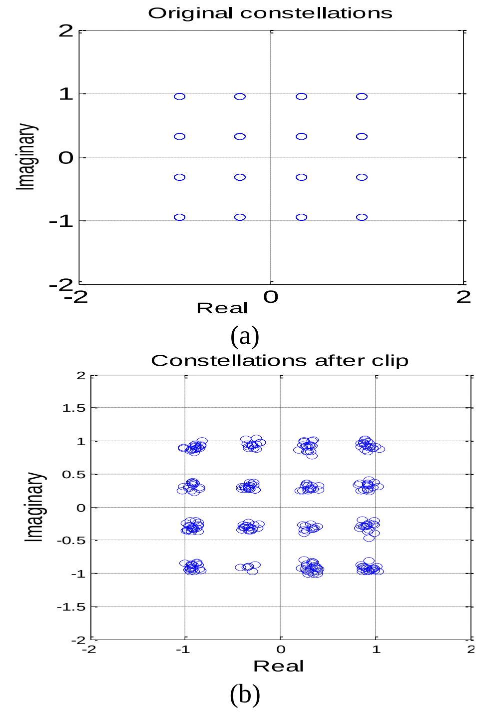


Fig. 8 Constellation diagram with ACE method using 16-QAM, N = 1024.

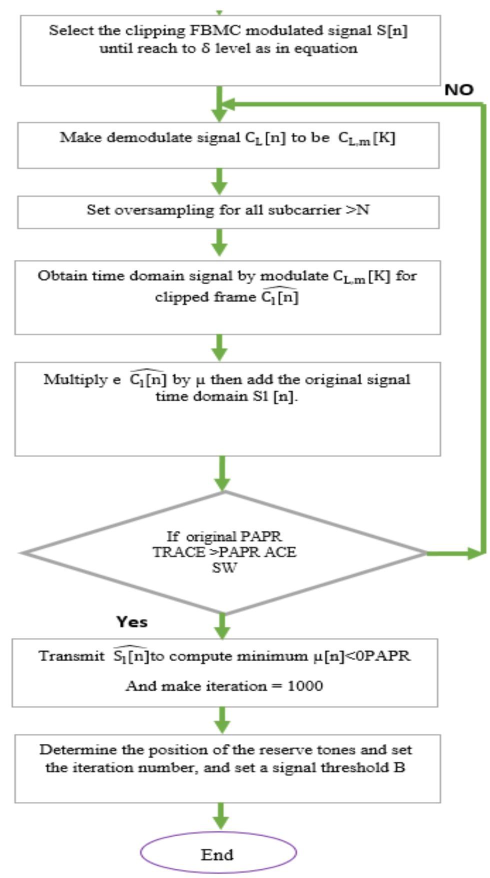


Fig. 9 Flow Chart of the Proposed Hybrid TR-ACE PAPR reduction Method in FBMC 5G system.

The flow chart illustrates the following:

Make the FBMC modulated base band frame $S_l[n]$ clipped until reach the δ amplitude such as:

$$\acute{S}_l[n] = \begin{cases} \delta e^{j\varphi[n]'} & |S_l[n]| > \delta \\ S_l[n] & |S_l[n]| < \delta \end{cases} \tag{6}$$

Which is applying the condition of:

$$0 \leq n \leq \frac{(M-1)N}{2} + L - 1$$

After the clipped signal occurred, select the negative portion of clipped frame which has known as $C_l[n]$ such that:

$$C_l[n] = \begin{cases} \delta e^{j\varphi[n]} - \acute{S}_l[n] & |S_l[n]| > \delta \\ \text{Zero} & |S_l[n]| < \delta \end{cases} \tag{7}$$

Demodulate the negative portion part of the clipped signal $C_l[n]$ and $C_{l,m}[k]$ where m and k are symbol and subcarrier of frequency domain respectively, which is used to obtain the extension of FBMC frame. Select the real components of symbols $C_m[k]$ which fall in allowable extension and set the oversampling for all null subcarrier $C_l[k]$which must be greater than N Obtain time domain signal by modulate $C_{l,m}[k]$ for FBMC clipped frame which is known as $\widehat{C}_l[n]$ Multiply $\widehat{C}_l[n]$ by μ then add it to the original signal $S_l[n] \xrightarrow{\text{yields}}$

$$\widehat{S}_l[n] = S_l[n] + \mu \widehat{C}_l[n], \qquad 0 \leq n \leq \frac{(M-1)N}{2} + L - 1 \tag{8}$$

The term of μ In equation 8 must represent the minimum value of $\mu = \min(\mu[n])$ is selected to be less than zero.

After referring to equation 14, Replace k by t as:

$$f_l^{`}(t) = \begin{cases} \sum_{m=G(l)}^{G(l)+P-1} C_m^n(t), (Gl-1)F \leq t \leq (G(l) + P - 1 + A)F \\ 0, \quad \text{otherwise} \end{cases} \tag{9}$$

Where $C_m^n(t)$ is the time domain sequence corresponding to C_m^n hence,

$$S_l^{TRACE} = S_l^{TRACE} + f_l^{`}(t) \tag{10}$$

To obtain the minimum value of PAPR in TRACE algorithm Transmit the value of S_l^{TRACE} Hence the PAPR equation that represent the result of the hybrid ACE and TR scheme will be

$$PAPR(S_l[t]) = 10 \log \left(\frac{\max_{0 \leq n \leq \frac{(M-1)N}{2} + L - 1} |S_l[t]|^2{}_{TRACE}}{E|S_l[t]|^2{}_{TRACE}} \right) \tag{11}$$

if equation (11) doesn`t meet minimum PAPR requirement so, refer to equation 6 again then repeat the procedure with several number of iterations, which is used to minimize the between the tones, also used to keep away from BER performance degradation, utilize useful signal to reduce the peak power, which only has nonzero signal on the reserved tones to produce. Table 2 shows the parameter setting used in the Hybrid TR-ACE algorithm.

Table 2 Parameter and Values used in Hybrid TRACE

Parameter	Label	Setting
Number of carriers	N	1024
Number of used carriers	Nd	512
Number of unused carriers	Nz	512
Number of reserved carriers	Nr	12 (5%)
Number of symbols	M	10000
Modulation type	FBMC	O-QAM

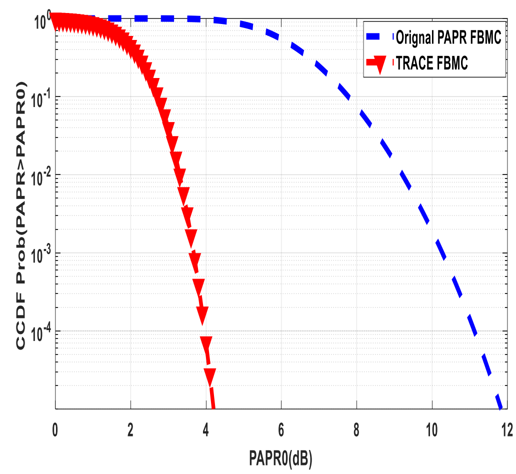


Fig. 10 PAPR reduction in FBMC system using Hybrid TR-ACE.

In figure 10 Shows maximum perfect PARR reduction result using proposed TRACE algorithm at approximately 3.5 dB which is decrease around 6.7dB compared with original FBMC PAPR value 10.3 dB, using ACE and TR equations and the distribution of the resulting extended FBMC/OQAM modulation type.

4.3 Hybrid tone reservation technique with deep learning

In recent years, artificial intelligence (AI), particularly deep learning, has achieved significant success in the fields of computer vision, natural language processing, and speech recognition [15-16]. The fundamental concept of intellectual communication is the integration of AI at several levels of wireless communication systems in order to enhance the performance of wireless communication systems. Deep learning is now doing well in end-to-end wireless systems, channel estimation, signal detection, channel decoding, and modulation recognition.

In terms of the PAPR reduction, an innovative tone reservation network (TRNet) is what we suggest that is based on deep learning to further enhance the PAPR performance of the conventional TR technique.

The baseband signal is copied to obtain two duplicates. 4-QAM modulation method and the IFFT operation are used to generate the upper path time domain signal of data $x(n)$ in a one duplication. The other duplicate is sent into the FFNN encoder together with the frequency domain reserved symbol vector C to create the peak-canceling signal $c(n)$ *in the lower path*.

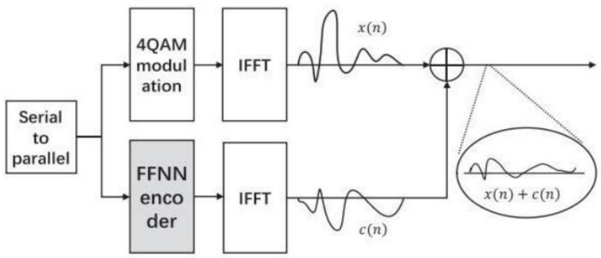


Fig. 11 TRNet structure.

C is then input to the IFFT module. The formula for the PAPR-reduced FBMC signal is $\hat{x}(n) = x(n) + c(n)$ as in figure 11.

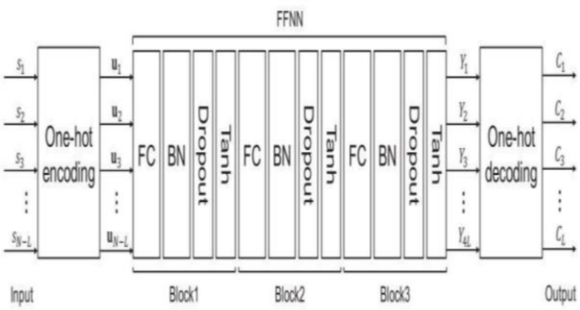


Fig. 12 Feed forward neural network (FFNN) structure.

The neural network in figure 12 part of the TRNet consists of five layers: one input layer, three hidden layers and one output layer .Each layer is linked to the others. Each hidden layer consists of a fully connected (FC) layer, batch normalization (BN), dropout [17], and the hyperbolic tangent (tanh) function.

The FFNN encoder is trained to generate the reserved symbol vector ***C*** and further reduce the PAPR of the composite transmitted signal. The training objective is to minimize the loss function by updating the parameters, which is expressed as:

$$\text{Loss} = PAPR\{\hat{x}\} = PAPR\{x + c\} = PAPR\{Q(X + C)\} \quad (12)$$

where $\{\hat{\boldsymbol{x}}\}$ is the transmitted signal that obtained by adding the peak-canceling signal **c**, produced by the FFNN encoder to the data signal x generated from python program. Table 3 shows the parameter setting used in the Hybrid TRNet algorithm.

Table 3 Parameter and Values used in TRNet

Parameter	Setting
Number of subcarriers	256
Number of reserved tones	8
Learning rate	0.001
Number of epochs	90
Modulation type	4-QAM

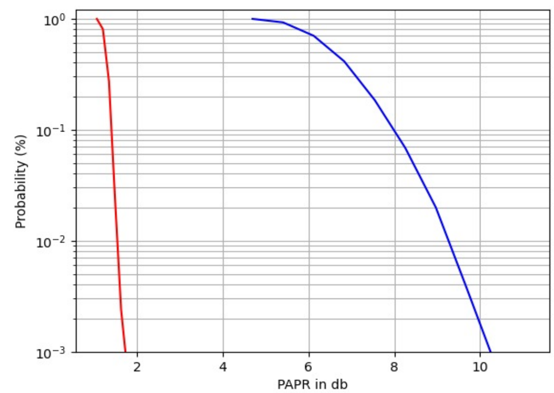


Fig. 13 PAPR reduction in FBMC system using TRNet.

The training process consists of 90 epochs. The network is optimized using the Adam algorithm with a learning rate of 0.001 and a batch size of 400. Here, the batch size indicates the number of training samples needed to update the model in one step. Figure 13 Shows maximum perfect PARR reduction result using proposed TRNet at approximately 1.7 dB which is decreased around 8.6 dB compared with original FBMC PAPR value 10.3 dB.

Table 4 Comparison of the results obtained of the four algorithms used from the point of view CCDF PAPR reduction values achieved.

PAPR reduction techniques	CCDF for PAPR values[dB]
Conventional tone reservation	9.4
Hybrid SW-TR	5.5
Hybrid TRACE	3.5
TRNet	1.7

In figure 14 presents the Bit Error Rate (BER) performance comparison for the proposed hybrid PAPR reduction techniques (TRnet-FBMC, TRACE-FBMC, and SWTR-FBMC) against the original signal without PAPR reduction. The results show that all hybrid techniques outperform the original signal, demonstrating improved BER performance. This improvement is primarily due to the reduction in PAPR, which mitigates nonlinear distortions caused by high-power amplifiers in communication systems. Among the hybrid techniques, TRnet-FBMC achieves the best BER performance, closely followed by TRACE-FBMC and SWTR-FBMC. The superior performance of TRnet-FBMC is attributable to its more effective PAPR reduction, which enhances signal robustness and reduces susceptibility to noise. TRACE-FBMC also performs well but demonstrates a slightly higher BER compared to TRnet-FBMC, indicating a trade-off between computational complexity and BER improvement. SWTR-FBMC shows the least improvement among the hybrid methods but still provides a noticeable reduction in BER compared to the original signal.

Overall, the figure illustrates the effectiveness of the hybrid techniques in improving BER performance, with TRnet-FBMC standing out as the most robust approach for error mitigation, despite its higher computational complexity.

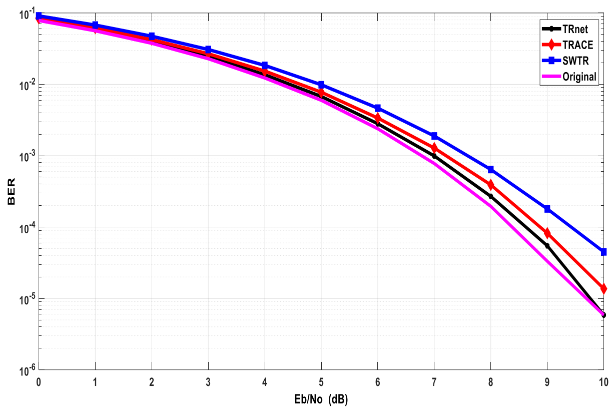


Fig. 14 BER performance of the proposed methods

The computational complexity of multiplications for the proposed PAPR reduction methods—TRnet-FBMC, TRACE-FBMC, and SWTR-FBMC—differs significantly due to variations in their underlying algorithms. TRnet-FBMC demonstrates the highest computational demand, as evident from its bar height in Figure 15. This is attributed to its iterative nature, where the iterative procedure scales linearly with the number of iterations. Combined with a relatively smaller number of subcarriers (256), this results in more computations per iteration. Specifically, the multiplication complexity in TRnet-FBMC is influenced by both the logarithmic growth of subcarrier processing and the linear growth due to iterations.

In contrast, TRACE-FBMC, designed with an alternative approach, requires fewer multiplications.

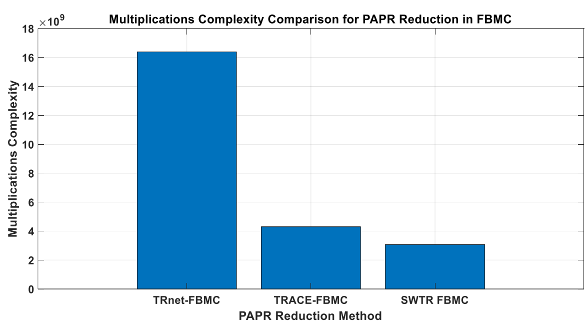


Fig. 15 Computation complexity (Addition) of the proposed methods.

Here, the algorithm operates over a higher subcarrier count (1024) but avoids the iterative processing step, leading to a significantly reduced complexity compared to TRnet-FBMC. This makes TRACE-FBMC suitable for systems where multiplication complexity is a critical constraint. SWTR-FBMC, the most efficient among the three methods, exhibits the lowest multiplication complexity. By optimizing its algorithm to reduce the impact of subcarrier processing, SWTR-FBMC achieves superior performance in minimizing computational demand. This efficiency makes it the most practical choice for scenarios requiring real-time implementation or energy-efficient processing.

In terms of additional complexity, as depicted in Figure 16, TRnet-FBMC also ranks highest among the three techniques. The iterative nature of this method again plays a pivotal role in driving its computational demand. The interaction of multiple iterations with a logarithmic dependency on subcarriers results in a substantial increase in addition operations, thereby making TRnet-FBMC the most computationally intensive.

TRACE-FBMC reduces this complexity by forgoing iterative procedures, relying instead on a direct computation model. The larger subcarrier count (1024) contributes to its addition's complexity, but the absence of iterative steps ensures that it remains significantly less demanding compared to TRnet-FBMC.

SWTR-FBMC, as with its multiplication complexity, maintains the lowest additions complexity. The algorithm's design focuses on simplifying operations by minimizing unnecessary computations and adopting efficient processing techniques. Consequently, SWTR-FBMC emerges as the lightweight option for additions, making it a compelling choice for power-constrained or latency-sensitive applications.

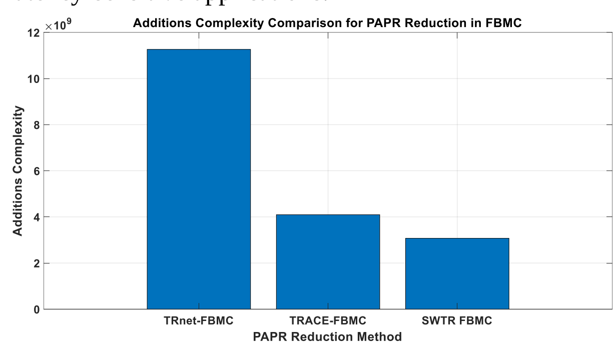


Fig. 16 Computation complexity (Addition) of the proposed methods.

5 Conclusions

This paper presented three hybrid techniques with tone reservation: sliding window technique with tone reservation technique (SWTR), Active constellation extension with tone reservation (TRACE) and deep learning with tone reservation (TRNet) to solve the problem of PAPR in FBMC 5G systems.Table 4 illustrates TRNet technique using the neural network is most effective in reducing the PAPR which give a result of PAPR value = 1.7dB compared with TRACE which represents PAPR value = 3.5 and the hybrid SW-TR in case of W=4F and V=3F that represent PAPR value = 5.5dB. On the other hand, as a distortion less scheme, TRNet does not need to compensate for the loss of BER, which greatly improves the speed of training [18]. An interesting extension of this work lies in the consideration of superposition coding for multicarrier non-orthogonal multiple access (NOMA) systems based on PAPR reduction techniques.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mohamed Hussien Moharam: Conceptualization, Methodology, Writing - Original Draft Preparation, Investigation, Resources, Visualization, Project Administration, Writing - Review & Editing, Conceptualization, Methodology, Investigation, Supervision.

Aya.W.Wafik: Formal Analysis, Software, Validation.

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mohamed Hussien and Aya Wael. The firstdraft of the manuscript was written by Mohamed Hussien. All authors read and approved the final manuscript.

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