Modified Alternating Signal (AS) scheme for Reducing PAPR of FBMC/OQAM Signal

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***Abstract* — the 5th generation upcoming applications require an alternative multicarrier modulation (MCM) scheme to support high data rate, high bandwidth efficiency, and low impulse noise. Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM) system is the most suitable scheme to meet this requirement for next wireless communication system. However, as an MCM, the high Peak to Average Power Ratio (PAPR) is a significant problem from which the FBMC/OQAM suffers causing reduced power efficiency. In this paper, a modified alternative signal with sequential optimization(MAS-SO) algorithm is proposed to reduce the PAPR of FBMC/OQAM signal. The traditional alternative signal (T-AS) algorithm is suggested to reduce the PAPR of the traditional multicarrier signal. However, it did not give a satisfactory PAPR reduction and so the algorithm has been modified to provide better PAPR reduction performance with low complexity.**

The simulation results from the complementary cumulative distribution function (CCDF) of PAPR show that the proposed scheme can achieve about 3.45 dB PAPR performance compared to existing T-AS scheme.

***Keywords* —**FBMC/OQAM, PAPR, 5G, MCM, AS, CCDF

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the most famous modulation techniques used in wireless communication systems as multicarrier modulation (MCM) techniques[1, 2]. But due to the insertion of a cyclic prefix (CP) in the OFDM transmission symbol, the data rate and spectral efficiency are reduced. To overcome the drawback of OFDM systems, the filter bank multicarrier modulation with Offset Quadrature Amplitude Modulation (FBMC/OQAM) has been suggested as one of the most modulation methods used for the next wireless communication systems [3]. However, one of the major drawbacks of FBMC/OQAM signal is the occasional high peak to average power ratio, which causes a reduction in the power efficiency of the system[4].

To solve the problem of high peak to average power ratio (PAPR) in FBMC/OQAM system, various PAPR techniques have been proposed by many researchers[5-9], the authors [10] proposed method based on sliding window tone reservation (SW-TR) technique employed to reduce the Peak tones of several consecutive data blocks. Partial transmit sequence PTS and selective mapping SLM schemes have been used for reducing PAPR of FBMC/OQAM[11], respectively. Moreover, these techniques search for better candidates jointly over the multiple FBMC symbols in which the consecutive symbols are overlapped due to pulse shaping. But these schemes have the drawback of Intersymbol interference burden which reduces the efficiency of the system, in addition, it increases its computational complexity.

PAPR reduction schemes originated on active constellation extension (ACE) and tone reservation (TR) is presented in [12]. The PTS, SLM, Potency of trellis-based SLM and Multi-Block Joint Optimization technique [13] are found to be effective in PAPR reduction. But they require additional processing and often an increased implementation complexity of the system. Clipping and filtering techniques improve the PAPR but they fail in BER[14], requiring advanced noise cancellation technique at the receiver.

In this paper, we introduce a scheme named as an alternating signal (AS) to reduce the PAPR of the FBMC/OQAM signals. Firstly we used traditional AS(T-AS)method, then we modified it to a new scheme namely modified alternating signal with sequential optimization(MAS-SO) algorithm to provide the more acceptable performance of the system.

The paper is organized as follows: Section II describes the building of FBMC/OQAM system model with SRRC filtering while introducing the problem of the peak to average power ratio of the system. Section III introduces the traditional AS algorithm and modified alternating signal with sequential optimization (MAS-SO). In section IV, the simulation results of FBMC/OQAM system with proposed schemes are presented. Last section V concludes the paper.

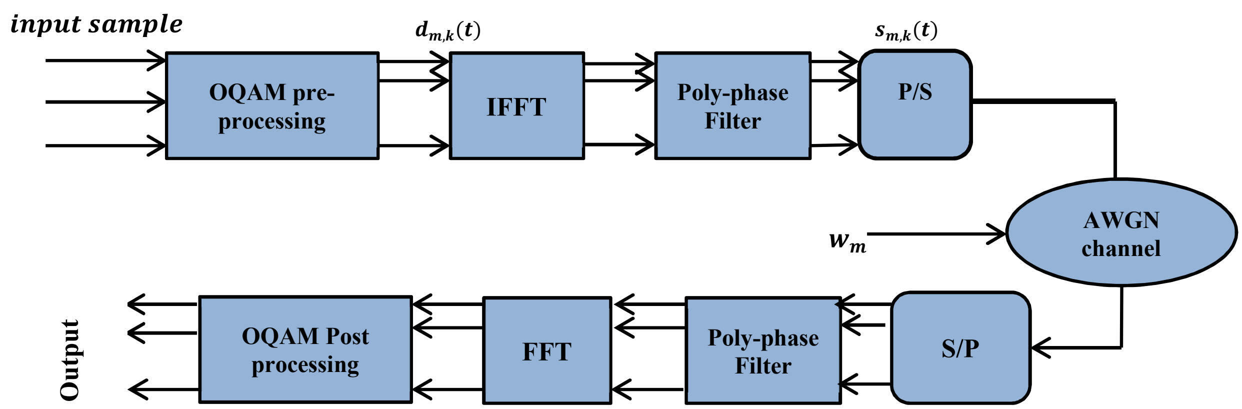

Fig. 1 Proposed Transceiver Structure of FBMC/OQAM system

Table I
List of symbols

$s_m(t)$	the modulated symbol with respect to the N subcarrier
$d_{m,k}(t)$	The input of the QAM data symbol for the mth block of kth subcarrier
F_0	Frequency
τ_0	Time offset
$g_m(t)$	pulse shape of the prototype filter
$\phi_{m,k}$	The phase term
N	the number of subcarriers
k	sub-carrier index
m	symbol index
$s_{m,k}(t)$	Baseband continuous time FBMC/OQAM
r	the roll-off factor of SRRC filter
Z	size of phase factor matrix x
w	an integer
x_{Z-1}	phase rotation vectors

II. FBMC/OQAM SYSTEM

1- The model of FBMC/OQAM signal

Figure 1 shows the FBMC/OQAM system, the transmitter consists of the OQAM preprocessing, IFFT followed by PolyPhase filter bank, where table 1 shows the list of the symbols used. However, the FBMC/OQAM system used to transmit the OQAM instead of transmitting QAM data [4, 15]. The signal in a multicarrier transmission system with N subcarriers and $x_{m,k}(t)$ QAM data symbol for the mth block of the kth subcarrier is composed of the real-valued transmitted signal shifted in time by τ_0, which is the duration of one real symbol, and shifted in frequency by F_0, which is the spacing between two successive carriers

The modulated m symbol with respect to the N subcarrier is given by

$$s_m(t) = d_{m,k}(t)e^{jk\left(\frac{2\pi t}{Ts}+\frac{\pi}{2}\right)} \quad ,k = 0,1,\ldots,N-1 \tag{1}$$

where $d_{m,k}(t)$ denotes the QAM data symbol for the mth block of the kth subcarrier, and N represents the number of subcarriers. Then the FBMC/OQAM symbol of mth block generated is given by

$$s_{m,k}(t) = \sum_{k=0}^{N-1} s_m(t)\ g_m(t) \tag{2}$$

Where $g_m(t)$ is the pulse shape of the prototype filter signal for pulse shaping which can be written as [15]

$$g_m(t) = g(t-k\tau_0)e^{j2\pi mF_0 t}e^{j\phi_{m,k}} \tag{3}$$

The phase term $\phi_{m,k}$ can be written as

$$\phi_{m,k} = \phi_0 + \frac{\pi}{2}(m+k) \tag{4}$$

Where k means sub-carrier index, m means symbol index and ϕ_0 is an additional phase[15].

The impulse response in the continuous time domain of square root raised cosine (SRRC) filter is expressed as[16-18]

$$g_m(t) = \frac{\sin(\pi(1-r)t) + 4rt\cos(\pi(1+r)t)}{\pi t(1-16r^2t^2)} \tag{5}$$

The ideal prototype of the square root raised cosine filter is a classical analog Nyquist filter with the roll-off factor ‘ r ’ with roll-off parameter $0 < r \leq 1$.

2- THE PEAK TO AVERAGE POWER RATIO (PAPR)

The Peak to Average Power Ratio (PAPR) of FBMC/OQAM signal $s_{m,k}(t)$ is ddescribed as the ratio of the peak power of $s_{m,k}(t)$ to its average power. The PAPR of FBMC/OQAM transmitting signal can be written as [7, 19]

$$PAPR = 10\ log_{10} \frac{Max\{|s_{m,k}(t)|^2\}}{E\{|s_{m,k}(t)|^2\}}\ dB \tag{6}$$

Where $E\{.\}$ expresses the expectation operation. As performance meausure for the PAPR one defines the complementary cumulative distribution function (CCDF) of PAPR giving the probability that the PAPR is above certain threshold level (γ) . It is given by [20]

$$CCDF(\gamma) = P_r\left(PAPR\left(s_{m,k}(t)\right) > \gamma\right) \tag{7}$$

$$CCDF(\gamma) \ \ = 1 - (1 - e^{-\gamma})^N \tag{8}$$

III. Conventional AS and Modified algorithms

1- *The traditional AS algorithms(T-AS)*

the T-AS algorithm reduces the PAPR by choosing one phase rotation vector from a given set for each FBMC/OQAM symbol [21]. Over different FBMC/OQAM symbols, the phase rotation vectors might be different.
Let us denote the set of candidate phase rotation vectors as

$$x = \{x_0, x_1, x_2, \dots \dots \dots, x_{Z-1}\} \tag{9}$$

Where Z denotes the size of the phase factor matrix, The phase factor for z^{th} block, where $0 \le z \le Z - 1$, is represented as

$$x_z = \{x_{Z,0}, x_{Z,1}, x_{Z,2}, \dots \dots \dots, x_{Z,N-1}\}^T \tag{10}$$

Where T specifies the transpose

Here $x_{z,k} = e^{j\left(\frac{2\pi kz}{N}\right)}$ (11)

Where $k = 0,1,2, \dots \dots, N - 1$. The traditional AS algorithm suggested for the FBMC/OQAM system can be presented by the subsequent steps:

T-AS algorithm for the FBMC/OQAM

1. Get the modulated symbols of FBMC/OQAM symbol for M[th] block over N subcarriers $s_0(t), s_1(t), \dots, s_m(t), \dots \dots, s_{M-1}(t)$

2. Get phase factor of z[th] block with 0<z<Z-1
$$x_z = \left\{x_{Z,0}, x_{Z,1}, x_{Z,2}, \dots \dots \dots, x_{Z,N-1}\right\}^T$$
Where x phase factor matrix , Z is the set of the factor matrix
3. Multiply the individual symbols with phase factors then we obtain new FBMC/OQAM symbols as $\tilde{s}_0(t), \tilde{s}_1(t), \dots, \tilde{s}_m(t), \dots \dots, \tilde{s}_{M-1}(t)$
4. Get new FBMC/OQAM signal by
$$\tilde{s}_{m,k}(t) = \sum_{k=0}^{N-1} \tilde{s}_{M-1}(t) \tag{12}$$
5. Get PAPR by
$$PAPR = \frac{max\left[\left|\left|\sum_{k=0}^{N-1} \tilde{s}_{m,k}(t)\right|\right|\right]}{E\left[\left|\sum_{k=0}^{N-1} \tilde{s}_{m,k}(t)\right|\right]^2} \tag{13}$$

2- *The MAS-SO algorithms*

The new modified concept of the T-AS algorithm uses the concept of sequential optimization (SO) to reduce the PAPR with reduced complexity, where the new scheme is called Modified Alternating Signal Sequential Optimization (MAS-SO).

MAS-SO algorithm decreases the PAPR to a minimum value by selecting the best optimum phase factor. After that, it will apply the new algorithm sequentially to the individual 'M-number of symbols.

Figure 2 illustrates the block diagram of the MAS-SO algorithm, with m[th] block of the system. It can reduce PAPR to a minimum value by taking the previous value of the symbol of FBMC/ OQAM. Where, for the 1[st] block, the output symbol $s_0(t)$ will be passed to the next block as the input, then it will be multiplied by the phase factor to get new FBMC/OQAM symbol which can reduce PAPR to the minimum value denoted by $\hat{s}_0(t)$. Then the output of the 1[st] block will be passed to the next 2[nd] block which is denoted by $\hat{s}_1(t)$. Then, the PAPR will be calculated from

$$PAPR_1 = \frac{max\left[\left|\left|\hat{s}_0(t) + \sum_{k=0}^{N-1} s_{1,k}(t)\hat{x}_{z,k}\right|\right|\right]^2}{E\left[\left|\hat{s}_0(t) + \sum_{k=0}^{N-1} s_{1,k}(t)\hat{x}_{z,k}\right|\right]^2} \tag{14}$$

This previous procedure will be repeated until finishing all M[th] block. Finally, the PAPR is optimized for the MAS-SO algorithm as

$$PAPR_{MAS-OS} = \frac{max\left[\left|\left|\sum_{p=0}^{m-1} \hat{s}_p(t) + \sum_{k=0}^{N-1} s_{m,k}(t)\hat{x}_{z,k}\right|\right|\right]^2}{E\left[\sum_{p=0}^{m-1} \hat{s}_p(t) + \sum_{k=0}^{N-1} s_{m,k}(t)\hat{x}_{z,k}\right]^2} \tag{15}$$

The MAS-SO algorithm being suggested for the FBMC/OQAM system taking into consideration the overlapping nature of the FBMC/OQAM signal and can be described by the subsequent steps:

MAS-SO algorithm for the FBMC/OQAM

1. Get the modulated symbols of M[th] block over N subcarriers $s(t), s_1(t), \dots, s_m(t), \dots \dots, s_{M-1}(t)$ then apply them to the M blocks as the input to the next stage
2. Get optimum phase factor of z[th] block with o<z<Z-1
$\hat{x} = \{x_0, x_1, \dots \dots \dots, x_{Z-1}\}$
Where $\hat{x}$ phase factors matrix , Z is the size of the factor matrix. The optimum phase factor for the z[th] block is $\hat{x}_z = \{\hat{x}_{z,0}, \hat{x}_{z,1}, \dots \dots \dots, \hat{x}_{z,N-1}\}^T$, with
$$\hat{x}_{z,k} = e^{j\left(\frac{2\pi kz}{N}\right)} \tag{16}$$
Where $k = 0,1,2, \dots \dots, N - 1$.
3. Multiply $s_0(t)$ with optimizd phase factor , then the result is denoted by $\hat{s}_0(t)$

4. In the m[th] block, we get PAPR optimization as PAPR

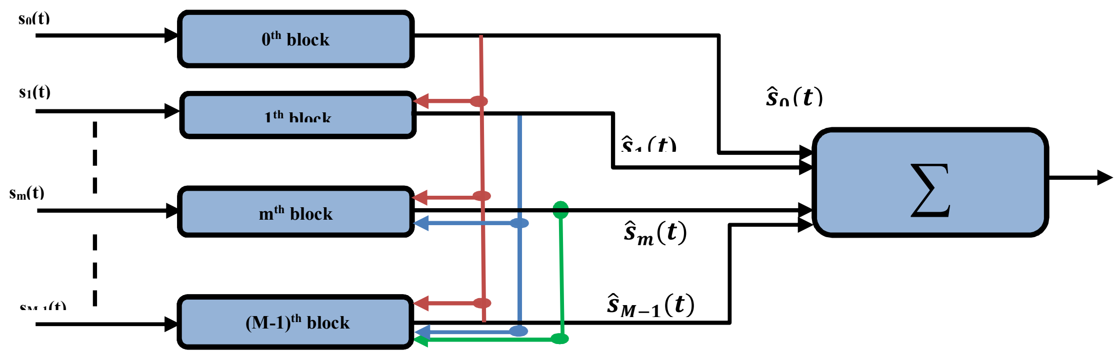

Figure 2: Block diagram of MAS-SO algorithm

$$PAPR_{MAS-OS} = \frac{max\left[\left|\left|\sum_{p=0}^{m-1} \hat{s}_p(t) + \sum_{k=0}^{N-1} s_{m,k}(t)\hat{x}_{z,k}\right|\right|\right]^2}{E\left[\sum_{p=0}^{m-1} \hat{s}_p(t) + \sum_{k=0}^{N-1} s_{m,k}(t)\hat{x}_{z,k}\right]^2} \quad (17)$$

5. For $m \leq M-1$, increment m by 1 and then go to step number 3 to finish the M^{th} blocks and get PAPR until finishing all symbol blocks
6. Compute

$$\hat{s}(t) = \sum_{m=0}^{M-1} \hat{s}_m(t) \quad (18)$$

Finally, display the final output

IV. Numerical Results and Discussion

In this section, the PAPR reduction capabilities of the abovementioned methods were verified through simulations. The CCDF diagrams of the above techniques, the bit error rate BER and also the power spectral density PSD for comparison are depiction. Simulations are conducted for an FBMC/OQAM signal that has been generated from 128-OQAM symbols. The SRRC prototype filter is used to design the PolyPhase filter. Table 1 presents the simulation model parameters.

Table 2 Simulation parameters of system model

Parameter	Description
Simulation method	Monte Carlo
Number of Subcarriers	256
Overlapping factor	4
Roll-off Factor	0.55
Modulation type	128OQAM
Channel model	AWGN
number of sub-blocks “ z ” is set to be	4,6,8,10

1- CCDFs Comparisons

In this part, one compares the PAPR reduction of the FBMC/OQAM system capability via the CCDFs diagram of the traditional SR (T-AS) and MAS-S algorithm.

In figure 3, one plots the CCDFs curves for Conventional FBMC/OQAM signal, T-AS and MAS-SO schemes with selected number of sub-blocks “Z” to be = 4, and phase factor $x_{z,k} = [1 \quad -1]$. The PAPR values at CCDF of 10^{-3} for conventional FBMC/OQAM signal, T-AS and MAS-S schemes are 17.09 dB, 10.67 dB and 5.972 dB, respectively. It is observed that the proposed MAS-SO scheme decreases PAPR effectively compared to T-AS scheme, by 11.118 dB

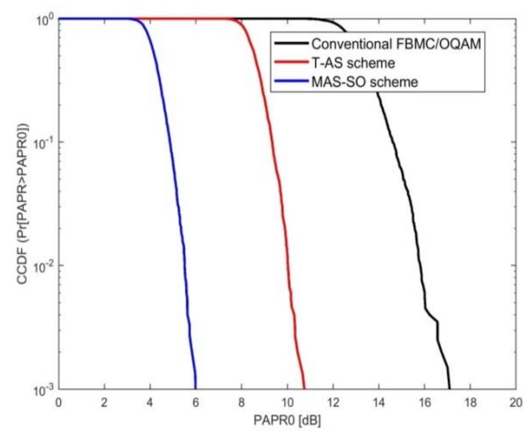

Figure 3 PAPR vs. CCDF plots for T-AS and MAS-SO algorithms for Z=4

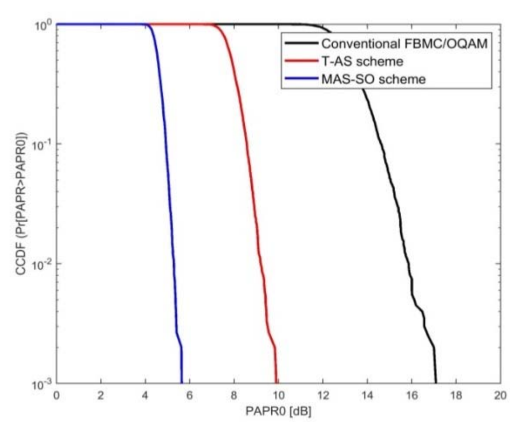

Figure 4 PAPR vs. CCDF plots for T-AS and MAS-SO algorithms for Z=4

Figure 4 represents the PAPR vs. CCDF plot when the phase rotation factors are $x_{z,k} = [1 \quad -1 \quad j \quad -j]$, Here the number of sub-blocks “Z” is set to 4 The PAPR values at the CCDF value of 10^{-3} for conventional FBMC/OQAM signal, T-AS and MAS-S schemes are 17.09 dB, 9.88 dB, and 5.132 dB, respectively. It is observed that the proposed MAS-SO scheme decreases PAPR effectively compared to T-AS scheme, by about 12.058 dB.

PAPR reduction performance of T-AS and MAS-SO algorithms with 6,8,10 are shown in Fig. 5. The values of PAPR at CCDF of 10^{-3} for a T-AS algorithm with 6,8,10 are about 12.01 dB, 8.956 dB, and 8.001 dB whereas the PAPR values for the MAS-SO algorithm are 5.011 dB, 4.053 dB and 2.357dB. It is clear that as the number of sub-blocks “Z” increases PAPR decreases for both methods. MAS-SO algorithm has good PAPR performance compared to that of the T-AS algorithm and reduces PAPR effectively.

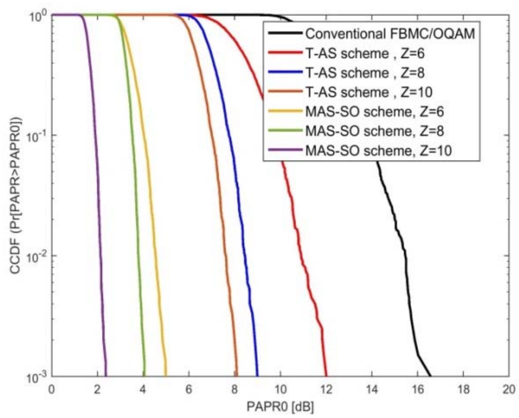

Figure 5 PAPR performance for T-AS and MAS-SO algorithms with Z=6, 8, and 10

2- BER Comparisons

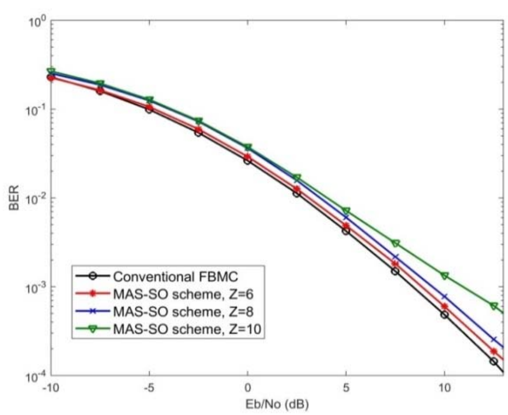

Figure 6 Comparison of BER of the MAS-SO schemes

Another parameter to evaluate the performance of any PAPR reduction method is the bit error rate BER. The Rapp model [22]is used to describe the nonlinearity of solid state power amplifier (SSPA) in the transmission. Eq. (19) defines the Amplitude/Amplitude (AM/AM) characteristic of the Rapp HPA**.**

$$F(\rho(t)) = \frac{\rho(t)}{\left[1+\left(\frac{\rho(t)}{A_{sat}}\right)^{2P}\right]^{\frac{1}{2P}}} \tag{19}$$

Where the A_{sat} is the input level of the HPA , and P is the smoothness factor to control the transition between the linear and limiting regions.

Fig. 6 depicts the BER performances of the proposed PAPR reduction scheme. For ideal situation, "Ideal" demonstrates the BER curve of the original FBMC/OQAM signal without nonlinear distortion through the SSPA. As illustrated in Fig. 6, the BER performance of MAS-SO algorithms with z 6, 8 and 10 are shown in Fig. 5. It is clear from the figure that the bit error rate performance for z=6 approach same that of the original signal. Finally, for low to moderate z , the proposed MAS-SO scheme achieves acceptable BER performance with appreciable PAPR reduction of the FBMC/OQAM signal.

3- PSD Comparisons

The spectral leakage of the proposed PAPR reduction methods is a matter of critical importance. When compared with the OFDM, the FBMC/OQAM system offers very low spectral leakage. However, when an HPA clips, severe spectral leakage occurs. This is one of the significant features of PAPR reduction techniques, they avoid HPA clipping and consequently reduce undesirable Out Of Band radiation.

In order to simulate and observe the results of the proposed MAS-SO PAPR reduction techniques in terms of PSD, an FBMC/OQAM system with 256 active subcarriers was used.

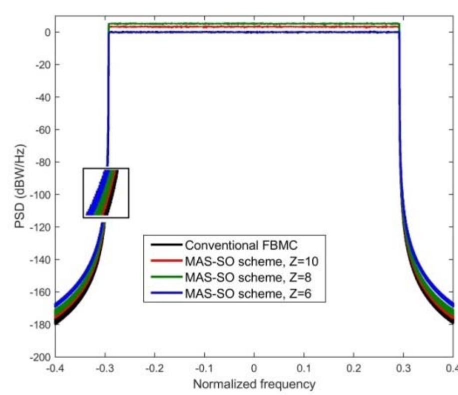

Figure 7 Comparison of PSD of the MAS-SO schemes

Fig. 7 compares the PSDs of the MAS-SO algorithm with varying the number of sub-blocks “Z” =6, 8 and10.

From the simulation results; one observes that the proposed MAS-SO scheme can achieve low out of band radiation (OBR) especially for higher values of z. Since the CCDF, the BER and the PSD performance of the MAS-SO method provide good behavior, one can conclude that the MAS-SO may be considered one of the suitable scheme for reducing the FBMC/OQAM high PAPR.

V. CONCLUSION

The FBMC/OQAM system technology may be used as one of the best modulation schemes for the next wireless communication system namely as a fifth generation (5G) system as it can improve the spectrum efficiency. However, the disadvantage of FBMC/OQAM system is high PAPR especially when signal access nonlinear devices, it may require wide dynamic range, or may cause nonlinear distortion due to that it degrades the overall performance. This paper introduced a scheme named as an alternating signal (T-AS) to reduce the PAPR of the FBMC/OQAM signals. Firstly we used conventional AS method, and then we modified it to new schemes namely modified alternative signal with sequential optimization (MAS-SO) algorithm.

From our simulation, we can say that our proposed MAS-SO scheme is able to provide a great reduction in PAPR while very slightly reduces BER performance. Therefore, we can find a justification for using our proposed technique for reducing PAPR in FBMC/OQAM for next-generation wireless communication.

REFERENCES

1. Andrews, J.G., et al., *What will 5G be?* IEEE Journal on selected areas in communications, 2014. **32**(6): p. 1065-1082.
2. Luo, F.-L. and C. Zhang, *Signal processing for 5G: algorithms and implementations*. 2016: John Wiley & Sons.
3. Nissel, R., S. Schwarz, and M. Rupp, *Filter Bank Multicarrier Modulation Schemes for Future Mobile Communications.* IEEE Journal on Selected Areas in Communications, 2017. **35**(8): p. 1768-1782.
4. Skrzypczak, A., J. Palicot, and P. Siohan, *OFDM/OQAM modulation for efficient dynamic spectrum access.* International Journal of Communication Networks and Distributed Systems, 2012. **8**(3-4): p. 247-266.
5. Moon, J.H., Y.R. Nam, and J.H. Kim, *PAPR Reduction in the FBMC-OQAM System via Segment-Based Optimization.* IEEE Access, 2018. **6**: p. 4994-5002.
6. Shaheen, I.A., et al. *PAPR Reduction of FBMC/OQAM Systems Based on Combination of DST Precoding and A-law Nonlinear Companding Technique*. in *2017 International Conference on Promising Electronic Technologies (ICPET)*. 2017.
7. Shaheen, I.A.A., et al. *Absolute Exponential Companding to Reduced PAPR for FBMC/OQAM*. in *2017 Palestinian International Conference on Information and Communication Technology (PICICT)*. 2017.
8. Sudha, V. and D.S. Kumar. *PAPR reduction of OFDM system using PTS method with different modulation techniques*. in *2014 International Conference on Electronics and Communication Systems (ICECS)*. 2014.
9. Xiao, H., et al., *Reduction of peak-to-average power ratio of OFDM signals with companding transform.* Electronics Letters, 2001. **37**(8): p. 506-507.
10. Lu, S., D. Qu, and Y. He, *Sliding Window Tone Reservation Technique for the Peak-to-Average Power Ratio Reduction of FBMC-OQAM Signals.* IEEE Wireless Communications Letters, 2012. **1**(4): p. 268-271.
11. Mohammad, A.S., A.H. Zekry, and F. Newagy. *A combined PTS-SLM scheme for PAPR reduction in multicarrier systems*. in *2013 IEEE Global High Tech Congress on Electronics*. 2013.
12. Laabidi, M., et al. *PAPR reduction in FBMC/OQAM systems using active constellation extension and tone reservation approaches*. in *2015 IEEE Symposium on Computers and Communication (ISCC)*. 2015.
13. Qu, D., S. Lu, and T. Jiang, *Multi-Block Joint Optimization for the Peak-to-Average Power Ratio Reduction of FBMC-OQAM Signals.* IEEE Transactions on Signal Processing, 2013. **61**(7): p. 1605-1613.
14. Zhao, J., S. Ni, and Y. Gong, *Peak-to-Average Power Ratio Reduction of FBMC/OQAM Signal Using a Joint Optimization Scheme.* IEEE Access, 2017. **5**: p. 15810-15819.
15. Rath, V. and T. Shilpa, *New Physical-layer Waveforms for 5G*, in *Towards 5G:Applications, Requirements and Candidate Technologies*. 2017, Wiley Telecom. p. 472.
16. Chia-Yu, Y. and C. Chiang-Ju. *Design of a square-root-raised-cosine FIR filter by a recursive method*. in *2005 IEEE International Symposium on Circuits and Systems*. 2005.
17. Kamal, S., C.A. Azurdia-Meza, and K. Lee, *Family of Nyquist-I Pulses to Enhance Orthogonal Frequency Division Multiplexing System Performance.* IETE Technical Review, 2016. **33**(2): p. 187-198.
18. Khan, A. and S.Y. Shin, *Wavelet OFDM-Based Non-orthogonal Multiple Access Downlink Transceiver for Future Radio Access.* IETE Technical Review, 2018. **35**(1): p. 17-27.
19. Shaheen, I., et al., *PAPR reduction for FBMC/OQAM using hybrid scheme of different Precoding transform and mu-law companding.* 2017, 2017. **6**(4): p. 9.
20. Shaheen, I.A., et al., *Performance evaluation of PAPR reduction in FBMC system using nonlinear companding transform.* ICT Express, 2018.
21. W. Saad, N. El-Fishawy, S. El-Rabiae, and M. Shokair, “Low Complexity Wizard Amplitude Shaping (WAS) System for PAPR Reduction,” IET Communications Journal, vol. 7, issue, 18, pp. 2005-2014, Dec. 2013.
22. Rapp, C., *Effects of HPA-nonlinearity on a 4-DPSK/OFDM-signal for a digitial sound broadcasting system.* Proc. Second European Conference on Satellite Communications, Liege, Belgium, Oct. 1991, 1991: p. 179-184.