Selective Mapping with Symbol Re-mapping for OFDM/TDM Using MMSE-FDE

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) signals have a problem with high peak-to-average power ratio (PAPR). A distortionless selective mapping (SLM) has been proposed to reduce the PAPR, but a high computational complexity prohibits its application to OFDM with a large number of subcarriers. Recently, OFDM combined with time division multiplexing (OFDM/TDM) using minimum mean square error frequency-domain equalization (MMSE-FDE) was proposed to improve the transmission performance of conventional OFDM in terms of the bit error rate (BER) and the PAPR. The PAPR problem, however, cannot be completely eliminated. In this paper, we propose a new SLM to further reduce the PAPR of OFDM/TDM. Unlike the conventional OFDM, where SLM is applied over subcarriers in the frequency domain, we propose the new SLM for OFDM/TDM by exploiting both time and frequency dimensions of OFDM/TDM signal. It is shown, by computer simulation that proposed SLM for OFDM/TDM increases the number of candidate sequences in comparison with the conventional SLM, while reducing the PAPR. Furthermore, OFDM/TDM with proposed SLM achieves a lower PAPR than the conventional OFDM with same or reduced computational complexity.**

***Index Terms*—OFDM/TDM, MMSE-FDE, selective mapping, PAPR, symbol re-mapping.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) signal, which is robust against multipath fading, has a behavior similar to that of a Gaussian random process. This yields a drawback of having a large amplitude dynamic range, i.e., a large peak-to-average power ratio (PAPR) [1]. Of late, there has been substantial work on PAPR reduction of OFDM. An overview of various techniques for reducing the PAPR has been presented in [2]. The simple and widely used method is amplitude clipping [3] that limits the PAPR below a threshold level, but it causes both in-band distortion and spectrum splatter. Block coding [4] of an input data into a phase code word with low PAPR is another well-known technique to reduce the PAPR, but it reduces the transmission data rate. Selective mapping (SLM) has been proposed to reduce the PAPR [5] with relatively small increase in redundancy and without signal distortion (i.e., without spectrum splatter), but with high computational complexity when a large number of subcarriers is utilized.

Recently, we proposed OFDM combined with time division multiplexing (OFDM/TDM) [6] using minimum mean square error frequency-domain equalization (MMSE-FDE) [7] to improve the transmission performance of the conventional OFDM in terms of the bit error rate (BER) and the PAPR. The PAPR, however, cannot be completely eliminated. To further reduce the PAPR some additional PAPR reduction technique must be applied. In [8], we analyzed the performance of amplitude clipped OFDM/TDM using MMSE-FDE, but the clipping causes the transmit signal distortion, spectrum splatter and the BER performance degradation. A comprehensive performance comparison of OFDM/TDM using MMSE-FDE and conventional OFDM, in [9], shows that spectrum side-lobs of OFDM/TDM are larger than the conventional OFDM. Consequently, a distortionless PAPR reduction technique should be considered with OFDM/TDM.

In this paper, we propose a new SLM technique for OFDM/TDM using MMSE-FDE to further reduce the PAPR by utilizing both time and frequency dimensions of OFDM/TDM signal. We note here that SLM can be directly applied to OFDM/TDM on a slot-by-slot basis, but the PAPR reduction capability reduces due to reduced size of phase codes. Unlike the conventional OFDM with SLM [5], where SLM is applied over the subcarriers in frequency domain, we propose SLM for OFDM/TDM by independently exploiting both time (i.e., time-slots of OFDM/TDM frame) and frequency (i.e., subcarriers) dimensions of OFDM/TDM signal. Consequently, the number of candidate sequences is increased achieving an additional gain for PAPR reduction. We also bring the reader's attention to the fact that the proposed SLM may be applied to the conventional OFDM, but the implementation may be limited due to long latency (i.e., processing delay) and a large computational complexity if a large number of subcarriers is considered. The benefit of the proposed technique with OFDM/TDM is twofold: (i) reduced PAPR and (ii) same or lower computational complexity as the conventional OFDM depending on the OFDM/TDM design.

The remainder of this paper is organized as follows. In Sect. II a brief overview of OFDM/TDM is given. Section III introduces SLM. The simulation results are shown in Sect. IV and finally, the concluding remarks are given in Sect. V.

Throughout this paper, following notations are adhered to. Bold lowercase letters are used to denote column vectors. Bold uppercase letters are used to denote matrices. $(\cdot)^T$, $(\cdot)^*$, $E\{\cdot\}$, $diag[\cdot]$, $\|\cdot\|$ and $\|\cdot\|_\infty$ denote transpose, complex conjugate, the ensemble average, diagonal matrix, Euclidean and maximum norm operations, respectively.

II. OFDM/TDM Using MMSE-FDE

In OFDM/TDM, the inverse fast Fourier transform (IFFT) time window (i.e., OFDM/TDM frame) of the conventional OFDM with N_c subcarriers is divided into K time slots. An example of the conventional OFDM with $N_c = 16$ subcarriers and OFDM/TDM with $K = 4$ is shown by Fig. 1.

The N_c data-modulated vector $\mathbf{d} = [d(0)d(1)\dots d(N_c - 1)]^T$ is transmitted during one OFDM/TDM frame. Data-modulated signal vector $\mathbf{d}$ is divided into K vectors $\mathbf{d}^0$, $\mathbf{d}^k \dots \mathbf{d}^{K-1}$ with $\mathbf{d}^k = [d^k(0)d^k(1)\dots d^k(N_m - 1)]^T$. Then, N_m-point IFFT is applied to each data vector $\mathbf{d}^k$ to generate a sequence of K OFDM signals with $N_m = N_c/K$ subcarriers. The OFDM/TDM transmit signal matrix is represented by $\mathbf{S} = [\mathbf{s}^0 \dots \mathbf{s}^k \dots \mathbf{s}^{K-1}]$. Here $\mathbf{s}^k = [s^k(0)\dots s^k(t)\dots s^k(N_m - 1)]^T$ is the kth slot OFDM signal with N_m subcarriers given by

$$s^k(t) = \sqrt{\frac{2E_s}{T_c N_m}} \sum_{i=0}^{N_m-1} d^k(i) \exp\left\{ j2\pi t \frac{i}{N_m} \right\} \quad (1)$$

for $k = 0 \sim K-1$, where $t = 0 \sim N_m{-}1$ is a discrete time index. In the above expression, E_s and T_c denote the data-modulated symbol energy and sampling period, respectively. After insertion of N_g-sample guard interval (GI) the OFDM/TDM signal is transmitted over a frequency-selective fading channel [7].

At the receiver, after removing the GI, N_c-point FFT is applied over the entire OFDM/TDM frame to decompose the received signal into its frequency components represented by $\mathbf{r} = [r(0)r(1)\dots r(N_c - 1)]^T$. One-tap MMSE-FDE is applied over the entire OFDM/TDM frame [7] with several concatenated OFDM signals to obtain frequency diversity gain as [10]

$$\hat{\mathbf{r}} = \mathbf{W}\mathbf{r}, \quad (2)$$

where the equalized signal vector $\hat{\mathbf{r}} = [\hat{r}(0)\hat{r}(1)\dots\hat{r}(N_c{-}1)]^T$. In the above expression, $\mathbf{W} = diag[w(0)\dots w(n)\dots w(N_c - 1)]^T$ is the MMSE weight diagonal matrix with nth element given by [11]

$$w(n) = \frac{H^*(n)}{|H(n)|^2 + \left(\frac{E_s}{N_0}\right)^{-1}}, \quad (3)$$

where N_0 denotes the single-sided power spectrum density.

The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\hat{\mathbf{r}}$ and then, OFDM demodulation is carried out using N_m-point FFT to obtain the decision variables for each OFDM signal [7].

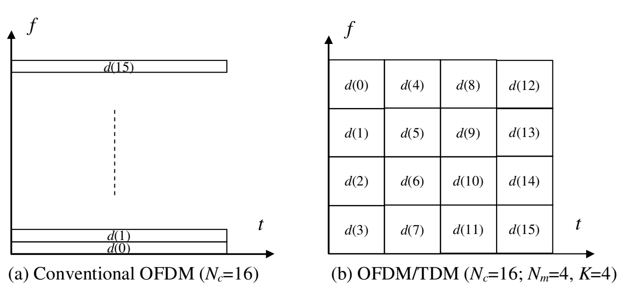


Fig. 1. Time and frequency data arrangement.

III. PAPR Reduction Using SLM

In this section, we first briefly survey the application of SLM to conventional OFDM. Then, we point out a problem that arises when SLM is directly applied to OFDM/TDM. Finally, we present the proposed SLM for OFDM/TDM.

A. Conventional SLM for OFDM [5]

In the discrete time domain, an OFDM signal with N_c subcarriers can be expressed by Eq. (1) for $K = 1$ (i.e., k=0) and $N_m = N_c$. The PAPR of an OFDM signal, defined as the ratio of the peak power to the ensemble average power, can be expressed as

$$PAPR(\mathbf{d}) = \frac{\max\{\|\mathbf{s}\|_\infty^2\}}{E\{\|\mathbf{s}\|^2\}}. \quad (4)$$

In conventional SLM for OFDM [5], an alternative input data-modulated vectors represented by $\mathbf{d}_u = [d_u(0)d_u(1)\dots d_u(N_c - 1)]$ for $u = 1 \sim U$ are generated by multiplying a phase codes represented by $\mathbf{p}_u = [p_u(0)p_u(1)\dots p_u(N_c - 1)]^T$ element-wise in frequency-domain to the original input data-modulated vector $\mathbf{d}$. Here an element-wise multiplication is denoted as $\mathbf{d}_u = \mathbf{d} \circ \mathbf{p}_u$ with $d_u(i) = d(i)p_u(i)$ for $u = 1 \sim U$ and $i = 0 \sim N_c{-}1$. Note that each symbol of the phase code is set to have unit magnitude to keep the same power. The first phase code $\mathbf{p}_1$ is set to all "1" sequence (i.e., $p_1(i) = 1$ for $i = 0 \sim N_c{-}1$). It was shown in [12] that the best phase code is random phase sequence with $\{p_u(i) = \pm 1;\ i = 0 \sim N_c{-}1\}$. Finally the OFDM signal $\mathbf{s}_{\hat{u}} = IFFT\{\mathbf{d}_{\hat{u}}\}$ with the lowest PAPR is transmitted, where $\hat{u}$ is selected as

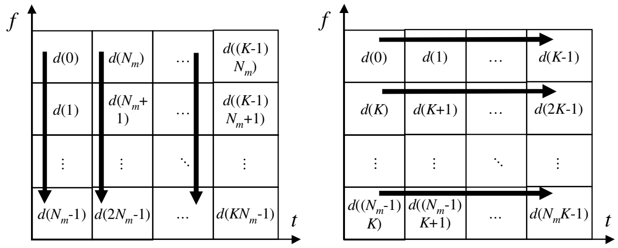
$$\hat{u} = \arg\min_{1 \le u \le U} PAPR(\mathbf{d}_u). \quad (5)$$

Notice that the SLM technique exploits only the frequency dimension (i.e., subcarriers) of the OFDM signal to generate alternative candidate sequences.

B. Direct Application of SLM to OFDM/TDM

A direct application SLM to OFDM/TDM is possible on a slot-by-slot basis, where conventional SLM is applied to each N_m (=N_c/K)-subcarrier OFDM signal independently as presented in previous section (i.e., N_c is replaced with N_m). The length of the phase code will also be reduced to N_m elements.

In this case, the phase code matrix is represented by $\mathbf{P}_u = diag[\mathbf{p}_u^1 \dots \mathbf{p}_u^k \dots \mathbf{p}_u^{K-1}]$, where the kth slot phase code is represented by $\mathbf{p}_u^k = diag[p_u^k(0)p_u^k(1)\dots p_u^k(N_m{-}1)]$. Consequently, the number of phase codes $U = 2^{N_m}$ is decreasing in K (i.e., N_m is reducing) and a natural consequence is that the further PAPR reduction capability is reducing. Same as in the conventional OFDM, direct application of SLM to OFDM/TDM exploits only frequency dimension (i.e., reduced number of subcarriers) of OFDM/TDM signal. Note that same



(a) Mapping of $\mathbf{D}_f$ (b) Mapping of $\mathbf{D}_t$

Fig. 2. Principle of SLM with symbol re-mapping.

or different phase vectors $\mathbf{p}_u^k$ for $k=0\sim K-1$ can be used that will not affect the PAPR reduction.

Nevertheless, to improve the PAPR reduction capability of SLM for OFDM/TDM the number of candidate sequences must be increased in comparison with the conventional SLM. To this end, we develop a new SLM to increase the number of alternative candidate by exploiting both time and frequency dimensions of OFDM/TDM signal.

C. Proposed SLM for OFDM/TDM

As we have emphasized in the previous section, opportunities for exploiting both time (i.e., time slots of OFDM/TDM frame) and frequency (i.e., subcarriers) dimensions of OFDM/TDM signal for PAPR reduction arise. The SLM for OFDM/TDM exploits time and frequency dimensions of OFDM/TDM signal to generate a larger set of candidate sequences yielding a larger potential for PAPR reduction and then, transmit the one with lowest PAPR. At first, we explain how to generate two sets of independent data-modulated symbols corresponding to input data-modulated matrices $\mathbf{D}_f$ (hereafter referred as frequency domain set) and $\mathbf{D}_t$ (hereafter referred as time domain set) using frequency and time dimensions of OFDM/TDM signal, respectively.

The elements of data matrix $\mathbf{D}_f$ are mapped by writing-in column-by-column elements of one dimensional data-modulated vector $\mathbf{d}=[d(0)d(1)\ldots d(N_c-1)]^T$ as shown by Fig. 2(a). In essence, $N_m \times K$ matrix $\mathbf{D}_f$ can be represented as

$$\mathbf{D}_f = \begin{pmatrix} d(0) & d(N_m) & \cdots & d((K-1)N_m) \\ d(1) & d(N_m+1) & \cdots & d((K-1)N_m+1) \\ \vdots & \vdots & \ddots & \vdots \\ d(N_m-1) & d(2N_m-1) & \cdots & d(KN_m-1) \end{pmatrix}. \quad (6)$$

Notice that columns and rows denote the time (i.e., time slot) and the frequency (i.e., subcarrier) dimensions of OFDM/TDM signal, respectively. Thus, in OFDM/TDM, the data-modulated symbols are transmitted over N_m (=N_c/K)-subcarriers using K time slots as shown by Fig. 1. We note that in the conventional OFDM (K=1), $\mathbf{D}_f$ reduces to one dimensional vector $\mathbf{d}$ with N_c data-modulated symbols transmitted within one time slot (i.e., OFDM signaling interval).

Here we bring the reader's attention to the fact that N_c data-modulated symbols in $\mathbf{d}$ are statistically independent and consequently, their re-mapping will produce a new set of candidate sequences. To generate time domain set we exploit time dimension (i.e., time slots for $k=0\sim K-1$) of OFDM/TDM signal. In this case, the time domain set $\mathbf{D}_t$ is generated by writing-in row-by-row elements of one dimensional data-modulated vector $\mathbf{d}=[d(0)d(1)\ldots d(N_c-1)]^T$ as shown by Fig. 2(b). In essence, $N_m \times K$ matrix $\mathbf{D}_t$ can be represented as

$$\mathbf{D}_t = \begin{pmatrix} d(0) & d(1) & \cdots & d(K-1) \\ d(K) & d(K+1) & \cdots & d(2K-1) \\ \vdots & \vdots & \ddots & \vdots \\ d((N_m-1)K) & d((N_m-1)K+1) & \cdots & d(N_mK-1) \end{pmatrix}. \quad (7)$$

The proposed SLM algorithm with symbol re-mapping is presented bellow:

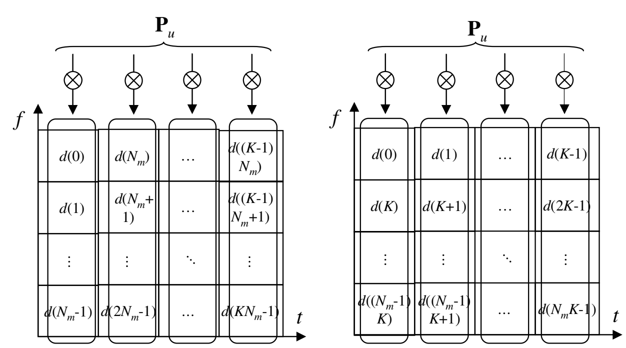
Step 1: Generate the frequency-domain candidate set of input data-modulated sequences $\mathbf{D}_f^u$ by multiplying columns of data matrix $\mathbf{D}_f$ with the phase code matrix $\mathbf{P}_u$ element-wise (i.e., $\mathbf{D}_f^u = \mathbf{P}_u \circ \mathbf{D}_f$) for $u=1\sim U$ (see Fig. 3(a)).

Step 2: Generate the time-domain candidate set of input data-modulated sequences $\mathbf{D}_t^u$ by multiplying columns of data matrix $\mathbf{D}_t$ with the same phase sequence vector $\mathbf{P}_u$ element-wise (i.e., $\mathbf{D}_t^u=\mathbf{P}_u\circ\mathbf{D}_t$) for $u=1\sim U$ as given by (see Fig. 3(b)).

Step 3: After all u (=1 $\sim U$) are exhausted the PAPR is evaluated for both time domain set $\mathbf{D}_t^u$ and frequency domain set $\mathbf{D}_f^u$ of generated candidate sequences to select the set with lower PAPR.

Step 4: The OFDM/TDM signal $\mathbf{s}^{\hat{u}}=IFFT\{\mathbf{D}_f^{\hat{u}},\mathbf{D}_t^{\hat{u}}\}$ with the lowest PAPR is transmitted, where $\hat{u}$ is selected as $\hat{u}=\arg\min_{1\le u\le U} PAPR(\mathbf{D}_f^u,\mathbf{D}_t^u)$.

To recover data, the side information has to be sent to the receiver. For the conventional OFDM with SLM using U phase codes the number of required information side bits is log_2U. The number of required side information bits for one



(a) Frequency domain set (b) Time domain set

Fig. 3. Time and frequency set generation.

TABLE I
COMPUTATIONAL COMPLEXITY COMPARISON: U=16.

No. of Subcarriers		N_c=256	N_c=1024	N_c=2048
Conventional OFDM		32768	163840	360448
OFDM/TDM	K=16	16384	98304	229376
	K=32	12282	81920	196608
	K=64	8192	65536	16384

OFDM/TDM frame is $log_2 U+1$, where the side information includes a direction (time or frequency) in which proposed SLM is applied (”1” denotes the side information bit regarding the direction (time or frequency) of SLM). In this work, we assume that the side information is known at the receiver side.

We note here that the proposed SLM may also be applied to conventional OFDM, but practical implementation of such PAPR reduction technique may not be feasible because of a large computational complexity and long latency (i.e., processing delay).

IV. SIMULATION RESULTS

In our computer simulation we assume an OFDM/TDM frame size of N_c=256 samples, GI length of N_g=32 samples and ideal coherent QPSK data modulation/demodulation. As the propagation channel, we assume an L=16-path block Rayleigh fading channel with uniform power delay profile. A perfect knowledge of the channel state information is assumed.

We note, however, that the comparison above is given under the constraint of same transmission data-rate and bandwidth efficiency. For example, suppose that we compare OFDM/TDM with $\{N_c = 256;\ N_m = 16,\ K = 16\}$ and the conventional OFDM with N_c=16. In both cases the same number of subcarriers is used and naturally, the PAPR distribution will be the same. However, the transmission data-rate and bandwidth efficiency of conventional OFDM will degrade in comparison with OFDM/TDM since the GI length needs to be kept the same for both systems.

A. Computational Complexity Issue

As mentioned above, a main drawback of conventional SLM is its high computational complexity that prohibits the implementation in practical OFDM system with a large number of subcarriers. The complexity of SLM increases in proportion to the number U of phase sequences because for each phase code, an IFFT should be computed to generate different candidate sequence. A straight forward way to reduce the complexity is to reduce the number of generated sequences, but the PAPR reduction capability reduces. On the other hand, the complexity can be reduced if the IFFT size is reduced, but the bandwidth efficiency of such OFDM system will degrade since the GI length needs to be kept the same.

The proposed SLM for OFDM/TDM reduces the complexity by dividing a large IFFT size of conventional OFDM into several smaller slots and process each slot separately, while keeping the same GI length to preserve same data rate efficiency. The complexity comparison between the conventional SLM for OFDM and OFDM/TDM is given in Table I. The complexity is evaluated by the number of complex multiplications. It can be seen that OFDM/TDM has significantly lower computational complexity than OFDM with conventional SLM. In the case of OFDM/TDM with K=16 complexity is two times lower than the conventional OFDM with N_c=256. Consequently, the number of phase sequences U for OFDM/TDM can be increased two times, while obtaining the same complexity requirements. This fact gives OFDM/TDM flexibility to increase the number of phase sequences to further reduce the PAPR for the same complexity as OFDM (see discussion on Fig. 4).

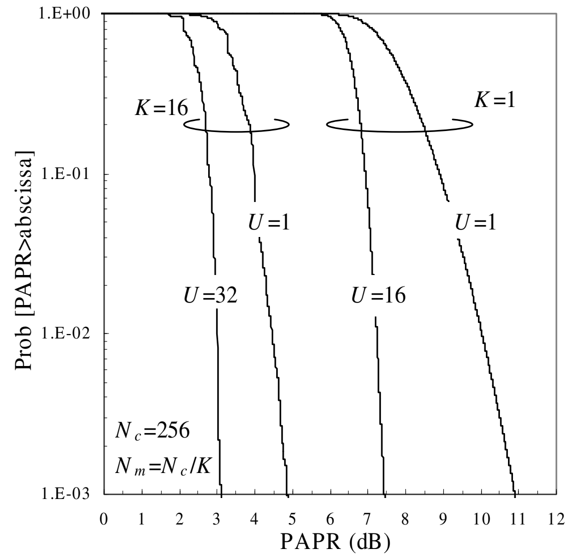


Fig. 4. PAPR distribution of OFDM/TDM and conventional OFDM.

B. PAPR Distribution

First we will show the results of PAPR distribution when conventional SLM is applied to both OFDM/TDM and the conventional OFDM under the constraint of same computational complexity. Figure 4 illustrates the complementary cumulative distribution function of the PAPR for OFDM/TDM (K=16) and the conventional OFDM (K=1) when N_c=256 under the constraint of same computational complexity. As can be seen from Fig. 4, OFDM/TDM with SLM (U=32) reduces the $\text{PAPR}_{30\%}$ level, which the PAPR of OFDM/TDM exceeds with probability of 30%, for about 1.75 dB in comparison with OFDM/TDM without SLM (U=1). It is further seen that, the OFDM/TDM with U=32 the $\text{PAPR}_{30\%}$ level is reduced for about 4.3 dB in comparison with the conventional OFDM with U=16, while obtaining the same computational complexity.

An additional reduction of PAPR for OFDM/TDM can be made using the proposed SLM. Figure 5 plots the PAPR distribution of proposed SLM for OFDM/TDM when K=16 with U as a parameter. As shown by Fig. 5, the $\text{PAPR}_{30\%}$ level of proposed SLM with U=16 in comparison with OFDM/TDM without SLM (labeled as U=1) is about 1.75 dB. It can be further seen that the PAPR reduction of $\text{PAPR}_{30\%}$ level over the conventional SLM with U=16 is about 0.25 dB as U

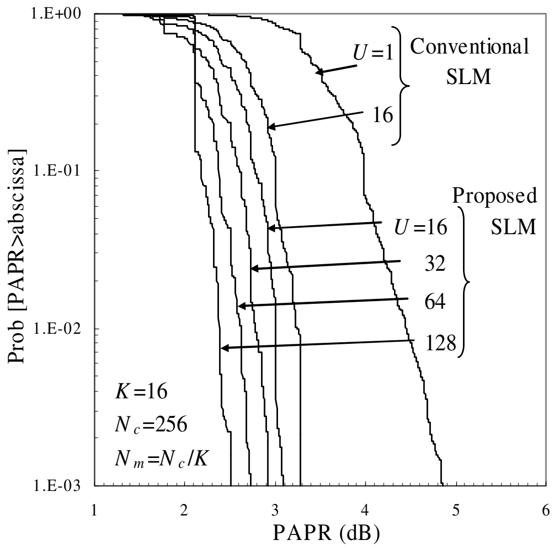


Fig. 5. PAPR distribution of the proposed SLM for OFDM/TDM.

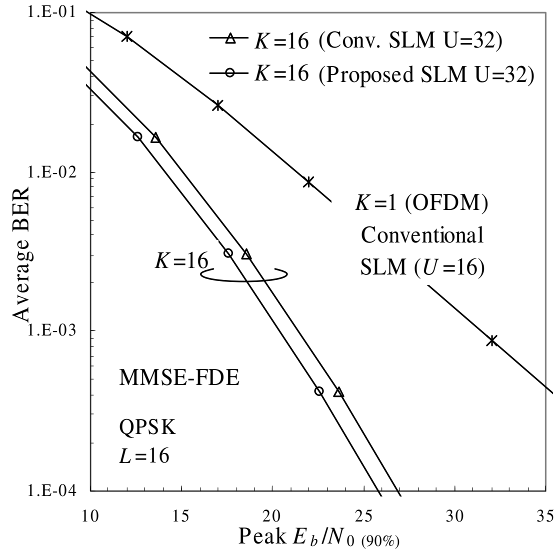


Fig. 6. Peak-transmit power efficiency.

increases. This clearly shows the benefit of the proposed SLM for OFDM/TDM in comparison with conventional SLM.

C. Reduction of Peak-transmit Power

We also consider the required peak transmit power of the proposed SLM for OFDM/TDM using MMSE-FDE because it is an important design parameter of transmit power amplifiers. We consider the $\text{PAPR}_{10\%}$ level of the proposed SLM for OFDM/TDM with U=32 and K=16 that is about 2.6 dB.

Figure 6 illustrates the achievable BER performance of the proposed SLM for OFDM/TDM and conventional SLM for OFDM as a function of peak transmit power under the same computational complexity constraint (i.e., OFDM/TDM with $K=16$ and $N_c=256$ can increase U two times with the same complexity as conventional OFDM (see Table I)). As shown by Fig. 6, the proposed SLM for OFDM/TDM, for the average BER=10^{-3}, reduces the required peak power by about 1.2 dB over the conventional SLM for OFDM/TDM with U=32. It can also be seen from the Fig. 6 that the proposed SLM for OFDM/TDM with U=32 reduces the required peak power by about 10 dB in comparison with conventional SLM for OFDM using U=16 under the same computational complexity constraint. This clearly shows the benefit of the proposed SLM for OFDM/TDM with respect to peak-transmit power in comparison with conventional SLM for OFDM.

V. Conclusion

In this paper, a new SLM for further PAPR reduction of OFDM/TDM is presented. The proposed SLM use both time and frequency dimensions of OFDM/TDM signal to increase the number of candidate sequences and obtain a lower PAPR. It is shown, by computer simulation that proposed SLM for OFDM/TDM obtains a lower PAPR in comparison with application of conventional SLM with same or reduced computational complexity as conventional OFDM depending on the OFDM/TDM design.

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