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Spectrum Efficient DSI-Based OFDM PAPR Reduction by Subcarrier Group Modulation

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***Abstract*—High peak-to-average power ratio (PAPR) is a long-standing problem of orthogonal frequency division multiplexing (OFDM) system. Although there have been a plethora of proposals presented to date, most of the proposals sacrifice spectral efficiency to attain low PAPR. In this paper, a concept of subcarrier group modulation (SGM) is proposed to transform those spectrum inefficient schemes into spectrum efficient ones. The SGM scheme groups available subcarriers, and assigns one extra bit to each group depending on one of two different sets of constellation, thereby freeing some subcarriers for PAPR reduction. At the receiver, the constellation set used in a particular group is determined by the maximum-likelihood detection. The SGM scheme can be integrated to different PAPR reduction schemes. In this paper, it is integrated with the dummy sequence insertion (DSI) scheme. The DSI with SGM can attain the same spectral efficiency as the conventional OFDM does. Through simulations, it is found that it can achieve PAPR almost similar to that the conventional DSI scheme does without degrading BER performance significantly over both additive white Gaussian noise and Rayleigh fading channels. In addition to the PAPR reduction application, the proposed scheme can be used to improve throughput of any conventional OFDM systems.**

***Index Terms*—OFDM, peak-to-average power ratio, spectral efficiency, dummy sequence insertion, tone reservation.**

I. Introduction

WIRELESS communication has seen an unprecedented growth in data rate demand in the last decade due to a massive development in multimedia communication. Since the spectrum is a limited resource, it is imperative to effectively use the spectrum to meet the growing demand of the data rate. Orthogonal frequency division multiplexing (OFDM) is seen as one of the most spectrally efficient waveform design techniques. Its other advantages include easy equalization, robustness against co-channel interference, and high immunity to the fading channel. For this reason, it has been included in a number of different applications such as digital audio broadcasting (DAB), digital video broadcasting (DVB) (both terrestrial digital television systems and mobile television systems) IEEE 802.11a/g/n, IEEE 802.15.3a, IEEE 802.16e, IEEE 802.20, downlink of fourth-generation mobile broadband standard, and so on. High peak-to-average power ratio (PAPR) is, however, a major drawback of this popular waveform generation technique. A signal having the high PAPR causes in-band distortion, out-of-band interference at the output of a nonlinear amplifier, and bit error rate (BER) performance degradation at the receiver. To avoid such shortcomings, the high power amplifier (HPA) is needed to run at the linear region where power efficiency degrades; that is, the spectral efficiency is obtained compromising the energy efficiency. This makes OFDM ineffective for low-power devices. One way to bring a trade-off between these two efficiencies is to reduce the PAPR.

There have been a plethora of work carried out to address this long-standing problem. A detail of each PAPR reduction scheme can be found in [1]. Existing schemes can be classified into two broad categories: signal distortion technique and distortionless technique. While clipping [2], [3] and companding [4], [5] belong to the former category, selected mapping (SLM) [6], [7], partial transmit sequence (PTS) [8], [9], tone reservation (TR) [10]–[21], and dummy sequence insertion (DSI) [22]–[24] are the latter one. The signal distortion technique suffers from in-band noise and out-of-band interference. Although the distortionless technique does not suffer from such problem, one major shortcoming of this group is bandwidth inefficiency. PTS and SLM need to send side information (SI) to the receiver, where the SI is required by the receiver to properly recover the transmitted data. A certain portion of the available spectrum is required to be reserved for transmitting the SI, which results in a reduction of the subcarriers for the data transmission, thereby reducing throughput. In addition, any loss in the SI results in BER degradation at the receiver. For this reason, a mechanism for protecting the SI is also required. Although the DSI and TR do not need to send the SI, these are not bandwidth efficient schemes; the reason is that a certain number of subcarriers are reserved for PAPR reduction, and these subcarriers do not carry any data. This reduces the number of subcarriers for data transmission, resulting in a loss of throughput. For this reason, these schemes cannot outperform the SLM and PTS in terms of bandwidth efficiency in one hand, and cannot attain as much PAPR reduction as achieved by the SLM and PTS. After the proposal of TR [10] in 2000, many work [11]–[21] have been carried out on TR. All the work, however, have either dealt with attaining more PAPR reduction or complexity reduction of the technique. Similarly, several work have been carried out on DSI scheme; most of which either investigate the applicability of it in different scenarios or improve the PAPR reduction capability of it. To the best of our knowledge, no work has yet been done to address the bandwidth inefficiency issue of these two schemes.

In this paper, the bandwidth inefficiency issue is addressed to make the schemes such as DSI and TR bandwidth efficient. In this endeavor, a concept of subcarrier group modulation (SGM) is proposed. In the SGM scheme, the available subcarriers are divided into a number of groups, and each group is modulated by one of the candidate constellations of the quadrature phase shift keying (QPSK); each group of the subcarriers is associated with an extra bit depending on the constellation used in the group. At the receiver, a maximum likelihood (ML) detection is used to identify the constellation used in a particular group. The extra bit sent with each group can compensate for the reduction of the number of transmitted bits due to the reservation of a certain number of subcarriers for PAPR reduction, hence both DSI and TR schemes do not need to compromise the throughput in attaining the low PAPR. Thus, the SGM makes both schemes bandwidth efficient. In this paper, the SGM scheme is integrated with the DSI scheme to show its performance. Through simulations, the SGM-integrated DSI scheme is found to attain the same PAPR as the

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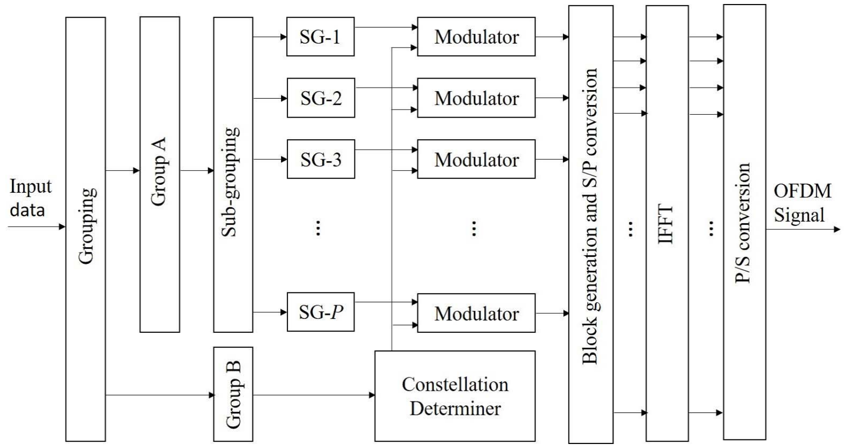

Fig. 1. Block diagram of OFDM with SGM.

TABLE I
LIST OF SYMBOLS

N	Number of subcarriers
x_n	n^{th} time-domain OFDM symbol
X_k	k^{th} frequency-domain symbol
L	Oversampling factor
$E\{.\}$	Mathematical expectation operator
$\lvert.\rvert^2$	Power of a sample
α	Number of bits transmitted in each OFDM symbol
α_A	Number of bits in group A
α_B	Number of bits in group B
N_A	Number of subcarriers for group A bits
N_B	Number of subcarriers for group B bits
δ	Energy associated with constellation set C_o
P	Number of subgroups for group A bits
M	Modulation order
σ^2	AWGN noise variance
Lcp	Cyclic prefix length
η_1	Spectrum efficiency of an OFDM system
$\eta_{1,d}$	Spectrum efficiency of the DSI scheme
η_{os}	Spectrum efficiency of the SGM integrated OFDM system
η_{dp}	Spectrum efficiency of the SGM integrated DSI scheme

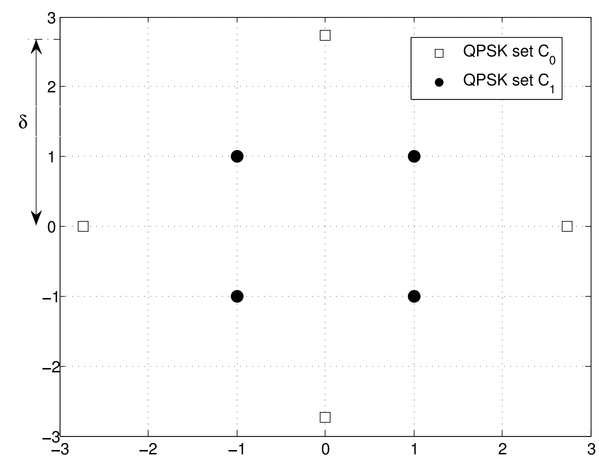

Fig. 2. A constellation design example for SGM.

DSI scheme does. In addition, the blind detection of modulation at the receiver does not degrade BER significantly.

The rest of the paper is organized as follows. Describing the cause of high PAPR of OFDM signal and formulating the problem in Section II, the proposed SGM scheme is explained in Section III. Section IV provides a short description of the DSI scheme before presenting a detail description of the proposed SGM-integrated DSI scheme. Analytical evaluation of the spectrum efficiency of the proposed scheme is also presented here. Section V provides a thorough performance evaluation of the proposed scheme through simulations with respect to the DSI scheme. A conclusion is drawn in Section VI. Table I provides a list of the symbols used in the paper.

II. PROBLEM FORMULATION

OFDM is a multicarrier communication system. The available bandwidth is divided into a number of narrow subbands in such a way that the channel bandwidth becomes less than the coherence bandwidth. For this reason, the frequency selective fading has no effect on OFDM; rather it is affected by the flat fading, and the effects of such fading can be mitigated by using a one-tap equalizer; this makes the OFDM receiver less complex and inexpensive. The OFDM time-domain signal can be obtained from the frequency-domain signal using the inverse fast Fourier transform (IFFT) in the following way:

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{\frac{j2\pi kn}{N}}, \tag{1}$$

where $j = \sqrt{-1}$, and $n = 0, 1, 2, \ldots, N-1$. Each frequency-domain symbol is multiplied by a respective sine wave having frequency which is an integer multiple of the fundamental frequency, which is followed by the addition of all the resulting sine waves, and doing sampling in the added complex signal. Since the sampling is a discrete process, taking of N samples for N subcarriers cannot provide the complete information of the continuous signal; rather, a loss of information occurs because all peaks of the continuous waveform cannot be captured. To mitigate this effect, L, where L is an integer, times more sampling is carried out; that is, for OFDM system of N subcarriers, a total of NL samples are taken. $L = 4$ can provide an accurate approximation of the continuous signal [31]. In this case, (1) becomes

$$x_n = \frac{1}{NL}\sum_{k=0}^{NL-1} X_k e^{\frac{j2\pi kn}{NL}}, \tag{2}$$

where $n = 0, 1, 2, \ldots, NL-1$. A sample at the time n can have a very high power if all sine waves get added coherently at the n^{th} instant; this makes a very high ratio of the peak power at that time to the average signal power. Although such high PAPR occurs very rarely, it makes difficult to design a HPA with a large operating range.

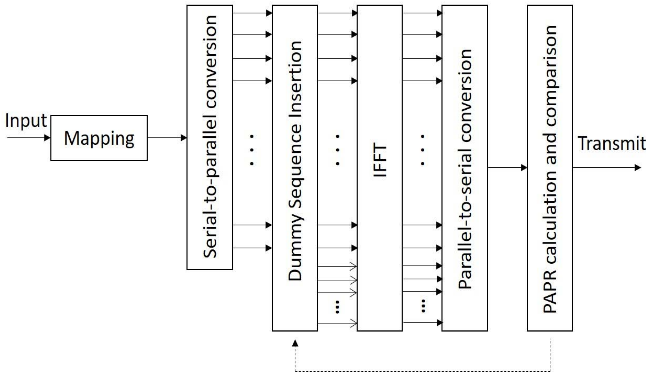

Fig. 3. Block diagram of the DSI scheme.

The PAPR of an OFDM signal is defined by:

$$PAPR = \frac{max(|x_n|^2)}{E\{|x_n|^2\}}, \tag{3}$$

where $max(.)$ represents maximum value function, $n = 1, 2, 3, \ldots, NL$.

III. Subcarrier Group Modulation

The proposed PAPR reduction scheme is based on the novel concept, SGM. It is a technique of sending more bits than the conventional OFDM system. The conventional OFDM system of N subcarriers can transmit $\alpha = Nlog_2M$ bits. However, the proposed OFDM with SGM can transmit more than α bits. Figure 1 shows a block diagram of the proposed SGM. The incoming bits of length α are first divided into two groups: group A and group B, where the length of the group A, α_A, must be greater than that of the group B, α_B, and $\alpha = \alpha_A + \alpha_B$. Out of the N subcarriers, N_A subcarriers are allocated for group A bits, and the rest $N_B = N - N_A$ subcarriers for the group B bits. The number of bits in the groups A and B are as follows:

$$\alpha_A = N_A log_2 M, \tag{4}$$
$$\alpha_B = N_B log_2 M. \tag{5}$$

The number of bits belong to each group mainly depends on how many extra bits are required to send by the SGM scheme: the larger α_B results in more extra bits transmission. For PAPR reduction, it affects PAPR performance. In addition, it also depends on the required BER performance. It will be further investigated in Section V. Then, the α_A bits are divided into P subgroups, where $P = \alpha_B$, with each subgroup which consists of $K = \frac{\alpha_A}{P}$ bits. Each of these subgroups is modulated by the QPSK modulation. However, not all subgroups are modulated according to the same constellation; rather, two different constellations are used. An example of such constellations is given in Fig. 2, which is recently independently proposed to use in OFDM with index modulation [26], [27]. In index modulation, the indices of all subcarriers are modulated based on input bits. The proposed scheme, on the other hand, modulates subgroups of subcarriers; this simplifies its design and implementation. Furthermore, all subcarriers must be modulated using QPSK modulation in the index modulation. This does not allow to use PAPR reducing sequences such as Zadoff-chu sequence which consists of complex numbers. The proposed scheme has no such limitation. In addition, a look-up table is required to use in [26] and [27] at the receiver, which affects system memory and speed of operation. However, the proposed scheme is free from such requirement. Overall, the motivation behind the proposed scheme is quite different from the index modulation. In Fig. 2, δ is a design parameter whose value depends on a specific scenario. The scenarios will be discussed in Section V. Either set C_0 or set C_1 as constellation will be used in a particular subgroup depending on the respective bit in the set B. Since $P = \alpha_B$, there is a one-to-one correspondence between a subgroup and a bit in the group B. The constellation set used to modulate the i^{th} subgroup depends on the i^{th} bit in the group B. Suppose that the constellation set C_0 corresponds to bit 0 and the set C_1 to bit 1. Thus, if the i^{th} bit in the group B is 0, the constellation set C_0 will be used to modulate the i^{th} subgroup of data; otherwise, the set C_1 will be used. Thus, the constellation set used in a particular group carries information about a bit in group B. The i^{th} bit in group B can be recovered at receiver if the constellation set used in i^{th} subgroup is correctly detected. In this way, one bit is associated to each subgroup. For this reason, it can be said that each group carries one bit more than K bits. The bits of the group B are never transmitted directly, rather, these are indirectly transmitted by associating these bits with the subgroups. Now, the subcarriers allocated for α_B bits become free. These N_B subcarriers can be used for transmitting α_B more bits. In this way, the OFDM with SGM scheme of N subcarriers can transmit $\alpha + \alpha_B$ bits, which is α_B bits more than that of the conventional OFDM system. The conventional OFDM cannot transmit these α_B bits. If it wants to transmit the α_B bits, it requires N_B more subcarriers. However, the OFDM with SGM transmits α_B more bits compared to the conventional OFDM without using any additional subcarriers. After the modulation, the outputs of the P modulators are rearranged to form a block of N symbols, which is followed by a serial-to-parallel (S/P) conversion. The parallel data block is then converted from the frequency-domain to the time-domain using the IFFT before it is again converted to a serial data block. Then a cyclic-prefix (CP) is appended at the beginning of the time-domain serial OFDM block to reduce the effects of intersymbol interference.

In the conventional OFDM, the same mapping scheme is used throughout an OFDM block, and the receiver knows the constellation of the mapping scheme. However, OFDM with SGM does not use the same constellation throughout the block; rather it changes the constellation from group to group. Thus, the receiver does not know the constellation with which a particular data group has been modulated. For this reason, the receiver needs to detect the constellation used in each group. Since no SI is sent to the receiver, it needs to detect the constellation set blindly. An optimal ML detection algorithm is proposed to use for detecting the constellation set used in a particular group of the received OFDM block. At the receiver, the CP is first removed, and the resulting signal of length N is converted to frequency-domain by the fast Fourier transform (FFT). If Y is the received frequency-domain OFDM symbol, then its k^{th} element, Y_k, can be modelled in the following way:

$$Y_k = X_k H_k + W_k, \tag{6}$$

where H_k and W_k are the frequency response of the fading channel and frequency domain additive white Gaussian noise, respectively, and X_k denotes the k^{th} transmitted symbol. Then the data block is partitioned into P groups with each group consisting of $\beta = K/log_2M$ symbols, thereby creating a new matrix Z such that $Z_{l,k}$ indicates the k^{th} element of the l^{th} group. To determine which set of constellation is used in each of the data groups, ML detection is carried out in each group. Given that S_l is the l^{th} group of the received OFDM symbol Y, the probability that S_l is modulated by the C_i constellation set is given by [28]

$$P(S_l|C_i) = \prod_{k=1}^{\beta}\left(\frac{1}{M\sqrt{2\pi\sigma^2}}\sum_{j=1}^{M} e^{\frac{|Z_{l,k}H_{l,k}^{-1} - c_j^i|^2}{2\sigma^2}}\right), \tag{7}$$

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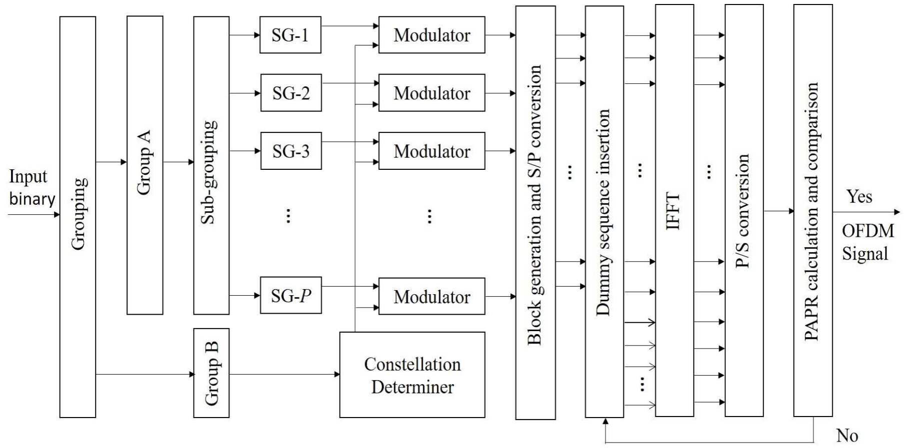

Fig. 4. Block diagram of the DSI scheme with SGM.

where C_i and M are the i^{th} constellation set and constellation size, respectively, and c_j^i is the j^{th} constellation point of the i^{th} constellation set. Since both constellations are equiprobable, the data group S_l will be considered as modulated by the q^{th} constellation if $P(S_l|C_i)$ is maximized at $i = q$. Upon the constellation detection, each group is demapped according to the detected constellation, and converted to a binary sequence.

IV. PAPR REDUCTION

A. DSI-Based PAPR Reduction

Although our proposed scheme is equally applicable to the DSI and TR schemes, for simplicity the proposed scheme will be presented and compared with respect to the DSI scheme only. The block diagram of the DSI scheme is shown in Fig. 3. The input data stream is first modulated before performing an S/P conversion. For a total of N subcarriers, N_A subcarriers are used for sending $\alpha_A = N_A \times log_2(M)$ data bits; the rest of the $N_B = N - N_A$ subcarriers are used for PAPR reduction purpose. To these N_B subcarriers, either a complementary sequence or a correlation sequence is assigned. The resulting N symbols are fed to the IFFT block for the frequency-to-time domain conversion, which is followed by the parallel-to-serial (P/S) conversion. The PAPR of the resulting sequence is calculated, and the sequence along with its PAPR is stored. Then a new sequence for PAPR reduction is assigned to the N_B subcarriers, while the data to the first N_A subcarriers remain unchanged. The resulting sequence is converted to a time-domain sequence and undergoes a P/S conversion. This sequence along with its PAPR is stored as before. Then, another sequence is tried, and this process continues until the allowable maximum number of sequences are tried. For R sequences, it produces R time-domain signals. Then the PAPRs of all signals are compared, and the time-domain signal having the lowest PAPR is selected for transmission.

In this scheme, N_B subcarriers are used for PAPR reduction rather than data transmission. For this reason, it transmits α_B bits less than that of the conventional OFDM system. This reduction of bit transmission causes spectral efficiency degradation. The spectral efficiency of an OFDM system in fading channel is given by [29]

$$\eta_1 = \frac{\alpha}{N + L_{cp}}, \tag{8}$$

where L_{cp} denotes CP length. In AWGN channel, there is no intersymbol interference issue, hence requires no CP. In this case, (8) becomes

$$\eta_2 = \frac{\alpha}{N}. \tag{9}$$

TABLE II
SIMULATION PARAMETERS

Parameter	Value
N	128
L	4
Modulation	QPSK
L_{cp}	$1/4$
No. of OFDM symbols	5×10^4

Combining (4), (5), and (8), η_1 can be rewritten as

$$\eta_1 = \frac{(N_A + N_B)log_2M}{N + L_{cp}}. \tag{10}$$

The spectral efficiency of the DSI scheme is

$$\eta_{1,d} = \frac{N_A log_2M}{N + L_{cp}}. \tag{11}$$

From (10) and (11), the $\eta_{1,d}$ can be written as

$$\eta_{1,d} = \frac{N_A}{N_A + N_B}\eta_1. \tag{12}$$

In the DSI scheme, $N_B > 0$; as a result $\eta_{1,d} < \eta_1$; in other words, the spectral efficiency of the DSI scheme is always less than that of the conventional OFDM system. It is $\frac{N_A}{N_A+N_B}$ times lower than that of OFDM system. It degrades more with the increase of N_B.

B. DSI With SGM PAPR Reduction Scheme

The DSI with SGM scheme combines the DSI scheme with the SGM scheme to eliminate the spectral efficiency degradation of the DSI scheme. A block diagram of the proposed scheme is shown in Fig. 4. Similar to the SGM scheme discussed in Section III, the incoming data of length α is first divided into two groups: A and B. Depending on the length of B, the group A is divided into a number of subgroups. Each subgroup is either modulated by the constellation C_0 or C_1 depending on the content of B. After the modulation, the content of B becomes indirectly embedded in N_A subcarriers. In this way, all α bits are transmitted. Even after this, there are still N_B unused subcarriers which are proposed to use for PAPR reduction. The remaining subcarriers can be used in any PAPR reduction scheme such as DSI or TR. If the DSI is used, the sequence for PAPR reduction is assigned to the rest N_B subcarriers, thereby making a frequency-domain data block of N symbols which are assigned to N subcarriers. Then this block is converted to a time-domain signal before converting back to the serial sequence. The PAPR of this time-domain signal is calculated, and the signal with its PAPR is stored

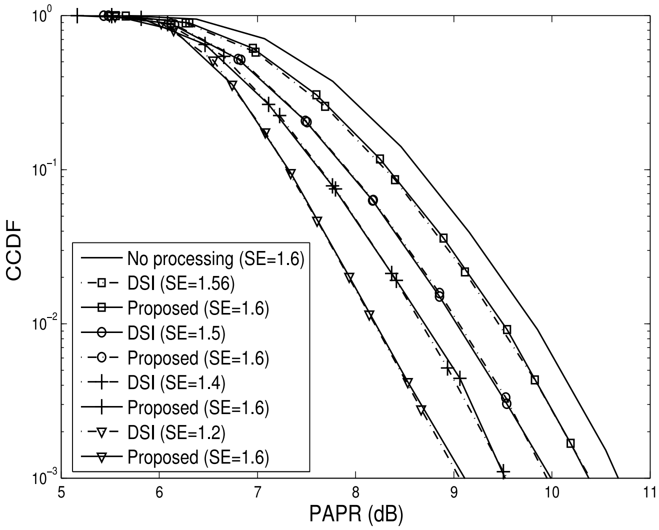

Fig. 5. Comparative PAPR for $\delta = 1.5$.

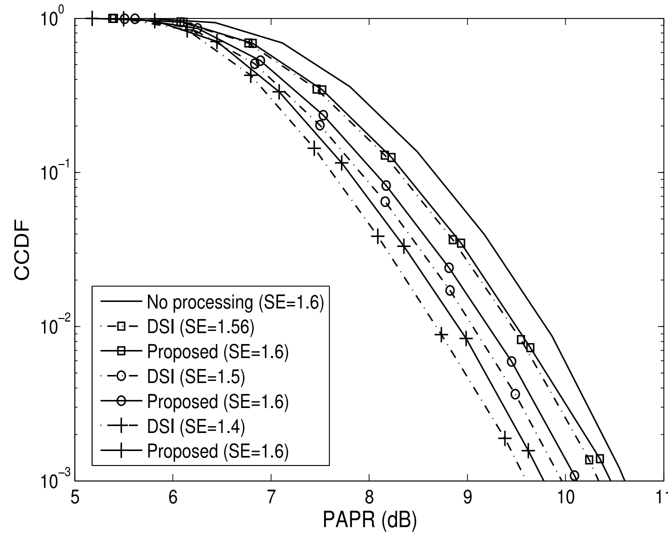

Fig. 6. Comparative PAPR for $\delta = 2.5$.

similarly to the DSI scheme. Then a new PAPR reducing sequence is assigned to the last N_B subcarriers in the dummy sequence insertion block before IFFT and P/S conversion are performed on the resulting signal. Like before, PAPR computation is carried out, and the signal along with the PAPR is stored. This process continues as long as the allowable maximum number of sequences for PAPR reduction are tried. Then the time-domain signal having the lowest PAPR signal is transmitted.

The spectral efficiency of an OFDM with SGM system is given by

$$\begin{aligned}\eta_{os} &= \frac{P\left(\frac{N_A log_2 M}{P} + 1\right) + N_B log_2 M}{N + L_{cp}} \\ &= \frac{(N_A log_2 M + N_B log_2 M) + N_B log_2 M}{N + L_{cp}} \\ &= \frac{\alpha + \alpha_B}{N + L_{cp}} \\ &= \eta_1 + \frac{\alpha_B}{N + L_{cp}}. \end{aligned} \quad (13)$$

Since the second term in the right side of the above equation is a positive number, the OFDM with SGM scheme attains more spectral efficiency compared to that of the conventional OFDM scheme. This shows the robustness of the SGM scheme in application other than PAPR reduction. The improved spectrum efficiency attained by the SGM can be enjoyed in 5G candidate waveforms as well. For example, filtered-OFDM, windowed-OFDM, universal filtered-OFDM and some other OFDM inspired waveforms [30] can avail the increased spectrum efficiency by integrating the SGM to them.

For OFDM systems with the SGM integrated for PAPR reduction, the spectrum efficiency will be investigated now. The spectral efficiency of the DSI with SGM scheme is given by

$$\begin{aligned}\eta_{dp} &= \frac{P\left(\frac{N_A log_2 M}{P} + 1\right)}{N + L_{cp}} \\ &= \frac{N_A log_2 M + P}{N + L_{cp}} \\ &= \frac{N_A log_2 M + N_B log_2 M}{N + L_{cp}} \\ &= \frac{\alpha_A + \alpha_B}{N + L_{cp}} \\ &= \eta_1. \end{aligned} \quad (14)$$

Thus, unlike the DSI scheme, the DSI with SGM attains PAPR reduction maintaining the same spectral efficiency of the conventional OFDM system. However, the improvement of the spectrum efficiency is attained at the expanse of increased computational overhead due to the ML detection at the receiver. The power-cost due to the increased computation for PAPR reduction is insignificant compared to the power saving obtained by the PAPR reduction [32]. For this reason, the considerable increase of computational complexity will not degrade the net power saving. Rather, the real impact of the increased complexity will be on the speed of operation of the wireless devices. The high speed operation is not an important issue in applications such as terrestrial DAB and DVB where the proposed scheme suits very well. Furthermore, over times, the integrated circuit technology improves and the scarcity of spectrum increases. The high data rate demand in the last decade has made the spectrum the scarcest resource in wireless communication. For this reason, it is more important to ensure the spectrum efficiency compared to the computational complexity.

V. Performance Evaluation

The spectral efficiency improvement of the proposed DSI with SGM scheme has been explained in detail analytically in Section IV-B. It is found that the proposed PAPR reduction scheme can attain the same spectral efficiency of the original OFDM system. To attain the spectral efficiency, the frequency domain signal is changed in the transmitter. Through simulations, the impact of such changes on some other performance factors, such as PAPR reduction capability and BER, will be investigated. The simulation parameters used throughout the paper are listed in Table II, unless otherwise stated.

A comparison of the PAPR reduction performance between the proposed DSI with SGM and conventional DSI schemes is shown in Fig. 5 for $\delta = 1.5$ with the help of complementary cumulative distribution function (CCDF), where SE stands for spectrum efficiency. It reveals that without degrading spectrum efficiency compared to the unmodified OFDM, the proposed scheme attains as much PAPR reduction as the DSI scheme does. The OFDM with no PAPR reduction technique, indicated as no processing in Fig. 5, has 1.6 bit/sec/Hz spectrum efficiency. The DSI scheme degrades the spectrum efficiency in improving PAPR. For example, the DSI scheme sacrifices 0.1 bit/sec/Hz spectrum efficiency to reduce 0.73 dB PAPR.

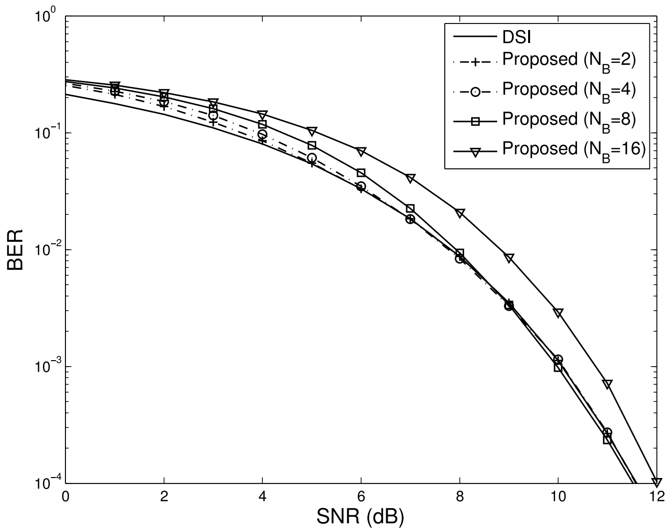

Fig. 7. BER comparison between the proposed and DSI scheme over AWGN channel.

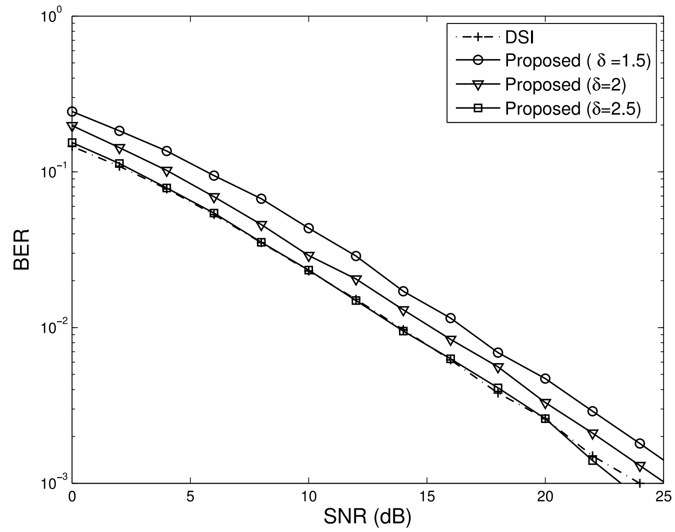

Fig. 8. BER comparison between the proposed and DSI scheme over Rayleigh fading channel.

However, the SGM integrated DSI scheme attains the PAPR similar to the SGM scheme maintaining the spectrum efficiency of 1.6 bit/sec/Hz. More PAPR reduction in the DSI scheme causes further degradation of the spectrum efficiency. For example, it degrades 25% spectrum efficiency compared to the unmodified OFDM in reducing about 1.6 (dB) PAPR. The SGM integrated DSI scheme, on the other hand, achieves the same PAPR reduction without causing any degradation of the spectrum efficiency. The impact of using the constellation C_0 with higher power is investigated in Fig. 6 for $\delta = 2.5$. It reveals that the proposed scheme results in a slight degradation of PAPR compared with the DSI scheme. This degradation is found to have a direct relationship with the number of subcarriers employed for PAPR reduction: a system having more PAPR reducing subcarriers experiences slightly more degradation. At CCDF level of 10^{-2}, 10% to 20% degradation of PAPR reduction capability occurs depending on the number of subcarriers used for PAPR reduction. The reason behind the degradation might be the fact that the comparatively larger power in constellation C_0 increases both the peak power and average power, but the peak power increase is slightly higher than the average power increase. For this reason, the corresponding ratio is increasing. However, it is pertinent to mention here that the proposed scheme results in the slight loss of PAPR reduction capability while preserving the spectrum efficiency of original OFDM system. On the other hand, the DSI scheme decreases the spectrum efficiency significantly.

The BER performance of the proposed scheme is evaluated over both AWGN and fading channels. A comparison of the BER performance of the proposed scheme with the DSI scheme over AWGN channel for $\delta = 1.5$ is shown in Fig. 7. A direct relation is observed between N_B and BER. For low N_B, the BER degradation compared to the DSI due to the proposed scheme is insignificant. In addition, the degradation increases to a maximum value for $N_B = 16$. With the larger N_B, the number of subgroups under group A increases; thus, for a specific N, the number of symbols in a specific group decreases. The reduced number of symbols make the ML detector difficult at the receiver to detect the constellation set properly, hence the error rate increases. This might be a reason behind the degradation of the BER performance in higher N_B. It is seen in Fig. 7 that the BER degrades with higher N_B. The worst case scenario is $N_B = 16$. Under this value, the effect of δ on the BER in fading channel is investigated. The BER performance over fading channel is investigated in Fig. 8. A slowly-varying frequency selective Rayleigh fading channel with four taps is used in the simulation in Fig. 8. It reveals that higher δ provides better BER compared to the lower ones, and $\delta = 2.5$ attains the same BER such as the DSI scheme. The increased δ helps symbols to combat the effect of fading channel, which results in better detection by the ML detector. However, the use of high power can be avoided in application such as wireless optical OFDM where fading is not an issue. In such an application, the PAPR reduction similar to the conventional DSI scheme can be achieved alongside 100% spectral efficiency without increasing constellation power markedly. Considering Figs. 5, 6, and 8, the impact of δ on the system performance can be assessed. On the one hand, the large δ degrades PAPR performance. It improves BER performance, on the other hand. Thus, the choice of δ is application dependent. If PAPR reduction is the most desired criterion, a lower δ such as $\delta = 1.5$ is more suitable. However, if any degradation of BER performance is not permitted, a higher δ such as $\delta = 2.5$ is more suitable.

VI. Conclusion

In this paper, a concept of SGM has been proposed to eliminate the spectral inefficiency issue of most of the existing PAPR reduction schemes. It can be integrated to a number of different PAPR reduction schemes such as DSI, TR, PTS, SLM and so on. In this paper, the performance of the SGM-integrated DSI scheme was investigated. It was shown analytically that the proposed scheme attained 100% spectral efficiency. Through simulations, it was found that it achieves PAPR similar to the DSI scheme in certain scenarios. In fading channel, a constellation with higher power is required to use to ensure perfect BER. The use of the constellation causes a degradation of 10% to 20% PAPR reduction capability. However, the advantage of the 100% spectral efficiency attainment outweighs the slight loss of the PAPR reduction capability. It is not required to sacrifice any PAPR reduction capability in applications such as wireless optical OFDM.

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