Hybrid PAPR Reduction Algorithm Using Low Complexity Dispersive Selective Mapping with Clipping and Filtering for FBMC/OQAM

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***Abstract*—This paper provides a low complexity dispersive selective mapping (LDSLM) algorithm to the problem of high peak-to-average power ratio (PAPR) problem in filter bank multicarrier with offset quadrature amplitude modulation (F-BMC/OQAM) system. The proposed algorithm considers the overlapping characteristics of signals, and employs the average power distribution of the signals to shorten search range and reduces the system complexity. Compared with the existing clipping and filtering (CAF) algorithm, the LDSLM algorithm ensures the non-distortion property, while the PAPR is not be significantly reduced. Furthermore, considering the advantages of LDSLM and CAF algorithms, a hybrid algorithm combining CAF and LDSLM is proposed to effectively improve the PAPR performance of the system without affecting the bit error rate (BER).**

Keywords–FBMC/OQAM; PAPR; Selective mapping; Clipping and filtering.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has low spectrum efficiency and needs high synchronization due to the interference of the cyclic prefix, these problems restrict the development of communication systems [1-2]. The filter bank multicarrier with offset quadrature amplitude modulation (FBMC/OQAM) is thought to be the effective means to solve the existing problem of OFDM, and is also suitable for the discontinuous spectrum cognitive radio communication [3].

As a multicarrier system, FBMC/OQAM system transmits signals that are superimposed by multiple subcarrier signals which lead to the high of peak to average power ratio (PA-PR). The high PAPR makes signals through the high power amplifier (HPA) nonlinear region, which will cause distortion and seriously affect bit error rate (BER) of the system [4].

In the undistorted [5-6] and distorted [7-8] algorithms proposed by OFDM, the PAPR and BER can be reduced. Due to the overlapping structure of FBMC/OQAM signals, if the original algorithms is directly applied to its system, it cannot achieve a good effect. According to the current research status, the dispersive selective mapping (DSLM) algorithm is proposed in [9], which considers the current signal and the previous signals when optimizing the current signal. In [10] utilizes the single carrier effect spread by discrete fourier transform (DFT), and generates multiple FBMC waveform signals according to different time shifts. A low complexity mixed scheme was proposed in [11], utilizing discrete sine transform (DST) in the precoding technology and nonlinear compression technique, this algorithm improves the performance of PAPR effectively under the given BER. Based on partial transmit sequence (PTS) algorithm, [12] puts forward sparse PTS algorithm, which directly optimizes the detected signal peak position, and combines with the tone reservation (TR) algorithm to reduce the PAPR of the system. In [13], the smart gradient-project active constellation extension (SGP-ACE) algorithm reduces the number of iterations of the active constellation extension (ACE) algorithm and quickly converges to a lower PAPR. In [14], the PAPR of the system is reduced directly by using A-law and μ-law companding algorithms at the expense of a certain BER performance.

This paper analyses the reason why selective mapping (SLM) algorithm is not feasible in FBMC/OQAM system, and provides a low complexity dispersive selective mapping (LDSLM) algorithm. The algorithm takes into account the overlapping characteristics of signals, and shortens the search range according to the power distribution. In order to further reduce PAPR, combining LDSLM algorithm with clipping and filtering (CAF) algorithm, the hybrid algorithm can weigh the performance of PAPR and BER. By choosing parameters reasonably, the PAPR is effectively reduced while the BER performance of the system is guaranteed.

II. FBMC /OQAM SYSTEMS

A. Basic principle of FBMC/OQAM system

The transmitter structure of FBMC/OQAM is shown in Fig. 1. The input of the FBMC/OQAM system is generally a complex signal, which can be expressed as:

$$X_{m,n} = a_{m,n} + j \times b_{m,n} \tag{1}$$

where $n \in [0, N-1]$, $m \in [0, M-1]$, $a_{m,n}$ and $b_{m,n}$ are the real part and the imaginary part signals on the m^{th} subcarrier of the n^{th} symbol respectively.

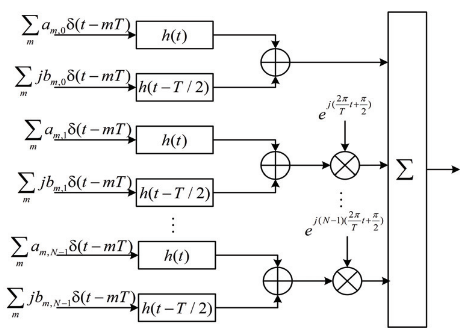

Fig. 1. FBMC/OQAM sender.

In Fig.1, OQAM is used to develop and transmit the real and imaginary parts of complex signals respectively, where the imaginary part of the signal in the time domain is delayed by $T/2$ relative to the real part of the signal, N is the symbol width. M transmitted signals pass through a set of prototype filters $h(t)$ and modulate to N subcarriers to obtain the output time-domain signal, which can be expressed as:

$$\begin{aligned} x(t) &= \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} x_{m,n}(\mathrm{t}) \\ &= \sum_{n=0}^{N-1}\sum_{m=0}^{M-1}\left[a_{m,n}h(t-mT) + jb_{m,n}h(t-mT-\tfrac{T}{2})\right] \\ &\cdot e^{in(\frac{2\pi t}{T}+\frac{\pi}{2})} \end{aligned} \tag{2}$$

where $x_{m,n}(t)$ is the time-domain signal form modulated by $X_{m,n}$.

Generally, the signal should be oversampled with sampling factor l. The PAPR of the sampled signal can be more approximate to the original continuous signal for $l \geq 4$. In this paper, the European PHYDYAS filter is used as the prototype filter $h(t)$ [15], which uses frequency sampling technology and introduces the overlapping factor K. Therefore, the length of the filter is $L = KN$, and the frequency domain coefficient of the filter satisfies the following equation:

$$\begin{aligned} &H_0 = 1, H_1 = 0.97196, H_2 = 1/\sqrt{2}, \\ &H_3 = \sqrt{1-H_1^2}, H_4 = 0 \quad (4 < k < L-1) \end{aligned} \tag{3}$$

The impulse response of the prototype PHYDYAS filter is:

$$h(t) = \begin{cases} \frac{1}{\sqrt{A}}\left[1 + 2\sum_{k=1}^{K-1}(-1)^{\mathrm{k}} H_{\mathrm{k}} \cos(\frac{2\pi kt}{KT})\right], t \in [0, KT] \\ \qquad 0, \quad \text{other} \end{cases} \tag{4}$$

Compared with fast fourier transform (FFT) filter, this prototype filter $h(t)$ has better out-of-band attenuation performance. The filter banks mentioned above can be generated by the prototype filter through polyphase network (PPN) or frequency domain expansion. Considering the complexity, PPN is selected in this paper.

B. Performance analysis of FBMC/OQAM

FBMC/OQAM as multicarrier system, each symbol is composed of multiple subcarrier modulated signals. When the subcarrier signals of the same phase are added together, a larger peak power will be generated. It will make modulated signals through the HPA nonlinear region, causing in-band distortion and out-of-band spectrum extension. At the receiving end, the decision of the signal will be affected and the BER will increase. In a period of time, the ratio between the peak power and the average power of the signal is called PAPR, the PAPR of the continuous time-domain signal in a period is expressed as:

$$PAPR_{x(t)} = \frac{\max_{0 \leq t \leq T}|x(t)|^2}{\frac{1}{T}\int_0^T \left|x(t)\right|^2 dt} \tag{5}$$

When continuous signal is sampled, take OFDM signal as an example, $\mathbf{x}[k]$ represents the output signal after modulation, that is: $\mathbf{x}[k] = \frac{1}{\sqrt{N}}\sum_{i=0}^{N-1} X(i)e^{j2\pi ik/N}$. Then, the PAPR of the discrete signal can be expressed as:

$$PAPR(\mathbf{x}[k]) = \frac{\max\left\{|\mathbf{x}[k]|^2\right\}}{E\left\{|\mathbf{x}[k]|^2\right\}} \tag{6}$$

Generally, the complementary cumulative distribution function (CCDF) is commonly used to measure the PAPR of a system. The CCDF represents the probability that the PAPR of a symbol in the time domain exceeds a given threshold, the expressions defined are as follows:

$$CCDF[PAPR(x(t))] = \Pr(PAPR(x(t)) > \gamma) \tag{7}$$

III. PAPR REDUCTION ALGORITHM

A. SLM algorithm for OFDM signals

In the classical SLM algorithm of OFDM, each group of input sequences is multiplied by different random phase sequences to obtain different groups of input sequences. After modulation, the PAPR values of each group of sequences are calculated in the current symbol period of OFDM. The lowest group of PAPR is selected as the optimal sequence of transmission, the corresponding optimal phase sequence is used as the side-band information. At the receiving end, the original signal is restored by using side-band information, which ensures the reliability of the signal and achieves undistorted transmission.

SLM algorithm designed for OFDM is no longer suitable for FBMC/OQAM system [16]. In order to match SLM algorithm with signal structure, we need to consider signal overlapping structure.

B. LDSLM algorithmfor FBMC/OQAM signals

In the FBMC/OQAM system, due to the introduction of the overlapping factor K and the imaginary part of the signal delays $T/2$, the signal is extended. The length of a single symbol changes from T to $4.5T$, so there is overlap between the signals. The Fig. 2 below is the comparison diagram of the symbol power distribution under OFDM system and FBMC system.

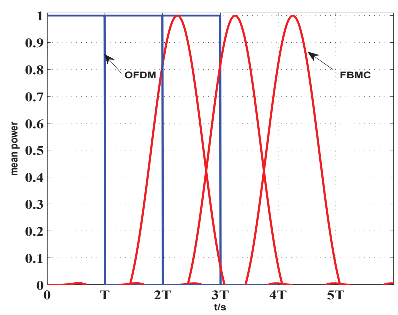

Fig. 2. Power distribution of OFDM and FBMC/OQAM symbols.

As can be seen from the Fig. 2, the average power of FBMC symbols is mainly concentrated in $[mT+T, mT+3T]$, that is, the next two time period intervals. However, in OFDM system, the duration of a single symbol is T, the signal power is mainly concentrated in its time period interval, each symbol is independent and non-overlapping. This also shows in the FBMC system directly using the classic SLM algorithm cannot achieve the purpose of effectively reducing PAPR.

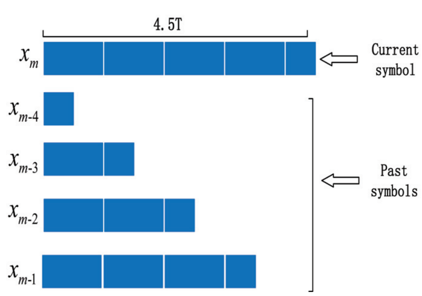

Fig. 3. The time domain form of the m th FBMC/OQAM symbol.

LDSLM algorithm is similar to classical SLM algorithm, but when optimizing current symbol, we need to combine current symbol and overlapping parts of symbols to optimize simultaneously. Most of the power of each symbol exists in the next two time period intervals, when calculating each group of PAPR, we only consider the PAPR in the symbol concentrated in $[mT+T, mT+3T]$. It can shorten the search time and saves 50% of the computation in calculating the PAPR of the signal. Then we need to select the optimal transmission sequence and the optimal phase sequence of the current symbol according to the above method. As shown in Fig. 3, for a given m^{th} symbol, we need consider to the first four symbols that overlap with it.

C. CAF algorithm for FBMC/OQAM signals

CAF algorithm is the pre-distortion algorithm to reduce PAPR. The algorithm adopts nonlinear operation at the peak of the signal and compares the signal amplitude with the preset threshold. If the signal amplitude is lower than the given threshold, then the signal remains unchanged; if the signal amplitude is greater than the given threshold, then the signal is limited within the given threshold. Obviously, clipping can greatly reduce PAPR. However, it will inevitably produce distortion and cause out-of-band interference.

The signal after clipping can be expressed as:

$$\mathbf{x}_c = \begin{cases} \mathbf{x}, |\mathbf{x}| < \mathrm{A} \\ \frac{\mathbf{x}}{|\mathbf{x}|} \cdot \mathrm{A}, \mathrm{other} \end{cases} \tag{8}$$

Clipping ratio (CR) is commonly used to measure the clipping level, which is given by $CR = A/\sigma$, σ is the root mean square of signal power. The clipping threshold A is smaller when the value of is smaller, and the PAPR inhibition effect is better.

The problem of out-of-band interference can be solved by adding filter after clipping. It is worth noting that after the constellation mapping of the input signal, $(l-1)*N$ zeros need to be inserted for over-sampling. When the time domain signal is clipped, the clipped signal is transformed to the frequency domain for filtering. The signal in the effective frequency band passes directly, and the signal outside the band is set to zero.

$$\mathbf{X'}_c = \begin{cases} \mathbf{X}_c, i \in [0, N-1] \\ 0 \quad \text{other} \end{cases} \tag{9}$$

where $\mathbf{X}_c$ is the frequency domain signal form of $\mathbf{x}_c$.

The main purpose of filtering is to filter the sidelobe leak caused by clipping amplitude (except the main lobe, which has a higher sidelobe). CAF algorithm does not cause serious out-of-band interference because of adding oversampling before modulation.

D. Hybrid algorithm for FBMC/OQAM signals

Although the LDSLM algorithm can make good use of the overlapping characteristics of signals and not cause distortion to the system, the PAPR reduction effect is not satisfactory. CAF algorithm can effectively reduce PAPR, but it can produce clipping noise, reducing the system BER performance. To sum up, the above two algorithms have some advantages and disadvantages.

The hybrid algorithm adopts cascade method. First, LDSLM algorithm is used to reduce the PAPR of the system to a certain extent, then its output time-domain signal is used as the input of CAF algorithm. On the basis of LDSLM algorithm, the signals exceeding the threshold will be less, the introduced clipping noise is less than the case of only using CAF algorithm. Therefore, the hybrid algorithm has less impact on the BER of the system with better PAPR performance. The flow of hybrid algorithm is shown in Fig. 4.

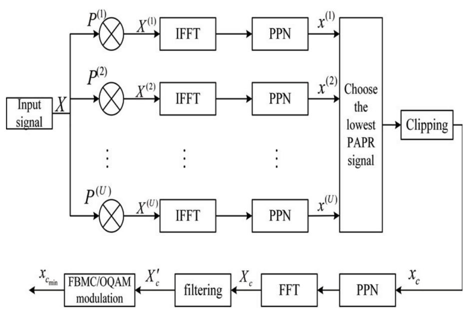

Fig. 4. Flowchart of Hybrid Algorithm.

The algorithm steps are summarized as follows:

Step 1 Initialize the phase sequence to generate U groups phase sequences with length of N, which is expressed as:

$$\mathbf{P}^{(u)}=[P_0^{(u)},P_1^{(u)},\cdots P_{N-1}^{(u)}]^T \tag{10}$$

where $P_{\mathrm{n}}^{(u)}=e^{i\varphi_n}$, $\varphi_n\in[0,2\pi)$,$n\in[0,N-1]$, $u\in[1,U]$

Step 2 The current input symbol is multiplied by the phase sequence to generate U groups of different input sequences.

$$\mathbf{X}_m^{(u)}=\mathbf{X}_m\cdot\mathbf{P}^{(u)} \tag{11}$$

where $\cdot$ denotes the point multiplication of two matrices.

Step 3 The output signals of different input sequences are modulated by PPN filter banks. The signal modulated by the m^{th} input symbol is represented as:

$$\begin{aligned}&\underbrace{x^{(u)}(t){=}\sum_{n=0}^{N-1}\sum_{\mathrm{m}\prime=0}^{m-1}(a_{m\prime,n}^{\mathrm{u_{min}}}h(t{-}mT)+\mathrm{j}b_{m\prime,n}^{u_{\min}}h(t{-}mT{-}\frac{T}{2}))f(t)}_{overlapping\ signals}\\&+\underbrace{\sum_{n=0}^{N-1}([a_{m,n}^{\mathrm{u}}h(t-mT)+\mathrm{j}b_{m,n}^{u}h(t{-}mT-\frac{T}{2}))f(t)}_{current\ signal}\end{aligned} \tag{12}$$

where $h(t)$ is a prototype filter, $f(t)=e^{in(\frac{2\pi t}{T}+\frac{\pi}{2})}$, $t\in[0,mT+4T+T/2)$, $a_{m\prime,n}^{\mathrm{u_{min}}}$ and $b_{m\prime,n}^{\mathrm{u_{min}}}$ is derived from the previously optimized $\mathbf{X}_m^{(u_{\min})}$, and $m\in[0,M-1]$.

Step 4 According to the energy distribution, the PAPR calculated for $T_0\in[mT+T,mT+3T]$:

$$PAPR_{(T_0)}^{u}=\frac{\max_{T_0}\left|x^{(u)}(t)\right|^2}{\frac{1}{T_0}\int\limits_0^{T_0}\left|x^{(u)}(t)\right|^2dt} \tag{13}$$

Step 5 According to the PAPR calculation results, the sequence in the smallest PAPR is selected from the U groups of transmission, and its corresponding phase sequence number is $u_{\min}$.

$$u_{\min}=\min_{0\le u\le U-1}PAPR^{(u)} \tag{14}$$

Step 6 Store $u_{\min}$, the original signal can be recovered according to the sideband information.

$$\mathbf{U}_{\mathrm{SI}}=[\mathbf{U}_{\mathrm{SI}}\quad u_{\min}] \tag{15}$$

Step 7 Update the current overlapping input symbol.

$$\mathbf{X}_m^{(u_{\min})}=\mathbf{X}_m\cdot\mathbf{P}^{(u_{\min})} \tag{16}$$

where $\mathbf{P}^{(u_{\min})}$ represents the optimal phase sequence corresponding to $u_{\min}$, return to step 2, repeat the above steps for $\mathbf{X}_{m+1}$ until $m=M-1$.

Step 8 Clip the time domain signal after LDSLM algorithm.

$$\mathbf{x}_{\mathrm{c}}=\begin{cases}\mathbf{x},|\mathbf{x}|<\mathrm{A}\\\frac{\mathbf{x}}{|\mathbf{x}|}\cdot\mathrm{A},\mathrm{other}\end{cases} \tag{17}$$

where $CR=A/\sigma$, σ is the root mean square of signal power, and $\mathbf{x}$ is regarded as the time domain signal after LDSLM algorithm.

Step 9 Demodulate the clipped signal $\mathbf{x}_c$ into a frequency domain signal $\mathbf{X}_c$, and filter the interference signal outside the frequency band.

$$\mathbf{X}_c{'}=\begin{cases}\mathbf{X}_c,\quad i\in[0,N-1]\\\quad 0\qquad \mathrm{other}\end{cases} \tag{18}$$

Step 10 Modulate the frequency domain signal $\mathbf{X}_{\mathrm{c}}{'}$ to obtain the final output signal $\mathbf{x}_{c_{\min}}$.

The comprehensive performance of the system should be taken into consideration when selecting threshold CR of the hybrid algorithm. The PAPR of the system is guaranteed to be lower under the condition that the BER of the system is as unaffected as possible.

IV. RESULTS ANALYSIS

A. Simulation analysis for performance

The number of sub-carriers of FBMC/OQAM and OFDM systems simulated in this paper is set to 64, $N=64$. The modulation mode is 4OQAM, the oversampling coefficient is l. The length of the prototype filter of FBMC/OQAM is $4T-1$, thus it can be known that one FBMC/OQAM symbol will overlap with four adjacent symbols. The number of input symbols is 100, that is $M=100$. The range of phase sequence set is $\{1\ \ -1\ \ \mathrm{j}\ \ -\mathrm{j}\}$, and the number of simulation is set to 500.

Fig. 5 simulates the LDSLM algorithm and DSLM algorithm in the FBMC/OQAM system for $U=4$. According to the simulation results, the LDSLM algorithm can achieve the same PAPR effect as the DSLM algorithm, while the LDSLM algorithm has lower complexity and higher feasibility than DSLM.

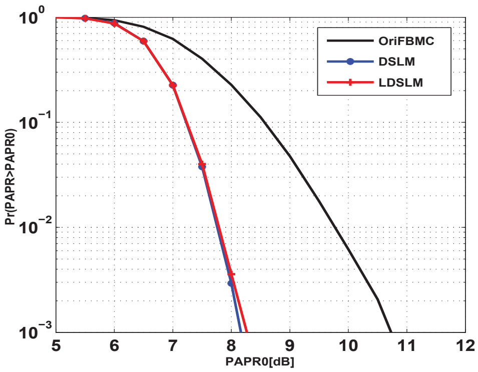

Fig. 5. PAPR performance of LDSLM and DSLM algorithm were compared in FBMC/OQAM system .

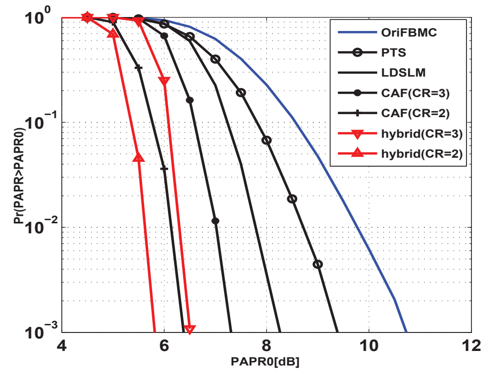

Fig. 7. BER performance comparison of FBMC/OQAM using LDSLM, CAF and hybrid algorithms.

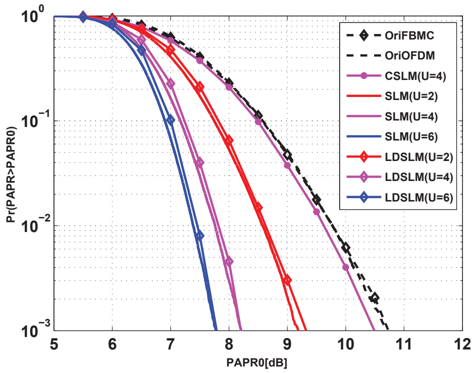

Fig. 6. PAPR performance comparison of SLM algorithm in OFDM system, CSLM algorithm and LDSLM algorithm in FBMC/OQAM system.

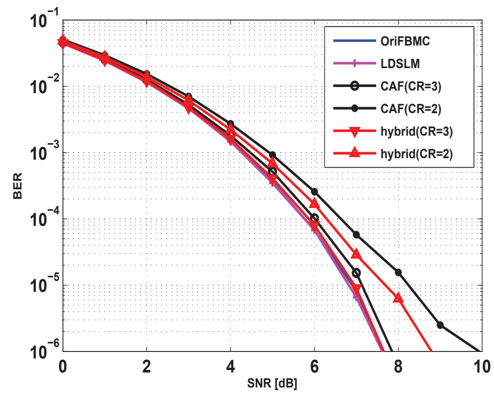

Fig. 8. BER performance comparison of FBMC/OQAM using LDSLM, CAF and hybrid algorithms.

Fig. 6 simulates the LDSLM algorithm applied to F-BMC/OQAM system under different grouping conditions, it compares the classical SLM(CSLM) algorithm directly used in FBMC/OQAM system and the SLM algorithm in OFDM system. The inhibitory effect becomes better with the increase of the number of groups. The CSLM algorithm directly applied to FBMC/OQAM signal is almost invalid, while the PAPR of LDSLM algorithm almost reach the same inhibition effect as the SLM algorithm in OFDM.

Fig. 7 compares the PAPRs of the PTS algorithm, LDSLM algorithm, CAF algorithm and hybrid algorithm under FBM-C/OQAM system when $U = 4$. For $CCDF = 0.001$, the PAPR reduction effect will be better with the decrease of CR. For $U = 4$, $CR = 3$, the hybrid algorithm reduces 4.3dB compared with original system, it can reduce the PAPR of the system more effectively than LDSLM algorithm and CAF algorithm.

As shown in Fig. 8, BER performance is almost same as the original system after the application of LDSLM algorithm in the FBMC/OQAM system. After the application of CAF algorithm, BER performance decreases with the reduction of threshold CR. BER of the hybrid algorithm almost overlaps the original system for $U = 4$ and $CR = 3$. CR value is not less than 3 to ensure BER of the system when the PAPR is satisfied.

B. Computational complexity analysis

For the sake of simplicity, the addition calculation is not taken into account in this paper. The algorithm complexity mainly comes from the calculation of phase dot product, IFFT/FFT, PPN and the calculation of PAPR. The real multiplications(RMs) of the input signal dotted with different phase sequences is $2UN$. The IFFT and FFT at point N require that the RMs should be $4 * (N/2) * logN$. The signal needs to be oversampled in the implementation scheme, and the IFFT at point N has $3N$ zero padding, so the actual RMs of IFFT is $4U * (lN/2 * logN + lN/2)$. Because the PPN input (IFFT output) of sample size is a complex value, and the impulse sample $h(t)$ is a real value function, PPN needs RMs to be $8lUN$, PAPR calculation needs $4UT_c$ RMs, where T_c is the specified PAPR calculation interval.

Table 1 compares the hybrid algorithm with other algorithms, including subcarrier number $N = 64$, grouping number $U = 4$ and oversampling factor $l = 4$.

TABLE I
COMPUTATIONAL COMPLEXITY OF VARIOUS ALGORITHMS

algorithm	complexity	RMs
SLM	$8UN * (logN + 3) + 2UN$	18944
LDSLM	$8UN * (logN + 9) + 2UN$	31232
DSLM	$8UN * (logN + 13) + 2UN$	39424
C-LDSLM	$o(LDSLM) + 16N(logN + 5)$	42496

As can be seen from Table 1, compared with DSLM algorithm, LDSLM algorithm reduces $32UN$ times of real multiplication calculation, and the overall computational complexity is reduced by about 20%, the computational complexity of LDSLM algorithm will be further reduced with the increase of U. The hybrid algorithm based on LDSLM algorithm introduces a small amount of computational effort. However, it achieves about the improvement of PAPR performance of the system.

V. CONCLUSION

This paper studies the high PAPR problem of FBMC/OQAM system. The proposed LDSLM algorithm reduces system complexity by 20% without affecting the PAPR reduction effect by considering the signal characteristics and analyzing the average power distribution of the signal. CAF algorithm can effectively reduce PAPR, and the distortion-free characteristic of LDSLM algorithm can compensate for the distortion caused by CAF algorithm. The hybrid algorithm weighs the performance of PAPR and BER in the system while increasing a little complexity. By setting CR value reasonably, PAPR of the hybrid algorithm can be effectively reduced under the condition of guaranteeing the BER performance of the system.

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