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Sliding the SLM-technique to Reduce the Non-Linear Distortion in OFDM Systems

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***Abstract*—In this paper, a novel technique that can be effectively used to reduce the peak-to-average power ratio (PAPR) of the orthogonal frequency division multiplexing (OFDM) system is proposed. The proposed technique, called sliding selected mapping (SSLM), is considered a modified version of the conventional selected mapping (CSLM) scheme. SSLM uses a window with a predefined size of less than N, which carries the phase rotation vector (PRV). In contrast to the CSLM, SSLM uses length-f·N *PRV*s (0<*f*<1). The window is shifted by a step size (sliding) on the data sequence. At each shift, the modified data sequence undergoes IFFT operations to check the PAPR, similar to the CSLM. Thereafter, the shift index that corresponds to the minimum PAPR is chosen as the side information. Meanwhile, for comparison, the CSLM uses the PRV index as side information. Simulation results and mathematical computations show that our proposed technique requires less computational complexity. In addition, the corresponding amount of side information is significantly reduced compared with that of CSLM.**

***Index Terms*—OFDM, peak to average power ratio, selected mapping, complexity.**

I. INTRODUCTION

The orthogonal frequency division multiplexing (OFDM) technique has become very popular in the last two decades. The current and next generations of communications systems depend mainly on such technique because of its ability to combat multipath fading channels using the corresponding concept of cyclic prefix (Guard Interval). In addition, it provides a high data rate and high spectrum efficiency compared with single carrier systems [1]. However, its major drawback is represented by high output peak-to-average power ratio (PAPR) events [2]. These events cause intermodulation distortion that results in nonlinearity, which affect the overall system performance.

A number of techniques were proposed to limit the PAPR, such as clipping and filtering [3], coding [4], partial transmit sequence (PTS) [5], selected mapping (SLM) [6], and others [7]. The clipping and filtering scheme significantly degrades the bit error rate (BER) performance of the system because of the nonlinear clipping operation, whereas the coding schemes exhibit higher performance but at the expense of low bit rates. In addition, the PTS- and SLM-based methods are probabilistic methods and are therefore distortionless PAPR reduction techniques. These approaches also suffer from a major disadvantage, i.e., increased computational complexity due to the number of inverse fast Fourier transform (IFFT) blocks.

In this paper, we focus on the SLM technique wherein a novel method, called sliding selected mapping (SSLM), was proposed to reduce the PAPR as well as the system complexity effectively, consequently reducing the side information. This technique depends on two parameters, i.e., window and step sizes. The former is considered the phase rotation vector (PRV) length, which shifts, i.e., slides, by a step size along the original data vector. At each step, an IFFT is performed to determine the PAPR. Accordingly, only the sliding index symbolizes the side information and maintains the window and step sizes as constant. Note that the proposed technique is not adaptive because of the optimal selection of the main parameters. In other words, the window and the step sizes are predefined at both the transmitter and the receiver.

As previously mentioned, this work discusses the SLM technique in terms of the reduction in computational complexity and the enhancement in PAPR reduction gain. However, the PAPR reduction increases with the increase in the number of PRV U. Consequently, the computational complexity increases because of the corresponding U-blocks of the IFFT operations, as will be shown in the next section.

A lower bound of the obtainable PAPR reduction gain with respect to a given level of complexity was introduced in [8]. This lower bound depends on the number of PRVs U. In literature, different methods were proposed to enhance the performance of the SLM scheme [9]–[34]. These proposals can be classified into two categories: frequency-domain-modified SLM approaches and time-domain-modified SLM schemes.

In the first category, special attention was given to the PRVs. Dae-Woon et al. [9], [10] showed that the best PRVs can be optimally achieved by introducing the following two conditions:

(i) The PRVs should be orthogonal to each other, and (ii) the PRV should not be periodic; otherwise, the PAPR

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reduction gain will decrease. In addition, the optimal PRVs can be selected by considering the rows of the Hadamard matrix instead of the Sylvester–Hadamard sequences because of periodicity [9], [10]. Zhou and Liang [11] proved the above conditions and showed that the optimal values of the phases of the PRV elements should be either 0 or π, with equal probabilities. In other words, the elements should have magnitudes of ±1. Alsusa and Yang [12] modified the PRVs so that the reduction in PAPR is similar to that of the conventional SLM (CSLM) technique but without the side information. However, the work reported in [12] is applicable only to small sizes of constellation mapping. Thus, the BER performance is degraded for large sizes. Hence, any modification in the phase sequence in the frequency domain should be performed to achieve a unity power of each element in the PRVs. In addition, the non-unity elements that appeared in the PRV change the constellation distances. Correspondingly, the BER performance is degraded.

The authors in [13] and [14] proposed the existence of such PRVs. In addition, the normalized Riemann sequences were used as PRVs in [15]. However, such sequences have elements with different magnitudes that may also reduce the minimum distance in the constellation mapping and subsequently degrade BER. Binary chaotic sequences are also utilized to modify the CSLM technique [16]. However, one phase sequence is generated and circularly shifted. Therefore, the candidates depend on one another, leading to the degradation in the PAPR reduction performance. PRVs that assist the receiver in recovering the original OFDM symbol was designed by Hong [17]. The PAPR was enhanced, but the complexity at the receiver increased because of the maximum likelihood decoder. In addition the BER was slightly degraded. The new PRVs used in [17], which improved the PAPR to a level higher than that of the low BER, was presented in [18], wherein more freedom in the pilot phase sequences was explored. Furthermore, other types of PRVs, such as pseudo-interferometry sequences [20], Fountain rotating vectors [19], Chu PRVs [21], and a class of perfect PRVs that reduce the PAPR [22], were examined. However, their performance is poorer than that of the CSLM technique.

A technique that mixes the frequency- and time domains was also developed to reduce complexity [26]. In this approach, some PRVs are generated in the frequency domain, whereas others are derived in the time domain according to the PRVs of the frequency domain. Hence, the number of IFFT blocks is reduced. In the same context, and as suggested in [27], when the circularly shifted phase sequences are first multiplied by the frequency-domain data vector, the candidates can be represented as the weighted sum of the circularly shifted OFDM time-domain data samples. Hence, a single IFFT block may be used to reduce the PAPR and the computational complexity at the transmitter. However, the complexity of the receiver increases. Thus, the number of IFFT blocks can be reduced to reduce the computations in the SLM method. To replace some of the IFFT blocks, conversion matrices, which depend only on two PRVs, were suggested in [23]. In that paper, the authors developed more conversion matrices to replace additional blocks of the IFFT operations [24] such that only one IFFT remains in the system. This process significantly reduced the complexity; however, the BER performance was also significantly degraded because of the different magnitudes of the PRV elements. In [25], the authors improved the BER degradation obtained in the aforementioned techniques [23], [24]; however, the corresponding overall BER performance is lower than that of the conventional SLM technique.

On the other hand, the time domain was also developed to reduce the computational complexity of CSLM further. For instance, Alsusa and Yand [28], [29] proposed the implementation of the SLM technique in the time domain rather than in the frequency domain. Therefore, only a single IFFT block is required in the system. Consequently, the computational complexity is significantly reduced compared with that of the conventional frequency-domain SLM scheme. Soo et al. [31] introduced a method involving the combination of cyclically delayed signals. In this technique, one IFFT block is used to avoid additional complexity. For comparison, the complexity was reduced to 50% with respect to the SLM for the same PAPR and coded BER performances [30]. The time-domain symbol combining (TDSC) technique is another method presented in [32], which can be also considered as a post-IFFT-modified SLM technique. TDSC reduces both the PAPR and the complexity of the system. One of the notable suggested modifications to the CSLM technique was reported in [33], wherein a time-domain selective filtering was used to obtain multiple scrambled OFDM symbols. The OFDM symbol with lower PAPR was selected for transmission, and the required number of IFFT blocks was maintained as only one block. This method was found very sensitive to the multipath channels. A notable technique was introduced in [34]. This technique generates PRV candidates in the time domain. However, its disadvantage is the degradation in the BER performance.

In general, the aforementioned techniques can be summarized as follows:

1) The modified PRVs can degrade the PAPR reduction and BER performance;

2) The mixed time–frequency domains also reduce the PAPR reduction performance, and sometimes even the BER degradation is also reduced, but exhibit reduced complexity; and

3) The time-domain operations reduce the BER and PAPR reduction performances but exhibit low computational complexity.

These findings motivated us to introduce the SSLM, which achieves a more significant PAPR reduction compared with that of CSLM (as well as with those of all the aforementioned methods) and exhibits no BER degradation. Our proposed technique follows the same procedure as that of CSLM, which results in a significant reduction in computational complexity.

II. PRINCIPLES OF OFDM AND SLM

A data vector of N bits, S_k, modulates N sub–channels, which is represented by the IFFT block. This operation produces the OFDM symbol and can be mathematically expressed as [8]

$$s_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi \frac{k}{N} n}, \quad 0 \le n \le N-1, \tag{1}$$

where samples S_0, $S_1 \ldots S_{N-1}$ are the input data sequences to the IFFT block. Up to this step, the system suffers from high PAPR because samples in the same phase are constructively added. Hence, a high power peak relative to the average power is detected, which results in high PAPR. The PAPR can be determined as follows [6]

$$\zeta = \frac{\max|s_n|^2}{E\left[|s_n|^2\right]}, \tag{2}$$

where s_n represents the time-domain OFDM samples, and $E[\bullet]$ is the expectation operation. Literature shows that ζ is expressed in decibels rather than in rational numbers. Therefore, throughout this paper, ζ is expressed in decibels as $10\log_{10}\zeta$. A discrete time signal sampled by the Nyquist rate could result in the loss of some peaks. Therefore, an upsampling factor is used to improve the performance and make it similar to that of the continuous-time version. The optimum upsampling factor is set at four [35]. The complementary cumulative distribution function of the PAPR can be used to measure the PAPR and can be expressed as

$$CCDF(\zeta) = \Pr(\zeta > \gamma), \tag{3}$$

where γ is the clipping level. The selection of the clipping threshold, γ, at which the minimum nonlinear effect can be attained, is essential. More than 60,000 OFDM symbols are simulated for this function. To reduce the PAPR, we need to use one of the PAPR reduction techniques. Here, we consider the SLM method because it is a probabilistic technique and can therefore produce no BER degradation. SLM [6] creates U candidates of S_k data sequences, which are multiplied component-wise by the U *PRV*s. Then results are then fed to the bank of the IFFT blocks (which is the CSLM). Mathematically, the CSLM operation can be expressed as

$$\mathbf{S}^u = \mathbf{p}^u \times \mathbf{S}. \tag{4}$$

where

$$\mathbf{S}^u = \begin{bmatrix} S_0^u \\ S_1^u \\ \vdots \\ S_{N-1}^u \end{bmatrix}, \ \mathbf{p}^u = \begin{bmatrix} p_0^u & 0 & \cdots & 0 \\ 0 & p_1^u & \cdots & 0 \\ \vdots & \vdots & & 0 \\ 0 & 0 & \cdots & p_{N-1}^u \end{bmatrix}, \ \mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ \vdots \\ S_{N-1} \end{bmatrix}. \tag{5}$$

In (5), $\mathbf{p}^u$ is the uth *PRV*, and $u = 1, 2 \ldots U$. PAPR should be determined for each branch, i.e., *PRV* $\mathbf{p}^u$. The branch with the minimum PAPR is chosen for the transmission, along with its corresponding rotating vector index $\hat{u}$ as side information. Thus, the output time-domain OFDM symbol can be expressed as

$$\mathbf{s}^{\hat{u}} = \mathbf{W}_N \times \{\mathbf{p}_{\hat{u}} \times \mathbf{S}\}, \tag{6}$$

where $\hat{u}$ represents the index of the *PRV* that produces a lower PAPR value, and $\mathbf{W}_N$ is the IFFT matrix. The amount of side information bits is given as [36]

$$SI_{CSLM} = \log_2 U. \tag{7}$$

From [36], the number of multiplication operations can be determined as

$$M_{CSLM} = 2UN \log_2 N, \tag{8}$$

whereas the number of addition operations is

$$A_{CSLM} = 4UN \log_2 N. \tag{9}$$

The advantages of our proposed technique in terms of significant reductions in PAPR as well as in the computational complexity and side information can be explained using these CSLM equations. In addition, the *PRV*s are chosen from the Hadamard matrix of length N because the Hadamard sequences are found to be the optimum choice [9,10,15].

III. Proposed Technique

In the proposed technique, the selection of the *PRV* is carefully performed because the proposed method uses only one *PRV*, which results in a significant improvement in the PAPR. Here, we select the *PRV* from the center of the Hadamard matrix, which is {+1, -1, +1….} (*successive sign negation*). As previously stated, we can use other types of *PRV*s and not necessarily within Hadamard matrix. However, as will be shown later, the corresponding *PRV* has an essential role in PAPR reduction. The rotating vector is selected; we need to illustrate how the SSLM scheme uses such a vector. The SSLM technique works as follows: A window that contains the *PRV* and is of size z samples can be expressed as

$$z = f \cdot N, \quad 0 < f < 1, \tag{10}$$

where z is smaller than the data vector, i.e., $z < N$. This window modifies only the samples of the data sequence. The resultant vector is then passed to the IFFT block to determine the PAPR. The window is shifted by a step size, r, along the data sequence toward the end. The PAPR is then determined at each corresponding shift. The symbol with the minimum PAPR is transmitted to the receiver along with its corresponding shift index η as side information. The number of shifts can then be calculated as

$$\psi = \frac{N - z}{r}. \tag{11}$$

Note that ψ increases as the shift step size r decreases. Hence, a small ψ is considered a disadvantage for the suggested method (SSLM), and the appropriate r should be selected to ensure that the complexity is as low as possible. Thus, the shift index is

$$\eta = \begin{bmatrix} 0 & r & 2r & 3r & \cdots & \psi - 1 \end{bmatrix}, \tag{12}$$

Equation (10) shows that z has a lower number of elements than N. Therefore, without any loss of generality, the other elements of z all have the value of one. For instance, we assume that N = 8, z = 4, and r = 1. This assumption results in ψ = 4 and η = 0, 1, 2, and 3. Thus, when η = 0 and z = [**1 -1 1 -1** 1 1 1 1], the first four elements represent the original z window, whereas the others are considered for mathematical convenience. Generally, z can be written as

$$\mathbf{z}^{\eta} = \begin{bmatrix} z_0^{\eta} & 0 & \cdot\cdot & 0 \\ 0 & z_1^{\eta} & \cdot\cdot & 0 \\ : & : & & 0 \\ 0 & 0 & \cdot\cdot & z_{N-1}^{\eta} \end{bmatrix}. \tag{13}$$

Similar to the CSLM scheme, the SSLM is expressed as

$$\begin{bmatrix} S_0^{\eta} \\ S_1^{\eta} \\ : \\ S_{N-1}^{\eta} \end{bmatrix} = \begin{bmatrix} z_0^{\eta} & 0 & \cdot\cdot & 0 \\ 0 & z_1^{\eta} & \cdot\cdot & 0 \\ : & : & & 0 \\ 0 & 0 & \cdot\cdot & z_{N-1}^{\eta} \end{bmatrix} \times \begin{bmatrix} S_0 \\ S_1 \\ : \\ S_{N-1} \end{bmatrix}. \tag{14}$$

By using (13), the discrete-time OFDM symbol can be written as follows

$$\mathbf{s}^{\tilde{\eta}} = \mathbf{W}_N \times \left\{ \mathbf{z}^{\tilde{\eta}} \times \mathbf{S} \right\}, \tag{15}$$

where the shift index $\tilde{\eta}$ produces a lower PAPR. In other words, $\mathbf{s}^{\tilde{\eta}}$ is the discrete-time OFDM symbol with the lowest PAPR. Fig 1 shows a simple block diagram of the suggested method, where **si** represents the side information.

For the analysis of the computational complexity, (10) and (11) show that the window size z and step size r exert a significant effect on the computational complexity as well as on the PAPR reduction performance. Note that the number of shifts, ψ, corresponds to the number of *PRV*s, U, of the CSLM scheme. However, this value should be increased by one because the first iteration in the proposed scheme is considered for all *PRV* equal to one in order to check the PAPR without using any modifications. In comparison, the CSLM approach (Table I) already includes such a *PRV* (the first one, u = 1). The number of multiplication operations performed in the SSLM scheme can be calculated as

$$M_{SSLM} = (\psi + 1)(1 + z + 2N \log_2 N). \tag{16}$$

Equation (16) shows that the computational complexity mainly depends on z and r because the number of subcarriers N is usually fixed. Hence, the side information can be written as

$$SI_{SSLM} = \lceil \log_2(\psi + 1) \rceil, \tag{17}$$

where $\lceil \cdot \rceil$ is the ceiling function (the nearest integer toward infinity). Table I illustrates the comparison between the computational complexities of the CSLM and SSLM approaches.

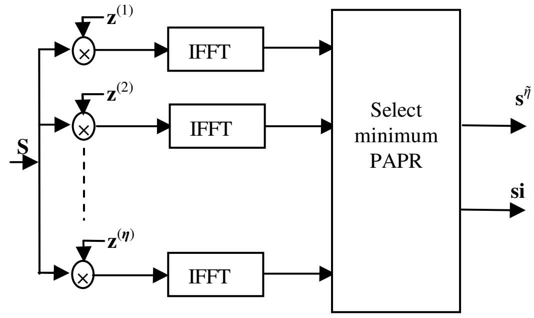

Fig. 1. Block diagram of the proposed sliding selected mapping (SSLM) technique.

TABLE I. COMPARISON OF THE COMPUTATIONAL COMPLEXITIES OF THE SELECTED MAPPING (SLM) AND SSLM TECHNIQUES.

Method	# of IFFT(s)	# of Multiplications	Side information
CSLM	U	$2UN \log_2 N$	$\log_2 U$
SSLM	$\lceil \psi + 1 \rceil$	$(\psi + 1)(1 + z + 2N \log_2 N)$	$\lceil \log_2(\psi + 1) \rceil$

Table I shows that the number of *PRV*s in CSLM corresponds to an increase of 1 in the number of shifts for SSLM (ψ+1). Therefore, if the number of shifts decreases, the side information also decreases (Table I, *fourth column*). The number of multiplications is also reduced. We can deduce that the PAPR performance can be improved by increasing the window size z or step size r. The former is proportionally related to the data vector size N, whereas the latter is inversely related to the vector length. However, this process may increase the complexity, even though the complexity remains approximately less than that of the CSLM technique. For instance, if we assume that the rotating vector is U = 16, the number of subchannels is N = 64, f = 0.5 [see (10)], and r = 4, then z is 32 and ψ = 8. Table I shows that the multiplication numbers are 12,288 and 6,408 for the CSLM and SSLM approaches, respectively. Thus, approximately 48% reduction in the complexity is achieved. In this example, we considered the worst case because the window size z is small compared to N. The highest performance can be obtained when $z > N/2$ (f >0.5, such as f = 0.75), as will be shown in the subsequent section where a comprehensive discussion is presented.

At the receiver side, we assume that the side information are perfectly received. Therefore, the received signal is recovered by reversing (15), as follows

$$\mathbf{s}_r = \mathbf{W}_N^{-1} \times \left\{ \mathbf{z}^{\tilde{\eta}} \times \mathbf{S}_r^{\tilde{\eta}} \right\} + \omega, \tag{18}$$

where $\mathbf{S}_r^{\tilde{\eta}}$ is the received OFDM symbol, and ω is an additional white Gaussian noise.

IV. Results and Discussion

The advantage of our new SSLM technique in terms of the reduction in complexity has been explained in the previous section. Here, we will show how the PAPR can be reduced more efficiently compared with that of the CSLM technique. We consider the case of 64 subcarriers (N = 64) that are modulated by 16-QAM symbols for all the scenarios included in the simulation. Unless otherwise stated, Table II shows the values of the parameters used in the calculation. We simulated four scenarios. The first scenario involves U = 8, 16, and 32, z = 8, 16, 32, and 48, and a step size r = 1 bit. The second, third, and fourth scenarios are simulated using the same settings as that of the first scenario but for step sizes r = 2, 4, and 8, respectively.

TABLE II. SIMULATED PARAMETERS FOR FOUR SCENARIOS.

Method	U	z	r for each z
CSLM	8, 16, 32	Non	Non
SSLM	$\lceil \psi + 1 \rceil$	8, 16 32, 48	1, 2, 4, 8

Scenario # 1 (r = *1*). Table II shows that the number of *PRVs* is U = 8, 16, and 32, whereas the window sizes are z = 8, 16, 32, and 48 (f = 0.75 or 75% of N). These parameters are simulated for approximately 60,000 OFDM symbols, where the step size r is considered as one sample. Fig. 2 shows the PAPR for each case. The figure shows that the SSLM method enhances the PAPR in all cases with respect to the original OFDM system (which does not use the PAPR-reduction method). In addition, the CSLM approach outperforms the first two cases of the SSLM method, i.e., z = 8 and 16. For the third case (z = 32), the SSLM outperforms all cases compared with the CSLM technique; thus, it almost has the same reduction gain. For the fourth case, the SSLM shows more reduction in PAPR compared with the CSLM method, wherein the PAPR is reduced by 3 and 1 dB compared with those of the original OFDM and CSLM, respectively. When r = 1, the computational complexity is very high, particularly for the three cases in the SSLM method and for z = 8, 16, and 32, which have complexities higher than that of the CSLM technique. Meanwhile, the fourth case (z = 48) has lower computational complexity than the CSLM method. However, its side information is 5 bits, which corresponds to the last case in the CSLM technique, i.e., U = 32. Thus, the percentage of reduction in the computational complexity with respect to the CSLM (U = 32) is ~44%. Table III shows the numerical comparison for this scenario in terms of the number of multiplications, amount of side information, and number of required IFFT blocks.

Scenario # 2 (r = 2). In this scenario, the sliding step size r is increased to two samples, whereas U and z are constant. Therefore, a reduction in the system's complexity is achieved. Fig. 3 shows that the PAPR reduction performance remains higher than that of SLM despite the slight decrease.

In addition, the PAPR reduction performance of SSLM is approximately similar to that obtained in the first scenario. The difference in the corresponding curves represents the gain in the computational complexity reduction. Table IV compares the complexity of the CSLM method with that of the modified one. The first case (z = 8) has 22,533 real multiplication operations, which is lower than the third case in the traditional SLM. However, the PAPR reduction gain was lower.

TABLE III. COMPARISON BETWEEN THE CONVENTIONAL SLM (CSLM) AND SSLM FOR R = 1 (WORST CASE SCENARIO).

Technique		IFFT blocks	Multiplication operations	Side information
CSLM	U = 8	8	6,144	3
	U = 16	16	12,288	4
	U = 32	32	24,576	5
SSLM	z = 8	57	44,289 ↑	6 ↑
	z = 16	49	38,465 ↑	6 ↑
	z = 32	33	26,433 ↑	6 ↑
	z = 48	17	13,889 ↓	5 ≡

The arrows "↑" and "↓" refer to increases and decreases, respectively, and "≡: represents matching values.

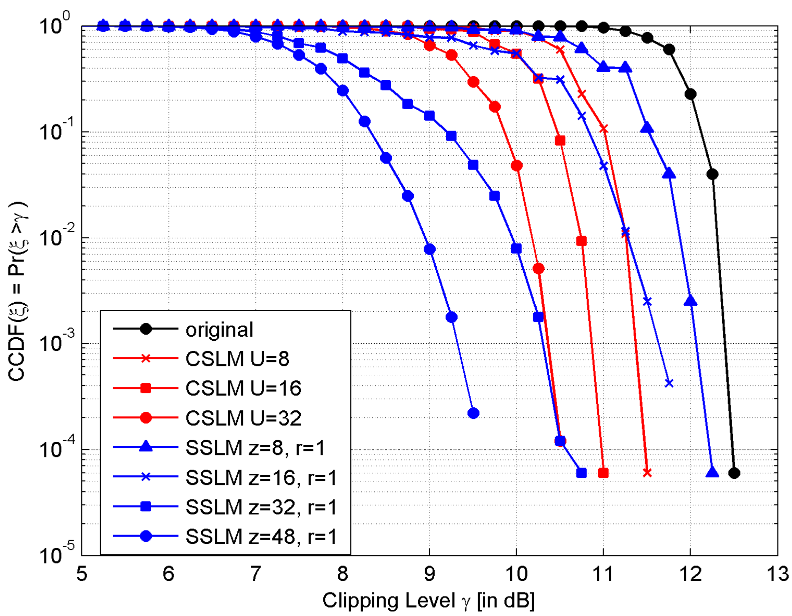

Fig. 2. The PAPR performance of the original system, CSLM, and SSLM (the proposed technique) for r = 1 (scenario #1).

For the second case (z = 16), the number of real multiplications is 19,625, which is also lower than that in the previous case, i.e., CSLM (U = 32). However the PAPR performance remains lower than that in the CSLM method.

The third case is for z = 32 samples (f = 0.5, or 50% of N). In this case, the PAPR performance significantly improves by ~1.8 dB. This result indicates the same performance as that of the third case in the original SLM method. Thus, the percentage reduction in the computational complexity with respect to the CSLM (U = 32) is approximately 45%. For the last case, when z = 48, the PAPR performance decreases to 9.8 dB, which is the highest value obtained for the SSLM method.

In addition, the proposed SLM technique reduces the computational complexity to 70% compared with the highest performance of the conventional method (U = 32). On the other hand, the number of side information samples decreased from 5 to 4. Improvements in the computational complexity as well as in the side information are achieved when the step size is increased to 4, as will be explained in the subsequent subsection.

TABLE IV. COMPARISON OF CSLM AND SSLM FOR r = 2.

Technique		IFFT blocks	Multiplication operations	Side information
CSLM	U = 8	8	6,144	3
	U = 16	16	12,288	4
	U = 32	32	24,576	5
SSLM	z = 8	29	22,533 ↕	5 ↕
	z = 16	25	19,625 ↕	5 ↕
	z = 32	17	13,617 ↕	5 ↕
	z = 48	9	7,353 ↓	4 ↓

The arrows “↑” and “↓” refer to increases and decreases, respectively.

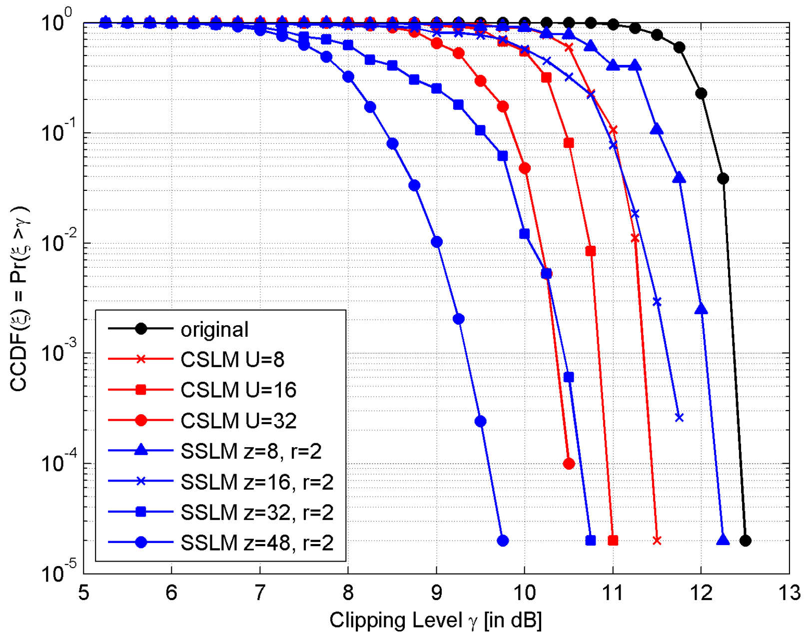

Fig. 3. The PAPR performance of the original system, CSLM, and SSLM (the proposed technique) for r = 1 (scenario #2).

Scenario # 3 (r = 4). Following the procedures of the two previous scenarios, Fig. 4 shows that the ability of the SSLM technique to reduce the PAPR gradually decreases when the shift step size r increases because the number of iterations is reduced. In other words, ψ is reduced in the CSLM compared with U. In addition, the performance of the SSLM method in the first and second cases is approximately unchanged because the window size remains small. At lower computations, particularly for the second case for CSLM and for the third and fourth cases for SSLM, the PAPR performance of CSLM in the third case (U = 32) changes and exceeds that of SSLM in the third case (z = 32). However, the performance remains higher than those of the other cases in the CSLM when U = 8 and 16. Furthermore, the computational complexity is lower than those of the second and third cases for the CSLM method (U = 16 and 32, respectively), wherein the achieved decreases are approximately 41% and 71%, respectively. Moreover, the number of side information bits is reduced from 5 samples (U = 32) to 4 samples, as shown in Table V.

The last case is considered when the window size z = 48 and the number of shifts is four. Through these shifts, the PAPR is more significantly improved than those of the other cases (Fig. 4). The PAPR is reduced from approximately 12.4 dB to 9.4 dB, whereas for the CSLM, the highest achieved reduction is 10.5 dB. Hence, improvements in the PAPR reduction performance, computational complexity reduction, and side information are achieved. Compared with the CSLM method, a 3 dB reduction gain in the PAPR and an 83.4% reduction in the computational complexity are obtained. In addition, the amount of side information is reduced from 5 bits to 3 bits only, indicating a 40% reduction (Fig. 4 and Table V).

TABLE V. COMPARISON BETWEEN CSLM AND SSLM FOR R = 4.

Technique		IFFT-blocks	Multiplication operations	Side information
CSLM	U = 8	8	6,144	3
	U = 16	16	12,288	4
	U = 32	32	24,576	5
SSLM	z = 8	29	11,655 ↕	4 ↕
	z = 16	25	10,205 ↕	4 ↕
	z = 32	17	7,209 ↕	4 ↕
	z = 48	9	4,085 ↓	3 ↓

The arrows “↑” and ↓ refer to increases and decreases, respectively.

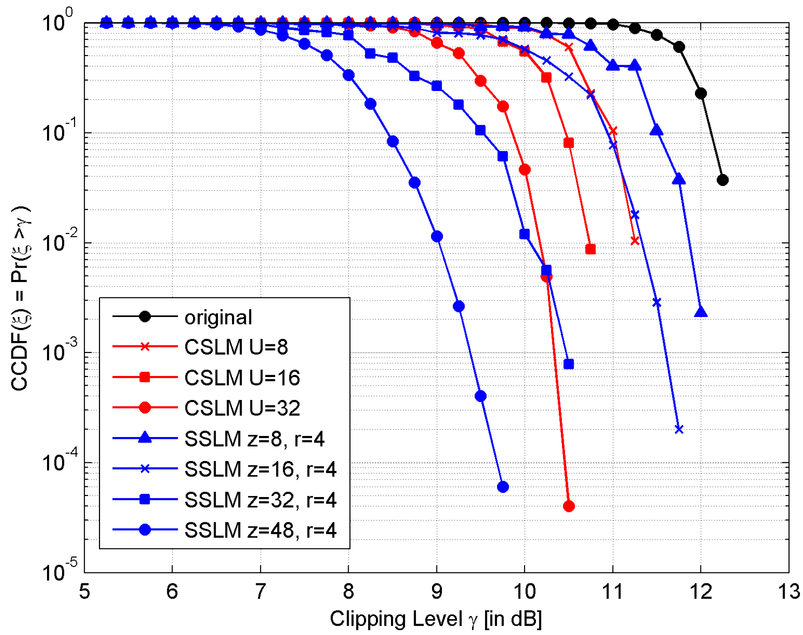

Fig. 4. The PAPR performance of the original system, CSLM, and SSLM (the proposed technique) for $r = 4$ (scenario #3).

Scenario # 4 (r = 8). The performance of the system decreases when the step size r is increased. In this scenario, r is increased to 8, whereas for the CSLM technique, the same number of *PRV*s and the same window sizes are considered. By increasing the step size, a higher reduction in the system complexity and almost the same PAPR as that of the last scenario are achieved as shown in Table VI. For instance, when the last case (z = 48) is considered, the computational complexity decreases by 90% with respect to the best case of the CSLM approach. Moreover, the number of side information bits is reduced from 5 to only 2 bits, which indicates a 60% reduction in the amount of side information at a PAPR gain of 2.5 dB compared with that of the original system. This result is higher than that of the original SLM by 1 dB as shown in Fig. 5.

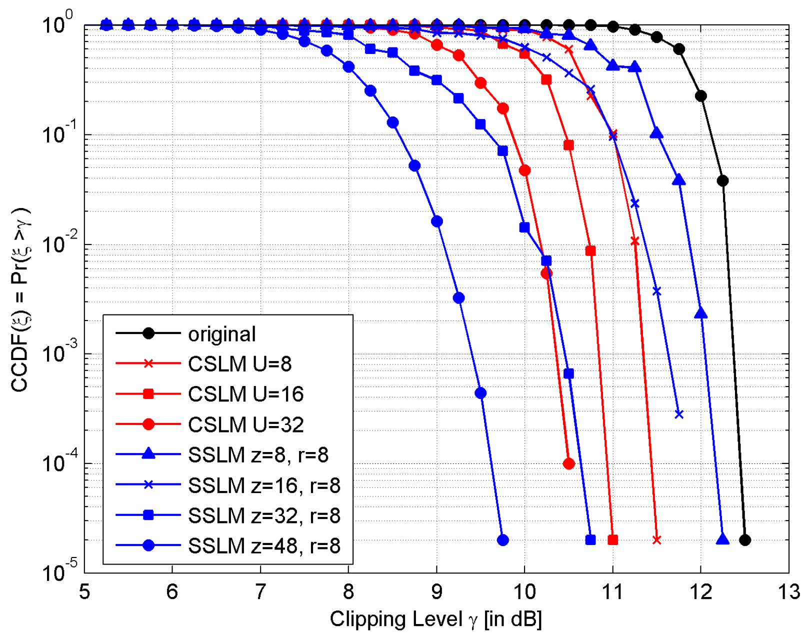

Fig. 5. The PAPR performance of the original system, CSLM, and SSLM (the proposed technique) for $r = 8$ (scenario #4).

V. SUMMARY OF SSLM

SSLM technique is based on the sliding of a window on the data vector (component-wise multiplication) unlike that in CSLM, where a number of *PRV*s were multiplied component-wise by the data sequence to identify the lowest PAPR among them. Meanwhile, the SSLM chose the lowest PAPR from a number of candidates that were generated by multiplying the window (which carries a constant-phase sequence) with the data vector based on selected sliding times. In our technique, we used the *PRV* [+1 -1 +1 -1 …], which has a unity power, to maintain the constellation points and prevent the degradation of the BER. We considered two main parameters, namely, the window size z and the shifting step size r. The window size enhances the PAPR reduction ability, whereas the step size improves the computational complexity as well as the side information. When the window size z, is reduced to only one bit, no enhancement in the PAPR is detected.

According to the simulation results, the optimum value for the window size is $z = 0.75\ N$ ($f = 0.75$). On the other hand, the step size r notably affects the PAPR reduction performance, particularly the computational complexity. When $r = 1$, the computational complexity increases. Meanwhile, other values of r produces lower computational complexities. We have simulated four scenarios of the same window sizes, namely, $z = 8$, 16, 32, and 48, at 16-QAM modulation, 64 subchannels (length of IFFT), and with U = 8, 16, and 32 as the number of *PRV*s used in the CSLM scheme. The only difference between these four scenarios is the value of the sliding step size r, which are 1, 2, 4, and 8 for the first, second, third, and fourth scenarios, respectively. Table VII summarizes the results of the four scenarios with respect to the PAPR reduction, complexity, and side information required for each technique without resulting in degradation in the BER performance.

TABLE VII. SUMMURY OF RESULTS.

Method	Scenario #1			Scenario #2		
	C	SI	PAPR	C	SI	PAPR
CSLM	-	5	10.5	-	5	10.5
SSLM	44	5	9.5	70	4	9.75
	Scenario #3			Scenario #4		
CSLM	-	5	10.5	-	5	10.5
SSLM	83	3	9.75	90	2	9.8

VI. CONCLUSIONS

A novel technique called SSLM has been proposed in this study. This technique can be effectively used to reduce PAPR as well as the system complexity and side information. As a remarkable conclusion, a *tradeoff between the window size and the shift step size can be made. Therefore, these values must be carefully chosen.* In all scenarios, the best choice for the window size and shift step size is 75% of N and eight samples, respectively, at which the PAPR performance, computational complexity reduction, and the amount of side information are significantly enhanced. In a way, most of the difficulties faced by the traditional SLM can be overcome using our proposed technique, which facilitates practical implementation where a low PAPR, low complexity, and low side information can be attained. The phase vector can be replaced by another one to achieve further reduction in the PAPR. This modification will be considered in a future work. However, because of the proposed technique is probabilistic, no BER was detected. The SSLM can be recommended for the systems that utilize the OFDM modulation such as the worldwide interoperability for microwave access (WiMAX) or the 4G technology represented by the long term evolution (LTE). Moreover, as a further future work, it is possible to test the SSLM with the MIMO systems where the computation complexity will be very low.

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