

Swapped SLM scheme for reducing PAPR of OFDM systems

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The selected mapping (SLM) scheme is a competent method for reducing the high peak-to-average power ratio (PAPR) of orthogonal frequency division multiplexing (OFDM) signals. One drawback of the conventional SLM (C-SLM) scheme is the high computational complexity. To reduce the complexity of C-SLM, the real and imaginary parts of the OFDM signals are treated separately. The even and odd sequences of the real and imaginary parts are obtained using the Fourier transform properties. More candidates are generated by the different combination of all the sub-sequences. The proposed scheme has a lower computational complexity using only M inverse fast Fourier transform (IFFT) operations to generate M^4 candidates. The simulation results show that the proposed scheme achieves good PAPR reduction performance and also reduces the computational complexity significantly compared with the C-SLM scheme.

Introduction: Orthogonal frequency division multiplexing (OFDM) is one of the core technologies for communication systems [1]. However, high peak-to-average power ratio (PAPR) is one major drawback for OFDM, which causes nonlinear distortion [2]. Partial transmit sequence and selected mapping (SLM) schemes have good PAPR reduction performance [3]. SLM is a popular method because of good PAPR performance and no signal distortion. In the conventional SLM (C-SLM) scheme, each candidate needs one inverse fast Fourier transform (IFFT) operation, which causes high computational complexity. Some modified SLM schemes have been proposed to overcome this drawback. An improved SLM was proposed in [4], which combined the dynamic SLM algorithm, time-domain linear combination and repeated the clip-and-filter operation to reduce the PAPR. The widely linear SLM (WL-SLM) scheme was proposed in [5], where the real and imaginary parts of the signal are separated and individually treated. The PAPR performance was greatly improved because of more degrees of freedom.

PAPR properties: For simplicity, let $X = [X(0) X(1) \dots X(N-1)]$ denote the OFDM signal in the frequency domain, where N is the sub-carrier number for the frequency domain signal. The time-domain OFDM signal is given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \exp(j2\pi kn/N) \quad (1)$$

The PAPR of the transmitted OFDM signal $x(n)$ is defined as

$$\text{PAPR} = 10 \log \frac{\max_{0 \leq n \leq N-1} |x(n)|^2}{\sigma^2} \quad (2)$$

where σ^2 is the average power of $x(n)$. Given the threshold value PAPR_0 , the complementary cumulative distribution function (CCDF) of the PAPR is defined as

$$\text{CCDF}[\text{PAPR}(x)] = \Pr(\text{PAPR} > \text{PAPR}_0) \quad (3)$$

C-SLM scheme: In C-SLM, the original OFDM signal X will multiply with different phase rotation vectors \mathbf{P} ($\mathbf{P} = [\mathbf{P}^1 \mathbf{P}^2 \dots \mathbf{P}^M]$) to obtain more frequency domain sequences as in Fig. 1a. The corresponding time-domain signal \mathbf{x}^m of the frequency domain signal \mathbf{X}^m can be obtained by the IFFT operation

$$\mathbf{x}^m = \text{IFFT}[\mathbf{X}^m] = \text{IFFT}[\mathbf{X} \otimes \mathbf{P}^m] \quad (4)$$

Then, the signal \mathbf{x}^* with the minimum PAPR among M alternative candidates is selected and transmitted.

Proposed swapped SLM (S-SLM) scheme: To reduce the complexity of the C-SLM scheme, in this Letter, we will use the real \mathbf{x}_R and imaginary \mathbf{x}_I parts of \mathbf{x} and the properties of the Fourier transform to obtain the subsequences $\mathbf{x}_{R,E}$, $\mathbf{x}_{I,E}$ and $\mathbf{x}_{R,O}$, $\mathbf{x}_{I,O}$. All the subsequences will be used to reconstruct the new candidates. The proposed method has a simple PAPR reduction procedure by the signal processing in the time domain. First, some properties of FFT will be introduced here which will be used in the proposed S-SLM scheme.

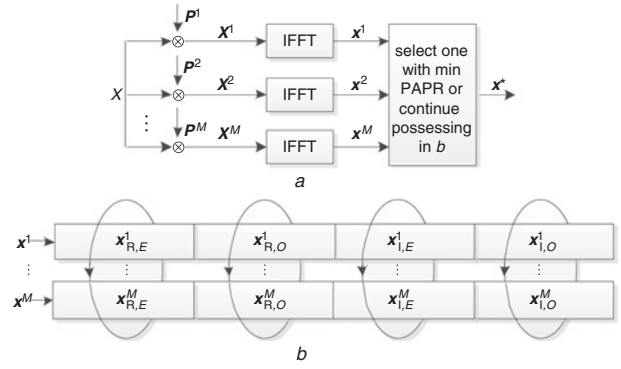


Fig. 1 Block diagram of SLM schemes

a C-SLM scheme with M IFFT operations or candidates
b Proposed S-SLM scheme with swapping sub-sequences

Property 1: Time-domain signal reversal

$$F_1[x(n)] = x(N-n)_{\text{mod}N} = \begin{cases} x(n), & n = 0 \\ x(N-n), & 1 \leq n \leq N-1 \end{cases} \quad (5)$$

According to Property 1 and the conjugate anti-symmetric properties of OFDM signal (i.e. $\text{FFT}[x^*((N-n)_{\text{mod}N})] = X^*(n)$), the \mathbf{x}_R and \mathbf{x}_I of signal \mathbf{x} is

$$\begin{aligned} \mathbf{x}_R &= \text{IFFT}[\mathbf{X}_R] = \text{IFFT}[(\mathbf{X} + \mathbf{X}^*)/2] = (\mathbf{x} + F_1[\mathbf{x}^*])/2 \\ \mathbf{x}_I &= \text{IFFT}[\mathbf{X}_I] = \text{IFFT}[(\mathbf{X} - \mathbf{X}^*)/2] = (\mathbf{x} - F_1[\mathbf{x}^*])/2 \end{aligned} \quad (6)$$

Property 2: Time-domain signal circular shift

$$F_2[x(n), k] = x((n-k)_{\text{mod}N}) \Leftrightarrow F_2[X(n), k] = X(n) \cdot e^{-j2\pi kn/N} \quad (7)$$

In (7), by selecting $k = N/2$, we obtain the corresponding frequency domain signal

$$F_2\left[X(n), \frac{N}{2}\right] = X(n) \cdot e^{-j\pi n} = \begin{cases} X(n), & n \text{ is even} \\ -X(n), & n \text{ is odd} \end{cases} \quad (8)$$

As can be seen from (8), using signal \mathbf{x} and its time-domain circular shift $F_2[x(n), N/2] = x((N-n/2)_{\text{mod}N})$, the corresponding time-domain signal for even and odd parts of \mathbf{X} will be obtained. In the rest of this Letter, $F_2[\mathbf{x}]$ will stand for $F_2[\mathbf{x}, N/2]$. The odd and even parts of the real and imaginary parts are, respectively,

$$\begin{aligned} \mathbf{x}_{R,E} &= (\mathbf{x}_R + F_2[\mathbf{x}_R])/2 \\ \mathbf{x}_{R,O} &= (\mathbf{x}_R - F_2[\mathbf{x}_R])/2 \\ \mathbf{x}_{I,E} &= (\mathbf{x}_I + F_2[\mathbf{x}_I])/2 \\ \mathbf{x}_{I,O} &= (\mathbf{x}_I - F_2[\mathbf{x}_I])/2 \end{aligned} \quad (9)$$

Therefore, the time-domain signal can be written as $\mathbf{x} = [\mathbf{x}_{R,E}, \mathbf{x}_{R,O}, \mathbf{x}_{I,E}, \mathbf{x}_{I,O}]$. Denote $\mathbf{x}^i = \text{IFFT}[\mathbf{X}^i]$, where \mathbf{X}^i stands for the i th candidate for the C-SLM scheme. In the proposed method, the corresponding subsequences of the signal will be swapped. With two time-domain candidates \mathbf{x}^1 and \mathbf{x}^2 , the corresponding sub-block has the information of the original part. For example, the first part $\mathbf{x}_{R,E}^1$ is generated by the original signal $\mathbf{X}_{R,E}$ where $\mathbf{x}_{R,E}^1 = \text{IFFT}[\mathbf{X}_{R,E}]$; $\mathbf{x}_{R,E}^2$ can be written as

$$\mathbf{x}_{R,E}^2 = \text{IFFT}[\mathbf{X}_{R,E}^2] = \text{IFFT}[\mathbf{X}_{R,E} \otimes \mathbf{P}^2] \quad (10)$$

We can obtain two candidates by performing the swapping for the first sub-block. That is, the original signal $\mathbf{x}^1 = [\mathbf{x}_{R,E}^1, \mathbf{x}_{R,O}^1, \mathbf{x}_{I,E}^1, \mathbf{x}_{I,O}^1]$ and $\mathbf{x}^2 = [\mathbf{x}_{R,E}^2, \mathbf{x}_{R,O}^2, \mathbf{x}_{I,E}^2, \mathbf{x}_{I,O}^2]$. Obviously, the two candidates have different PAPR performance. The same operations are performed for all other sub-blocks. Using the swapping of all the subsequences for the two signals, we can obtain in total $2^4 = 16$ candidates. Out of these 2^4 sequence sets, one of them with a minimum PAPR is selected for transmission. If there are M candidates in the C-SLM scheme, a total of M^4 candidates will be obtained by swapping all the subsequences in the S-SLM scheme. The specific steps of the S-SLM scheme are shown in Fig. 1b.

Computational complexity: It is well known that an LN -point IFFT operation requires numbers of complex multiplication and complex addition, which are $LN/2 \log_2 LN$ and $LN \log_2 LN$, respectively. The C-SLM scheme with M^4 candidates requires M^4 IFFT operations. Hence, the total numbers of complex multiplication and complex addition are $M^4 LN/2 \log_2 LN$ and $M^4 LN \log_2 LN$, respectively. To generate the same number of M^4 candidates, the proposed S-SLM scheme requires M IFFT operations to obtain the time-domain signals and $(3M^4 - M)LN$ numbers of complex addition are required to obtain all candidates. Hence, the total numbers of complex multiplication and complex addition are $MLN/2 \log_2 LN$ and $MLN \log_2 LN + (3M^4 - M)LN$, respectively.

The computational complexity reduction ratio (CCRR) of the proposed S-SLM scheme over the C-SLM scheme is defined as

$$\text{CCRR} = \left(1 - \frac{\text{Complexity of the S-SLM}}{\text{Complexity of the C-SLM}}\right) \times 100\% \quad (11)$$

In Table 1, Mu and Ad are the numbers of complex multiplication and complex addition, respectively. The Table shows that the proposed S-SLM scheme can reduce the computation complexity of the C-SLM scheme efficiently and the complexity is reduced rapidly with the increase of M .

Table 1: Computational complexity of C-SLM scheme and S-SLM scheme when $N=256$, $L=4$ and $M=2, 3$ (M is IFFT operation number of S-SLM scheme)

	Name	C-SLM	S-SLM	CCRR (%)
$M=2$, 16 candidates	Mu	81 920	10 240	87.5
	Ad	163 840	67 584	58.8
$M=3$, 81 candidates	Mu	414 720	15 360	96.3
	Ad	829 440	276 480	66.7

Simulation result: For the simulation, 10^5 independent OFDM signals are randomly generated when the subcarrier numbers are $N=256$, quadrature phase shift keying modulation with the oversampling factor $L=4$.

Fig. 2 shows the CCDF of the C-SLM scheme, WL-SLM scheme in [5] and S-SLM scheme with M^4 candidates. With 16 (when $M=2$) and 81 (when $M=3$) candidates, the PAPR performance of the S-SLM scheme is only inferior to the C-SLM scheme by about 0.3 and 0.15 dB, respectively. It is also inferior to the WL-SLM scheme by about 0.2 and 0.1 dB, respectively. However, the S-SLM scheme has a much lower computational complexity because it requires only M IFFT operations compared with the C-SLM scheme with M^4 IFFT operations and the WL-SLM scheme with M^2 IFFT operations when all of them generate M^4 candidates.

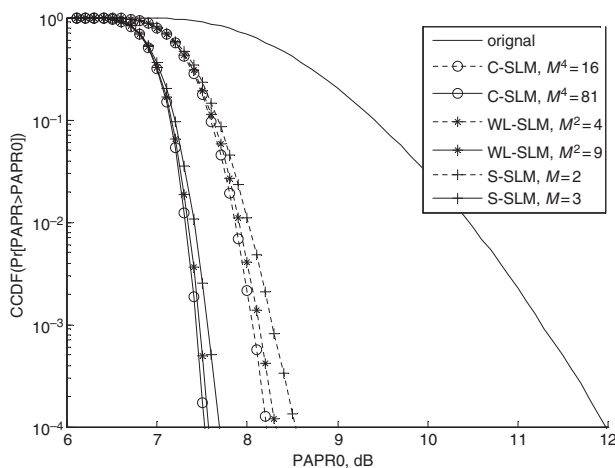


Fig. 2 CCDF of C-SLM, WL-SLM and S-SLM with M^4 candidates (M is IFFT operation number of S-SLM scheme)

Conclusion: In this Letter, an S-SLM scheme is presented to reduce the PAPR of the OFDM signal. In the proposed scheme, candidates are generated using the properties of the Fourier transform and different combinations of the subsequences. Simulation results show that the proposed scheme has performance similar to the C-SLM scheme when they both have the same number of candidates, but the proposed scheme has a lower computational complexity because of fewer numbers of IFFT operations.

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