Analysis of PAPR Reduction Schemes to Develop Selection Criteria for OFDM Signals

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ABSTRACT

This paper presents a review of different PAPR (Peak to Average Power Ratio) reduction schemes of OFDM (Orthogonal Frequency Division Multiplexing) signals. The schemes that have been considered include Clipping and Filtering, Coding, ACE (Active Contstellation Extension), SLM (Selected Mapping), PTS (Partial Transmit Sequence), TI (Tone Injection) and TR (Tone Reservation). A comparative analysis has been carried out qualitatively. It has been demonstrated how these schemes can be combined with MIMO (Multiple Input Multiple Output) technologies. Finally, criteria for selection of PAPR reduction schemes of OFDM systems are discussed.

Key Words: Orthogonal Frequency Division Multiplexing, High Power Amplifier, Peak to Average Power Ratio, Clipping and Filtering, Selected Mapping, Tone Reservation, Tone Injection, Active Contstellation Extension and Multiple Input Multiple Output.

1. INTRODUCTION

OFDM also termed as transmission with multicarrier or DMT (Discrete Multi-Tone), is a promising modulation scheme that can support high data rate transmission in harsh propagation environments. Thus, it is adopted in several wireless standards [1]. Also it has been implemented not only in UMTS (Universal Mobile Telecommunication System) but also in 4G (Fourth Ggeneration) networks such as LTE (Long Term Evolution). However, the major issue of the OFDM system is the high value of PAPR because of its multi-carrier nature. This issue may lead to high (deviated from band) emission of radiated waves as the signal is transmitted through radio frequency HPA (High Power Amplifier). When an OFDM signal is transmitted through a nonlinear HPA, it decreases its power consumption efficiency and results in band distortion and spectral spreading which are undesired. Therefore, it may be concluded that ensuring a high PAPR is one of the most significant challenges that are being faced by designers of OFDM systems [2]. The OFDM signal gets clipped when transmitted through a nonlinear HPA at transmitter side. This kind of clipping deteriorates the performance by affecting BER (Bit Error Rate) and leads to spectral spreading [3].To overcome the complex mechanism of search, few search schemes with simplified framework have been proposed in [4-14]. But either the computational complexity is very high for all such search methods or the PAPR reduction performance is not very practical. Several schemes are established to counter the PAPR issue. These include clipping based schemes, coding schemes and

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probabilistic schemes. Some schemes are based on both clipping and filtering as given in [4-5], peak cancellation [6], coding [7], and there are other schemes having continuous solutions such as TR [8-9] and ACE [10]. Few schemes can provide discrete solutions such as TI [11], and signal multiplicative scheme representations like PTS [12], SLM [13], and schemes based on interleaving [14]. Therefore, there is still need to analyze further the methods developed so as to motivate information for reduction of power and performance of HPA as well as ADC (Analog to Digital Converters) in OFDM systems. We have also identified the standards for selecting PAPR reduction schemes. Finally, the PAPR reduction in MIMO OFDM is also presented.

2. CATEGORIZATION OF THE PAPR PROBLEM

The research on PAPR can be widely classified into two categories, PAPR distribution and BER evaluation in regard to attempt more efficient PAPR reduction methods as shown in Fig. 1. PAPR reduction schemes can largely be classified as distortion and distortion less schemes. Schemes involving distortion are dependent on signal clipping and result in OFDM signals being continuously modified. Such methods include iterative clipping, filtering and companding. Furthermore, distortion involving schemes require distortion cancellation schemes to be used to reduce the BER loss that comes as a consequence. Compared to distortion schemes, distortion-less PAPR reduction provides the advantage that they do not increase the BER of the signal. Moreover, BER can also be reduced by the exploitation of the redundancy in the signal. Distortion less schemes are classified in to three types, which include the schemes having continuous output such as TR and ACE, other types of distortion-less schemes are SLM, PTS and TI which tend to give a discrete output. It should be kept in mind; however, that distortion less schemes might require side information for proper detection of the signal. For both type of reduction schemes, it is imperative that low complexity algorithms be developed.

3. SYSTEM DESCRIPTION

3.1 Model of OFDM System

The OFDM model is shown in Fig. 2. Let $X = [X_0, X_1, \ldots, X_{N-1}]^2$ denote an input symbol sequence in the frequency domain, where X_K represents the K^{th} sub-carrier in the complex data and N the number of sub carriers of the OFDM signal. The numbers of subcarriers N are selected as orthogonal leading us to the relationship, $f_m = m\Delta f$, where $\Delta f = 1/NT$. The required signal with multiple carriers is being generated by taking sum of all N modulated sub carriers which are split by 1/NT from each other. Under these conditions, the composite form of the signal with multiple carriers is described in time domain by Equation (1).

$$X_n = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X_i e^{j2\pi ni/LN} \qquad 0 \leq n \leq N-1 \qquad (1)$$

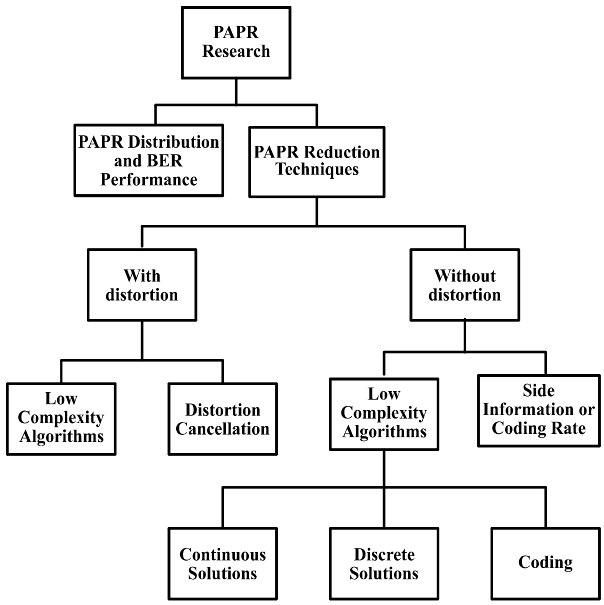

FIG. 1. CATEGORIZATION OF THE PAPR PROBLEM

Where it can also be written in matrix form as:

$X = [X_0, X_1, \ldots, X_{N-1}]^2 = \mathbf{XD}$, where **D** is the DFT matrix with the entry $d_{n,k} = (1/\sqrt{N})e^{2\pi mk/N}$ where $j = \sqrt{-1}$, and n is positioned as discrete time index. L is the over sampling factor and a value of L=4 is sufficient enough to provide the PAPR as an accurate approximation. x_n is the n^{th} signal component in OFDM output symbol.

3.2 Peak to Average Power Ratio

The high value of PAPR of a signal in OFDM scheme occurs by taking sum of the IDFT (Inverse Discrete Fourier Transform) components. The PAPR of an OFDM signal in the analog domain is expre`ssed as the relative value of the maximum and the average power.

$$\mathrm{PAPR}[x(t)] = \frac{P_{max}}{P_{av}} = \frac{\max\limits_{0 \le t \le NT}\left[|x(t)|^2\right]}{E\left\{|x(t)|^2\right\}} \tag{2}$$

Where P_{av} is the average power of signal x(t) and is calculated in the frequency domain, E{.} represents the value operator. The nonlinear distortion in the HPA occurs in the analog domain. But, the majority of the signal processing to reduce PAPR OFDM signal is used in the digital domain. In general, the PAPR in the digital domain is not necessarily the same as PAPR in the analog domain.

The PAPR (in dB) of the transmitted OFDM signal can be written as in Equation (3).

$$CFR_{max} = 10 \log(N) \text{ db} \tag{3}$$

It is a random variable, because PAPR is a function of input data. The CF (Crest Factor) is generally characterized by the square root of the PAPR.

$$CF = \sqrt{PAPR} \text{ or } PAPR = (CF)^2 \tag{4}$$

The CR (Clipping Ratio) is define as follows:

$$CR = \frac{A_{max}}{A_{ave}} \tag{5}$$

Where A_{max} is the maximum amplitude of the output signal after clipping, and A_{ave} is the average amplitude of input signal before clipping.

On the other side, input signal to the clipping process is expressed as in Equation (6).

$$X_{clipped}(n) = \begin{cases} -A, & x(n) \le -A \\ x(n), & x(n) < A \\ A, & x(n) \ge A \end{cases} \tag{6}$$

Where A is the predefined clipping level.

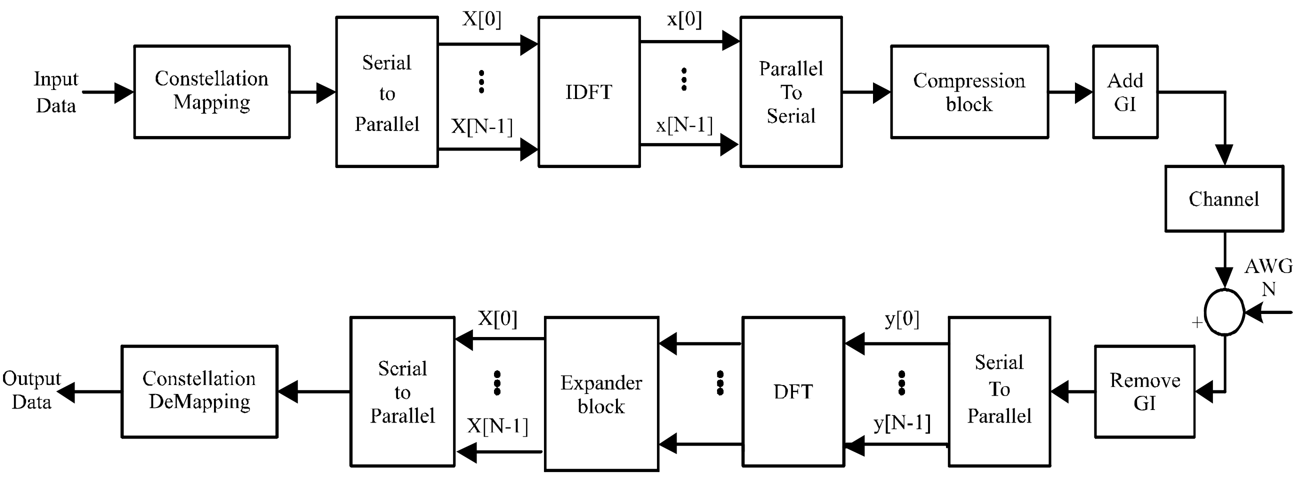

FIG. 2. A TYPICAL OFDM SYSTEM MODEL

4. THE CCDF MEASUREMENT TOOL

In modern telecommunication world CDF (Cumulative Distribution Function) measurement has proven to be one of the most precious tools. The CDF is widely used to gauge the efficiency of PAPR reduction schemes. The CCDF (Complementary Cumulative Distribution Function) is commonly used instead of CDF to calculate the value of PAPR in dB. CCDF of the PAPR provides vital information about a number of factors. This include an estimate for the output back-off for HPA, calculation of the BER, estimation of the achievable information rates as well as an estimation of the bounds on redundancy bit (to keep it minimum) needed to determine the PAPR reduction progression. Therefore, the use of an analytic solution to precisely determine the distribution of PAPR which can surely simplify the process of system design for OFDM systems is highly preferred.

In general, the PAPR is represented by CCDF and is defined as in Equation (7).

$$\text{CCDF } P_{rob}\,[PAPR > PAPR_0] \tag{7}$$

Where $PAPR_0$ is a positive value and P_{rob} [.] is a probability function when the number of subcarriers N is comparatively small.

5. CAUSES OF PAPR REDUCTION

5.1 Power Saving

When the HPA has a large dynamic range, it has reduced efficiency when power is considered. It is observed that reducing PAPR contributes to reducing the power significantly, the net power which is proportional to the average power required, is highly dependent on the level of clipping probability.

Assuming HPA as an ideal linear model, the saturation point of linear amplification was achieved, therefore, we get:

$$\eta = \frac{0.5}{PAPR} \tag{8}$$

Where η is the HPA efficiency and it is defineds $\eta = P_{out,ave}/P_{DC}$, where $P_{out,ave}$ is the average power and P_{DC} is the consistent power available in consideration of input power. From above description, it is clear that a lower efficiency is a prime aim to lessen the PAPR in OFDM systems.

5.2 Performance of HPA and ADC in OFDM Systems

The HPA is widely used in radio systems to generate adequate transmission power. The characteristics of the HPA require that it is operated near or equal to its saturation values in order to satisfy the required maximum efficiency of output power. Furthermore, the nonlinearity in the HPA output is sensitive to changing amplitudes of the input signals. This in-turn introduces interference to OFDM systems because of the high PAPR in the OFDM signal. As a result, the BER increases and thus steps need to be taken to linearize the HPA characteristics so that it can be operated in its linear region which has high dynamic range. Unfortunately, such a linear amplifier exhibits poor efficiency and is costly. Since a high power efficiency is pivotal in all wireless communication systems so as to address issues of area coverage, saving power that is consumed and allowing for small sized terminals etc., it is essential to target the efficient and effective function of the nonlinear HPA while keeping back-off values as low as possible and develop solutions to the interference problems brought about by this action. One approach to avert interference in the OFDM signal is to decrease the PAPR of the transmitted signals by manipulating the OFDM signal itself.

Moreover, signals with large PAPR require that the DAC used should have sample dynamic range so as to be able to tend to the high peaks of the incoming OFDM signals.

High precision DACs offer such PAPR capabilities while keeping quantisation noise low. However, they prove to be too costly given the high sampling rate of the system. On the contrary, a DAC with low accuracy may address the cost issues but the high quantisation noise will render the SNR (Signal to Noise Ratio) too low as the active range of the DAC is improved in accordance with the high value of PAPR. OFDM signals demonstrate a Gaussian distribution when many subcarriers are used which infer that the maximum signal hardly ever appears and constant quantization performed with the DACs is unsuitable. In such a case, clipping may introduce out of band radiation and band distortion to degrade the performance of the communication system. It is therefore concluded that reducing the PAPR of the OFDM signal before they are given to the HPA and the DAC is a suitable solution to this problem. Therefore, best solution is to reduce PAPR in OFDM signal transmission for the nonlinear HPA and DAC.

6. PAPR REDUCTION SCHEMES IN OFDM SYSTEMS

6.1 Clipping and Filtering Scheme

Clipping is the simplest PAPR reduction scheme. This means that clipping can be implemented without any significant computational overhead to the OFDM modulator. Clipping works by fixing a threshold for the OFDM signal. If, the signal has greater power than the threshold, the threshold power is then used to transmit the signal. Clipping is also advantageous in the sense that it does not require an increase in bandwidth. However, the simplicity comes at a cost because clipping causes loss of information as a portion of the OFDM signal is removed altogether. The loss of information increases the BER, which means that for applications which require lower BER such as real-time video transmission, out-of-band interference can be reduced by filtering but it cannot reduce in-band distortion.

In Fig. 3 shows that the Clipping and Filtering reduces PAPR. A greater number of iterations of Clipping and filtering lead to a greater reduction in PAPR of OFDM. This method improves the PAPR with no increase in complexity. However it may increase the bit error rate, which may cause distortion.

6.2 Peak Reduction Carrier Scheme

This scheme uses bearings to reduce the PRCs (Peak Reduction Carriers) data to reduce the effective PAPR in the OFDM system [15]. It includes the use of a higher order modulation scheme to represent a lower order modulation symbol. The amplitude and phase of the PRC is positioned within the constellation region symbolizing the data symbol to be transmitted. This method is suitable for PSK (Phase Shift Keying) modulation; where the envelopes of all subcarriers are the same. When QAM (Quadrature Amplitude Modulation) scheme is implemented in the OFDM system, the carrier envelope scaling will results in serious BER degradation. To limit the BER degradation, amount of the side information would also be excessive when the number of subcarriers is large.

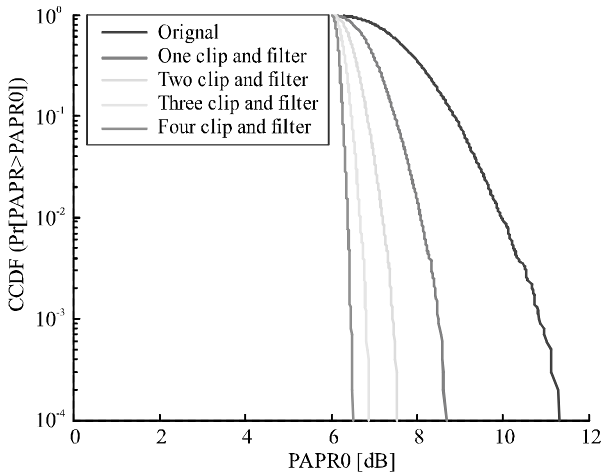

FIG. 3. DISTRIBUTION OF PAPR OF OFDM SIGNAL SAMPLES BY CLIPPING AND FILTERING

6.3 Envelope Scaling Scheme

Envelope scaling technology was proposed in [16].This scheme uses 256 subcarriers with QPSK (Quadratic Phase Shift Keying) modulation schemes to make the envelope subcarriers equivalent. The main idea of the scheme is to make the input packet of some subcarriers so as to achieve a minimum amount of peak to average power ratio at the output of the IFFT. Hence, the receiver of this system does not require further additional information to the receiver to decode the sequence. This scheme is suitable for QPSK modulation; all subcarriers envelopes are equal.This scheme may reduce peak to average ratio by 4db.

6.4 Coding Scheme

In this method FEC (Forward Error Correction) codes are used for PAPR reduction. The FEC codes help scramble the data so that the OFDM symbol created has a smaller PAPR. The advantage of PAPR reduction using Coding is that this method not only provides error correction but also PAPR reduction. The disadvantage is that coding reduces the information rate (bit rate) since redundant information needs to be transmitted. However, since FEC are typically used in communication systems, therefore the idea of using FEC for PAPR reduction is quite attractive. To develop a CBC (Complement Block Coding) scheme, this helps to reduce the PAPR of the OFDM signal. A reduction of about 3dBs is achieved using this method. The convolutional codes are also used to reduce the PAPR of OFDM signals. The motivation is that convolutional codes are already used for various communication systems such as UMTS, LTE, WiMAX etc., so using this scheme for PAPR reduction will be efficient. The use of LDPC (Low Density Parity Check) codes for PAPR reduction show that the use of LDPC can reduce the PAPR of OFDM by about 60%. Also, the combination of LDPC codes and PTS for PAPR reduction of OFDM shows that such schemes can reduce the PAPR by about 3.7 dBs for 8 partitions. In [2], the authors have compared the PAPR reduction capabilities of CC (Cyclic Coding), SBC (Simple Block Coding), CBC (Complement Blocking Coding) and MCBC (Modified Complementary Block Coding). They propose the use of CBC and MCBC codes since they offer high coding rates and provide flexibility between coding rate choices and complexity.

6.5 PTS and SLM Schemes

Another class of PAPR reduction schemes includes multiple signal representation methods such as PTS and SLM. These schemes do not degrade the BER performance but are computationally expensive.

PTS is one of the most popular distortion less PAPR reduction schemes in that it does not increase the BER. However, PTS is computationally complex and is thus comparatively slow. This is a serious disadvantage when compared to other available techniques. During OFDM transmission, it is critical that the side information is received without errors. The performance of PTS generally depends upon two factors i.e. the phase factors being used and the segmentation method utilized. In practice the phase factors, segmentation method and number of segments, are all fixed so that the computational load of the search process can be limited.

For PTS, the data is divided into non-overlapping parts and the subcarriers within each part are applied a phase shift so as to reduce the overall PAPR as much as possible as shown in Fig. 4.

The block diagram shows the functional steps of the PTS method as follows:

- We start with a serial sequence of incoming data.
- In the next step, the incoming data having N subcarriers is divided into non-overlapping parts by the serial to parallel converter.

- This is followed by the IFFT (Inverse Fast Fourier Transform) being performed on the data blocks.
- The individual signals now need to be assigned phase factors having a complex value; this is achieved by means of the PTS method to determine the best possible phase shifts for each data part so as to reduce the overall PAPR to the minimum value.
- It is therefore our aim to determine the best possible phase to bring the PAPR to the lowest value.
- On the receiver end, the reverse operation is performed.

In this method, the input data block U is assigned so that it does not intersect the sub-block, which is represented by a vector $[U^{(w)}, w=1,2,\dots,W-1]$, as shown in Fig. 4. Therefore, we get Equation (9).

$$U = \sum_{w=0}^{W-1} U^{(w)} \qquad (9)$$

Where $[U^{(w)} = \{U^{(w)}_1 U^{(w)}_2 \dots U^{(w)}_{N-1}\}$ with $U^{(w)}_k = U_k$ or 0 ($0 \le w \le W-1$). In PTS, the partitioning methods for sub-blocks are categorized in to three types, the interleaved partition, pseudo random partition and adjacent partition. Then, the sub-blocks U^w are converted in to W which are the time-domain partial transmit sequences as in Equation (10).

$$U^{(w)} = \left[u_1^{(w)} u_2^{(w)} \dots u_{LN-1}^{(w)}\right] = IFFT_{LNxN}\left[U^{(w)}\right] \qquad (10)$$

These sectional arrangements are individually rotated by phase factors $sb = \{b_w = e^{j\theta w}, w=1,2,\dots,W-1\}$. The object is to optimally attach the W sub-blocks to achieve the time domain OFDM signals having least value of PAPR as in Equation (11).

$$\tilde{U} = \sum_{w=0}^{W-1} b_w U^{(w)} \qquad (11)$$

Therefore, there are two important issues that must be resolved for the PTS: high computational complexity to find the information optimal phase lateral displacement factor and optimal phase factors as desired for the over

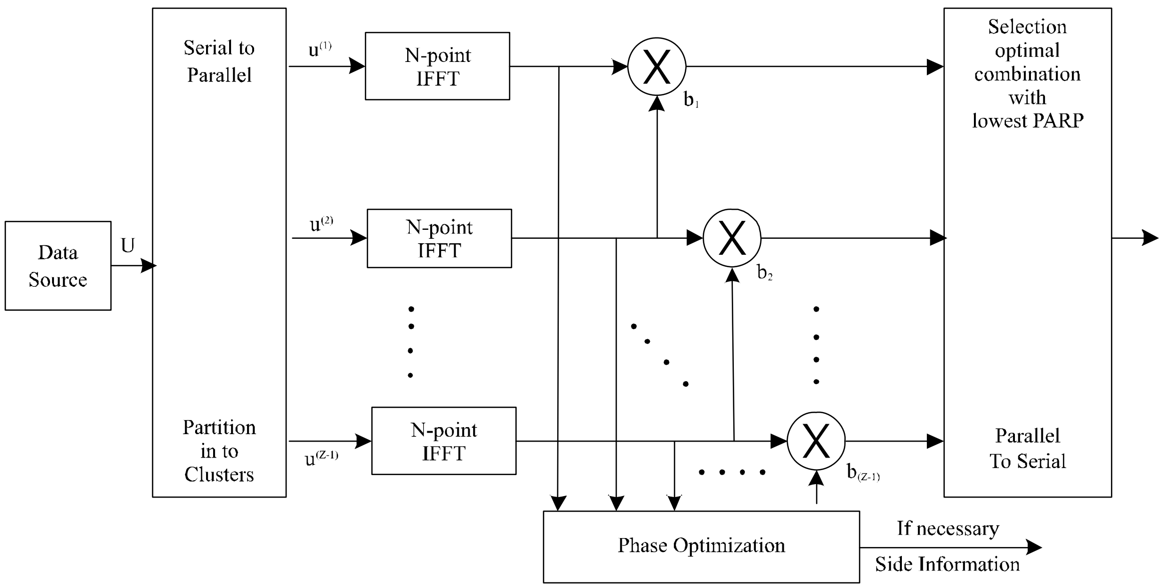

FIG. 4. BLOCK DIAGRAM OF PTS SCHEME

head to transmit to the receiver to decode the transmission correctly.

Fig. 5(a) shows that PTS which uses 4 different phase rotation and 16 different segmentation, number of sub-band 64, Over sampling factor L=8, combinations can reduce the PAPR of an OFDM signal by about 2dB.

The Fig. 5(b) shows that PTS which uses 4 different phase sequences and 256 different segmentation combinations can reduce the PAPR of an OFDM signal by about 5.8 dB.

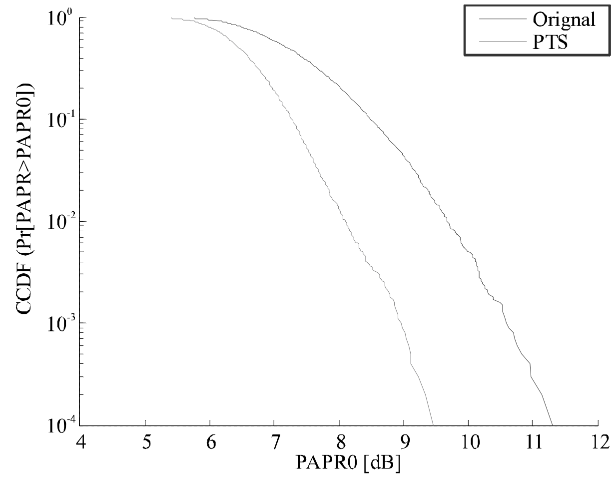

FIG. 5(a). CCDF GRAPH FOR PAPR OF OFDMWITH AND WITHOUT PTS

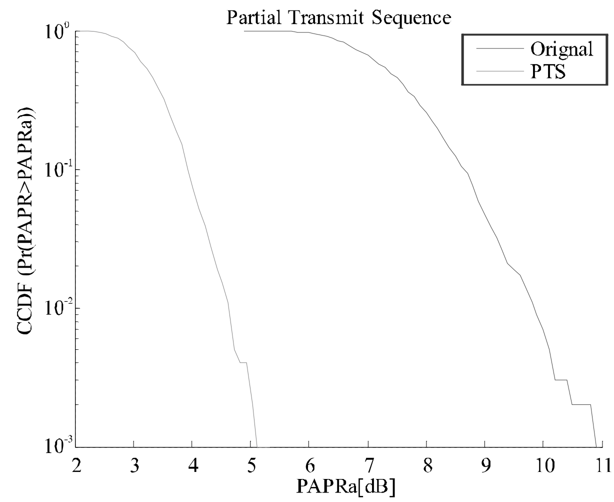

FIG. 5(b). CCDF GRAPH FOR PAPR OF OFDM WITHAND WITHOUT PTS

Similarly SLM is one of the promising PAPR reduction schemes of OFDM. In SLM schemes statistically independent data blocks are generated from OFDM data blocks, using a set of phase sequences and one of the lowers is chosen and transmitted. SLM is a scheme which can reduce the probability of a major PMEPR (Peak-to-Mean Envelope Power Ratio) for multicarrier transmission scheme. Our goal is to perform a change of phase on the modulated symbols (before IFFT) in order to reduce the probability of constructive interference between the subcarriers (after IFFT) has been computed. A block diagram of SLM is represented in Fig. 6. Each block of data is multiplied with phase rotator Z for different length N.

$B_z = [b_z, 0, b_z, 1, ..., b_z, N\text{-}1]^T, Z = 1,2,...,Z\text{-}1$

Resulting in Z different data blocks, so the z^{th} phase sequence after multiplying is given as:

$U^Z = [U_1\, b_{z,1}, U_2\, b_{z,2}, ..., U_{N-1}\, b_{Z,N-1}]^2, (z = 1,2,...,Z\text{-}1)$

Therefore, OFDM signal becomes as given in Equation (12).

$$u^z(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} U_n b_{z,n} e^{j2\pi fnt} \qquad (12)$$

Where $0 \le t \le NT, = 1,2,...,U$.

Among the data blocks $U^{(z)}(z=0,1,...,Z\text{-}1)$ only one of the modified data block, which has the smallest PAPR is selected for transmission. After that the data is transmitted along with the phase sequences as side information. At the receiver, reverse operation is performed to recover the original data. For usage of SLM in OFDM, the SLM scheme needs Z IFFT operations, and the quantity of bits as side data is $[\log^V{}_2]$ for every information block. This methodology is calculable with a wide range of modulation and the number of sub carriers. Therefore, the capability of PAPR diminishment in SLM relies upon the number of phase factors Z and the design of the phase components.

The Fig. 7(a) shows that Selected Mapping which uses 04 different phase sequences can reduce the PAPR of an OFDM signal by as much as 3dB, which is quite significant.

The Fig. 7(b) shows that SLM which uses no: of OFDM Symbol candidates C=8, 4 different phase sequences, number of sub band 64, Oversampling factor L=4, combinations can reduce the PAPR of an OFDM signal by about 3.7dB.

Under the above description, it is clear that the objective in PTS is to ensure that the data of subcarriers of OFDM do not add constructively, hence reduce PAPR. PTS scheme has similar concept as SLM scheme. Only the difference is in SLM phase rotate before the IFFT operation and in PTS scheme phase rotates after the IFFT operation.

6.6 The Interleaving Scheme

The interleaving scheme is much similar to SLM scheme. The difference between these two is that, this interleaving

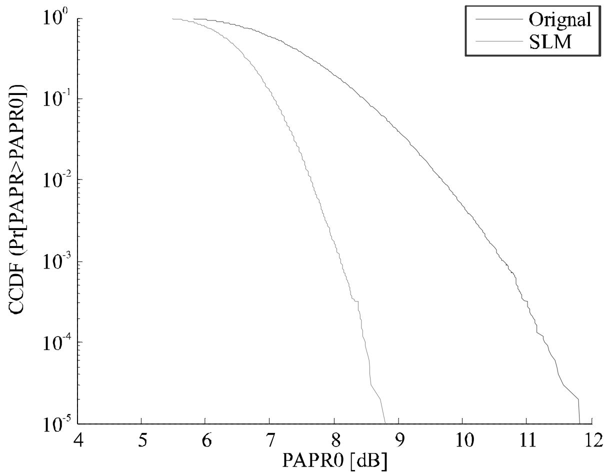

FIG. 7(a). CCDF GRAPH FOR PAPR OF OFDM WITHAND WITHOUT SLM

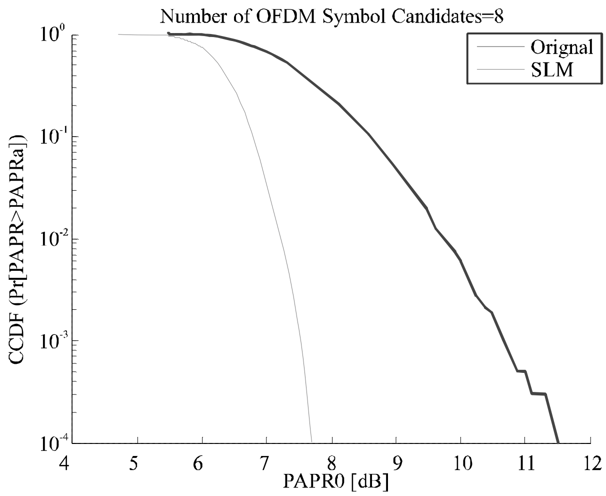

FIG. 7(b). CCDF GRAPH FOR PAPR OF OFDM WITH AND WITHOUT SLM

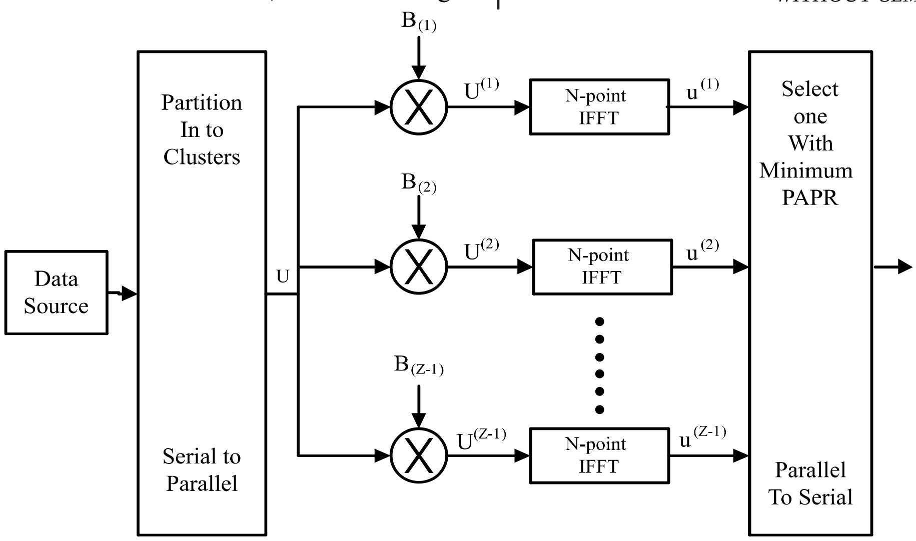

FIG. 6. BLOCK DIAGRAM OF SLM SCHEME

scheme uses intervals instead of using phase sequences. By using interleaver, the modified data blocks are generated, which are actually permuted to the data blocks of the original one. At the end, one of them will be selected that will have least PAPR. However, the PAPR reduction depends heavily on the amount and design of intervals [17]. The interleaveris a device on the N symbols, and a block or reordering permutes where in the operation of the data block $U = [U_0, U_1, \ldots, U_{N-1}]^T$ becomes as:

$U = [U_{\pi(0)}, U_{\pi(1)}, \ldots, U_{\pi(N-1)}]^T$. Where $\{n\} \leftrightarrow \{\pi(n)\}$ is a one to one mapping $\pi(n) \in \{0,1,\ldots N-1)$ and for all n. To make *L* adjusted data blocks, interleavers are used to generate permuted data blocks from identical data blocks. PAPR (L-1) is arranged in the data block, and is calculated using the L-IDFT computation of original data block; the data block having the minimum PAPR is selected for transmission. To retrieve the original data block, the receiver only needs to know which interleaver is used at the transmitter; so that, the number of bits needed for side information to write is $[\log_2 K]$. The transmitter and the receiver store the permutation index $\{\eth\,(n)\}$ in memory. So that, interleaving and de-interleaving can be easily performed. The quantity of PAPR reduction depends on the number of interleaved components (L-1) of the interleaver design.

6.7 Tone Reservation and Tone Injection Schemes

Among various methods which reduce the PAPR of an OFDM signal, two of them are TR and TI. From literature review it is found that TR and TI are two efficient schemes to reduce the PAPR of the OFDM signals.

In contrast to the other PAPR reduction methods discussed above, TR method is efficient in terms of both complexity and BER requirements. Since TR does not manipulate data subcarriers therefore it does not cause any errors to it.TR utilises a set of reserved subcarriers for PAPR reduction. The task is to optimise the signal of non-data bearing subcarriers, while keeping the data subcarriers unchanged.

In TR, the receiver does not need to share the complexity of this PAPR reduction algorithm. That is the processing loads for the selection of TR carriers need to be performed by the transmitter only. LTE, LTE-Advanced and WiMAX (Wireless Interoperability for Microwave Access) are some of the standards which rely on downlink transmission using OFDM and are potential applications for the use of TR for PAPR reduction. Another application is for Digital Subscriber Line (ADSL2 and ADSL2+).

It can be observed from Fig. 8(a-b) that the PAPR reduction is inversely related to the number of PRCs. Therefore, the lower the PRC sum, more is the reduction in the PAPR and vice versa.

Similarly, TI is among one of the popular PAPR reduction schemes. It is advantageous in several aspects. One of the main advantages is that it does not incur a loss in data-rate and does not need the transmission of side information. On the other hand, the main disadvantage of TI is that it requires exhaustive search for the best constellation from a large number of constellations. This means that it has large computational complexity and requires a lot of processing power. In TI, the constellation of the OFDM signal is extended so that the same information can be carried by larger sets of constellation points. The extra constellation points can be exploited for the reduction of the PAPR. The runtime for TI scheme is much smaller than a comparable runtime to the SLM scheme.

However, the method of TI is more complex than TR. This is because both the injected and information signal occupy the same frequency bands. Apart from this, the alternative constellations points lead to increase the requirements for transmit power as well as the computational complexity.

6.8 Active Contstellation Extension Scheme

The method of ACE is used to minimize the PAPR and falls in to the same line of methods as TI. This is a non-linear method utilized for reduction of the PAPR of OFDM signal in addition to using companding and clipping. ACE has a major edge over other techniques in that it improves the BER without affecting the rate of data exchange which is a very important requirement for wireless communication. Nevertheless, the advantage of good BER comes at the cost of computational complexity as it is intensive to determine the best possible constellation which is an iterative process.

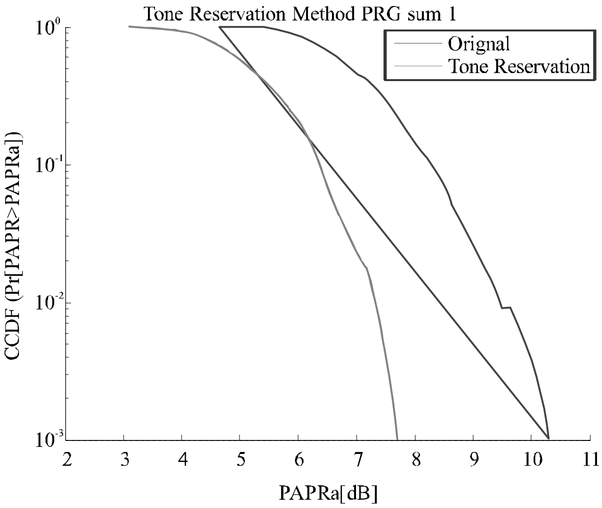

FIG. 8(a). SHOW THE TR-OFDM SIGNAL WITH 12 SUBCARRIERS AND 4 PEAK CANCELLATION SUBCARRIERS, SUM 1 = R1+R2+R3+R4 (2.4 dB)

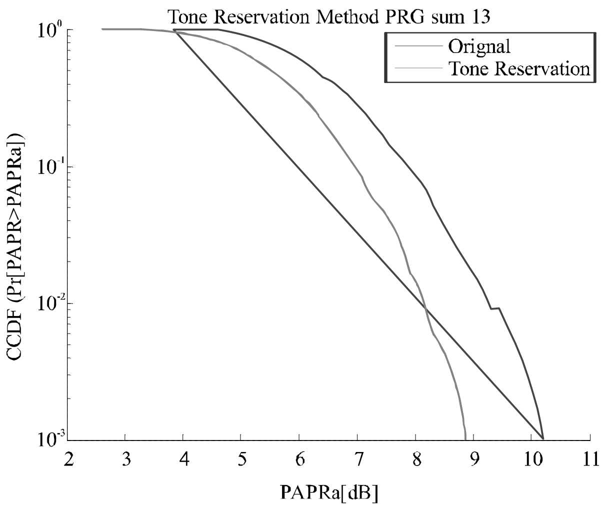

FIG. 8(b.) SHOW THE TR-OFDM SIGNAL WITH 12 SUBCARRIERS AND 4 PEAK CANCELLATION SUBCARRIERS, SUM 13= +R1+R2-R3+R4 (1 dB)

This principle is illustrated in Fig. 9, where the shaded region represents the region of increased margin for the data symbol in the first quadrant. If adjusted intelligently, a combination of these additional signals can be used to partially cancel time domain peaks in the transmitted signal. The ACE idea can be applied to other constellations as well, such as QAM and MPSK constellations, because data points that lie on the outer boundaries of the constellations have room for increased margin without degrading the error probability for other data symbols. This scheme simultaneously decreases the BER slightly while substantially reducing the peak magnitude of a data block. Furthermore, there is no loss in data rate and no side information is required. However, these modifications increase the transmit signal power for the data block, and the usefulness of this scheme is rather restricted for a modulation with a large constellation size.

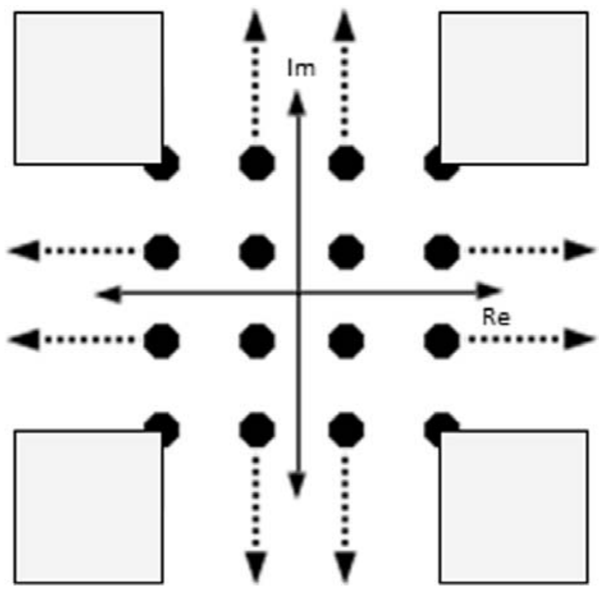

FIG. 9. THE ACE SCHEME FOR QPSK MODULATION

7. CRITERIA FOR SELECTION OF PAPR REDUCTION SCHEMES IN OFDM SYSTEMS

Large PAPR is one of the main demerits of OFDM signals when used in a communication system, especially wireless communication systems are used. Table 1 gives comparison of Various PAPR reduction schemes discussed earlier.

Power Increase in Transmit Signal: Some PAPR reduction techniques actually increase the required transmission power when they reduce the PAPR. One such example is TR, which requires more signal power because some of its power must be used for the PRCs. TI uses a set of equivalent constellation points for every original constellation point to reduce PAPR. Since all the equivalent constellation points require more power than the original constellation points, the transmitted signal will in turn require more power after application of TI. When the transmit signal power is equal to or less than that before using a PAPR reduction technique, the transmit signal should be normalized back to the original power level, resulting in BER performance degradation in these techniques. This is a serious issue and should be considered accordingly.

PAPR Reduction Capability: This is the most important selection criteria when it comes to choosing a particular PAPR reduction technique. Cautious attention must be paid to the fact that the technique being proposed does not result in detrimental effects. For example, the Amplitude Clipping Technique which reduces the PAPR by removing signals peaks, results in in-band distortion and out-of-band radiation.

BER Increase at the Receiver: The increase in the number of bit errors is also an important factor and is closely related to the power increase in the transmitted signal. Some techniques, like Clipping, may have an

TABLE 1. COMPARISON OF DIFFERENT PAPR REDUCTION SCHEMES

Existing Reduction Schemes	CFR Reduction Schemes				
	Power Increase	Implementation Complexity	Bandwidth Expansion	BER Degradation	Requires Processing at TX and RX
Clipping/Filtering	No	Low	No	Yes	Tx: Amplitude clipping filtering Rx: None
Coding	No	Low	Yes	No	Tx: Encoding Rx: Decoding
TR	Yes	High	Yes	No	Tx: IDFTs, final value of PRCs Rx: Ignore non-data-bearing subcarrier
ACE	Yes	High	YES	No	Tx: IDFTs, projection onto "shaded area" Rx: None
PTS	No	High	Yes	No	Tx: M IDFT, Wm-1complex vector sums Rx: Side information extraction, Inverse PTS
SLM	No	High	Yes	No	Tx: UIDFTs Rx: Side information extraction, inverse SLM
Interleaving	No	Low	Yes	No	Tx: K IDFTs, (K-1) interleavings Rx: Side information extraction, inverse Interleaving
TI	Yes	High	Yes	No	Tx: IDFT, search for maximum point in time, tones to be modified, value of p and q Rx Modulo-D- operation

increase in BER at the receiver if the transmitted signal power is fixed or equivalently may require larger transmit signal power in order to maintain the BER after applying the PAPR reduction technique. For example, the BER after applying ACE will be degraded if the transmit signal power is fixed. In some techniques such as SLM, PTS, and interleaving, the entire data block may be lost if the side information is received in error. This may also increase the BER at the receiver.

Computational Complexity: Computational complexity is one of the most important factors which should be taken into consideration while selecting a particular PAPR reduction technique. Techniques such as PTS find a solution for the PAPR reduced signal by using a lot of iterations. The PAPR reduction capability of the interleaving technique is better for a larger number of inter leavers. In, general, more complex techniques have better PAPR reduction capability.

Loss in Data Rate: Some techniques may require the data rate to be reduced because they need to transmit side information along with the data stream. As mentioned before, the block coding technique requires one out of four information symbols to be dedicated to controlling PAPR. In SLM, PTS, and interleaving, the data rate is reduced due to the side information used to inform the receiver of what has been done in the transmitter. It is also possible that the side information may be received in error unless some form of protection such as channel coding is employed, in which case we will have BER increase in addition to a decrease in data rate. When channel coding is used, the loss in data rate due to side information is increased further.

Without Additional Power Needed: The design of a wireless system should always take into consideration the efficiency of power. If an operation of the technique which reduces the PAPR needs more additional power, it degrades the BER performance when the transmitted signals are normalized back to the original power signal.

No Bandwidth Expansion: The bandwidth of the system is a rare resource. Bandwidth expansion directly affects the data coding rate loss of information (such as the phase factors in PTS and complementary bits in Complementary Block Coding). Furthermore, the side information is received in error unless some aspects of protection such as channel coding are employed. Therefore, when the channel coding is used, the data rate loss due to the side information is further increased. Therefore, this should be avoided or at least minimized due to the loss of side information bandwidth.

No Spectral Spillage: Any PAPR reduction techniques can not destroy OFDM attractive technical features such as immunity to the multipath fading. Therefore, the spectral spilling should be avoided in the PAPR reduction.

Other Considerations: A number of PAPR reduction techniques fail to consider the effect of the components in the transmitter such as the transmit filter, D/A (Digital-to-Analog) converter, and transmit power amplifier. Therefore, in practice PAPR reduction techniques can be used only after careful performance and cost analyses for realistic environments.

8. PAPR REDUCTION FOR MIMO-OFDM SYSTEMS

The combination of MIMO technology and OFDM is a viable solution for future wireless communication systems. MIMO methods can improve the error performance, signal quality, and system capacity. When we increase the number of transmit and receive antennas from a SISO (Single-Input Single-Output) manner, we can provide a better performance for practical narrowband channels i.e. those which suffer from Rayleigh fading.

However, for wideband channel where the channel effects become more significant, we need to utilize OFDM along with MIMO systems. This can provide us benefits such as inter symbol interference and improved capacity. Even though MIMO-OFDM systems have many advantages, they have the same problem of PAPR which are inherent with OFDM. In the following section, some PAPR reduction techniques are discussed for MIMO-OFDM systems.

8.1 PTS for MIMO-OFDM

In this section, three known approaches for reduction of PAPR in MIMO-OFDM systems are discussed. The first two methods which use PTS considereach transmit antenna separately. The third method is also based on PTS but uses a cooperative scheme to jointly consider all transmit antennas and reduce the PAPR of MIMO system.

8.1.1 Ordinary PTS

O-PTS (Ordinary PTS) method is derived by applying PTS to each of the transmit antennas [18]. In O-PTS, MN IFFT operations are needed to obtain the partial sequences at all transmit antennas. The same number of sub blocks (U) and allowed phase factors (W) are considered for all transmit antennas. The candidate sequence at the tth transmit antenna is expressed as shown in Equation (13).

$$\tilde{X}_t = \sum_{u=1}^{U} b_t^{(u)} X_t^{(u)} \tag{13}$$

Where $\left\{b_t^{(u)}\right\}_{t=1,\ldots,N_t}^{u=1,\ldots,U}$ are chosen from the set $\{\pm 1\}$(W=2) or $\{\pm 1, \pm j\}$(W=4). To determine the candidate with the lowest PAPR at each transmit antenna, W(U-1) different candidate sequences should be searched. So, this method induces very high computational complexity. Also $N_t[\log_2(W^{(U/2)}]$ side information bits should be transmitted.

8.1.2 Alternate PTS

Due to high computational complexity of O-PTS, A-PTS (Alternate PTS) has been proposed [19]. In A-PTS, starting from the first sub block, every alternate sub block is kept unchanged and the phase factors are optimized only for even sub block. Therefore, the computational complexity is reduced significantly at the cost of slight performance degradation. In this method, $N_t W^{(U/2)}$ candidate sequences are generated and the number of side information bits is reduced to $N_t[\log_2(W^{(U/2)})]$ compared to O-PTS.

8.1.3 Cooperative PTS

The aim of Co-PTS (Cooperative PTS) method [20] is to compensate for the performance degradation in A-PTS approach. A-PTS reduces the computational complexity by decreasing the number of candidate sequences. To compensate for the performance degradation and increase the number of candidate sequences, Co-PTS uses spatial circular permutation for the same odd sub-blocks across all transmit antennas. Then, the PTS method is applied to even sub-blocks at each transmit antenna, separately. This cooperative method generates $N_t^{(u/2)}[N_t(W^{(U/2)})]$ candidate sequences for all transmit antenna. Thus, it requires $[\log_2(N_t^{(U/2)})] + N_t[\log_2(W^{(U/2)})]$ side information bits and only the number of complex additions is increased compared to A-PTS.

8.2 TR for MIMO-OFDM

It is also possible to use tone reservation scheme for MIMO-OFDM systems. In this approach a number of subcarriers are reserved for this purpose which is PAPR reduction. The served positions of the subcarriers are usually same for all transmit antennas and this information is also communicated to the multiple antennas at the receiver. One of the features for TR-MIMO-OFDM is that each transmit antenna works to reduce the PAPR on its own channel, whereas the data received on the reserved subcarriers is simply ignored.

9. CONCLUSION

OFDM is a form of multicarrier transmission scheme; it is also known as DMT, with high spectral efficiency, multipath delay spread tolerance, power efficiency, robustness to channel fading and immunity to the frequency fading channels. It is recently being used for both wireless and wired high data rate communication. Despite of its many advantages, the PAPR problem is one of the important issues to be addressed in developing OFDM systems. In this paper we reviewed various PAPR reduction schemes for OFDM systems. Numerous methods has been suggested to alleviate this problem, all of which can possibly give significant decrement in PAPR at the expense of BER increase, computational complexity increase, transmit signal power increase, loss in data rate etc. No specific PAPR reduction scheme is the best solution for all systems. Rather than PAPR reduction scheme should be carefully chosen according to various system requirements. This paper provides a concise and thorough discussion of the various schemes available for the reduction of PAPR in OFDM systems. In this paper we have highlighted some of the requirements for selecting PAPR reduction schemes and discussed as well as compared the advantages and disadvantages of each technique according to suitable selection criteria. Finally, we have briefly described PAPR reduction in MIMO-OFDM.

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