IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 29, 2018, accepted January 10, 2019, date of publication February 8, 2019, date of current version February 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2894527

A Review of Partial Transmit Sequence for PAPR Reduction in the OFDM Systems

YASIR AMER JAWHAR[1,2], LUKMAN AUDAH[1], MONTADAR ABAS TAHER[3], KHAIRUN NIDZAM RAMLI[1], NOR SHAHIDA MOHD SHAH[4], MUSTAFA MUSA[3], AND MUSTAFA SAMI AHMED[1]

[1]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Malaysia
[2]Iraqi Ministry of Communications, Baghdad, Iraq
[3]Faculty of Information and Communication Technology, Universiti Teknikal Malaysia Melaka, Durian Tunggal 76100, Malaysia
[4]Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Tinggi Pagoh 84600, Malaysia

Corresponding author: Yasir Amer Jawhar (free_cccc@yahoo.com)

This research is funded by the Ministry of Higher Education Malaysia under Fundamental Research Grant Scheme (Vot No. 1627) and partially sponsored by Universiti Tun Hussein Onn Malaysia.

ABSTRACT Orthogonal frequency division multiplexing (OFDM) is a superior technology for the high-speed data rate of wire-line and wireless communication systems. The OFDM has many advantages over other techniques such as its high capacity and immunity against multipath fading channels. However, one of the main drawbacks of the OFDM system is the high-peak-to-average power ratio (PAPR) that leads the system to produce in-band distortion and out-of-band radiation because of the non-linearity of the high-power amplifiers. Therefore, numerous techniques have been proposed to overcome the PAPR problem such as selective mapping, partial transmit sequence (PTS), clipping, and nonlinear companding. In this paper, the PTS technique was analytically reviewed as one of the important methods to reduce the high PAPR problem. The PAPR performance and the computational complexity level are discussed in terms of modifying the PTS technique in the frequency domain, time domain and modulation stage (inverse fast Fourier transform block). Moreover, the numerical statistic comparison of the current modified-PTS methods is introduced, and the criteria for selecting the suitable modified-PTS method in the OFDM system are also given. The simulation and the numerical calculations results show that the rows exchange-interleaving PTS scheme is the best method for reducing the PAPR value with low complexly in the frequency domain, and the cooperative PTS method is the best among the modulation stage methods, while the cyclic shift sequence PTS method achieves the superior performance in PAPR reduction and computational complexity for the time domain methods.

INDEX TERMS OFDM, PAPR, PTS, modified-PTS, computational complexity.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is regarded as a superior technique for the high-speed data rate of wire-line and wireless communication systems. The OFDM system has many advantages over other techniques such as its high data transmission rate, immunity against frequency selective fading and impulse interference, and tolerance to multipath delay spread. Moreover, the OFDM system exhibits high spectral power efficiency, smooth equalization, and flexibility for hardware implementation with utilizing the Fast Fourier Transform (FFT) technique [1]–[6].

The associate editor coordinating the review of this manuscript and approving it for publication was Pallab K. Choudhury.

Furthermore, the OFDM system is better than other multicarrier techniques because it has unique features such as efficient bandwidth utilization, less vulnerability to echoes, and less non-linear distortion. In addition, OFDM had immunity against the narrowband co-channel interference (NBCCI) and it can increase the system capacity to provide a reliable transmission [7]–[17].

OFDM has become the modulation technique for many communication systems, therefore; OFDM was adopted by many wireless standards and wire-line communication systems such as broadcast radio access network (BRAN), wireless local area network (WLAN) IEEE.802.11a/b/g/n [18], worldwide interoperability for microwave access (WiMAX) IEEE.802.16 [19], broadcast radio access network (BRAN), European telecommunication standards Institute (ETSI) [1], digital video broadcasting (DVB), digital audio broadcasting (DAB) [20], digital television broadcasting (DTVB) [21], [22], Long Term Evaluation (LTE) standard for 4G mobile communication networks [23], digital subscriber line (DSL) interneta access, and asynchronous digital subscriber line (ADSL) [24]–[26]. Quite recently, considerable attention has been paid to optimal OFDM releases as the reliable candidates in next generation (5G) communication frameworks such as Filtered-OFDM (F-OFDM), universal filter-OFDM (U-OFDM), Filter Bank Multicarrier (FBMC), and Generalized Frequency Division Multiplying [27].

Although OFDM has many distinctive features, the high peak-to-average power ratio (PAPR) is considered as the main drawback which causes the OFDM system suffer from in-band distortion (IB) and out-of-band radiation (OOB) [28]. This can be attributed to the non-linearity nature of the high-power amplifier (HPA) in the transmitter. Also, the high PAPR value increases the complexity when using some devices such as analog to digital converter (ADC) and digital to analog converter (DAC). Hence, the OFDM system requires HPA with large input back-off power (IBO), and long word length to follow the high PAPR value [29].

The relative solution for the high PAPR problem is to find a suitable technique which can combat the PAPR value before transmitting the signal, instead of the conventional solution which uses an expensive amplifier with a large linear region. Many techniques have been proposed to reduce the PAPR value and they can be classified into two categories, the first category consists of signal distortion techniques such as clipping [30], clipping and filtering [31], [32], peak windowing [33], active constellation extension (ACE) [34], non-linear companding transforming [35]–[37], and trellis assisted constellation subset selection (TACSS) [38]. The second category includes of signal scrambling techniques such as selective mapping (SLM) [39]–[41], partial transmit sequence (PTS) [42], [43], block coding [44], interleaving technique [45], tone reservation (TR) [46], [47], and tone injection [48].

In the literature, several papers discussed the high PAPR problem in the OFDM systems such as Han and Lee [1] introduced the important PAPR techniques and the criteria for selecting the best PAPR reduction technique. Moreover, Wang and Tellambura [49] reviewed several PAPR reduction techniques and concluded that the cost of using the PAPR reduction techniques is lower than the cost of power efficiency degradation. Likewise, Jiang and Wu [20] discussed the characteristic of the OFDM signals, and they placed eight points as the criteria for selecting the PAPR reduction method. In 2009, Lim *et al.* [4] reviewed some ordinary PAPR reduction methods and their adjustments; they concluded that none of the PAPR reduction methods could be considered as the standard for communication applications. However, some of the modified PAPR reduction methods with low complexity could be used to the high-speed data rate in OFDM systems. In recent years, studying the PAPR reduction techniques have become very popular. Taspinar *et al.* [50] and [51] proposed a PTS based on an artificial bee colony (ABC) algorithm scheme in order to reduce the computational complexity of the PTS technique without bit error rate (BER) degradation depending on the foraging behavior of a honeybee swarm. In 2015, Taspinar and Yildirim [52] returned again and introduced the Parallel Artificial Bee Colony (P-ABC) Algorithm to reduce the mathematical complexity performance of his previous method. Other solutions for reducing the computational complexity were described in [53]–[55] so that the authors improved the computational complexity with a bit degradation in PAPR performance by applying Parallel Tabu Search (Parallel TS) algorithm, Backtracking Search Algorithm (BSA), and Genetic Algorithm (GA), respectively. Recently, several authors have proposed new methods to enhance the PTS technique, for example, Joo *et al.* [56] proposed a PTS method without side information (SI) by applying phase offset to the rotation vectors, while Tokur *et al.* [57] developed the PAPR reduction performance with low computational complexity using differential evolution algorithm-based PTS scheme in lifting-based wavelet packet modulation (LBWPM) system. However, our previous research [58] and [59] have documented new subblock partitioning schemes for the PTS technique, where the new partitioning schemes enhanced the PAPR reduction performance better than that of the ordinary partitioning schemes without any extra cost on the system.

In this paper, the PTS method as one of the distinguished PAPR reduction techniques is discussed. The ordinary PTS method and the various modified-PTS schemes are reviewed in three aspects: frequency-domain (F.D), modulation-stage (IFFT unit), and time-domain (T.D). Furthermore, the ordinary and the new subblock partitioning schemes of PTS techniques are introduced and discussed in terms of PAPR reduction performance and computational complexity compared with the other modified-PTS methods, while the criteria for selecting the suitable modified-PTS method in the OFDM systems are addressed. Finally, there is a trade-off between the PAPR reduction performance and the computational complexity in the PTS technique, while the simulation results and the numerical calculations of the various modified-PTS methods appear the rows exchange-interleaving PTS method, the cooperative PTS method, and the cyclic shift sequence PTS method are the best methods in the frequency domain, the modulation stage, and the time domain, respectively.

This paper is organized as follows. Section II describes the OFDM system and PAPR. Section III analyzes the PTS technique. Section IV introduces the current modified-PTS methods. The numerical analysis for the modified-PTS methods is discussed in Section V. Lastly, the study conclusions are given in Section VI.

II. OFDM SYSTEM

The OFDM sequence is generated by summing all N modulated subcarriers when applying IFFT operation, with the consideration that; the subcarriers are allowed to be orthogonally one another. To understand the concept of OFDM, let $X = \{X_k, k = 0, 1, \ldots\ldots, N-1\}$ is the complex representation of the input data block symbols after constellation mapping operation, where X_k represents the block data of kth subcarrier, and N is the number of subcarriers. Therefore, the complex baseband OFDM signal is defined as [60]

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi k \Delta \mathrm{f} t} \quad 0 \le t \le T \tag{1}$$

where $e^{j2\pi \Delta \mathrm{f} t}$ is the twiddle factor of the kth subcarrier, T represents the total time of symbol, Δf is the frequency space between subcarriers, and $j = \sqrt{-1}$. The bandwidth of the symbol is $B = N.\ \Delta f$, and Δf is set as $1/T$ to ensure the orthogonally between the subcarriers of the symbol. Therefore, the baseband OFDM signal can be written as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T} \quad 0 \le t \le T \tag{2}$$

The baseband OFDM signal is sampled by applying Nyquist rate ($\mathrm{t} = T/N$). Therefore, the discrete OFDM signal in the time-domain can be expressed as,

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N} \quad 0 \le n \le N-1 \tag{3}$$

where n represents the discrete sampling index, whereas the discrete OFDM signal vector is written as

$$x(n) = [x_0, x_1, \ldots, x_{N-1}]^{\mathrm{T}} \tag{4}$$

A. PAPR

The PAPR of OFDM signal is the ratio of the maximum peak power divided by the average power of the signal, which can be written as [61]

$$PAPR = 10 \log_{10} \frac{\max |x(n)|^2}{E\{|x(n)|^2\}} \tag{5}$$

where $E\ \{.\}$ denotes the mean value. The continuous time of the OFDM signal can be obtained when applying the oversample operation. Hence, this operation ensures to catch some peaks of the signal that do not appear in the PAPR calculation. Sampling the discrete baseband signal with $L \ge 4$ is sufficient to increase the accuracy of the PAPR calculations, and this operation is done by inserting $(L\text{-}1)N$ zero-padding between the samples, where L is the oversampling factor [62]. Therefore, the oversampled OFDM signal is written as

$$x(n) = \frac{1}{\sqrt{NL}} \sum_{k=0}^{NL-1} X_k e^{j2\pi k \frac{n}{NL}} \quad 0 \le n \le NL-1 \tag{6}$$

and then,

$$\mathrm{PAPR} = \frac{\begin{matrix}\max |x(n)|^2 \\ 0 \le n \le NL-1\end{matrix}}{P_{av} x(n)} \tag{7}$$

B. PAPR DISTRIBUTION

The complementary cumulative distribution function (CCDF) is one of the popular methods to measure the PAPR performance. The CCDF of the PAPR performance is the probability of the PAPR value that exceeds a certain threshold [63]. Based on central limit theorem [20], for a large number of subcarriers N, the real and imaginary parts of the OFDM signal in the time-domain follow the Gaussian distribution random variable with the mean and variance equal to zero and 0.5, respectively. Moreover, the amplitude of the signal $|x(n)|$ uses Rayleigh distribution, whereas the power distribution of the signals become a central chi-square with two degrees of freedom. The CCDF of the time-domain signal with the sampling Nyquist rate is calculated as

$$\Pr(PAPR \ge PAPR_0) = 1 - (1 - \exp(-PAPR_0))^N \tag{8}$$

where the $PAPR_0$ is the threshold value. Furthermore, when oversampling L is conducted, the CCDF of the OFDM signal can be written as

$$\Pr(PAPR \ge PAPR_0) = 1 - (1 - \exp(-PAPR_0))^{NL} \tag{9}$$

As a result, the CCDF of the OFDM signal is quite accurate when the number of subcarriers N is large enough ($N \ge 128$) [62].

C. PAPR REDUCTION TECHNIQUES

In the literature, many PAPR reduction approaches have been suggested to control the PAPR problem, and it can be classified into two categories, the distortion techniques, and the distortionless techniques [20]. The former reduces the PAPR by destroying the high peak of the OFDM signal in the time-domain before passing the signal to the HPA, while the latter improves the signal characteristics in the frequency domain or time domain in order to mitigate PAPR before the transmission. Each one of the PAPR reduction techniques has PAPR reduction performance (PAPR-per), computational complexity level (CCL), BER performance (BER-per), power increasing (P-inc), and data rate losses (DRL) differ to another.

In signal distortion techniques, the PAPR value is significantly reduced at the expense of in-band distortion and out-of-band radiation [64]. Hence, the OFDM system will suffer from undesirable degradation in BER performance and frequency spectrum. The signal distortion techniques include signal clipping [65], clipping and filtering [32], peak windowing [20], peak cancellation [49], and companding transformations [66], [78]. On the other hand, distortionless techniques which also called signal scrambling techniques consist of three groups: the first one is named coding techniques [44], which are depended on encoding the data block bits in the transmitter and then applying error correction technique to combat the large PAPR of the OFDM signal. These approaches include some types of codes such as linear block coding, Golay codes, and Read-Mullar codes. The second group of distortionless techniques is called the multiple signal representation (MSR) techniques [67]. These techniques consider the probabilistic methods and they depend on producing several representations of the OFDM sequence, where the sequence that has the lowest PAPR is chosen for transmission. The advantage of these approaches is to maintain the BER performance without degradation. The MSR techniques include selected mapping [39], interleaving technique [45], and partial transmit sequences [42]. The last group of the signal scrambling techniques contains the constellation shaping schemes [1]; these methods depend on re-shaping of constellation points to re-orientation the energy of data symbol and then reducing the peak power of the transmitted signal. The constellation shaping techniques include tone reservation (TR) [1], active constellation extension (ACE) [33], tone injection (TI) [48], and constellation reshaping (CR) [4]. Table 1 illustrates the comparison between the different PAPR reduction techniques.

TABLE 1. Comparison of different PAPR reduction techniques.

PAPR reduction technique	Distortion-less	PAPR-pre	CCL	P-inc	BER-per	BRL
Clipping	No	High	Low	No	Yes	No
Clipping & filtering	No	High	Low	No	Yes	No
Companding	No	High	Low	No	Yes	No
Coding	Yes	Medium	High	No	No	Yes
PTS	Yes	High	High	No	No	Yes
SLM	Yes	Medium	Medium	No	No	Yes
Interleaving	Yes	Low	Medium	No	No	Yes
TR	Yes	High	High	Yes	No	Yes
TI	Yes	High	High	Yes	No	No
ACE	Yes	High	High	Yes	No	No

In addition, the hybrid combination algorithms between PTS and the other PAPR reduction techniques have been suggested. the PTS technique and the interleaving technique is combined in [68]. Furthermore, the PTS technique has been integrated with the ACE technique in parallel [16]. Sravanti and Vasantha [69] combined Precoding technique and PTS technique to improve the PAPR reduction performance. On the other hand, the PTS technique also combined with distortion techniques, such as PTS-Clipping algorithm in [70], and PTS-companding algorithm in [71]. Also, the DFT-spread technique [72], the Discrete Hartley Transform (DHT)-spread technique [73] and single carrier frequency division multiplexing (SC-FDM) technique [74], [75] are utilized with OFDM for reducing the PAPR value effectively in an intensity modulation and direct detection (IM/DD) optical systems. Furthermore, the DFT-spread with PTS has been introduced for further PAPR reduction in the OFDM system [76], as well as, the Discrete cosine transform (DCT)-spread is combined with the PTS technique for reducing the PAPR value without requiring side information [77], [78].

III. PARTIAL TRANSMIT SEQUENCE (PTS)

The PTS is one of the multiple signal representation techniques, which divides the data block into several groups, which are scrambled to choose the transmission signal. The concept of the PTS technique is to partition the input data symbols into the disjoint subsets and these subsets are rotated with different rotation factors. After that, the modified partitioned subsets are combined again to generate set of the candidate signals named partial transmit sequences (pts_s). Finally, one of candidate sequence which has the minimum PAPR value is chosen for transmission [61]. In the PTS technique, the number of the inverse fast Fourier transform (IFFT) blocks is the same as the number of subsets. The PTS technique can achieve better PAPR reduction performance than the other probabilistic techniques such as selective mapping (SLM) and interleaving techniques [1]. However, the PTS technique holds a high computational complexity when finding the optimum rotation factor and needs to send side information (SI) as index information in order to recover the original data at the receiver side [42].

On the other hand, PTS is regarded as a distortionless method because it relies on the scrambling signal technique to reduce the PAPR value. Hence, PTS considers a probabilistic method to reduce the PAPR of the OFDM signal. Therefore, the PTS method does not suffer from the bit error rate (BER) degradation or the power signal distortion. In literature, many papers have been proposed to modify the PTS technique, especially in terms of reducing the computational complexity and improving the PAPR reduction performance. In this paper, three aspects have been adopted to evaluate the existing modified PTS techniques, which are the frequency-domain methods, the time-domains methods, and the modulation-stage methods. Furthermore, the computational complexity and the PAPR reduction performance are considered as a criterion to evaluate and classify the modified PTS methods.

A. THE CONVENTIONAL PTS METHOD (C-PTS)

The main principal of the conventional PTS method is to partition the input data block into the disjoint subblocks. Each subblock is then passed to the IFFT block to transform the data from the frequency to the time domain. The phase weighting factors are employed to minimize the PAPR value, such that, the subblocks are multiplied by the phase factor vectors and combined to generate a set of the candidate signals. The candidate signal which has the minimum PAPR value is selected for transmission. The index of the optimum phase factor which achieves the minimum PAPR value must be transmitted as side information to the receiver to recover the original data. Figure 1 illustrates the C-PTS block diagram, where the input data block X is partitioned into non-overlapping subblocks Xv, which can be expressed as

$$X = \sum_{v=1}^{V} X_v \tag{10}$$

where V is the number of subblocks, and the subscript $v = \{1, 2, \ldots, V\}$.

In the C-PTS scheme, the subblocks must be equaled in size, and the data is usually partitioned by one of the segmentation methods, such as interleaving, adjacent, and pseudo-

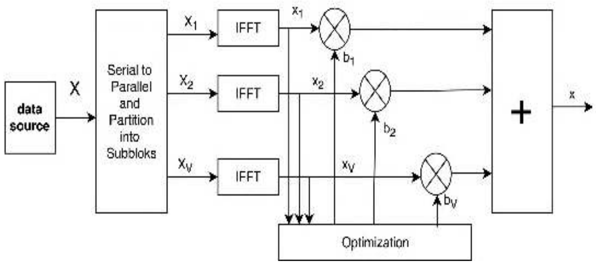

FIGURE 1. PTS block diagram [79].

random schemes. Moreover, each subblock is multiplied by the unity amplitude complex phase factor. The elements of the phase factors are usually constant to avoid the complex multiplication operations thus the phase factor is restricted to $\{\pm 1\}$ or $\{\pm 1, \pm j\}$ [79]. Therefore, the phase factor vector can be written as

$$b = [b_1, b_2, \ldots, b_V] \tag{11}$$

where b can be obtained by

$$b = \{b_v = e^{j2\pi v/W} | v = 0, 1, \ldots\ldots, W-1\} \tag{12}$$

where b_v denotes to phase rotation factor, and W is the number of the allowed phase factors. Also, the linear property of the inverse discrete Fourier transform (IDFT) is employed to transform the phase factors into the time-domain. Thus, the time-domain signal of the OFDM after combining the subblocks is given by

$$x = IFFT\{\sum_{v=1}^{V} b_v X_v\} = \sum_{v=1}^{V} b_v IFFT\{X_v\} = \sum_{v=1}^{V} b_v x_v \tag{13}$$

The objective is to find the optimum phase factor that can achieve minimum PAPR value of the OFDM signal. Therefore, the optimum phase factor can be obtained as

$$\{b_1, b_2, \ldots, b_v\} = \underset{1 \le w \le W}{\arg\min} \left(\underset{0 \le n \le NL-1}{\max} |\sum_{v=1}^{V} b_v x_v| \right) \tag{14}$$

where arg min denotes to the minimum value that can be obtained after applying the phase rotation factors. In addition, two parameters should be considered when using the PTS technique, the computational complexity and the side information, where W^{V-1} should be searched for finding the optimum phase factor; with the consideration that the first element of the phase factors b_1 is set 1 without any loss of performance [80]. Furthermore, it is equally important to note that the side information bits $= \log_2 W^{V-1}$ and the index information of these bits should be sent to the receiver in order to recover the original data.

The PTS technique has high computational complexity and some of the spectrum efficiency is relatively wasted (bit rate loss) because of the side information occupies a part of the bandwidth, where the phase rotation factors indexes should send to the receiver to inform it about the optimum phase rotation factor that used in transmitter. Therefore, a part of the carrier spectrum is wasted. There are some methods have been suggested in [81]–[83] to embed the side information bits with the transmitted OFDM signal in order to save the spectrum efficiency. Moreover, the coding techniques also can be used with the PTS technique for reducing the spectrum efficiency wasted [84]–[86]. Furthermore, the precoding methods like Discrete Fourier Transform (DFT) Precoder, Discrete Hartley Transform (DHT) Precoder and Walsh-Hadamard Transform (WHT) Precoder are merited with PTS to improve the PAPR performance without side information, but these techniques increase the transmission power and require more complexity at the receiver for decoding operations [69], [87].

B. SUBBLOCKS PARTITIONING SCHEMES IN PTS

The three common types of segmentation schemes in the C-PTS method are the pseudo-random, adjacent, and interleaving partitioning schemes, as shown in Figure 2. In the PR-PTS, the subcarriers are assigned randomly in the subblocks, and AP-PTS allocates N/V successive subcarriers within one subblock, sequentially. However, the IL-PTS allocates the subcarriers with a certain distance interval, depending on the number of V, within one subblock [88]. Among the three types of segmentation methods, the PR-PTS scheme achieves the best PAPR reduction performance, and the next best is the adjacent method. However, both schemes have high computational complexities, as shown in Figure 3. The interleaving method fulfills the worst PAPR reduction performance, among the partitioning schemes, but it has the lowest computational complexity compared with the other schemes [89].

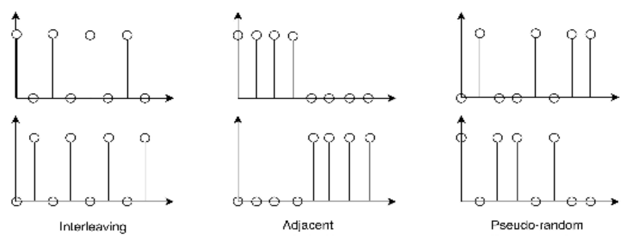

FIGURE 2. The conventional PTS segmentation schemes [88].

C. COMPUTATIONAL COMPLEXITY ANALYSIS

The computational complexity of the C-PTS method in transmitter consists of three parts as the following subsequences:

1) IFFT COMPUTATIONAL COMPLEXITY

This part depends on the type of the partitioning subblock schemes. The three common types of the partitioning subblocks are the adjacent partitioning (AP-PTS), the pseudo-random partitioning (PR-PTS), and the interleaving partitioning (IL-PTS). The computational complexity of the AP-PTS and PR-PTS record the same amount, because these methods need to perform all the stages of the IFFT

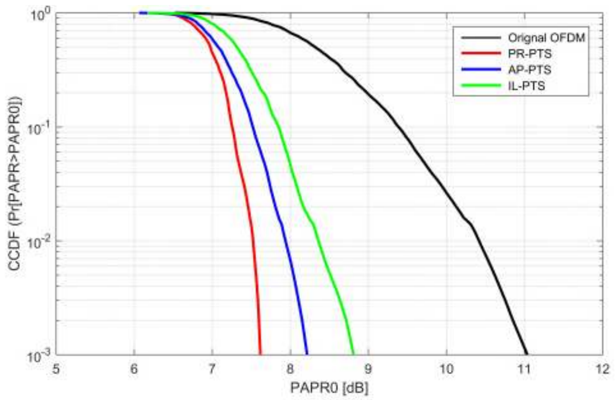

FIGURE 3. PAPR comparison of the conventional PTS segmentation schemes when $N = 256$, $V = 4$, and $W = 4$.

unit to transform the samples to the time-domain. Therefore, the computational complexity of the AP-PTS and PR-PTS methods when applying the Cooley-Tukey IFFT algorithm can be determined as [89]

$$C_{add} = V(N \log_2 N) \tag{15}$$

and,

$$C_{mult} = V(\frac{N}{2} \log_2 N) \tag{16}$$

where C_{add} represents the number of the addition operations, and Cmult is the number of the multiplication operations. On the other hand, when using the Cooley-Tukey IFFT algorithm to the IL-PTS method, the computational complexity is lower than the other ordinary schemes, because the PTS scheme needs a few stages to convert the samples to the time-domain. Accordingly, the number of the addition and multiplication operations of the IL-PTS method can be calculated as [89]

$$C_{add} = V(\frac{N}{V} \log_2 \frac{N}{V}) \tag{17}$$

and,

$$C_{mult} = V(\frac{N}{2V} \log_2 \frac{N}{V} + N) \tag{18}$$

2) FINDING OPTIMUM PHASE FACTOR COMPUTATIONAL COMPLEXITY

This complexity increases exponentially with the number of the subblocks. The number of the addition and multiplication operations for finding the optimum phase factor can be calculated as [90]

$$C_{add} = W^{V-1}N(V-1) \tag{19}$$

and,

$$C_{mult} = W^{V-1}N(V+1) \tag{20}$$

3) CANDIDATES COMPUTATIONAL COMPLEXITY

This computational complexity is because of the comparison among the candidate signals to choose the best OFDM signal with lowest PAPR value. The computational complexity of the comparison process of the candidate signals (C_{comp}) can be given as [6]

$$C_{comp} = W^{V-1}N - 1 \tag{21}$$

TABLE 2. Comparison of the computational complexity of the ordinary partitioning subblocks; (a) $N = 64$, (b) $N = 256$, (c) $N = 1024$.

(a)

$N = 64$								
V	W	PR-PTS or AP-PTS complexity		IL-PTS complexity		Optimum phase factors complexity	
		C_{add}	C_{mult}	C_{add}	C_{mult}	C_{add}	C_{mult}
4	2	1536	768	256	384	1536	2560
	4	1536	768	256	384	12288	20480
8	2	3072	1536	192	608	57344	73728
	4	3072	1536	192	608	7340032	9437184

(b)

$N = 256$							
V	W	PR-PTS or AP-PTS complexity		IL-PTS complexity		Optimum phase factors complexity	
		C_{add}	C_{mult}	C_{add}	C_{mult}	C_{add}	C_{mult}
4	2	8192	4096	1536	1792	6144	10240
	4	8192	4096	1536	1792	49152	81920
8	2	16384	8192	1280	2688	229376	294912
	4	16384	8192	1280	2688	29360128	37748736

(c)

$N = 1024$							
V	W	PR-PTS or AP-PTS complexity		IL-PTS complexity		Optimum phase factors complexity	
		C_{add}	C_{mult}	C_{add}	C_{mult}	C_{add}	C_{mult}
4	2	40960	20480	8192	8192	24576	40960
	4	40960	20480	8192	8192	196608	327680
8	2	81920	40960	7186	11776	917504	1179648
	4	81920	40960	7168	11776	117440512	150994944

Table. 2 illustrates the summary of the computational complexity level in the PR-PTS, AP-PTS, and IL-PTS schemes when the number of the subcarriers N is 64, 256, and 1024 with various numbers of the V and W. It is clear that the IL-PTS scheme has lower computational complexity than the PR-PTS, Ad-PTS schemes in the frequency domain because the IL-PTS scheme needs a smaller number of the IFFT stages to transform its subcarriers. While the conventional subblocks partitioning schemes in the time domain have the same complexity (optimizing the phase factors complexity), which is depends on the V, W, and N.

IV. REVIEWING THE MODIFIED-PTS METHODS

This section reviews and analyzes the PAPR performance and the computational complexity level of the various modified-PTS methods in the literature. These methods are classified into the three types: frequency-domain methods, time-domain methods, and modulation stage methods.

A. THE MODIFIED-PTS METHODS IN THE FREQUENCY-DOMAIN

Several methods have been introduced to improve the PAPR reduction performance and/or the computational complexity level in the frequency-domain. The important modified PTS schemes that deal with the frequency-domain part are discussed in the following subsequent subsections.

1) PSEUDO-RANDOM AND INTERLEAVING SEGMENTATION SCHEME

The pseudo-random and interleaving segmentation PTS method (PR-IL-PTS) [91] is proposed to enhance the PAPR reduction performance better than IL-PTS with low computational complexity. In the PR-IL-PTS method, the V subblocks are divided into two equal parts, where the subblocks of the first part adopts the PR-PTS scheme, and the second part applies the IL-PTS scheme. After that, the modified subblocks are merged again, and the rest PTS procedure is applied to generate the OFDM signal.

The PR-IL-PTS scheme can improve the PAPR performance better than the AP-PTS and IL-PTS schemes. While, the modified scheme achieves PAPR reduction performance lower than that of PR-PTS. Furthermore, the advantage of the PR-IL-PTS method is that the computational complexity can be reduced to level which is lower than that of the PR-PTS method.

2) NEW SUBBLOCKS PARTITIONING SCHEMES

Based on our earlier work that was presented in [59], the purpose of this paper is to enhance the PAPR reduction capacity higher than the ordinary schemes without additional computational complexity on the system. In [59], we introduced new subblock partitioning schemes lead to improving the PAPR lessening performance and reducing the mathematical calculations. The first method is named the adjacent shifting PTS (AP-Sh-PTS) scheme, in which each row of the AP-matrix is set to include only one group of the samples, and the other positions of the row are set to zero. Afterward, every group is divided into two equal parts, and thus the first part is fixed at its position and the second part is shifted by V-1. This fashion continues until the last row of the AP matrix. Finally, the new generated matrix represents the AP-Sh-PTS matrix, where each row refers to the subblock of the AP-Sh-PTS scheme.

On the other hand, the second method which was proposed in this reference is named the rows exchange-interleaving PTS (IL-Ex-PTS) scheme. In IL-Ex-PTS, the input sequence is segmented into V subblocks by using IL-scheme. Next, each row of the IL-matrix is subdivided into two equal parts, the first part contains only the odd groups, while the second part includes the even groups. After that, in each part, the groups are exchanged with each other to generate the new matrix represented the IL-Ex-PTS scheme.

The PAPR reduction performances of the AP-Sh-PTS and IL-Ex-PTS methods outperform both IL-PTS method and AP-PTS method, this due to that the proposed methods have less correlation among its subcarriers than the other two ordinary methods. On the other hand, the computational complexity of the AP-Sh-PTS scheme is similar to that of the AP-PTS method, while the computational complexity of the IL-Ex-PTS is lower than that of the AP-PTS scheme.

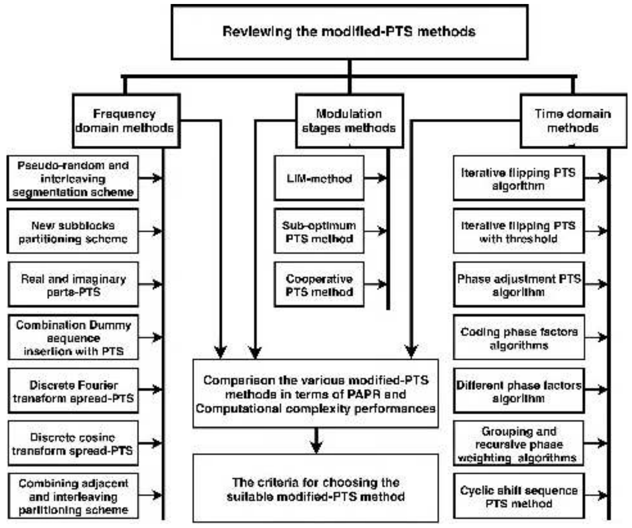

FIGURE 4. The taxonomy of reviewing the modified-PTS methods.

3) REAL AND IMAGINARY PARTS-PTS

The real and imaginary parts-PTS method (R&I-PTS) [92] is based on separation the real and imaginary parts of the baseband data sequence. After that, the generated candidate signals are optimized separately by the phase rotation factors. In Figure 5, the data block X is divided into the real and imaginary part sequences X_R and X_I, respectively, and then each part partitions into V subblocks $X_{R(v)}$ and $X_{I(v)}$. Next, the real and imaginary part subblocks are transformed into the time domain by the N-point IFFT to generate the time domain real and imaginary parts, $x_{R(v)}$ and $x_{I(v)}$. Afterwards, the real part and imaginary part are accordingly multiplied by the real and imaginary phase factors parts, b_R and b_I, separately. Finally, the imaginary part sequences x_{q-I} are multiplied with (j) and combined with the real part candidate sequences x_{p-R} to generate the candidate signals x_M.

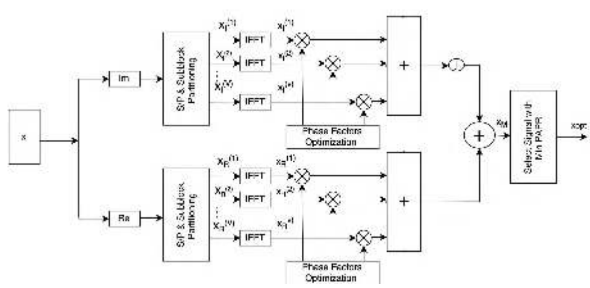

FIGURE 5. Block diagram of the R&I-PTS method [92].

The final candidate sequences can be written as

$$x_M = x_{p-R} + jx_{q-I} \tag{22}$$

Combining the M candidates in the real and imaginary parts will generate the M^2 time domain candidate signals. Hence, the PAPR performance of the R&I-PTS method is better than the PAPR performance of the C-PTS method when the both approaches have the same value of V and W. However, the computational complexity of the R&I-PTS method is higher than the C-PTS method.

4) COMBINATION DUMMY SEQUENCE INSERTION WITH PTS

The combination dummy sequence insertion and PTS method (DSI-PTS) is based on inserting a dummy sequence with an input data sequence in the frequency domain and then combined with the C-PTS method [93]. The block diagram of the DSI-PTS technique is shown in Figure 6. Firstly, the dummy sequence is generated and then added to the input data sequence. The new sequence vector S is given as

$$S = [X_K, R_D] \tag{23}$$

where $X_K = [X_0, X_1, \ldots, X_{K-1}]^T$ is the input data sequence, and $R_D = [R_0, R_1, \ldots, R_{D-1}]^T$ is the dummy sequence.

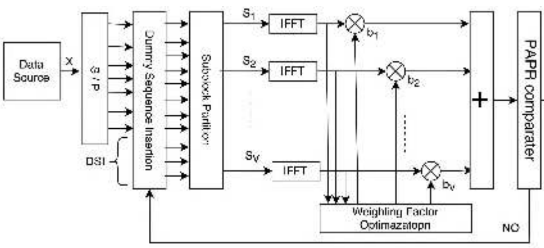

FIGURE 6. Block diagram of the DSI-PTS method [93].

The total number of the subcarriers for the new vector S is $N = K + D$, and D can be set any number less than K [94]. The new sequence generated is partitioned into V subblocks and applied IFFT for each subblock, and then the time domain partial transmits sequences are weighted with phase factors to produce the candidate signals. The PAPR value of each candidate is calculated and checked with predetermined threshold. If the PAPR value is lower than the threshold value, the OFDM signal is transmitted directly. Otherwise, insert new dummy sequence and repeat the operation again. In the same manner, Varahram *et al.* [95], [96] used the insertion dummy random Gaussian method combined with the C-PTS method, where the PAPR reduction performance is the same as that of DSI-PTS. But the difference is that the Gaussian distribution is used instead of the dummy sequence.

The PAPR performance of the DSI-PTS method is better than that of the C-PTS method and is less complex because only half of IFFTs is needed to achieve the same PAPR value as C-PTS. However, the DSI-PTS leads to an increase in the BER of the system and leads to the reduction in the transmission efficiency.

5) DISCRETE FOURIER TRANSFORM SPREAD-PTS

In 2014, Fulia proposed a new scheme called combination discrete Fourier transform spread-PTS (DFT-S-PTS) to reduce the PAPR value [76]. The DFT-S-PTS method is stationed on the combination of the discrete Fourier transform with the C-PTS method as shown in Figure 7. The DFT-spread is a linear process, and it can reduce the autocorrelation among the subcarriers by expanding the frequency domain signal [76]. Owing to the association of the PAPR values with the autocorrelation function, the PAPR value can be reduced by using the DFT–spread method [77]. The principle idea of the DFT-S-PTS is to partition the data block X into non-overlapping subblocks, and then the partitioned subblocks are applied to the bank of DFT-S to generate the transformed sequences. Finally, the IFFT bank are applied to the transformed sequences in order to reduce the PAPR value.

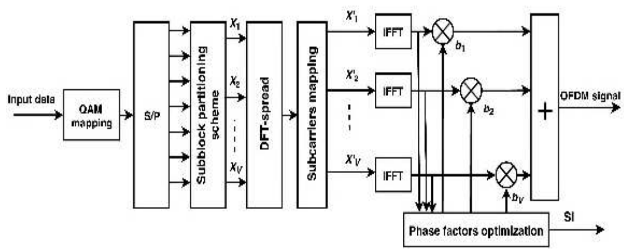

FIGURE 7. DFT-S-PTS method block diagram [76].

The PAPR performance of the DFT-S-PTS is better than that of the C-PTS method because the active influencing of the DFT operations to reduce the autocorrelation between the subcarriers leads to the mitigation of PAPR value. On the other hand, the computational complexity of the DFT-S-PTS is higher than that of the C-PTS method because of additional processing of the DFT bank. However, the DFT-S-PTS can achieve a lower computational complexity than the C-PTS method, when the PAPR values of both approaches are equated. In this case, the DFT-S-PTS method requires only the half numbers of the IFFT operations to achieve the same PAPR performance as that of the C-PTS method.

6) DISCRETE COSINE TRANSFORM SPREAD-PTS

The discrete cosine transforms spread-PTS technique (DCT-S-PTS) [78] was proposed based on applying the discrete cosine transform spread to the PTS techniques in the frequency domain. This method reduces the PAPR value in the OFDM system, where the DCT unit works to reduce the autocorrelation among the subcarriers on each subblock in the frequency-domain and this leads to reducing the PAPR value [77]. The data sequence X is passed to the DCT block, which extend the input data sequence so that the autocorrelation among the subcarriers is reduced. Finally, the PTS technique is implemented for decreasing the PAPR value, as shown in Figure 8.

The PAPR value of the DCTS-PTS method is better than that of the C-PTC, because the DCT function influences to the

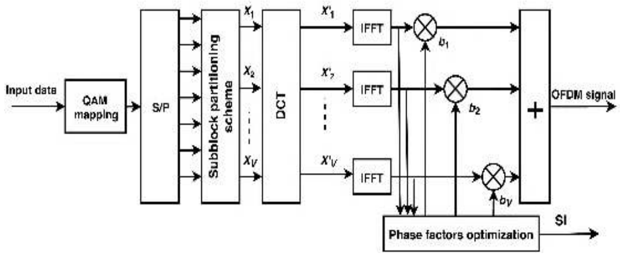

FIGURE 8. DCT-S-PTS method block diagram [78].

subcarrier's correlations in the frequency domain. However, the computational complexity of the DCT-S-PTS is higher than that of the C-PTS because an additional complexity is imposed using the DCT function. On the other hand, the computational complexity of the DCT-S-PTS can be reduced to be lower than that of the C-PTS method, if the PAPR performance of both techniques is equated.

7) COMBINING ADJACENT AND INTERLEAVING PARTITIONING SCHEMES

In the combining adjacent and interleaving partitioning PTS method (AP-IL-PTS) [97], the adjacent segmentation scheme is combined with the interleaving segmentation scheme to reduce the PAPR value. In the AP-IL-PTS method, the data sequence is partitioned firstly according to the adjacent segmentation scheme into V subblocks. Next, each subblock is divided into equal sized groups, and then the interleaving technique is applied to the groups for each subblock with V equally spaced parts [90]. Finally, the new segmentation scheme is applied to the PTS technique.

The hybrid scheme AP-IL-PTS can reduce the PAPR value better than that of the AP-PTS and IL-PTS, but the shortcoming of the AP-IL-PTS approach is that it utilizes the AP-PTS scheme which has the PAPR reduction efficiency lower than PR-PTS with a computational complexity equal to that of the PR-PTS scheme. Moreover, the proposed method has computational complexity higher than that of the IL-PTS scheme. Hence, the AP-IL-PTS method has large computational complexity with slight enhancement of PAPR reduction compared with the PR-PTS scheme.

B. COMPARISON THE MODIFIED-PTS METHODS IN THE FREQUENCY-DOMAIN

The parameters of various PTS methods in this comparison are included in Table 3.

The PAPR reduction performances of the various modified PTS methods are compared with the AP-PTS method. As can be seen from Figure 9, the IL-Ex-PTS method outperforms the rest modified PTS methods because the IL-EX-PTS scheme can break down the correlation peak between the subcarriers better than the other methods, where IL-Ex-PTS depends on exchanging a certain group of subcarriers with each other. Moreover, the AP-Sh-PTS scheme is the second best because its subcarriers are shifted by (V-1) inside each subblock. The Ad-IL-PTS scheme is better PAPR than the PR-IL-PTS schemes because it has been purposed based on reshaping the subcarriers within the subblocks, while the PR-IL-PTS scheme has been suggested by combining the pseudo-random scheme with the interleaving scheme. Therefore, the correlations peak between the subcarriers inside the subblocks plays an essential role to reduce the PAPR value of the modified-PTS method in the frequency domain.

TABLE 3. The parameters of comparison the various modified PTS methods in the frequency domain.

Type of partitioning scheme	Adjacent scheme, pseudo-random scheme
Type of constipation mapping	16-QAM
Number of subblocks (V)	4
Oversampling factor (L)	4
Number of allowed phase factors (W)	4
Number of subcarriers (N)	256
Number of simulated OFDM symbols	1000
Number of DSI related to (DSI-PTS	55

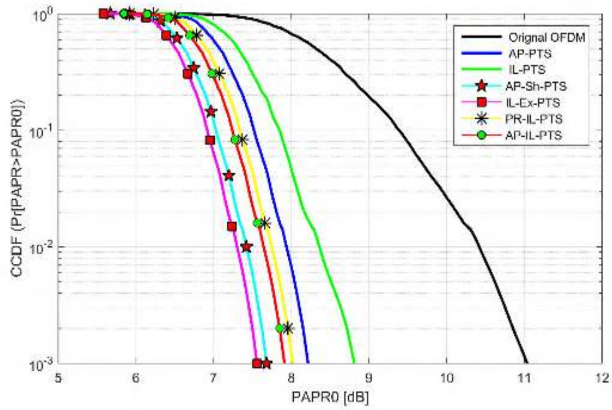

FIGURE 9. Comparison the PAPR performance of the modified-PTS methods and the AP-PTS method in frequency-domain when $N = 256$, $V = 4$, and $W = 4$.

Also, another simulation is conducted among the rest modified PTS methods in the frequency-domain and the PR-PTS method, as shown in Figure 9. The simulation indicates that the DSI-PTS method achieves the superior PAPR reduction gain compared with the other methods, with the consideration that the high PAPR performance of these methods at the expense of degradation in the computational complexity.

On the other hand, the computational complexity reduction ratio (CCRR) is adopted to measure the reduction ratio of the various modified PTS methods compared to C-PTS method, therefore, the CCRR can be defined as [98]

$$CCRR = (1 - \frac{\text{complexity of modified methods}}{\text{complexity of C-PTS method}}) \times 100\% \tag{24}$$

Table 4 illustrates the PAPR reduction performance and the CCRR percentage of various frequency-domain methods compared with the C-PTS method. The number of the subcarriers N is fixed at 256, whereas the number of the subblocks

TABLE 4. CCRR of the modified-PTS methods in the frequency domain.

$N = 256$, $V = 8$, $W = 2$				
Method	PAPR Performance compared with C-PTS	Complexity Calculations Location	CCRR%	
			CCRR^{+}	CCRR$^{\times}$
C-PTS	----	IFFT	----	----
IL-PTS	Lower	IFFT	92.18	67.18
AP-Sh-PTS	better	IFFT	----	----
IL-Ex-PTS	better	IFFT	84.37	59.37
PR-IL-PTS	Slightly better	IFFT	40.6	28.1
AP-IL-PTS	Slightly better	IFFT	92.18	67.18
R&I-PTS	Same	IFFT + Phase Factors	76.66	71.62
DSI-PTS	Same	IFFT + phase factors	94.16	95.27
DFT-S-PTS	Same	IFFT + phase factors	93.33	94.59
DCT-PTS	Same	IFFT + phase factors	93.02	94.93

V and the number of different phase factors W, are 8 and 2, respectively. From the results in Table 4, the DSI-PTS, DFT-S-PTS, and DCT-PTS methods are performed lower computational complexity than the other methods, when its PAPR reduction performances are similar to that of the PR-PTS scheme. The PAPR reduction performance of the DSI-PTS method is the best among the methods in Figure 10 because the added DSI sequence reduces the correlation among the subcarriers. This enhancement is at the expense of increasing the computational complexity level. In order to compare the computational complexity level of the DSI-PTS with the conventional PTS method (PR-PTS), the PAPR value of the DSI-PTS and PR-PTS methods has been assumed to be equal in both methods. Hence, the DSI-PTS method needs a smaller number of subblocks (V) and IFFT units compared with PR-PTS. Therefore, the computational complexity of the DSI-PTS method is lower than the PR-PTS and the other methods in the frequency domain; with the consideration that the PAPR value of DSI-PTS and the other methods is equaled. In addition, the IL-Ex-PTS scheme improves both the computational complexity and PAPR reduction performance compared with AP-PTS scheme. However, the AP-Sh-PTS scheme enhances the PAPR reduction capacity better than the AP-PTS scheme without increasing the complexity.

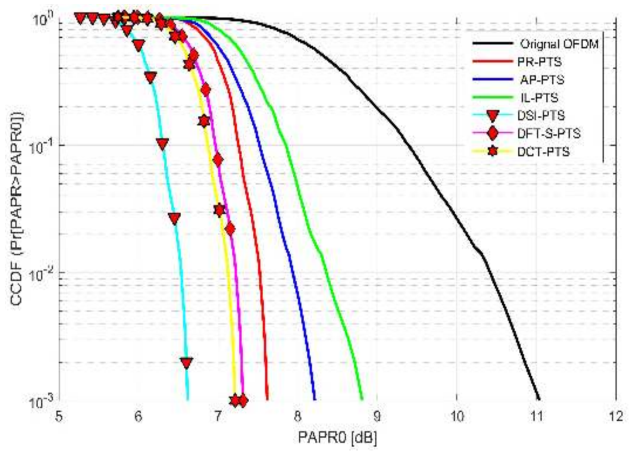

FIGURE 10. Comparison the PAPR performance of the modified-PTS methods and the PR-PTS method in frequency-domain when $N = 256$, $V = 4$, and $W = 4$.

C. THE MODIFIED-PTS METHODS IN MODULATION- STAGE

Several techniques are enhanced to improve the PAPR performance and/or the computation complexity level in the modulation-stage (IFFT unit) of the PTS technique. The methods that deal with the modulation stage are presented in the following subsequent sections:

1) LIM-METHOD

Lim *et al.* [98], [99] proposed a new method to reduce the computational complexity of the PTS technique. Unlike the C-PTS method, the Lim-PTS method has two stages of IFFT, as shown in Figure 11. The IFFT block based on the decimation-in-time algorithm (DIT) is divided into two parts, the l and (n-l) stages. Firstly, the input data sequence is partially transformed by using the l stages of IFFT into an intermediate data sequence. After that, the intermediate data sequence is partitioned into subsequences and then fed to the remaining (n-l) stages of the IFFT. The transformed subblocks are multiplied by the rotation factor vectors in the time-domain to generate a set of the candidate signals. Finally, the candidate sequence that has the lowest PAPR value is selected for transmission.

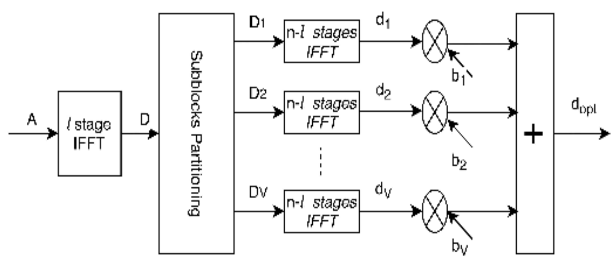

FIGURE 11. Block diagram of the Lim-PTS method [98].

The PAPR reduction performance of Lim-PTS is the same as that of the C-PTS method [99], when (n-l) = 5. Accordingly, the PAPR reduction performance is improved with increasing in the number of (n-l) stages. In case of the computational complexity, the Lim-PTS approach is better than that of the C-PTS method, because the common intermediate sequences of the V subsequences lead to reducing the number of IFFTs used. Therefore, Lim-PTS is suitable for a large number of subcarriers in the OFDM system.

2) SUB-OPTIMUM PTS METHOD

The sub-optimum PTS (Sub-OPTS) method [100] was proposed to reduce the computational complexity, and to improve the PAPR performance compared with the C-PTS technique. The Sub-OPTS method is a combination of the alternate optimization PTS (A-OPTS) method, and the linear property of inverse discrete Fourier transform (IDFT). The A-OPTS [101] can achieve low computational complexity compared with the C-PTS method, but the cost is significant degradation of the PAPR performance. This degradation of the PAPR value can be attributed to that the phase weighting factors are only performed for the half of subblocks, where the odd subblock numbers are kept unchanged, and the even sub-block numbers are optimized using the phase factors. In the Sub-OPTS method, the conjugate property of the IDFT is employed for all the odd subblocks (except the first one) to provide more candidate signals, as shown in Figure 12.

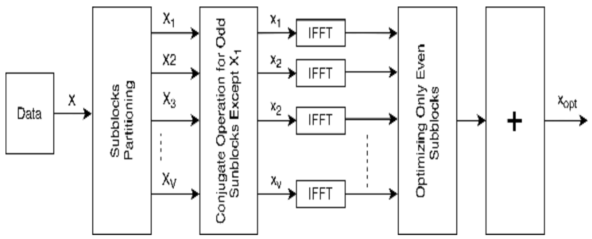

FIGURE 12. Sub-OPTS method block diagram [100].

The Sub-OPTS method improves the PAPR reduction performance because the candidate signals are increased. Furthermore, the computational complexity of the Sub-OPTS method is lower than that of the C-PTS scheme, because the Sub-OPTS method no needs of using the complex multiplication operations, as long as the conjugate operation is performed for the odd subblocks, and the phase rotation factors operation is only performed for the even subblocks

3) COOPERATIVE PTS METHOD

The cooperative PTS technique (CO-PTS) [102] was introduced to reduce the computation complexity, and to improve PAPR reduction performance compared with the C-PTS method. The CO-PTS method is a combination of A-OPTS [101] and the special subblocks circular permutation method (SSCP). Figure 13 illustrates the CO-PTS method, in which the special subblocks circular permutation method is employed for the odd subblocks (except the first one) and all the weighted even subblocks are exploited once more to increase the number of the candidate signals.

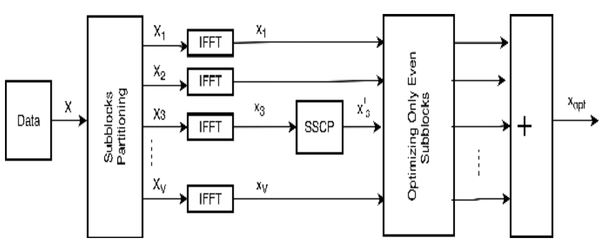

FIGURE 13. Cooperative PTS method block diagram [102].

The PAPR reduction performance of the CO-PTS method outperforms the C-PTS method because the number of the candidate signals is increased using the SSCP operation. Moreover, the computational complexity of the CO-PTS method is also reduced because the number of complex multiplication operations is less than that of the conventional method.

D. COMPARISON OF THE MODIFIED-PTS METHODS IN MODULATION STAGE

The parameters of this comparison are illustrated in Table 5.

TABLE 5. The parameters of comparison the various modified PTS methods in the modulation stage.

Type of partitioning scheme	Pseud-random scheme
Type of constipation mapping	16-QAM
Number of subblocks (V)	4
Oversampling factor (L)	4
Number of allowed phase factors (W)	4
Number of subcarriers (N)	256
Number of simulated OFDM symbols	1000
(n-l) stages related to (LIM-PTS method)	5
Number of conjugate subblock related to (Sub-PTS method)	1
Number of SSCP related to (CO-PTS method)	1

Figure 14 presents the comparison of the modified PTS methods and the PR-PTS methods in the modulation stage. It is evident that the Sub-OPTS and CO-PTS methods achieve slightly improvement regarding the PAPR reduction performance, while Lim's method is slightly degraded the PAPR performance compared with PR-PTS.

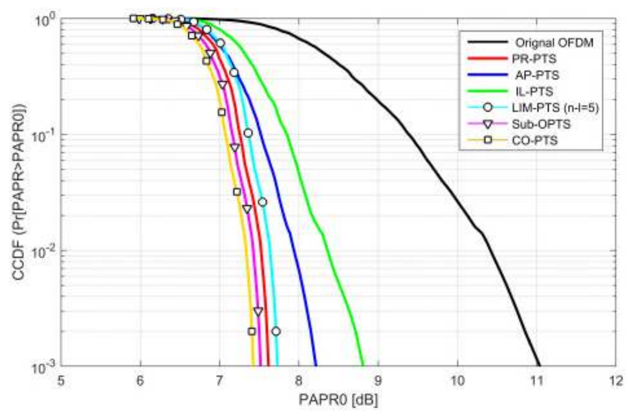

FIGURE 14. Comparison the PAPR performance of the modified-PTS methods and the PR-PTS method in modulation stage when $N = 256$, $V = 4$, and $W = 4$.

In addition, Table 6 shows the PAPR performance and the CCRR of the modified PTS methods in the modulation stage. Both the Sub-OPTS and CO-PTS methods can achieve CCRR^{+} and $\text{CCRR}^{\times}$ by 50% and 93% compared with the PR-PTS method, whereas, LIM-PTS achieves CCRR^{+} and $\text{CCRR}^{\times}$ about 12.5% and 25%. Moreover, the PAPR

TABLE 6. CCRR of the modified PTS in the modulation stage.

$N=256$, $V=8$, $W=2$				
Method	PAPR Performance compared with C-PTS	Complexity Calculations Location	CCRR%	
			CCRR^{+}	CCRR$^{\times}$
LIM-PTS	Almost the same	Phase factor	12.5	25
Sub-OPTS	same	Phase factor	50	93.05
CO-PTS	Slightly better	Phase factor	50	93.05

reduction performance of Sub-OPTS and CO-PTS is better than Lim-PTS method [82]–[84]. The CO-PTS method depends on special subblocks circular permutation (SSCP) to produce an additional number of the candidate signals, where increasing the number of the candidate signals in the time domain leads to enhancing the PAPR reduction performance. On the other hand, the computational complexity of the CO-PTS methods is less than the Lim-PTS method. This can be attributed that the CO-PTS method no requires using the complex multiplication operations when weighing the subblocks that produced by SSCP, where the additional candidate signals need only the complex addition operations between the even weighted subblocks and the subblocks that produced by SSCP. Therefore, the number of the complex multiplications is reduced significantly compared with the LIM-PTS and conventional PTS methods.

E. THE MODIFIED-PTS METHODS IN THE TIME DOMAIN

Many of methods have been proposed to deal with the PTS technique in the time domain part, most of them focused on treating the high computational complexity of the PTS technique. Given that many communication applications need low computational complexity, the PAPR reduction methods should be without imposing a heavy burden on the system [49]. The important methods which deal with PTS technique in the time domain are given in the following subsequent sections

1) ITERATIVE FLIPPING PTS ALGORITHM

In 1999, Cimini and Sollenberger [103] proposed Iterative Flipping PTS (I-PTS) method to reduce the computational complexity of optimizing partial transmit sequences in the PTS scheme. I-PTS can achieve a computational complexity level lower than that of the C-PTS at the expense of degradation in the PAPR reduction performance. Cimini's method is conducted with the condition that the number of the possible phase factor is $W = \{1, -1\}$. The algorithm starts after dividing the input data sequence into V subblocks and then assuming the initial phase rotation factor vector $b_v = 1$ for all v to compute the initial PAPR value, where $v = \{1, 2, \ldots, V\}$. Next, the first phase factor $b_1 = 1$ is inverted and the PAPR value is recomputed and compared with the initial PAPR value, if the new PAPR is lower than the initial PAPR value, retain $b_1 = -1$ and set it as part of the final phase factor. Otherwise, $b_1 = 1$, which is the previous value. The algorithm continues in this fashion iteratively until the end of all b_v elements. Accordingly, the I-PTS algorithm considered as a simple implementation for finding the optimum phase rotation factor in the PTS technique. See Figure 15.

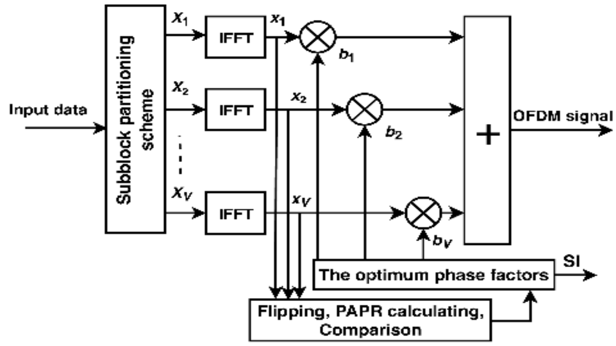

FIGURE 15. Iterative flipping PTS method block diagram [103].

In addition, Gao in 2009 proposed a cyclic iteration PTS (C-I-PTS) [104], in which the optimum phase factor that is obtained by applying Cimini's method is set to the initial phase factor for the next iteration. After U times of repetition, the optimum phase factor with minimum PAPR value is obtained.

The PAPR reduction performance of the I-PTS and C-I-PTS is lower than that of the C-PTS because the optimum phase factor of the I-PTS and C-I-PTS may not be exactly the best phase factor which achieves the minimum PAPR value. Nevertheless, the computational complexities of the I-PTS and C-I-PTS are much lower than that of the C-PTS method, especially for a large number of subblocks.

2) ITERATIVE FLIPPING-PTS WITH THRESHOLD

The iterative flipping with threshold method (I-TH-PTS) [105], [106] was introduced to depress the computational complexity for finding the optimum weighting factor. As mentioned in the previous section, the I-PTS method [103] increases the PAPR value, but the computational complexity is degraded. In contrast, the threshold-PTS method that has been proposed in [106] works to terminate the weighting factors optimization as soon as the PAPR value of OFDM signal falls below the threshold value. The procedure of the I-TH-PTS method is based on setting the number of the processing levels equal to the number of the phase factor vector bits. In each level, the optimum bit of the phase rotation factors which leads the PAPR value to be lower than that of the previous state must be fixed at the next levels processing. Afterwards, each PAPR value is compared with the threshold value. Hence, if the PAPR value is lower than the threshold value, the weighting factors optimization is terminated, as shown in Figure 16. This fashion continues until the last level; with the consideration that the optimum bit of the weighting factors is fixed at the current level,

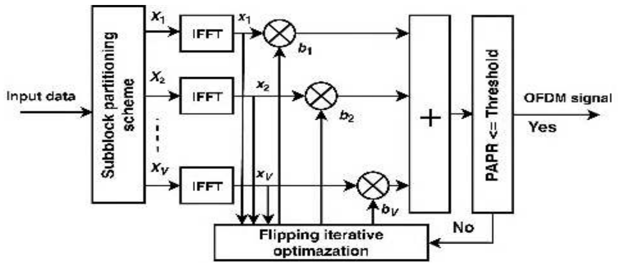

FIGURE 16. Iterative flipping PTS method block diagram [106].

so it is not considered in the next level processing. In the I-TH-PTS algorithm, there are two methods that can stop the optimization, the same PAPR condition and the threshold condition.

Likewise, improving I-TH-PTS (IM-I-TH-PTS) method [107] is proposed by changing the search tactics of the flipping operation. The flipping operation changes two or more bits of the weighting factor in each processing level. Similarly, Zhu *et al.* [108] proposed the extended iterative flipping PTS (E-I-PTS) method to reduce the mathematical complexity of the PTS technique. The idea of the E-I-PTS method is to partition the subblocks sequences in the time domain into several groups, and the pts_s in each group are optimized by using the I-PTS method. Hence, combining the groups and selecting the optimum phase factor will achieve the minimum PAPR value.

The PAPR reduction performance of the I-TH-PTS, IM-I-TH-PTS, and E-I-PTS is slightly lower than that of C-PTS method, but they achieve PAPR reduction performance better than the I-PTS method because the number of the candidate signals is increased. In contrast, the computational complexity level of the iterative flipping methods is that I-PTS < IM-I-TH-PTS < E-I-PTS < I-TH-PTS < C-PTS.

3) PHASE ADJUSTMENT PTS ALGORITHM

A phase adjustment PTS method (PH-A-PTS) [109] is proposed to improve the PAPR reduction performance and to reduce the computational complexity of the PTS technique. This method is stationed on rotating the phases of each subblock with an arbitrary angle through a predetermined number of iterations. The principal idea of the PH-A-PTS method depends on updating the phase factor for the data subblocks at each iteration operation with a predetermined phase increment, and then a set of the candidate signals is generated.

The PAPR reduction performance of the PH-A-PTS method is almost the same as that of the C-PTS method and depends on the total number of the iterations K, where the large number of iterations leads to better PAPR reduction performance and vice versa. However, the computational complexity of the PH-A-PTS method is lower than that of the C-PTS method, because the number of iterations is almost lower than that of C-PTS.

4) CODING-PHASE FACTORS ALGORITHMS

Several algorithms have been proposed to reduce the high computational complexity level for finding the optimum phase rotation factors in the PTS technique. The m-sequence PTS (m-S-PTS) method [110] was proposed to reduce the computational complexity and to control the PAPR performance of the PTS technique. This method is stationed on mapping an m-sequence code to produce the phase factor vectors in a certain rule. The m-sequence code with length M digits can produce (2^{M-1}) binary strings by summing the first two digits in modulo-2 manner to produce the last digit, and then immediately applying the feedback shift to the left in order to produce the next string, as shown in Figure 14.

In the m-S-PTS method, the mapping operation is accomplished by adding any two rows of m-sequence based on the rule $(1+1=1, 0+0=-1, 1+0=j, 0+1=-j)$, and then the output vectors can be used as the phase factors in the PTS method.

In addition, Hu *et al.* [111] proposed a new algorithm in order to reduce the computational complexity of the PTS technique. The algorithm starts when choosing a stochastic integer number (P), the range of this number is $P \in [0, 2^V]$, where V is the number of subblocks. For each iteration, the algorithm changes the number P into binary digits depending on the number of subblocks V. After that, each binary digit is mapped into an angle (i.e. "0" is mapped to "0" and "1" is mapped to π). Accordingly, the vectors which are generated by mapping operations can be used as the phase factor vectors to rotate the pts combinations in the time-domain. Moreover, the algorithm is repeated Q times, where $Q \ll W^{V-1}$, therefore; the computational complexity for finding the optimum phase factor is reduced. The P-PTS method can achieve low computational complexity depending on the number of iterations, Q. However, the PAPR performance of the P-PTS algorithm will be degraded.

In the same side, another approach is presented to reduce the computational complexity of the PTS scheme by employing Gray code nature to produce the phase rotation factors, so this method is named Gray code PTS (G-PTS) algorithm [112]. The key point of the G-PTS algorithm is to make use of a Gray code nature and the inherent relationship between the phase factor sequences; with the consideration that the weighting factors are constrained to $\{1, -1\}$. In the G-PTS algorithm, the nature of the Gray code is that the adjacent code strings differ by only one-bit position. Therefore, the code strings can be mapped into the phase factor vectors, and then the relationship between the vectors can be exploited to generate the next candidate sequence from the previous one.

The PAPR reduction performance of the G-PTS method can achieve almost the same as that of C-PTS, whereas the PAPR reduction performance of the P-PTS method is lower than that of the C-PTS method. In addition, the PAPR reduction performance of the m-S-PTS method outperforms the C-PTS method, because the scope for choosing the phase rotation factors is increased thus the candidate signals will be more independent and this leads to improve the PAPR performance. On the other hand, the computational complexities of the three coding phase factor types are lower than that of the C-PTS method, due to the process for finding the optimum phase factor is less than that of the C-PTS method.

5) THE DIFFERENT PHASE FACTOR ALGORITHM

A new phase factor PTS method (α-PTS) method [113] is proposed to determine the best weighting factor of the PTS method. The α-PTS method outperforms the C-PTS method in the computational complexity. The principle idea of the α-PTS is to partition the input data block into several subblocks similar to the ordinary PTS technique, and then each subblock is divided into two parts in the time domain, as shown in Figure 15.

The first and second parts are weighted by different phase factors, therefore; the OFDM signal can be expressed as

$$x^{v} = \sum_{v=1}^{V} (b_1^{(v)} x_1^{(v)}) + \left(b_2^{(v)} x_2^{(v)}\right) \tag{25}$$

where the phase factor of the first part is $b_1^{(v)} = e^{\text{Ø}_1^{(v)}}$, and the second part of the phase factor is $b_2^{(v)} = e^{\text{Ø}_2^{(v)}}$, so that the relationship between $\text{Ø}_1^{(v)}$ and $\text{Ø}_2^{(v)}$ is $\text{Ø}_2^{(v)} = \alpha\text{Ø}_1^{(v)}$, where α is a constant value, and $\alpha \in [0, 1]$. In the case of $\alpha = 0$, the phase value for the second part of the subblock is $\text{Ø}_2^{(v)} = 0$; therefore, the phase factor $b_2^{(v)} = \mathrm{e}^0 = 1$. This scenario means that the second part of the subblock is the same as the original data without multiplying by the phase factors. As a result, the α-PTS method can realize a good PAPR reduction performance with inferior computational complexity compared with the C-PTS method because the variation of the phases and the number of the phase factor vectors is reduced.

In the same manner, Boonsrimuang [114] used the phase coefficient $\text{Ø}_2^{(v)} = 0.5\text{Ø}_1^{(v)}$ to enhance the PAPR reduction performance, so it is named the different phase PTS (D-PTS) method. The PAPR performance of the D-PTS method outperforms the C-PTS method. However, the computational complexity of the D-PTS method is the same as that of the C-PTS method because the same number of phase factors is used.

6) THE GROUPING AND RECURSIVE PHASE WEIGHTING FACTORS ALGORITHMS

The low computational complexity methods were proposed by Wang and Liu [115], these schemes including the grouping phase weighting PTS (GPW-PTS) method and the recursive phase weighting PTS (RPW-PTS) method. The proposed methods can realize the PAPR reduction performance similar to that of the C-PTS method. However, the computation complexities of the proposed methods are lower than that of the C-PTS method. In the GPW-PTS method, the subblocks are split into several groups, and then each group produces

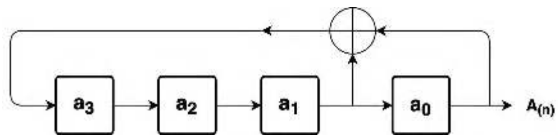

FIGURE 17. Mechanism of m-sequence [110].

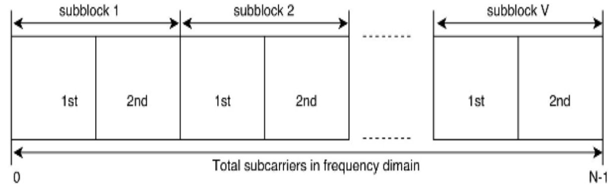

FIGURE 18. Dividing the subblocks block diagram [113].

its sub-candidate sequences by using the same set of phase factors. The total candidate sequences are generated by applying the complex addition operations among the sub-candidate sequences for different groups. The number of the candidate sequences of the GPW-PTS and C-PTS methods is equaled, so that the PAPR performance for both methods is identical. However, the computational complexity of the GPW-PTS method is lower than that of the C-PTS method, because the elements number of the phase factors in the groups of the GPW-PTS method is lower than that of the C-PTS method.

Likewise, the RPW-PTS method was proposed to reduce the computational complexity of the C-PTS technique. The RPW-PTS method exploited the relationship between the phase factors by using two conditions [116]. The first condition is that the number of different weighting factors W should be an even number. The second condition is that the set of allowed phase weighting is limited to $\{e^{\frac{j2\pi r}{W}} | r = 0, 1, 2, \ldots\ldots, W-1\}$. The RPW-PTS method exploits the relationship among the weighting factors to generate the candidate sequences with low computational complexity.

As a result, the PAPR reduction performance of the GPW-PTS and RPW-PTS methods is the same that of the C-PTS method, due to the fact that the number of the candidate sequences of the modified methods and C-PTS method are same. Nevertheless, the computational complexity is decreased significantly.

7) THE CYCLIC SHIFT SEQUENCE PTS METHOD

The cyclic shift sequence-PTS (CSS-PTS) method [117] is one of the affective PAPR reduction methods, and it can improve the PAPR performance without using the phase rotation factors. The CSS-PTS method can generate the candidate sequences by cyclically shifting each subblock sequence in the time domain, as shown in Figure 19. As mentioned, the C-PTS method needs an exhaustive search for finding the optimum phase rotation factor, whereas the CSS-PTS method generates the candidate sequences without using multiplication operations by applying shifting samples operation for each subblock. The cyclic shift operation does not obliterate the orthogonal relationships among the data sequences

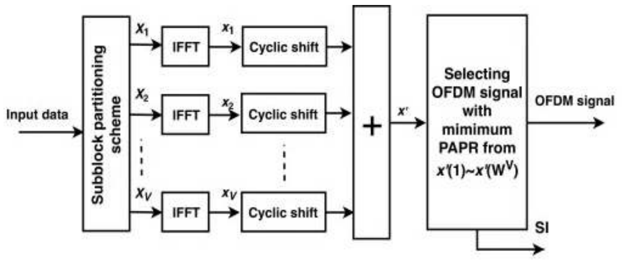

FIGURE 19. Dividing the subblocks block diagram [118].

because the cyclical shifting in the time domain is equivalent to multiplying corresponding linear phase vectors in the frequency domain [118].

The PAPR reduction performance of the CSS-PTS method is better than that of C-PTS method because the number of the candidate sequences for the CSS-PTS method is more than that of the C-PTS method. Furthermore, the computational complexity of the CSS-PTS method is lower than the C-PTS method, because the CSS-PTS method no needs multiplication operations when producing the candidate sequences.

F. COMPARISON OF THE MODIFIED-PTS METHODS IN THE TIME DOMAIN

The parameters of various PTS methods in the time domain are illustrated in Table 7.

TABLE 7. The parameters of comparison the various modified PTS methods in the time domain.

Type of partitioning scheme	random scheme
Type of constipation mapping	16-QAM
Number of subblocks (V)	8
Oversampling factor (L)	4
Number of allowed phase factors (W)	2
Number of subcarriers (N)	256
Number of simulated OFDM symbols	1000
Number of repetitions (U) related to (C-I-PTS method)	2
Number of groups related to (E-I-PTS method)	2
Number of the iterations (K) related to (PH-A-PTS method)	40
Number of the iterations (Q) related to (P-PTS method)	100
Constant value (α) related to (α-PTS method)	0.5
Number of groups related to (GPW-PTS method)	4
Number of cyclically shifting operations related to (CSS-PTS method)	256

The modified-PTS methods in the time-domain are simulated and compared with the PR-PTS method, when $N = 256$, $V = 8$, and $W = 2$, see Figure 20. The results show that the modified-PTS methods have difference performance regarding the PAPR reduction. It has been found that the CSS-PTS method is the best in terms of the PAPR reduction performance, while the I-PTS was the worse among the modified PTS methods. Also, Figure 21 illustrates the PAPR reduction capacity of the traditional PTS methods depending on the parameters above.

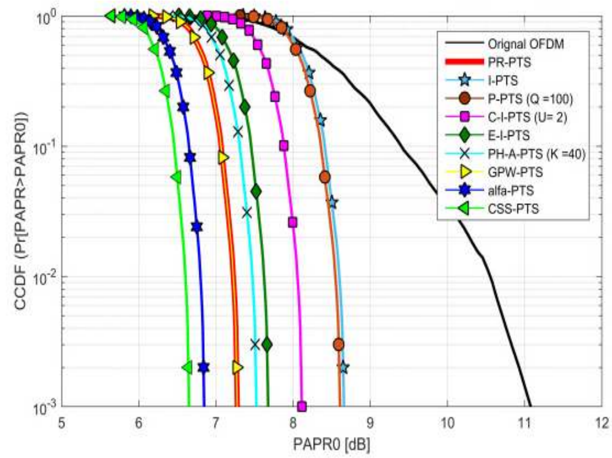

FIGURE 20. Comparison the PAPR performance of the modified-PTS methods and the PR-PTS method in the time-domain when $N = 256$, $V = 8$, and $W = 2$.

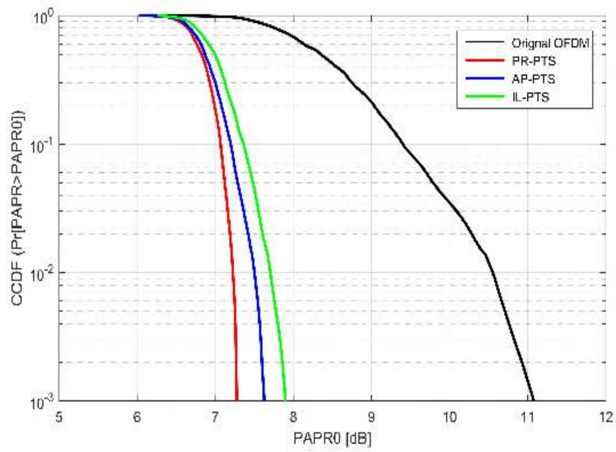

FIGURE 21. Comparison of PAPR for the ordinary PTS schemes when $N = 256$, $V = 8$, and $W = 2$.

On the other hand, Table 8 illustrates the PAPR reduction performance and the CCRR gain of the modified PTS methods in the time-domain compared with the C-PTS method. In this table, the numbers of the subblocks V and the subcarriers N are 8 and 256, respectively. It is clear that the CSS-PTS method outperforms the C-PTS method for both the PAPR reduction performance and the computational complexity. Moreover, the GPW-PTS method can achieve better CCRR$^{\times}$ than the C-PTS method by 92.96%; with the consideration that the PAPR reduction performance is the same for both. The PAPR reduction performance of the GPW-PTS method is the same as that of the C-PTS method because the candidate signals for both methods are equaled. On the other hand, the computational complexity of the GPW-PTS method is lower than the C-PTS method. This can be attributed that the GPW-PTS method splits the subblocks into several groups and each group produce sub-candidates by applying the same set of the phase weighting factors; with the consideration that the elements of the phase weighting

TABLE 8. CCRR of the modified PTS methods in the time domain.

$N = 256$, $V = 8$, $W = 2$				
Method	PAPR Performance compared with C-PTS	Complexity Calculations Location	CCRR%	
			$CCRR^{+}$	$CCRR^{\times}$
I-PTS	Lower	Phase factor	93.75	93.75
C-I-PTS	Lower	Phase factor	81.25	81.25
PH-A-PTS	Almost the same	Phase factor	37.5	37.5
m-PTS	Better	Phase factor	87.5	87.5
P-PTS	Lower	Phase factor	21.9	21.9
G-PTS	Almost the same	Phase factor	88.2	88.2
α-PTS	Better	Phase factor	49.6	49.6
D-PTS	Better	Phase factor	zero	zero
I-TH-PTS	Slightly lower	Phase factor	71.87	71.87
IM-I-TH-PTS	Slightly lower	Phase factor	92.18	92.18
E-I-PTS (2 groups)	Slightly lower	Phase factor	76.56	76.56
GPW-PTS	Same	Phase factor	----	92.96
RPW-PTS	Same	Phase factor	57.14	75
CSS-PTS	Better	Cyclic shift	Zero	97.22

sequence in each group has fewer elements, thereby the lower computational complexity can be needed for generating one candidate sequence. The total candidate sequences are generated by applying the complex addition operations among the sub-candidate sequences for different groups. Therefore, the complex multiplication operations in GPW-PTS can be reduced significantly compared with the C-PTS method. Furthermore, the m-PTS and G-PTS methods can realize a high $CCRR^{\times}$ gain without reducing in the PAPR performance by 87.5% and 88.2%, respectively. Moreover, the I-PTS and IM-I-TH-PTS methods can increase the $CCRR^{\times}$ gain by 93.75% and 92.18%, respectively, but this advantage at the expense of degradation in the PAPR reduction performance. Also, the rest modified PTS methods in Table 8 lead to increase the $CCRR^{\times}$ gain with various performance in PAPR reduction.

V. DISCUSSION

The modified PTS methods are reviewed in three aspects depending on the original PTS structure: the frequency domain part, modulation stage (IFFT-unit), and time-domain part. Moreover, the modified PTS methods are discussed in terms of PAPR reduction performance and computational complexity.

Table 4 shows the comparison among the modified PTS methods in the frequency-domain based on the ability of the PAPR reduction and the computational complexity compared with the traditional PTS technique. There is a trade-off between the PAPR reduction performance and the computational complexity of the different modified PTS algorithms so that the best PAPR reduction performance can be achieved at the expense of increasing in the computational complexity and vice versa. Therefore, the modified PTS methods have different values of the computational complexity depending on the method that is utilized to improve the PAPR reduction performance. In Table 4, the modified PTS methods were calculated based on setting the number of subblocks $V = 8$, the number of subcarriers N and the number of different phase factors W is 256 and 2, respectively. It is clear that the DSI-PTS method could achieve $CCRR^{+}$ and $CCRR^{\times}$ better than the other methods at 94.16% and 95.27%, respectively. Moreover, the DFT-S-PTS method and the DCT-PTS method could fulfill the high percentages of the $CCRR^{+}$ and $CCRR^{\times}$ by 93 % and 94%, respectively. However, the PAPR reduction performance of these modified PTS methods is similar to the C-PTS method. Moreover, the IL-Ex-PTS scheme achieved PAPR reduction performance better than the AP-PTS scheme with a good computational complexity reduction level. Therefore, the modified PTS algorithms in the frequency-domain improve the PAPR reduction capacity with a significant reduction in the computational complexity.

Besides, the modified PTS methods in this study that deal with the modulation stage of the PTS scheme are LIM-PTS method, Sub-OPTS method, and the CO-PTS method. The Sub-OPTS and CO-PTS could achieve a high percentage of the $CCRR^{+}$ and $CCRR^{\times}$ by 50% and 93.05%, respectively. However, LIM-PTS method achieved $CCRR^{+}$ and $CCRR^{\times}$ by 12.5% and 25%, respectively, as shown in Table 6. On the other hand, the PAPR reduction performances of the Sub-OPTS and C-PTS, and LIM-PTS methods were almost the same values of the C-PTS method. Accordingly, modified PTS methods in the modulation stage of the PTS technique could reduce the computational complexity of the system with a slight degradation of the PAPR reduction performance.

On the other hand, the computational complexity of the modified PTS methods in the time domain is restricted by searching the optimum phase factor. The CSS-PTS method recorded the superiority regarding the PAPR reduction performance, and the computational complexity compared with the other modified PTS methods, in which its $CCRR^{\times}$ was 97.22%. Moreover, the GPW-PTS method achieved a high percentage of the $CCRR^{\times}$ by 92.96%; with the consideration that the PAPR reduction performance is similar to the C-PTS method, as shown in Table 8. However, some modified PTS methods such as I-PTS and C-I-PTS achieved low computational complexity with degradation in the PAPR reduction performance. In addition, the m-PTS and α-PTS methods improved the PAPR reduction performance better than that of the traditional method with low computational complexity. Therefore, the modified PTS methods in the time-domain could reduce the computational complexity significantly, but the PAPR reduction performances of them were varied between low and high depending on the method used.

A. THE CRITERIA FOR CHOOSING THE SUITABLE MODIFIED-PTS METHOD

In brief, the following factors should be considered when choosing the convenient modified PTS method

- The capability of PAPR reduction is the first factor that should be taken into account when selecting the modified PTS method with considering the influence of the other factors.
- The computational complexity is also an essential factor in choosing the modified PTS method because the low computational complexity makes the modified PTS method more acceptable.
- The Side information bits (SI) is used to inform the receiver side about what the transmitter did. If the side information obtained at the receiver's end contains some errors, then some or entire data may be lost. Therefore, SI should be protected by using some techniques such as channel coding. Moreover, the loss in data rate should be considered because the PTS method usually suffers from the loss in data rate because the side information uses some of the bandwidth. Hence, the loss in data rate caused by the side information should be kept to a minimum.
- The bit error rate (BER) is infrequent in the PTS methods because the PTS method is a probabilistic technique. However, the BER performance is degraded, when the side information is received with an error.

In general, the PTS method of the OFDM system depends on the requirements of the communication system such as the type of application, cost, complexity, weight, quality, and data transmission rate. For instance, the high-speed data rate system demands a low computational complexity, whereas the high-quality system needs an excellent PAPR reduction performance. Hence, there is a trade-off between the PAPR reduction performance and the computational complexity in the PTS technique. Therefore, the points above should be taken into consideration when the PTS technique is used as a PAPR reduction method for OFDM.

B. USING PTS WITH THE OTHER MULTICARRIER SYSTEMS

The PTS technique is considered as one of the efficient methods for solving the PAPR problem of the OFDM system, thereby it can be employed in other multicarrier systems. The orthogonal frequency division multiple access (OFDMA) and multiple input multiple output OFDM (MIMO-OFDM) are based on the OFDM system in its operation. Hence, these systems suffer from high PAPR value [119]. Therefore, the PTS technique can be implemented in the OFDMA and MIMO-OFDM systems to combat the high PAPR value.

The OFDMA system is used in the high-speed data rate wireless communication system such as 4G-LTE because of its advantages, especially in the downlink. In addition, the MIMO-OFDM system can be used to improve the capacity of the wireless communication system, but it also suffers from the high PAPR value [60]. Therefore, the PTS technique can be employed to reduce the PAPR value of this system [59]. As the MIMO-OFDM system has an extra degree of freedom provided by MIMO, the PTS method can be exploited to decrease the high PAPR value with low computational complexity by selecting the optimum phase factor that achieves the lowest PAPR value on all antennas [120].

Recently, several types of research are stationed on the OFDM concept to produce the new waveform design of the next generation (5G). The new systems such as OFDM-offset quadrature amplitude modulation (OFDM-OQAM) [121], generalized frequency division multiplexing (GFDM) [122], filter bank multi-carrier (FBMC) [123], universal filtered multi-carrier (UFMC) [124], and filtered-OFDM (F-OFDM) [125] are introduced to overcome the shortcomings, which are faced the OFDM system in 5G. Although the new systems should be designed to meet the requirements of the 5G applications such as asynchronous transmission and high spectral efficiency, the high PAPR problem is still the challenge that should be considered when designing the waveform in 5G. Therefore, the PTS technique can be used to enhance the PAPR reduction performance in the 5G waveform candidates.

VI. CONCLUSION

The high PAPR is regarded as a major drawback for transmitting signals in OFDM systems and the waveform design candidates in the next generation because of the non-linearity of equipment in transmitter. In this paper, we introduced an analytical review of the ordinary PTS technique and its modifications in three aspects, which are the frequency-domain, modulation stage, and time-domain. More than 26 modified PTS methods have been analyzed in terms of their ability to enhance the PAPR reduction performance and the computational complexity level. Based on the analytical results, the DSI-PTS method performs a lower computational complexity compared with the other frequency domain methods, whereas the CO-PTS method can reduce the computational complexity of the system better than the rest of the modulation-stage methods. Besides, the GPW-PTS method achieves low computational complexity without increasing the PAPR value in the time domain methods. On the other hand, the IL-Ex-PTS method improves the PAPR reduction performance better than that the frequency domain methods with the consideration that its computational complexity is reduced significantly. However, the CSS-PTS method is still the preeminent technique for the PAPR reduction performance with a significant reduction in the computational complexity. Moreover, the criteria for choosing the suitable modified-PTS method is summarized based on influencing parameters on the PTS technique. Accordingly, there is a trade-off between the PAPR reduction performance and the computational complexity in the PTS method; therefore, the requirements of the communication systems should be considered when choosing the modified PTS method.

REFERENCES

[1] S. H. Han and J. H. Lee, "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," *IEEE Wireless Commun.*, vol. 12, no. 2, pp. 56–65, Apr. 2005.

[2] Y.-R. Tsai and S.-J. Huang, "PTS with non-uniform phase factors for PAPR reduction in OFDM systems," *IEEE Commun. Lett.*, vol. 12, no. 1, pp. 20–22, Jan. 2008.

[3] P. Varahram, B. M. Ali, S. Mohammady, and A. W. Reza, "Prototype of a peak to average power ratio reduction scheme in orthogonal frequency division multiplexing systems," *KSII Trans. Internet Inf. Syst.*, vol. 9, no. 6, pp. 2201–2216, Jun. 2015.

[4] D. W. Lim, S. J. Heo, and J. S. No, "An overview of peak-to-average power ratio reduction schemes for OFDM signals," *J. Commun. Netw.*, vol. 11, no. 3, pp. 229–239, Jun. 2009.

[5] J. Wang *et al.*, "Spectral efficiency improvement with 5G technologies: Results from field tests," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 8, pp. 1865–1875, Aug. 2017.

[6] F. Sandoval, G. Poitau, and F. Gagnon, "Hybrid peak-to-average power ratio reduction techniques: Review and performance comparison," *IEEE Access*, vol. 5, pp. 27145–27161, Nov. 2017.

[7] C. Chang, H. Huan, J. Guo, and R. Tao, "Complementary peak reducing signals for TDCS PAPR reduction," *IET Commun.*, vol. 11, no. 6, pp. 961–967, 2017.

[8] H. Rhee, "A low complexity PTS technique using threshold for PAPR reduction in OFDM systems," *KSII Trans. Internet Inf. Syst.*, vol. 6, no. 9, pp. 2191–2201, 2012.

[9] P. Mukunthan and P. Dananjayan, "A modified PTS combined with interleaving and pulse shaping method based on PAPR reduction for STBC MIMO-OFDM system," *WSEAS Trans. Commun.*, vol. 12, no. 3, pp. 121–131, 2012.

[10] H. Müller and B. Huber, "A novel peak power reduction scheme for OFDM," in *Proc. 8th Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Helsinki, Finland, Sep. 1997, pp. 1090–1094.

[11] D. C. Park and S. C. Kim, "Partial transmit sequence scheme for envelope fluctuation reduction in OFDMA uplink systems," *IEEE Commun. Lett.*, vol. 22, no. 8, pp. 1652–1655, Aug. 2018.

[12] S. Peng, A. Liu, L. Song, I. Memon, and H. Wang, "Spectral efficiency maximization for deliberate clipping-based multicarrier faster-than-Nyquist signaling," *IEEE Access*, vol. 6, pp. 13617–13623, Mar. 2018.

[13] K. Anoh, B. Adebisi, M. Rabie, and C. Tanriover, "Root-based nonlinear companding technique for reducing PAPR of precoded OFDM signals," *IEEE Access*, vol. 6, pp. 4618–4629, 2018.

[14] Z. Abdullah, M. S. Hossain, and M. N. Islam, "Comparative study of PAPR reduction techniques in OFDM," *ARPN J. Sys. Softw.*, vol. 1, no. 8, pp. 263–269, 2011.

[15] M. Hossain, S. Ahmed, E. Ullah, and M. Islam, "PAPR reduction of OFDM system through iterative selection of input sequences," *Proc. IJECCT*, vol. 3, pp. 1–4, Mar. 2013.

[16] K. Pachori and A. Mishra, "An efficient combinational approach for PAPR reduction in MIMO–OFDM system," *Wireless Netw.*, vol. 22, no. 2, pp. 417–425, 2016.

[17] M. Sundararajan and U. Govindaswamy, "Multicarrier spread spectrum modulation schemes and efficient FFT algorithms for cognitive radio systems," *Electronics*, vol. 3, no. 3, pp. 419–443, 2014.

[18] Y. A. Jawhar, R. A. Abdulhasan, and K. N. Ramli, "Influencing parameters in peak to average power ratio performance on orthogonal frequency-division multiplexing system," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 6, pp. 4322–4332, 2016.

[19] W. Yi and H. Leib, "OFDM symbol detection integrated with channel multipath gains estimation for doubly-selective fading channels," *Phys. Commun.*, vol. 22, pp. 19–31, Mar. 2017.

[20] T. Jiang and Y. Wu, "An overview: Peak-to-average power ratio reduction techniques for OFDM signals," *IEEE Trans. Broadcast.*, vol. 54, no. 2, pp. 257–268, Jun. 2008.

[21] M. Vidya, M. Vijayalakshmi, and K. Ramalingareddy, "Performance enhancement of efficient partitioning technique for PAPR reduction in MIMO-OFDM system using PTS," in *Proc. IEEE Conf. Power, Control, Commun. Comput. Technol. Sustain. Growth (PCCCTSG)*, Kurnool, India, Dec. 2015, pp. 247–253.

[22] Y. A. Jawhar, R. A. Abdulhasan, and K. N. Ramli, "A new hybrid sub-block partition scheme of PTS technique for reduction PAPR performance in OFDM system," *ARPN J. Eng. Appl. Sci.*, vol. 11, pp. 3904–3910, Apr. 2016.

[23] S. P. Mohammad and K. Gopal, "Hybrid technique for BER and paper analysis of OFDM systems," *Indian J. Sci. Technol.*, vol. 9, no. 15, pp. 1–5, 2016.

[24] N. B. Raja and A. Gangatharan, "A new low complexity DHT based weighted OFDM transmission for peak power reduction," *Indian J. Sci. Technol.*, vol. 9, no. 17, pp. 1–4, 2016.

[25] B. H. Alhasson and M. A. Matin, "PAPR distribution analysis of OFDM signals with partial transmit sequence," *J. Commun.*, vol. 7, no. 11, pp. 784–789, 2012.

[26] J. S. Chow, J. C. Tu, and J. M. Cioffi, "A discrete multitone transceiver system for HDSL applications," *IEEE J. Sel. Areas Commun.*, vol. 9, no. 6, pp. 895–908, Aug. 1991.

[27] R. Gerzaguet *et al.*, "The 5G candidate waveform race: A comparison of complexity and performance," *EURASIP J. Wireless Commun. Netw.*, vol. 2013, pp. 1–13, Dec. 2013.

[28] E. Costa and S. Pupolin, "M-QAM-OFDM system performance in the presence of a nonlinear amplifier and phase noise," *IEEE Trans. Commun.*, vol. 50, no. 3, pp. 462–472, Mar. 2002.

[29] G. T. Zhou and J. S. Kenney, "Predicting spectral regrowth of nonlinear power amplifiers," *IEEE Trans. Commun.*, vol. 50, no. 5, pp. 718–722, May 2002.

[30] P. Miao, P. Chen, and Z. Chen, "Low-complexity PAPR reduction scheme combining multi-band Hadamard precoding and clipping in OFDM-based optical communications," *Electronics*, vol. 7, no. 2, pp. 1–16, 2018.

[31] M. Taher, J. Mandeep, M. Ismail, S. Samad, and T. Islam, "Reducing the power envelope fluctuation of OFDM systems using side information supported amplitude clipping approach," *Int. J. Circuit Theory Appl.*, vol. 42, no. 4, pp. 425–435, 2014.

[32] J. Armstrong, "Peak-to-average power reduction for OFDM by repeated clipping and frequency domain filtering," *Electron. Lett.*, vol. 38, no. 5, pp. 246–247, 2002.

[33] S. Krongold and L. Jones, "PAR reduction in OFDM via active constellation extension," *IEEE Trans. Broadcast.*, vol. 49, no. 3, pp. 258–268, Sep. 2003.

[34] C. Ni, Y. Ma, and T. Jiang, "A novel constellation amplitude modification method for PAPR reduction in OFDM systems," *Wireless Commun. Mobile Comput.*, vol. 16, no. 18, pp. 3307–3315, 2016.

[35] H. Bindu and M. Chandrika, "Combined DCT and companding for PAPR reduction in OFDM signals," *Int. J. Innov. Res. Sci. Technol.*, vol. 2, no. 2, pp. 730–735, 2016.

[36] X. Wu, J. Wang, B. Zhou, Z. Mao, and Z. Gao, "Companding schemes based on transforming signal statistics into trigonal distributions for PAPR reduction in OFDM systems," *Int. J. Commun. Syst.*, vol. 24, no. 6, pp. 776–788, 2011.

[37] C. Kang, Y. Liu, M. Hu, and H. Zhang, "A low complexity PAPR reduction method based on FWFT and PEC for OFDM systems," *IEEE Trans. Broadcast.*, vol. 63, no. 2, pp. 416–425, Jun. 2017.

[38] R. Yoshizawa and H. Ochiai, "Trellis-assisted constellation subset selection for PAPR reduction of OFDM signals," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2183–2198, Mar. 2017.

[39] M. A. Taher, M. J. Singh, M. Ismail, S. A. Samad, and M. T. Islam, "Sliding the SLM-technique to reduce the non-linear distortion in OFDM systems," *Elektron. Elektrotechn.*, vol. 19, no. 5, pp. 103–111, 2014.

[40] H. Breiling, S. H. Müller-Weinfurtner, and J. B. Huber, "SLM peak-power reduction without explicit side information," *IEEE Commun. Lett.*, vol. 5, no. 6, pp. 239–241, Jun. 2001.

[41] M. M. Rahman, M. N. A. S. Bhuiyan, M. S. Rahim, and S. Ahmed, "A computationally efficient selected mapping technique for reducing PAPR of OFDM," *Telecommun. Syst.*, vol. 65, no. 4, pp. 637–647, 2017.

[42] S. H. Müller and J. B. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Electron. Lett.*, vol. 33, no. 5, pp. 368–369, 1997.

[43] Y. Jawhar *et al.*, "New low-complexity segmentation scheme for the partial transmit sequence technique for reducing the high PAPR value in OFDM systems," *Electron. Telecommun. Res. Inst. J.*, vol. 40, no. 6, pp. 699–713, Jun. 2018.

[44] D. D. Falconer, "Linear precoding of OFDMA signals to minimize their instantaneous power variance," *IEEE Trans. Commun.*, vol. 59, no. 4, pp. 1154–1162, Apr. 2011.

[45] A. D. S. Jayalath and C. Tellambura, "Reducing the peak-to-average power ratio of orthogonal frequency division multiplexing signal through bit or symbol interleaving," *Electron. Lett.*, vol. 36, no. 13, pp. 1161–1163, 2000.

[46] H. Liang, H.-C. Chu, and C. B. Lin, "Peak-to-average power ratio reduction of orthogonal frequency division multiplexing systems using modified tone reservation techniques," *Int. J. Commun. Syst.*, vol. 29, no. 4, pp. 748–759, 2016.

[47] B. Horvath and B. Botlik, "Optimization of tone reservation-based PAPR reduction for OFDM systems," *Radioengineering*, vol. 26, no. 3, pp. 791–797, 2017.

[48] S. H. Han, J. M. Cioffi, and J. H. Lee, "Tone injection with hexagonal constellation for peak-to-average power ratio reduction in OFDM," *IEEE Commun. Lett.*, vol. 10, no. 9, pp. 646–648, Sep. 2006.
[49] L. Wang and C. Tellambura, "An overview of peak-to-average power ratio reduction techniques for OFDM systems," in *Proc. IEEE Int. Symp. Signal Process. Inf. Technol.*, Vancouver, BC, Canada, Aug. 2006, pp. 840–845.
[50] N. Ta pınar, D. Karaboğa, M. Yıldırım, and B. Akay, "PAPR reduction using artificial bee colony algorithm in OFDM systems," *Turkish J. Elect. Eng. Comput. Sci.*, vol. 19, no. 1, pp. 47–58, 2010.
[51] N. Ta pınar, D. Karaboğa, M. Yıldırım, and B. Akay, "Partial transmit sequences based on artificial bee colony algorithm for peak-to-average power ratio reduction in multicarrier code division multiple access systems," *IET Commun.*, vol. 5, no. 8, pp. 1155–1162, 2011.
[52] N. Ta pınar and M. Yıldırım, "A novel parallel artificial bee colony algorithm and its PAPR reduction performance using SLM scheme in OFDM and MIMO-OFDM systems," *IEEE Commun. Lett.*, vol. 19, no. 10, pp. 1830–1833, Oct. 2015.
[53] N. Ta pınar, A. Kalinli, and M. Yıldırım, "Partial transmit sequences for PAPR reduction using parallel tabu search algorithm in OFDM systems," *IEEE Commun. Lett.*, vol. 15, no. 9, pp. 974–976, Sep. 2011.
[54] N. Ta pınar and Y. T. Bozkurt, "Peak-to-average power ratio reduction using backtracking search optimization algorithm in OFDM systems," *Turkish J. Elect. Eng. Comput. Sci.*, vol. 24, no. 4, pp. 2307–2316, 2016.
[55] N. Ta pınar and Y. T. Bozkurt, "PAPR reduction using genetic algorithm in lifting-based wavelet packet modulation systems," *Turkish J. Elect. Eng. Comput. Sci.*, vol. 24, no. 1, pp. 184–195, 2016.
[56] H.-S. Joo, K.-H. Kim, J.-S. No, and D.-J. Shin, "New PTS schemes for PAPR reduction of OFDM signals without side information," *IEEE Trans. Broadcast.*, vol. 63, no. 3, pp. 562–570, Sep. 2017.
[57] Y. T. Bozkurt and N. Ta pınar, "Peak-to-average power ratio reduction in lifting based wavelet packet modulation systems using differential evolution algorithm," *Wireless Pers. Commun.*, vol. 94, no. 3, pp. 1073–1086, 2017.
[58] Y. A. Al-Jawhar, N. S. M. Shah, M. A. Taher, M. S. Ahmed, and K. N. Ramli, "An enhanced partial transmit sequence segmentation schemes to reduce the PAPR in OFDM systems," *Int. J. Adv. Comput. Sci. Appl.*, vol. 7, no. 12, pp. 66–75, 2017.
[59] Y. A. Jawhar, N. S. Shah, M. A. Taher, M. S. Ahmed, K. N. Ramli, and R. Abdulhasan, "A low PAPR performance with new segmentation schemes of partial transmit sequence for OFDM systems," *Int. J. Adv. Appl. Sci.*, vol. 4, no. 4, pp. 14–21, 2017.
[60] K.-S. Lee, Y.-J. Cho, J.-Y. Woo, J.-S. No, and D.-J. Shin, "Low-complexity PTS schemes using OFDM signal rotation and pre-exclusion of phase rotating vectors," *IET Commun.*, vol. 10, no. 5, pp. 540–547, 2016.
[61] S. H. Müller, R. W. Bäuml, R. F. H. Fischer, and J. B. Huber, "OFDM with reduced peak-to-average power ratio by multiple signal representation," in *Proc. Int. Conf. Ann. Telecommun.*, Ntirnberg, Germany, Dec. 1997, pp. 58–67.
[62] C. Tellambura, "Computation of the continuous-time PAR of an OFDM signal with BPSK subcarriers," *IEEE Commun. Lett.*, vol. 5, no. 5, pp. 185–187, May 2001.
[63] H. Ochiai and H. Imai, "On the distribution of the peak-to-average power ratio in OFDM signals," *IEEE Trans. Commun.*, vol. 49, no. 2, pp. 282–289, Feb. 2001.
[64] A. Kakkar, S. N. Garsha, and O. Jain, "Improvisation in BER and PAPR by using hybrid reduction techniques in MIMO-OFDM employing channel estimation techniques," in *Proc. IEEE 7th Int. Adv. Comput. Conf. (IACC)*, Hyderabad, India, Jun. 2017, pp. 170–173.
[65] R. O'neill and L. Lopes, "Envelope variations and spectral splatter in clipped multicarrier signals," in *Proc. 6th IEEE Int. Symp. Pers., Indoor Mobile Radio Commun., Wireless, Merging Inf. Superhighway (PIMRC)*, Toronto, ON, Canada, Sep. 1995, pp. 71–75.
[66] X. Wang, T. T. Tjhung, and C. S. Ng, "Reduction of peak-to-average power ratio of OFDM system using a companding technique," *IEEE Trans. Broadcast.*, vol. 45, no. 3, pp. 303–307, Sep. 1999.
[67] A. Gangwar and M. Bhardwaj, "An overview: Peak to average power ratio in OFDM system & its effect," *Int. J. Commun. Comput. Technol.*, vol. 1, no. 2, pp. 22–25, 2012.
[68] P. Mukunthan and P. Dananjayan, "PAPR reduction by modified PTS combined with interleaving technique for OFDM system with QPSK subcarriers," in *Proc. Int. Conf. Adv. Eng., Sci. Manage. (ICAESM)*, Nagapattinam, India, Mar. 2012, pp. 410–415.
[69] T. Sravanti and N. Vasantha, "Precoding PTS scheme for PAPR reduction in OFDM," in *Proc. Int. Conf. Innov. Elect., Electron., Instrum. Media Technol. (ICEEIMT)*, Coimbatore, India, Feb. 2017, pp. 250–254.
[70] J. Wang, Y. Guo, and X. Zhou, "PTS-clipping method to reduce the PAPR in ROF-OFDM system," *IEEE Trans. Consum. Electron.*, vol. 55, no. 2, pp. 356–359, May 1999.
[71] C. Anjaiah and H. K. P. Prasad, "Mu-Law companded PTS for PAPR reduction in OFDM systems," in *Proc. Int. Conf. Elect., Comput. Commun. Technol. (ICECCT)*, Coimbatore, India, Mar. 2015, pp. 1–4.
[72] Y. Wang, Y. Jianjun, and C. Nan, "Demonstration of 4×128-Gb/s DFT-S OFDM signal transmission over 320-km SMF with IM/DD," *IEEE Photon. J.*, vol. 8, no. 2, Apr. 2016, Art. no. 7903209.
[73] J. Zhou and Y. Qiao, "Low-peak-to-average power ratio and low-complexity asymmetrically clipped optical orthogonal frequency-division multiplexing uplink transmission scheme for long-reach passive optical network," *Opt. Lett.*, vol. 40, no. 17, pp. 4034–4037, 2015.
[74] J. Zhou *et al.*, "Interleaved single-carrier frequency-division multiplexing for optical interconnects," *Opt. Express*, vol. 25, no. 9, pp. 10586–10596, 2017.
[75] X. Tang *et al.*, "Experimental demonstration of 40-Gb/s I-SC-FDM with 10G-class optics and low-complexity DSP for next-generation PON," *IEEE Photon. J.*, vol. 10, no. 3, Jun. 2018, Art. no. 7202509.
[76] Z. Fulai, L. Luokun, and Y. Jinjin, "DFT-spread combined with PTS method to reduce the PAPR in VLC-OFDM system," in *Proc. 5th IEEE Int. Conf. Softw. Eng. Service Sci.*, Beijing, China, Jun. 2014, pp. 629–632.
[77] S. Tabassum, S. Hussain, and A. Ghafoor, "Peak to average power ratio reduction in NC–OFDM systems," *J. Elect. Eng.*, vol. 66, no. 3, pp. 154–158, 2015.
[78] R. Jayashri, S. Sujatha, and P. Dananjayan, "DCT based partial transmit sequence technique for PAPR reduction in OFDM transmission," *ARPN J. Eng. Appl. Sci.*, vol. 10, no. 5, pp. 2182–2186, 2016.
[79] T. Jiang, W. Xiang, P. C. Richardson, J. Guo, and G. Zhu, "PAPR reduction of OFDM signals using partial transmit sequences with low computational complexity," *IEEE Trans. Broadcast.*, vol. 53, no. 3, pp. 719–724, Sep. 2007.
[80] K. Ramli *et al.*, "An enhanced partial transmit sequence based on combining Hadamard matrix and partitioning schemes in OFDM systems," *Int. J. Integr. Eng.*, vol. 10, no. 3, pp. 1–7, Jul. 2018.
[81] S.-J. Ku and C.-L. Wang, "A new side-information free PTS scheme for PAPR reduction in OFDM systems," in *Proc. 8th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2012, pp. 108–112.
[82] C.-C. Feng, Y.-T. Wu, and C.-Y. Chi, "Embedding and detection of side information for peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences," in *Proc. 58th Int. Conf. Veh. Technol. Conf. (VTC-Fall)*, Oct. 2003, pp. 1354–1358.
[83] T. Giannopoulos and V. Paliouras, "A low-complexity PTS-based PAPR reduction technique for OFDM signals without transmission of side information," *J. Signal Process. Syst.*, vol. 56, no. 2, pp. 141–153, 2009.
[84] E. Kalaiselvan, P. Elavarasan, and G. Nagarajan, "PAPR reduction of OFDM signals using pseudo random PTS without side information," in *Proc. IEEE Int. Conf. Commun. Signal Process. (ICCSP)*, Apr. 2013, pp. 29–33.
[85] A. D. S. Jayalath and C. Tellambura, "SLM and PTS peak-power reduction of OFDM signals without side information," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2006–2013, Sep. 2005.
[86] A. Goel, P. Gupta, and M. Agrawal, "Joint ICI cancellation and PAPR reduction in OFDM systems without side information," *Wireless Pers. Commun.*, vol. 71, no. 4, pp. 2605–2623, 2013.
[87] T. Sravanti and N. Vasantha, "Performance analysis of precoded PTS and SLM scheme for PAPR reduction in OFDM system," in *Proc. IEEE Int. Conf. Innov. Elect., Electron., Instrum. Media Technol. (ICEEIMT)*, Coimbatore, India, Feb. 2017, pp. 255–260.
[88] Y. A. Al-Jawhar, K. N. Ramli, M. S. Ahmed, R. Abdulhasan, H. Farhood, and M. Alwan, "A New Partitioning Scheme for PTS Technique to Improve the PAPR Performance in OFDM Systems," *Int. J. Eng. Technol. Innov.*, vol. 8, no. 3, pp. 217–227, May 2018.
[89] S. G. Kang, J. G. Kim, and E. K. Joo, "A novel subblock partition scheme for partial transmit sequence OFDM," *IEEE Trans. Broadcast.*, vol. 45, no. 3, pp. 333–338, Sep. 1999.

[90] Z. T. Ibraheem, M. M. Rahman, S. N. Yaakob, M. S. Razalli, R. A. Kadhim, and K. K. Ahmed, ''Performance of PTS techniques with varied partition size in PAPR reduction of OFDM system,'' in *Proc. IEEE Int. Conf. Comput., Commun., Control Technol. (I4CT)*, Langkawi, Malaysia, Sep. 2014, pp. 21–25.
[91] C. Hong, Q. Qin, and T. Chao, ''An PTS optimization algorithm for PAPR reduction of OFDM system,'' in *Proc. IEEE Int. Conf. Mech. Sci., Electr. Eng. Comput. (MEC)*, Shengyang, China, Dec. 2013, pp. 3775–3778.
[92] X. Wu, Z. Mao, J. Wang, and B. Zhou, ''A novel PTS technique with combinative optimization in real part and imaginary part for PAPR reduction in OFDM systems,'' in *Proc. IEEE 3rd Int. Conf. Next Gener. Mobile Appl., Services Technol. (NGMAST)*, Cardiff, U.K., Sep. 2009, pp. 215–218.
[93] P. Varahram, W. F. Al-Azzo, and B. M. Ali, ''A low complexity partial transmit sequence scheme by use of dummy signals for PAPR reduction in OFDM systems,'' *IEEE Trans. Consum. Electron.*, vol. 56, no. 4, pp. 2416–2420, Nov. 2010.
[94] H.-G. Ryu, J.-E. Lee, and J.-S. Park, ''Dummy sequence insertion (DSI) for PAPR reduction in the OFDM communication system,'' *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 89–94, Feb. 2004.
[95] P. Varahram, B. M. Ali, and W. Al-Azzo, ''Low complexity ADRG-PTS scheme for PAPR reduction in OFDM systems,'' in *Proc. 13th IEEE Int. Conf. Adv. Commun. Technol. (ICACT)*, Seoul, South Korea, Feb. 2011, pp. 331–334.
[96] P. Varahram, W. Al-Azzo, and B. M. Ali, ''IDRG–PTS scheme with low complexity for peak-to-average power ratio reduction in OFDM systems,'' *J. Chin. Inst. Eng.*, vol. 36, no. 6, pp. 677–683, 2013.
[97] Z. T. Ibraheem, M. M. Rahman, S. N. Yaakob, M. S. Razalli, S. R. F. Salman, and K. K. Ahmed, ''PTS method with combined partitioning schemes for improved PAPR reduction in OFDM system,'' *Indonesian J. Elect. Eng. Comput. Sci.*, vol. 12, no. 11, pp. 7845–7853, 2014.
[98] D.-W. Lim, S.-J. Heo, J.-S. No, and A. Chung, ''A PTS OFDM scheme with low computational complexity,'' in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, Adelaide, SA, Australia, Sep. 2005, pp. 1141–1144.
[99] D.-W. Lim, S.-J. Heo, J.-S. No, and H. Chung, ''A new PTS OFDM scheme with low complexity for PAPR reduction,'' *IEEE Trans. Broadcast.*, vol. 52, no. 1, pp. 77–82, Mar. 2006.
[100] L. Wang and Y. Cao, ''Sub-optimum PTS for PAPR reduction of OFDM signals,'' *Electron. Lett.*, vol. 44, no. 15, pp. 921–922, Jul. 2008.
[101] A. D. S. Jayalath, C. Tellambura, and H. Wu, ''Reduced complexity PTS and new phase sequences for SLM to reduce PAP of an OFDM signal,'' in *Proc. IEEE 51st Int. Conf. Veh. Technol. (VTC-Spring)*, Tokyo, Japan, May 2000, pp. 1914–1917.
[102] L. Wang and J. Liu, ''Cooperative PTS for PAPR reduction in MIMO-OFDM,'' *Electron. Lett.*, vol. 47, no. 5, pp. 351–352, 2011.
[103] L. J. Cimini and N. R. Sollenberger, ''Peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences,'' in *Proc. IEEE 1st Int. Conf. New Technol. Inf. Commun. (NTIC)*, Mila, Algeria, Nov. 1999, pp. 511–515.
[104] J. Gao, J. Wang, and B. Wang, ''Peak-to-average power ratio reduction based on cyclic iteration partial transmit sequence,'' in *Proc. IEEE 3rd Int. Symp. Intell. Inf. Technol. Appl.*, Shanghai, China, Nov. 2009, pp. 161–164.
[105] O.-J. Kwon and Y.-H. Ha, ''Multi-carrier PAP reduction method using sub-optimal PTS with threshold,'' *IEEE Trans. Broadcast.*, vol. 49, no. 2, pp. 232–236, Jun. 2003.
[106] A. D. S. Jayalath and C. Tellambura, ''Adaptive PTS approach for reduction of peak-to-average power ratio of OFDM signal,'' *Electron. Lett.*, vol. 36, no. 14, pp. 1226–1228, Jul. 2000.
[107] F. Wang, F. Wang, Z. Wang, and L. Chen, ''A novel sub-optimal PTS algorithm for controlling PAPR of OFDM signals,'' in *Proc. IEEE Int. Conf. Inf. Theory Inf. Secur.*, Beijing, China, Dec. 2010, pp. 728–731.
[108] X. Zhu, G. Zhu, T. Jiang, L. Yu, Y. Zhang, and P. Lin, ''Extended iterative flipping algorithm for PAPR reduction in OFDM systems,'' in *Proc. IEEE 3rd Int. Conf. Commun. Netw.*, Hangzhou, China, Aug. 2008, pp. 1018–1022.
[109] P. Liu, W.-P. Zhu, and A. Ahmad, ''A phase adjustment based partial transmit sequence scheme for PAPR reduction,'' *Circuits, Syst. Signal Process.*, vol. 23, pp. 329–337, Aug. 2004.
[110] W. Lan-Xun and Y. Li-Bin, ''A modified PTS method using m sequences for PAPR reduction,'' in *Proc. IEEE Int. Conf. Meas., Inf. Control*, Harbin, China, May 2012, pp. 837–840.
[111] L. Hu, C. Li, and G. Wan, ''A modified sub-optimal algorithm for reducing PAPR of multicarrier communication systems,'' in *Proc. IEEE 1st Int. Conf. Innov. Comput., Inf. Control (ICICIC)*, Beijing, China, Aug. 2006, pp. 175–178.
[112] L. Junjun, Z. Wei, Y. Zhu, and M. Teng, ''Low complexity PTS algorithm based on Gray code and its FPGA implementation,'' in *Proc. IEEE 10th Int. Conf. Electron. Meas. Instrum. (ICEMI)*, Chengdu, China, Aug. 2011, pp. 208–211.
[113] J. Sarawong, T. Mata, P. Boonsrimuang, and H. Kobayashi, ''Interleaved partitioning PTS with new phase factors for PAPR reduction in OFDM systems,'' in *Proc. IEEE 8th Int. Conf. Electr. Eng./Electron. Comput., Telecommun. Inf. Technol. (ECTI-CON)*, Khon Kaen, Thailand, May 2011, pp. 360–364.
[114] P. Boonsrimuang, K. Mori, T. Paungma, and H. Kobayashi, ''Proposal of improved PTS method for OFDM signal,'' in *Proc. IEEE 18th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Athens, Greece, Sep. 2007, pp. 1–5.
[115] L. Wang and J. Liu, ''PAPR reduction of OFDM signals by PTS with grouping and recursive phase weighting methods,'' *IEEE Trans. Broadcast.*, vol. 57, no. 2, pp. 299–306, Jun. 2011.
[116] P. Elavarasan and G. Nagarajan, ''Performance analysis of PTS using GPW and RPW to reduce PAPR in OFDM systems,'' in *Proc. IEEE Int. Conf. Commun. Signal Process. (ICCSP)*, Chennai, India, Apr. 2012, pp. 36–41.
[117] L. Yang, K.-K. Soo, S. Li, and Y.-M. Siu, ''PAPR reduction using low complexity PTS to construct of OFDM signals without side information,'' *IEEE Trans. Broadcast.*, vol. 57, no. 2, pp. 284–290, Jun. 2011.
[118] K.-H. Kim, ''On the shift value set of cyclic shifted sequences for PAPR reduction in OFDM systems,'' *IEEE Trans. Broadcast.*, vol. 62, no. 2, pp. 496–500, Jun. 2016.
[119] A. S. Namitha and S. M. Sameer, ''A bandwidth efficient selective mapping technique for the PAPR reduction in spatial multiplexing MIMO-OFDM wireless communication system,'' *Phys. Commun.*, vol. 25, pp. 128–138, Dec. 2017.
[120] S. S. Hassaneen, H. Y. Soliman, K. A. Elbarbary, and A. E. Elhennawy, ''Modified PTS with circular shifting for PAPR reduction in MIMO OFDM systems,'' in *Proc. IEEE 2nd Japan-Egypt Int. Conf. Electron., Commun. Comput. (JEC-ECC)*, 6th of October, Egypt, Dec. 2013, pp. 1–6.
[121] Z. Sharifian, M. J. Omidi, H. Saeedi-Sourck, and A. Farhang, ''Linear precoding for PAPR reduction of GFDMA,'' *IEEE Wireless Commun. Lett.*, vol. 5, no. 5, pp. 520–523, Oct. 2016.
[122] D. Qu, S. Lu, and T. Jiang, ''Multi-block joint optimization for the peak-to-average power ratio reduction of FBMC-OQAM signals,'' *IEEE Trans. Signal Process.*, vol. 61, no. 7, pp. 1605–1613, Apr. 2013.
[123] B. Farhang-Boroujeny, ''OFDM versus filter bank multicarrier,'' *IEEE Signal Process. Mag.*, vol. 28, no. 3, pp. 92–112, May 2011.
[124] Y. Liu *et al.*, ''Waveform design for 5G networks: Analysis and comparison,'' *IEEE Access*, vol. 5, pp. 19282–19292, 2017.
[125] J. Abdoli, M. Jia, and J. Ma, ''Filtered OFDM: A new waveform for future wireless systems,'' in *Proc. 16th IEEE Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Stockholm, Sweden, Jul. 2015, pp. 66–70.

YASIR AMER JAWHAR received the B.S. degree in electrical engineering from the College of Engineering, University of Al-Mustansiriya, Baghdad, Iraq, in 1998, and the M.S. degree in engineering from the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, in 2015, where he is currently pursuing the Ph.D. degree in communication engineering. His current research interests include signal processing in communication, OFDM, PAPR reduction in multicarrier systems, 5G waveform design, and wireless networks.

LUKMAN AUDAH received the B.S. degree in electrical engineering from University Technology Malaysia, Johor, Malaysia, in 2005, and the M.S. and Ph.D. degrees in communication networks and software from the University of Surrey, U.K., in 2007 and 2013, respectively. Since 2014, he has been with the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, where he is currently a Lecturer. His current research interests include wireless and mobile communications, the Internet traffic engineering, network system management, data security, and satellite communications.

MONTADAR ABAS TAHER received the B.S. degree in electronics and communications engineering and the M.S. degree in satellite engineering from Al-Nahrain University, Baghdad, Iraq, in 2000 and 2003, respectively, and the Ph.D. degree from Universiti Kebangsaan Malaysia, Kula Lumpur, Malaysia, in 2015. Since 2010, he has been with the Department and Communication, University of Diyala, Diyala, Iraq, where he is currently a Senior Lecturer. His current research interests include OFDM, CDMA, MC-CDMA, PAPR reduction in multicarrier systems, and DSP for telecommunication.

KHAIRUN NIDZAM RAMLI received the B.S. degree in electrical engineering from the University of Manchester Institute of Science and Technology, Manchester, U.K., in 1997, the M.S. degree in engineering from Universiti Kebangsaan Malaysia, Kula Lumpur, Malaysia, in 2004, and the Ph.D. degree for research in electromagnetic analysis from the University of Bradford, U.K., in 2011. Since 2011, he has been with the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, where he is currently a Senior Lecturer. His current research interests include wireless technologies, antennas, electromagnetics, and engineering computing.

NOR SHAHIDA MOHD SHAH received the B.S. degree in electrical engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2000, the M.S. degree from the University of Malaya, Kula Lumpur, Malaysia, in 2003, and the Ph.D. degree from Osaka University, Tokyo, Japan, in 2012. Since 2011, she has been with the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, where she is currently a Senior Lecturer. Her current research interests include optical fiber devices, optical communication, nonlinear optics, optical signal processing, antenna and propagation, and wireless communication.

MUSTAFA MUSA received the B.S. degree in computer science from the University of Baghdad, Baghdad, Iraq, in 2005, and the M.S. degree in internetworking technology and the Ph.D. degree from University Technical Malaysia Melaka, Melaka, Malaysia, in 2012 and 2017, respectively. Since 2006, he has been with the Iraq Ministry of Interior. His current research interests include counter terrorism, E-tools in intelligence field, information sharing, information systems, and research methods.

MUSTAFA SAMI AHMED received the B.S. degree in computer communication engineering from the Al-Rafidain

University College, Baghdad, Iraq, in 2011, and the M.S. degree in engineering from the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia, in 2015, where he is currently pursuing the Ph.D. degree in communication engineering. His research interests include digital signal processing and wireless communication.