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Hybrid Peak-to-Average Power Ratio Reduction Techniques: Review and Performance Comparison

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ABSTRACT Orthogonal frequency division multiplexing (OFDM) is an efficient multi-carrier modulation technique for wireless communication. However, one of the main drawbacks encountered in implementing it is its resultant high peak-to-average power ratio (PAPR). Many techniques have been proposed in the literature to substantially decrease the peaks in the OFDM signal. The problem with these, however, is that their effects on other parameters are not always positive. These effects include a decrease in the bit error rate (BER), an increase in complexity, or a reduction in the bit rate. The objective of this paper is to describe the PAPR problem in a bid to reduce the peaks in the OFDM signal. The paper proposes a classification, performance evaluation and optimization of PAPR reduction techniques for commercial, public safety, and tactical applications. In the taxonomy proposed herein, we also include a new category, namely, hybrid techniques. Furthermore, we compare the principal characteristics through a complementary cumulative distribution function and BER evaluation, and conclude on the importance of hybrid techniques, when the goal is to both improve the BER and reduce the PAPR.

INDEX TERMS Orthogonal frequency division multiplexing, peak-to-average power ratio, high power amplifier, hybrid PAPR reduction technique, commercial communication, tactical communication.

I. INTRODUCTION

Recent developments in new wireless communication technologies have come about in response to a growing demand for higher data rates due to the popularity of multimedia services, including real-time stream media, gaming, and other social media services. While this demand naturally calls for high bandwidth technologies [1], high quality of service (QoS) is nevertheless crucial as well. For example, in [2], it was predicted that 5th generation (5G) mobile networks should achieve 1000 times the system capacity, 10 times the spectral efficiency, higher data rates, 25 times the average cell throughput and other improvements, of the present generation 4G systems.

Orthogonal frequency division multiplexing (OFDM) underlies all 4G wireless communication systems; for instance, it is included in the IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE) standards. LTE is currently the chosen standard for interoperable Public Safety communications in the US and in other countries. Moreover, multiple tactical waveforms, such as the Universal Networking Waveform (UNW), and Wideband Network Waveform (WNW), leverage the OFDM technology for its inherent mobility robustness. As well, the technology is a popular modulation technique for other wireless digital communication systems, such as IEEE 802.11 a/g/n/ac wireless LANs, Digital Audio Broadcasting (DAB), Digital Video Broadcasting-Terrestrial (DVB-T), and Digital Video Broadcasting by Satellite (DVB-S). Further, combining OFDM with multiple-input multiple-output (MIMO) wireless communication systems results in MIMO-OFDM, one of the most promising techniques for broadband wireless access schemes because in high data rate transmission situations, OFDM decreases the complexity of the MIMO receiver by transforming a frequency-selective MIMO channel into a set of parallel frequency-flat MIMO channels [3].

However, transmit signals in an OFDM system, where the output is the superposition of multiple subcarriers via an inverse fast Fourier transform (IFFT) operation, can have a high peak-to-average power ratio (PAPR), which is effectively one of the main implementation disadvantages of the OFDM system.

If the transmitter has a high PAPR, the average power is significantly reduced, with reference to a constant saturation power. In modern commercial wireless systems, the PAPR problem is more significant in uplink [4] because this is the limiting link in terms of coverage and range [5], and as the mobile terminal is limited in battery power, the efficiency of the power amplifier is critical. A trend in 5G is to enable higher frequency bands to obtain more unused spectrum, and previous research has led to fruitful researches [6]. In the future 5G smartphones where beamforming technique is used, PAPR reduction is more important considering the general low power efficiency of mmWave PAs and poor battery performance investigated in [7]. Moreover, in tactical communications, the coverage is a critical point, and vehicle-to-vehicle broadband communication require a strong output power. The problem here is that power amplifiers (PA) equipped with very high power scopes have low cost efficiency and are very expensive [8]. As a result, a practical OFDM implementation must consider all measures to reduce the high PAPR. Many authors have considered the PAPR reduction problem and proposed different strategies.

This paper also aims to develop a systematic approach for PAPR reduction under different propagation, topology or traffic conditions. As well, unlike the surveys such as [9] and [10], the work presents a detailed analysis of the motivations to reduce the PAPR in the current communication systems, emphasizing two main motivations such as power savings and coverage gain. The work summarizes the recent literature on hybrid PAPR reduction techniques, compares the important parameters it incorporates, and concludes on its usability in current commercial, public safety and tactical communications systems. Additionally, the net gain concept is introduced and evaluated as a tool to choose the best PAPR reduction technique under different scenarios.

The rest of this paper is broken down into six sections. Section II looks at how an OFDM system is affected by the PAPR problem, and presents an OFDM model. Section III presents the advantages that can be obtained when the PAPR is reduced. The core of this paper is presented in section IV, where the PAPR techniques available in the literature are classified and described, and the hybrid category is included and some examples are given. Section V introduces a simple hybrid PAPR reduction technique, and it compares PAPR reduction rates and BER performance using different techniques. Finally, section VI summarizes and concludes this paper.

II. OFDM SYSTEM MODEL AND PAPR PROBLEM

Orthogonal frequency division multiplexing or OFDM is a multicarrier modulation technique that divides available bandwidth into a number of orthogonal subcarriers which are transmitted with equal intervals, and provides numerous advantages, such as resilience to RF interference, lower multi-path distortion, and ease of integration with MIMO, which increase the spectral efficiency. Fig. 1 shows a block diagram of a typical OFDM transmitter and receiver.

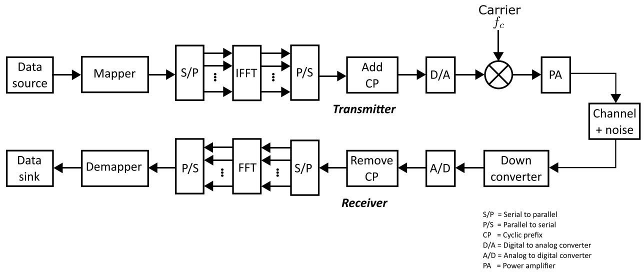


FIGURE 1. Block diagram of transmitter and receiver in an OFDM system.

In an OFDM system, a collection of K complex data symbols $X(k)$ are modulated on a set of K orthogonal subcarriers. Hence, an input symbol vector on a frequency domain, called a data block, can be represented by $\mathbf{X} = [X(0), X(1), \ldots, X(K-1)]^T$, and the continuous-time baseband OFDM signal $x(t)$, defined as the sum of all K subcarriers with subcarrier spacing $1/Kt_s$, is given by

$$x(t) = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} X(k) e^{j2\pi \frac{k}{Kt_s} t}, \quad 0 \leq t < Kt_s. \tag{1}$$

where t_s is the sampling period and $j = \sqrt{-1}$.

Frequently, the instantaneous output of an OFDM signal has large peaks that can be expressed as a PAPR, which is sometimes referred to as PAR. The PAPR of the continuous-time baseband OFDM signal $x(t)$ is defined as the ratio between the maximum instantaneous power and its average power [11], that is:

$$\mathrm{PAPR}(x(t)) \triangleq \frac{\max\limits_{0 \leq t \leq Kt_s} |x(t)|^2}{\frac{1}{Kt_s} \int_0^{Kt_s} E\left\{|x(t)|^2\right\} dt}. \tag{2}$$

where $E[\cdot]$ denotes the expected value. If the $x(t)$ signal is sampling at the Nyquist rate $t = nt_s$, with integer n, the discrete-time baseband OFDM signal $x(n)$ can be written as:

$$x(n) = \frac{1}{\sqrt{K}} \sum_{k=0}^{K-1} X(k) e^{j2\pi \frac{k}{K} n}, \quad n = 0, 1, \ldots, K-1, \tag{3}$$

and the PAPR in terms of discrete-time baseband OFDM signal can be expressed as:

$$\mathrm{PAPR}(x(n)) \triangleq \frac{\max\limits_{0 \leq n \leq K-1} |x(n)|^2}{\frac{1}{K} \sum_{n=0}^{K-1} |x(n)|^2}. \tag{4}$$

In most cases, the PAPR of the discrete OFDM signal is less than the PAPR of the continuous OFDM signals by

0.5 ∼ 1 dB [12]. Hence, the relationship between PAPRs is given by

$$\mathrm{PAPR}(x(n)) \leq \mathrm{PAPR}(x(t)). \tag{5}$$

A. THE CCDF OF THE PAPR

The time domain OFDM signal $x(t)$ is a complex number. Assuming that the real and imaginary parts follow a Gaussian distribution, with 0.5 variance and zero mean, in agreement with the central limit theorem when K is sufficiently large, the amplitude of the OFDM signal $|x(t)|$ becomes a Rayleigh distribution and the power distribution is exponential [13]. The cumulative distribution function (CDF) of the amplitude of a signal sample is

$$F(z) = 1 - e^{-z}. \tag{6}$$

If we assume that the average power of $x(t)$ is equal to one, that is, $E|x(t)|^2 = 1$, the probability distribution function for PAPR less than a certain threshold value is

$$\begin{aligned}\Pr(\mathrm{PAPR} < z) &= (F(z))^K \\ &= (1 - e^{-z})^K. \end{aligned} \tag{7}$$

However, when the performance of PAPR reduction techniques is evaluated, the CCDF of the PAPR is more frequently used. The probability that PAPR exceeds a threshold value (i.e., the CCDF) is described by [13]

$$\begin{aligned}\Pr(\mathrm{PAPR} > z) &= 1 - \Pr(\mathrm{PAPR} \leq z) \\ &= 1 - (1 - e^{-z})^K. \end{aligned} \tag{8}$$

In the literature, the CCDF of PAPR is usually expressed in terms of the number of subcarriers K. For example, Fig. 2 shows the theoretical CCDFs of OFDM signals with different subcarriers (i.e., $K = 64,\ 128,\ 256,\ 512$ and 1024) that are obtained by evaluating (8). The graph shows that the probability of occurrence of a given OFDM symbol decreases with an increase in the number of subcarriers K when compared to a fixed value of PAPR thresholds, PAPR0 (x-axis).

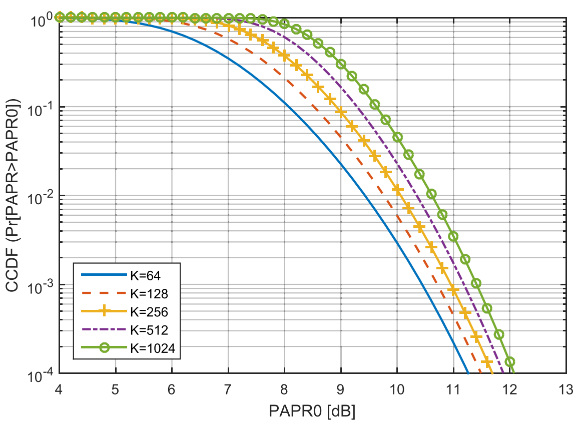


FIGURE 2. Theoretical CCDFs of OFDM signals with different subcarriers.

A conventional analysis of the PAPR of OFDM signals (equation (8)) provides a good approximation when the number of subcarriers K is relatively small [11], [14]. Ochiai and Imai [14] and Wei *et al.* [15] work in an exact distribution of the PAPR in OFDM systems. For instance, [14] employed the level-crossing rates method, and deduced the following approximation for a large number of subcarriers:

$$\Pr(\mathrm{PAPR} > z) \cong 1 - \exp\left\{-Ke^{-z}\sqrt{\frac{\pi}{3}z}\right\}. \tag{9}$$

Meanwhile, [11] developed an approximation of the PAPR of a practical OFDM by employing the extreme value theory; according to that theory, if the number of subcarriers goes to infinity, the complex envelope of a bandlimited uncoded OFDM converges weakly to a Gaussian random process [11]. The derived expression in [11] can be written as:

$$\Pr(\mathrm{PAPR} > z) \cong 1 - \exp\left\{-Ke^{-z}\sqrt{\frac{\pi}{3}\log K}\right\}. \tag{10}$$

In the case of a coded OFDM signal, the literature provides an approximation of when to use codes that can be modeled as uncorrelated. Many of the standard codes meet this condition; for example, block codes (except repetition codes, and low-rate codes [16, p. 527]), some convolutional codes, and turbo codes. Under this condition, [11] demonstrated that the CCDF of the PAPR of coded OFDM can be approximated by the equation (10).

B. NET GAIN

In order to compare the PAPR reduction techniques for a given requirement, it is important to consider the global gain (net gain) in the system. In this paper, the net gain is composed of the PAPR reduction and the BER performance. Hence, the net gain is defined as a particular case of the fitness function-based approach [17] where under given channel conditions (AWGN or multi-path), the relative PAPR reduction is

$$Y_1 = -10\log_{10}\left(\frac{\mathrm{PAPR_{after}}}{\mathrm{PAPR_{before}}}\right), \tag{11}$$

and the relative degradation in BER performance at certain signal to noise ratio (SNR) level can be written as

$$Y_2 = -10\log_{10}\left(\frac{\mathrm{BER_{after}}}{\mathrm{BER_{before}}}\right). \tag{12}$$

The aggregate fitness value of the PAPR reduction technique is given by [17]

$$\Gamma = \sum_{k=1}^{2} \alpha_k \cdot Y_k, \tag{13}$$

where

$$\sum_{k=1}^{2} \alpha_k = 1, \tag{14}$$

and α_k represents the weights of factors related with the importance level of BER and PAPR reduction in the system.

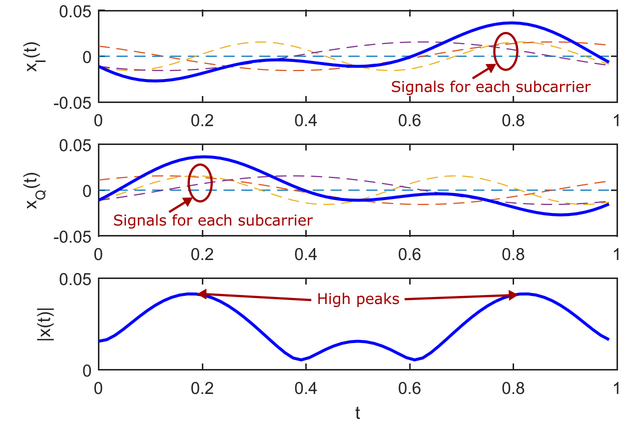
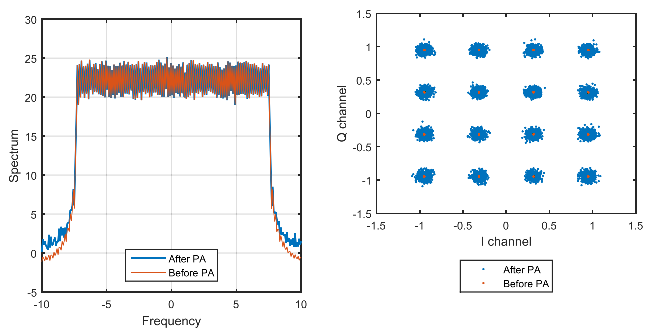


FIGURE 3. Time domain OFDM signals with $K = 4$ for real, imaginary parts and the sum $|x(t)|$, when the modulation is QPSK [18].

III. MOTIVATION

Transmit signals in an OFDM system can have high peak-to-average power ratio (PAPR), for example, Fig. 3 illustrates time domain OFDM subcarriers with $K = 4$ in a QPSK-OFDM system and their sum $|x(t)|$. We see that when the subcarriers have high peaks aligned simultaneously, a high peak appears in the resulting OFDM signal.

An ideal OFDM transmitter requires a linear PA where the output is equal to the input affected by a gain. However, in a real PA, the linear region has a limit, after which the output is equal to the saturation value (or its maximum possible level). The nonlinear PA causes changes in the spectrum and in the constellation signal of the input. As an example, Fig. 4 represents the effects of PA on a 16-QAM signal, with the IFFT length being equal to 128. Therefore, the high peaks in the OFDM signal can produce spectral spreading (see Fig. 4a) and changes in the constellation signal how cloud-like shaping (see Fig. 4b), attenuation and rotation or warping.



(a) (b)

FIGURE 4. Effects of nonlinear PA on (a) signal spectrum and (b) signal constellation [19].

The PA is employed in radio systems transmitters to obtain sufficient transmit power, and it usually operates at or near the saturation region to achieve the maximum output power efficiency. This can be seen in Fig. 5, which presents a typical

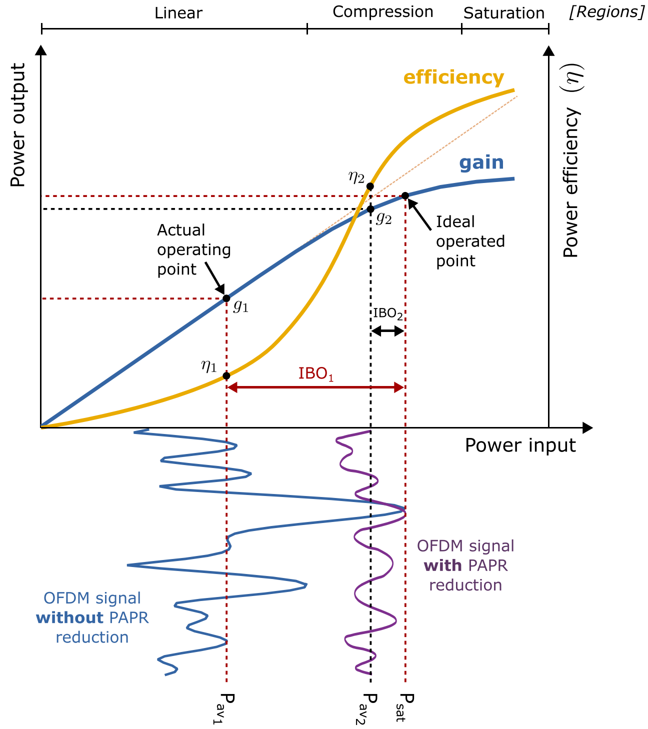


FIGURE 5. Input power versus output power characteristics and efficiency curves for a solid state power amplifier (SSPA).

input power P_{in} versus output power P_{out} characteristics curve (gain) for a PA. The nonlinear distortion in the PA depends on the back-off of the amplifier, and can be calculated as the input back-off (IBO), which is defined as:

$$\text{IBO} = 10\log_{10}\left(\frac{P_{\text{sat}}}{P_{\text{av}}}\right), \tag{15a}$$

or

$$\text{IBO} = [P_{\text{sat}}]_{\text{dB}} - [P_{\text{av}}]_{\text{dB}}, \tag{15b}$$

where P_{sat} and P_{av} are the saturation power of the PA and the average power of the input signal, respectively. Moreover, $[P_{\text{sat}}]_{\text{dB}}$ and $[P_{\text{av}}]_{\text{dB}}$ represent the saturation and average powers in dB. The maximum possible output is limited by P_{sat}. To ensure that the peaks in the OFDM signal do not exceed the saturation threshold in the PA, the input back-off should be at least equal to PAPR [9], i.e., $\text{IBO}_1 \leq \text{PAPR}$. However, the result of this solution is that the power amplifier works with reduced efficiency [9]. For instance, an OFDM signal, such as the one presented in Fig. 5 (blue signal, i.e., OFDM signal without PAPR reduction), with an average power P_{av_1}, needs a large input back-off (IBO_1), and consequently, works with very low PA gain (g_1), and low efficiency (η_1). As well, it works with very high nonlinearity. In contrast, an OFDM signal with a good PAPR reduction (Figure 5, purple signal) requires very low input back-off (IBO_2), and works with very high PA gain (g_2), high efficiency (η_2), and small nonlinearity.

With a high PAPR, there are very wide variations in the multi-carrier envelope, and as a result, the nonlinear characteristic of PA, excited by a large input, causes in-band distortions and out-of-band radiation. Therefore, the PA will introduce additional interference into the systems, leading to an increase in BER for high peaks in the OFDM signal. To reduce the signal distortion and improve the BER, we could try to modify the nonlinear components of the system, i.e., the PA or the DAC. With a high PAPR in the system, we require a PA with a wide dynamic range. However, such a PA is not power-efficient, more complex, and is expensive. On the other hand, with a wide variation in the OFDM signal, we need a high precision DAC, which is however, equally expensive. If we were to use a low precision DAC, then we could face the possibility of having significant quantization noise. Since, modifying the nonlinear components to support high PAPR requires drastic sacrifices, the best alternative would be to try to decrease the wide variations in the OFDM signal before tackling the nonlinear devices.

Two additional important motivations for introducing a PAPR reduction technique in commercial and tactical wireless communication systems—power savings and coverage gain—are considered in more detail next.

A. POWER SAVINGS

Reducing the PAPR in an OFDM signal can provide significant power savings [17], [20]. Power savings becomes more relevant when we have mobile terminals in the system, since these have limited battery life. That is the case with the uplink in a wireless commercial system, and with all nodes in a tactical communications system.

Let us consider Class A power amplifiers, which are the most linear amplifiers, and have a maximum PA efficiency ($\eta_{\max}$) of 50% [20]. Assuming an ideal linear model for the power amplifier, where the linear amplification is achieved up to the saturation point [20], the PA efficiency in this amplifier is given by:

$$\eta = \frac{\eta_{\max}}{\text{PAPR}} = \frac{0.5}{\text{PAPR}}, \tag{16}$$

where the PAPR is expressed in linear units. To better understand why the PAPR reduction in the OFDM signal may saves power, let us look at an example. Given an OFDM signal when QPSK is assumed to be the modulation scheme, the oversampling rate is $L = 4$, and the number of subcarriers is $K = 64$ (see Fig. 2). Hence, we need to use an input back-off (IBO) equivalent to $\text{PAPR}_{\text{dB}} = 11.4$ dB ($\approx$13.80), which is the PAPR at the 10^{-4} probability level, in order to guarantee that no more than 0.01% frames are clipped. Thus, the PA efficiency in this case is $\eta = \frac{0.5}{13.80} \approx 3.6\%$. Now, let us consider the case when a PAPR reduction technique is applied to this system and we achieve a PAPR reduction of 3 dB, i.e., $\text{PAPR}_{\text{dB}} = 8.4$ dB, which is 6.92. So, the PA efficiency is $\eta = \frac{0.5}{6.92} \approx 7.23\%$, which is tantamount to doubling the efficiency.

TABLE 1. A comparison of the PA efficiency with and without PAPR reduction of different PA classes.

Class	$\eta_{\max}$ (%) [21]	PAPR_1 (linear)	η_1	PAPR_2 (linear)	η_2
A	50	13.80	3.62	6.92	7.23
B	78.5	13.80	5.69	6.92	11.35
C	100	13.80	7.24	6.92	14.45

Table 1 analyze the PA efficiency when three type of linear PA are considered, i.e., Class A, B, and C. The maximum PA efficiency is 50%, 78.5%, and 100% for Class A, B, and C, respectively [21]. In Table 1, PAPR_1 and η_1 represented the PAPR at the 10^{-4} probability level, and the PA efficiency without PAPR reduction technique, respectively, and PAPR_2 and η_2 are the PAPR at the 10^{-4} probability level, and the PA efficiency, respectively when a PAPR reduction technique is applied to this system and we achieve a PAPR reduction of 3 dB. Similar results are obtained in all cases. Therefore, achieving low power efficiency is thus a strong motivation for using a PAPR reduction technique in the OFDM system.

B. COVERAGE GAIN

As with power savings, increasing the coverage and range become more important when we have mobile users on the network. For this reason, coverage and range are key points in tactical communications, where all users are mobile, and therefore have limited battery power and smaller antennas, as compared to base stations in a commercial system.

In general, a commercial network has user equipment (UE) associated with a Node-B (eNB). A eNB is typically located on a fixed tower and defines a coverage zone, the cell. They are interconnected by an X2 interface [5]. The third component is the mobility management entity/gateway (MME/GT), whose main function is idle-mode UE reachability, and is interconnected with the eNBs by an S1 interface [5]. In contrast, tactical communications need a highly complex network that is organized in tiers of subnets (Joint Tactical Radio System (JTRS) structure). All the infrastructure's units are mobile, and the nodes are distributed by air, ground or sea. There are two types of subnets: global, which function as gateways in all or part of the network, and local, which use different frequencies. A tier can be comprised of multiple subnets, and only selected nodes can have multichannel capability [22]. For example, one tier can be the soldier radio waveform (SRW) divided in two categories of subtiers (soldier-to-soldier communications and networking sensors). Another tier is the wideband networking waveform (WNW), which uses an OFDM physical layer and has two subtiers (local subnets for vehicle-to-vehicle communications and global connectivity) [22].

The preceding discussion shows that commercial and tactical networks differ in structure, and therefore, increasing coverage poses various challenges. In commercial communications, in order to increase the network coverage, we could, for example, increase the number of cells, and use overlapping cells of different sizes. In addition, as the BS are

TABLE 2. Commercial and tactical communications parameters comparison [23].

	Commercial Communications	Tactical Communications	
	Base Station (BS)	*Manpack*	*Vehicle*
Transmit power [W]	200	5	50
Rx antenna gain [dBi]	0	0	0
Tx/Rx antenna height [m]	15/1	1.7/1.7	2.8/2.8

fixed, the nodes face fewer restrictions in terms of resources, such as transmit power, gain, or height of the antennas. By contrast, in tactical networks, there are no fixed elements, and coverage there is related to the range of each node, and the nodes have limited resources. For instance, an estimation of the range over mountain blockages is modeled by an ITU-R model (Single-Knife Edge) for commercial and tactical applications in [23]. The authors conclude that the range of commercial communication is more than four times that of tactical communication with a similar link margin. The research in [23] compares a commercial application BS versus a Manpack node in tactical communication with the parameters described in Table 2. Also, Table 2 shows the parameters used for a vehicle-mounted mobile node in a tactical communication network, for comparison.

Common PAPR reduction techniques can reduce the PAPR by about 2 to 4 dBs. This represents a transmit power gain of a few dBs and can have an impact on the range and coverage of the system. Now, an important question is how much a small gain in transmit power can improve the range and coverage of a wireless system. In order to answer this question, we start with a propagation analysis in free space, and then present a model to analyze the range and coverage as a function of transmit power gain. This analysis is based on the work of [5].

Wireless signal strength decreases as the propagation distance increases. Hence, we need a model which predicts the mean signal strength at the receiver, as a function of the separation between the transmitter and the receiver. A free space model predicts the received signal strength when there is an unobstructed propagation path between the transmitter and the receiver, and it is governed by the Friis free space equation, and can be written as [5]:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2, \tag{17}$$

where P_R is the received power, P_T represents the radiated power of a source (isotropic radiator), and G_T and G_R are the transmitter and receiver antenna gains, respectively. Also, $4\pi d^2$ is the surface area of a sphere of radius d, and the wavelength of the radiation is represented by $\lambda = c/f$, where c and f denote the speed of light and the frequency, respectively. Then, the total path loss in free space is described by [5]:

$$\begin{aligned} PL_{\mathrm{FS}} = {} & 32.44 + 20\log_{10}(d) + 20\log_{10}(f) \\ & - 10\log_{10} G_T - 10\log_{10} G_R \; [dB]. \end{aligned} \tag{18}$$

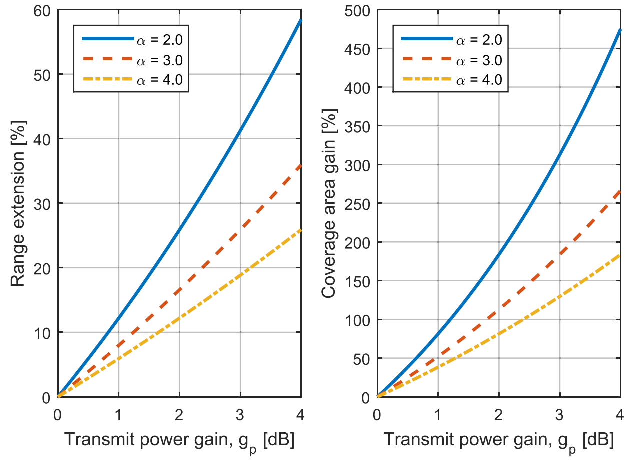


FIGURE 6. Range extension (left) and Coverage area (right) as a function of transmit power gain g_p [5].

Here, d is given in meters and f in GHz. Therefore, in free space, when the distance is doubled, the path loss increases by $20\log_{10}(2) = 6$ dB. For instance, the additional gain can come from increasing the transmit power by reducing the PAPR in the OFDM system.

Generally, in a practical communication system, path loss increases more than it does in free space, over the same distance. For example, if we consider a two-ray reflection model, which predicts path loss when the signal received consists of two principal components such as the line of sight and a reflected wave, the electric wave power at the receiver is attenuated as $1/d^4$ rather than $1/d^2$ experienced in free space [5]. Usually, the power attenuation factor α is denominated path loss exponent, and is a function of the environment. Thus, the received power P_R can be described by [5]

$$P_R \propto \left(\frac{1}{d}\right)^{\alpha}. \tag{19}$$

Assuming a pat loss exponent α and considering that d_0 is the original range and d_1 is the range with a power gain of g_p dBs, the incremental range extension ΔR by a power gain of g_p dBs is given by [5]

$$\Delta R = \frac{d_1 - d_0}{d_0} = \left(10^{(g_p/10)}\right)^{\frac{1}{\alpha}} - 1. \tag{20}$$

Finally, if a circular shape omni-cell is considered, the gain in coverage area ΔA is described by [5]

$$\begin{aligned} \Delta A &= \frac{A_1 - A_0}{A_0} \\ &= \frac{\pi d_1^2 - \pi d_0^2}{\pi d_0^2} \\ &= \pi\left(\left[\left(10^{(g_p/10)}\right)^{\frac{1}{\alpha}}\right]^2 - 1\right). \end{aligned} \tag{21}$$

The range extension and the coverage area as a function of transmit power gain g_p are plotted in Fig. 6. We note that the range extension is small for bigger path loss exponent α, similar to the coverage area. Also, in Fig. 6 (left) we can see that a transmit power gain g_p of 3 dB can extend the communication range by ∼19 to over ∼26% for a path loss exponent α in the range of 3 to 4. On the other hand, in Fig. 6 (right), with the same value of transmit power gain g_p, i.e., 3 dB, the coverage area gain is between ∼130 to ∼184% for a path loss exponent α in the 3 to 4 range.

In conclusion, it can be seen that reducing the PAPR in the OFDM signal by a few dBs could result in huge improvements in range and coverage area [5].

IV. PAPR REDUCTION TECHNIQUES

Many authors have considered the PAPR reduction problem and proposed different strategies for reducing the peaks in the multi-carrier signal, and more recently, in the OFDM system. Further, there are different ways to divide the PAPR reduction techniques as detailed next.

Cho *et al.* [18] argue that there are five broad categories of PAPR reduction techniques, namely: clipping (includes block-scaling, clipping and filtering, peak windowing and peak cancellation) [24]–[27], coding schemes, adaptive pre-distortion, discrete Fourier transform (DFT) spreading and probabilistic (scrambling) [28]–[30], which includes selected mapping, partial transmit sequence, tone reservation, and tone injection techniques.

Alternatively, the work in [10] classified the PAPR techniques into two broad types: signal distortion and signal scrambling. Signal distortion techniques such as signal clipping, peak windowing or nonlinear companding transform (NCT), reduce high peaks in the OFDM signal by distorting the signal before the amplification, and the signal scrambling techniques are all variations of how to scramble codes to decrease the PAPR [10]. The scrambling techniques may be divided into two main sub-groups: without explicit side information, for instance, the Hadamard transform method or Dummy sequence insertion, and with explicit side information including coding-based schemes, such as block coding schemes, sub-block coding schemes or block coding with error correction. We also have probabilistic schemes, including, for example, selected mapping (SLM), partial transmit sequence (PTS), tone reservation (TR), tone injection (TI) and active constellation extension.

Another categorization is described by [17], who divided the PAPR reduction techniques into deterministic and probabilistic approaches. The deterministic schemes try to ensure that the PAPR of the signal does not exceed a predefined limit, in contrast to probabilistic schemes which minimize the probability that the PAPR of a signal exceeds a predefined limit.

Finally, [9] defined three main categories in their taxonomy: signal distortion, multiple signaling techniques and probabilistic techniques, and coding techniques.

The taxonomy presented by [9] is selected here for describe the PAPR reduction techniques. However, in this work, we add a new category, namely, hybrid techniques, which groups together the methods that combine two or more than two techniques for PAPR reduction. Hybrid methods have gained interest in recent years as they can combine the advantages present in two or more techniques. They can achieve better overall results such as an improved PAPR reduction, an increase in performances of the system, at the cost of only a slight increase in complexity.

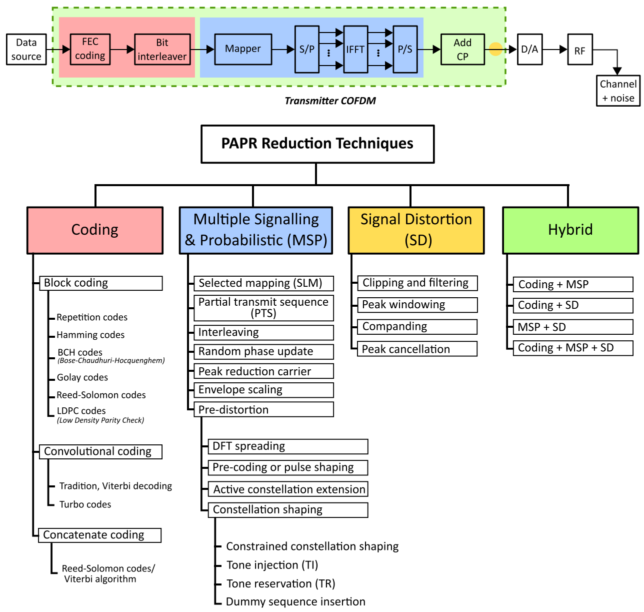


FIGURE 7. PAPR reduction techniques.

Fig. 7 shows the four categories of PAPR reduction techniques and examples of each category. Next, we will briefly describe some schemes in each category of the PAPR reduction classification, and discuss the advantages and disadvantages of these techniques.

A. CODING BASED TECHNIQUES

The coding PAPR reduction technique consists in choosing the codewords that minimize the PAPR. By way of illustration, Fig. 8 shows the PAPR of a four subcarrier signal as a function of time, for all possible data words d, increasing sequentially from $0_{dec}('0000'_{bin})$ to $15_{dec}('1111'_{bin})$. As can be seen from Fig. 8, four words result in the maximum PAPR: the two code sequence with all bits equal, i.e., the words $0_{dec}('0000'_{bin})$ and $15_{dec}('1111'_{bin})$, and the two data words with all bits alternating, i.e., $5_{dec}('0101'_{bin})$ and $10_{dec}('1010'_{bin})$. It is understandable that we could reduce the PAPR of this OFDM signal by avoiding the use of these words.

The PAPR reduction techniques classification proposed here suggest three types of coding-based PAPR reduction schemes, namely, block coding schemes, convolutional codes schemes, and concatenate coding schemes in concordance with the forward error correction (FEC) categorization. Examples of coding schemes are presented below.

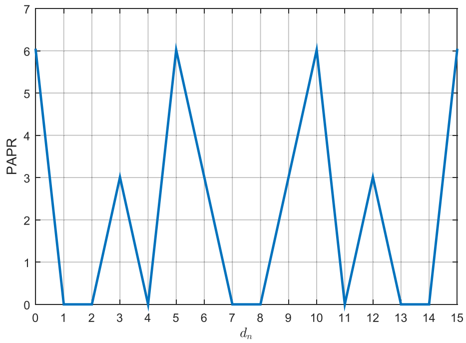


FIGURE 8. PAPR of a four subcarrier signal for all possible data words d_n.

1) SIMPLE ODD PARITY CODE

Reference [31] proposed PAPR reduction using a simple odd parity code (SOPC). Based on the idea presented as an example in Fig. 8, [31] showed that the PAPR of a four-carrier signal can be reduced from 6.02 dB to 2.48 dB with a 3/4 rate block code by avoiding the transmission of words with high PAPR; in the case of 4 bits, [31] used 3 bits for data transmission and one bit for the odd parity check (see Fig. 9a).

2) MODIFIED CODE REPETITION

A reduction of the peaks in a multi-carrier signal by a modified code repetition (MCR) is presented in [32] for a BPSK OFDM signal. Code repetition is a basic forward error correction code, where the idea is to repeat the message several times. For example, for $k = 4$ number of repetitions, the input bit 0 produces the output ′0000′, and with the input 1, the output will be ′1111′. Ngajikin *et al.* [32] used a repetition code and modified the last bit of the word (less significant bit (LSB)), by toggling up, i.e., with $k = 4$ the output will be ′1110′ if the input is 1 and ′0001′ if the input is 0. It is clear from Fig. 8 that these words dot not have the maximum PAPR.

The decoding process for a repetition code word can be run by maximum likelihood, or simply by choosing the output bit based on the majority bits in the code word [32].

MCR is restricted by modulation, and to a small number of subcarriers. However, MCR provides error correction, and using it with an interleaver could increase the PAPR reduction capabilities.

3) COMPLEMENT BLOCK CODING

In the complement block coding (CBC) PAPR reduction technique [33], a complementary sequence is added to the information sequence. If the code length K is the number of subcarriers, and we use k complement bits (CBs), where one CB is the inverse of the selected information bit (IB), the number of information bits in a block code is therefore $K - k$ (see Fig. 9b).

The CBC technique can provide detection and correction capabilities. Additionally, as CBC does not generate alternate or all-equal bit sequences, it reduces the PAPR of the OFDM signal.

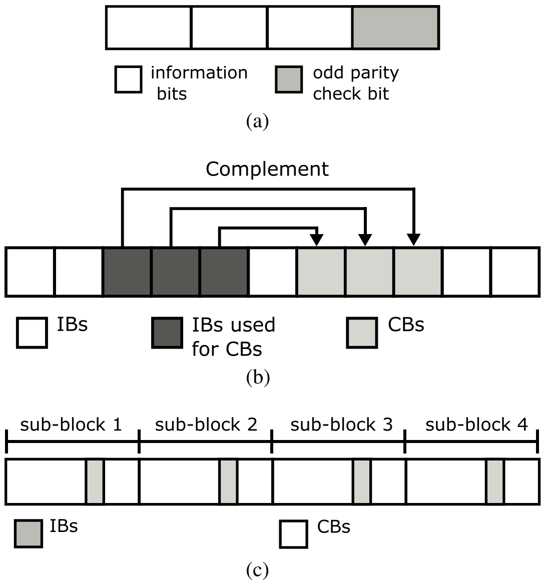


FIGURE 9. Examples of Coding-based techniques. (a) Simple Odd Parity Code (SOPC). (b) Complement Block Coding (CBC). (c) Sub-block complementary coding (SBCC).

4) SUB-BLOCK COMPLEMENTARY CODING

Sub-block complementary coding (SBCC) [34] is an effective technique involving large frame sizes, since it breaks the long information sequence into several equal-sized sub-blocks, with each sub-block encoded with a complementary error correction code (see Fig. 9c). Reference [34] demonstrated that over a BPSK-OFDM system with $K = 16$ subcarriers and a code rate $R = 3/4$, the PAPR reduction is 6.03 dB when the SBCC is used.

5) GOLAY COMPLEMENTARY SEQUENCES

References [31] and [35] used Golay complementary sequences to achieve PAPR reduction, and showed that applying these sequences can reduce the PAPR by about 3 dB. [36] reported that the power spectrum of the Golay complementary sequences present the complementary property, and the spectrum is approximately flat. Also, [37] proposed error correcting codes to achieve lower PAPR by determining the connection between Golay complementary sequences and second-order Reed-Muller codes.

In addition, [38] showed the possibility of using Golay complementary codes both for error correction and PAPR reduction.

B. MULTIPLE SIGNALING AND PROBABILISTIC TECHNIQUES

Multiple signaling techniques, generate a permutation of the multi-carrier signal and choose the signal with the minimum PAPR for transmission, while probabilistic techniques, modify different parameters in the OFDM signal, and optimize them to minimize the PAPR.

These techniques have the advantages of introducing no distortion in the transmitted signal and achieving significant

PAPR reduction. However, they also involve certain drawbacks, such as a loss in data rate due to the transmission of several side information bits or increased complexity and transmission delay [39]. Next, we present examples of such techniques.

1) SELECTED MAPPING

Selected mapping (SLM) is an important PAPR reduction technique, which has been used extensively as it provides considerable gains. SLM was proposed for the first time by [28] in 1996, and then by [29] in 1997.

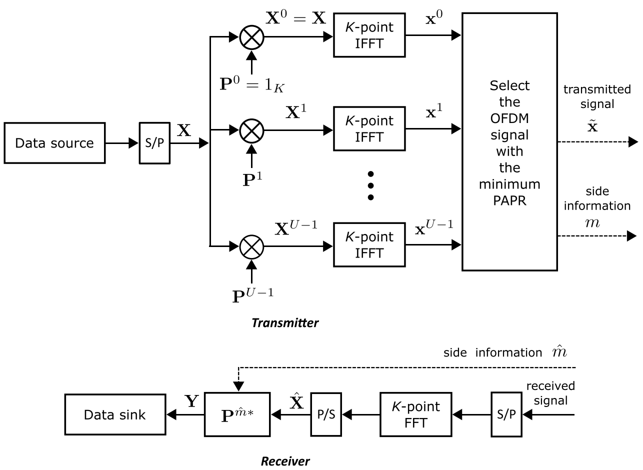


FIGURE 10. **Block diagram of selected mapping technique for PAPR reduction.**

The structure of the conventional SLM technique for PAPR reduction is presented in Fig. 10. The input data block $\mathbf{X} = [X_0, X_1, \cdots, X_{K-1}]^T$ after a serial-to-parallel conversion is multiplied by U different phase sequences $P^u = \left[P_0^u, P_1^u, \cdots, P_{K-1}^u\right]^T$, where $P_v^u = e^{j\varphi_v^u}$ and $\varphi_v^u \in [0, 2\pi)$ for $v = 0, 1, \cdots, K-1$ and $u = 1, 2, \cdots, U$. As a result, U statistically independent sequences $\mathbf{X}^u = \left[X_1^u, X_2^u, \cdots, X_{K-1}^u\right]$, which represent the same input data block, are generated and forwarded to the IFFT operation simultaneously to produce the U independent sequences $\mathbf{x}^u = \left[x_0^u, x_1^u, \cdots, x_{K-1}^u\right]^T$. Finally, the PAPR of the $\mathbf{x}^u$ vectors are evaluated separately and the sequence $\tilde{x} = x^{\tilde{u}}$ with the lowest PAPR is selected for final serial transmission [18], as

$$\tilde{u} = \underset{u=1,2,\cdots,U}{\operatorname{argmin}} \left(\max_{k=0,1,\cdots,K-1} \left| x_k^u \right| \right). \tag{22}$$

The conventional selected mapping technique needs to send the index u that identifies the selected phase sequence P^u as side information to allow the receiver to recover the original data block. Also, we note that U IFFT operations are needed in implementing the SLM method: for each data block, the technique requires $\lfloor \log_2 U \rfloor$ bits of side information, where $\lfloor x \rfloor$ denotes the greatest integer less than x. In the SLM technique, the side information is very important at the receiver, and as a result, channel coding is usually used to guarantee a reliable transmission.

In recent years, most research efforts have paid particular attention to reducing the disadvantages of the conventional SLM technique. To that end, two basic approaches are currently adopted: SLM algorithms without side information [40]–[45], and SLM algorithms with low-complexity [46]–[50].

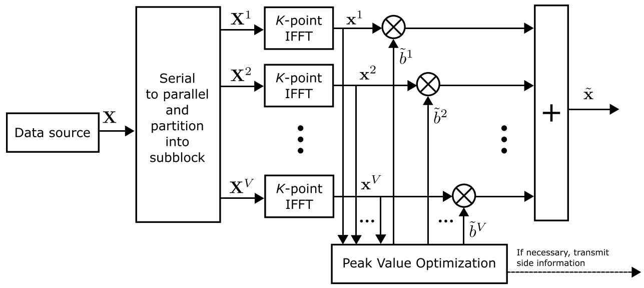


FIGURE 11. **Block diagram of PTS technique for PAPR reduction [18].**

2) PARTIAL TRANSMIT SEQUENCE (PTS)

A flexible PAPR reduction technique for the OFDM system, which combines partial transmit sequences was presente in [29]. In the PTS scheme (Fig. 11), the input symbol sequence $\mathbf{X}$ of K symbols is partitioned into V non-overlapping subsequences $\mathbf{X}^1, \cdots, \mathbf{X}^V$, the IFFT is applied to each symbol subsequence, and then the resulting signals are multiplied by a set of different rotation vectors $\tilde{\mathbf{b}}^1, \cdots, \tilde{\mathbf{b}}^V$. When all the signals are processed, subsequences are summed, and the PAPR is computed for each resulting subsequence. Finally, the signal sequence with the minimum peak-to-average power ratio is transmitted.

When the PTS scheme is used, the search complexity is an important parameter in the transmitter because it increases exponentially with the number of subsequences. Therefore, the selection of the rotation vectors must be limited to a set with a finite number of elements. Also, we should note that, like the SLM scheme, the classical PTS technique requires side information.

The PAPR reduction performance with PTS scheme depends on the number of subsequences, the number of rotation vectors, and finally, the method used to divide the sequences into multiple non-overlapping subsequences. Three subsequence partitioning types are available, namely, adjacent, interleaved, and pseudo-random partitioning [51].

3) INTERLEAVING

In the interleaving technique, introduced by [52], a $K-1$ permuted sequence from the same information is generated by $K-1$ random interleaved signals. Then, the PAPR of the original information and the permuted sequences are computed using K oversampled FFTs, and similarly to the selected mapping technique, the sequence with the lowest PAPR is chosen for transmission. The transmitter needs only transmit the information about which interleaver is used to recover the original data block at the receiver. Two interleaver types are proposed in [52], namely, random interleavers (RI) and periodic interleavers.

Although this technique is less complex than the PTS method, it however achieves comparable results, and the PAPR reduction performance depends on the number and the design of interleavers. Additionally, an interleaving block is considered on systems which use forward error correcting technique to spread the burst of errors. In tactical communication it reduces the effects of pulsed jamming. [53].

4) DFT-SPREADING TECHNIQUE

This is a useful technique that can achieve a similar PAPR as a single-carrier transmission. Here, the input signal is spread by a DFT, which can be following by the IFFT. Nowadays, the DFT-spreading technique is used for uplink transmissions in mobile communications. The technique, also known as the Single Carrier-FDMA (SC-FDMA) (see Fig. 12), has been adopted for uplink transmissions in the 3GPP LTE standard [54]–[57].

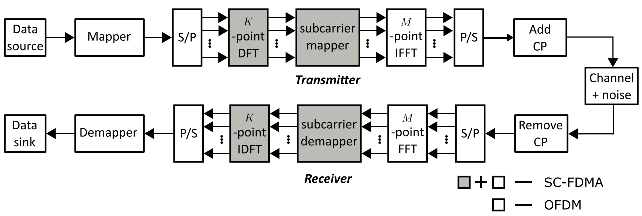


FIGURE 12. Block diagram for single carrier-FDMA (SC-FDMA) technique for PAPR reduction.

While in a downlink transmission in mobile communications with an orthogonal frequency division multiple access (OFDMA) system, the subcarriers are partitioned and assigned to multiple mobile terminals (users), in uplink, each terminal uses a subset of subcarriers M to transmit its data, and the rest of the subcarriers are filled with zeros [18]. Hence, an M-point DFT is used for spreading in the DFT-spreading technique, and the output of DFT is assigned to the subcarriers of the IFFT. The PAPR reduction performance of this technique depends on how the subcarriers are assigned to each terminal [56]. Two options are described in the literature for apportioning subcarriers: the localized SC-FDMA (LFDMA), in which each terminal uses a set of adjacent subcarriers to transmit its symbols, and the distributed SC-FDMA (DFDMA), in which the subcarriers used by a terminal are spread over the entire signal band. When DFDMA distributes occupied subcarriers at an equidistance, it is referred to as an interleaved FDMA (IFDMA) [56].

SC-FDMA has similar overall complexity and throughput performance as OFDMA, but while the PAPR performance of IFDMA is better than that of LFDMA, LFDMA with channel-dependent scheduling does result in higher throughput.

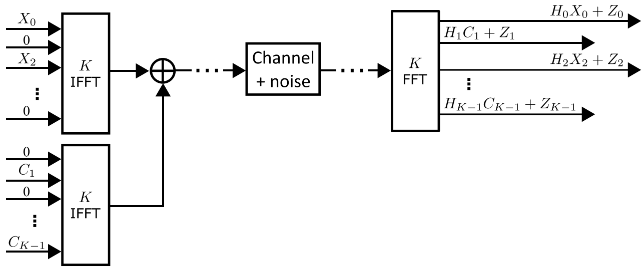


FIGURE 13. Block diagram of tone reservation technique for PAPR reduction [18].

5) TONE RESERVATION

This method partitions the K subcarriers (tones) into peak reduction tones (PRTs) and data tones [58], i.e., it reserves a small set of subcarriers and peak reduction tones that are optimized for PAPR reduction (see Fig. 13). The receiver and the transmitter need to know the positions of the PRTs.

An interesting problem to solve here is the strategy for calculating the PRTs that reduce the PAPR; to that end, [58] demonstrated that this problem can be solved if it is considered as a convex problem. [58] further showed that reserving a small part of subcarriers leads to a large PAPR reduction; moreover, this scheme does not require a complex algorithm in the transmitter, and there is no added complexity at the receiver. On the other hand, with the TR technique, the subcarriers reserved for the PRTs cause data rate decreases, and additional processing power is required in the transmitter. Thus, the amount of PAPR reduction seen when the tone reservation scheme is used depends on various factors, such as the complexity that can be used, and the number of peak reduction tones and their location.

6) TONE INJECTION

A tone injection [58] is another transformed input constellation method that can be used to reduce the PAPR without decreasing the data rate.

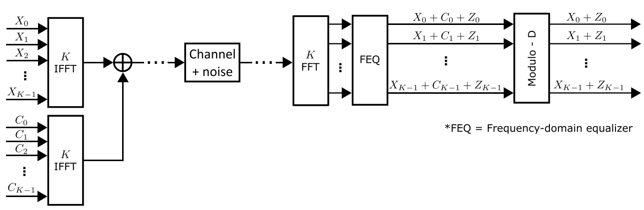


FIGURE 14. Block diagram of tone injection technique for PAPR reduction [18].

The TI technique expands the original constellation size into equivalent points in the larger constellation that is like to injecting a tone into the OFDM signal, with a specific frequency and phase to minimize the PAPR (see Fig. 14), hence the name of the technique. Although the TI technique does not decrease the data rate, as it does not use an additional subcarrier for PRTs, its method requires extra signal power to transmit the symbols due to the increased constellation size.

Furthermore, the technique can add problems in the transmitter because the injected and information signals occupy the same frequency band.

7) DUMMY SEQUENCE INSERTION

In the dummy sequence insertion (DSI) method, suggested in [59], a dummy sequence is added to the input data before the IFFT stage to reduce the peaks in the OFDM signal. Originally, [59] proposed four methods for using a dummy sequence in this DSI method. Method 1 inserts the complementary sequence, method 2 uses a correlation sequence as the dummy sequence. In method 3, the all-zero sequence is the dummy sequence, and the all-one sequence is the dummy sequence in method 4. In all cases, a dummy sequence is inserted before IFFT, and after the parallel-to-serial conversion, the PAPR is checked. If the PAPR is lower than a given limit, it is transmitted. Otherwise, a feedback is used to provide notification that the DSI process must be repeated using another sequence.

One advantage of the dummy sequence method is that it does not require side information as the dummy sequence is only used for peaks reduction and at the receiver, and can be discarded after the FFT operation. Hence, unlike the conventional partial transmit sequence (PTS) and selected level mapping (SLM) techniques, the DSI method does not increase the receiver system complexity, and is independent of the dummy sequence error.

The dummy sequence insertion method got better results than the PTS technique in terms of BER performance, and is more efficient in transmitting than the conventional block coding technique. However, the DSI method performs worse than the block coding and conventional PTS techniques in terms of PAPR reduction. Additionally, [59] proved that the DSI method 1 is better than the other methods.

C. SIGNAL DISTORTION TECHNIQUES

Signal distortion techniques, such as signal clipping, peak windowing and nonlinear companding transform (NCT), reduce high peaks in the OFDM signal by distorting the signal before amplification. A major advantage of these techniques is their simplicity. Signal distortion methods do not require extra side information, but these techniques introduce both in-band and out-of-band interference and complexity.

1) AMPLITUDE CLIPPING

Amplitude clipping [24] is the simplest scheme for PAPR reduction, and limits the peak envelope of the input signal to a pre-specified level. The output signal of a soft threshold can be given as:

$$B(x) = \begin{cases} x, & |x| < A \\ Ae^{j\phi(x)}, & |x| \geq A \end{cases} \tag{23}$$

where A represents the clipping level and $\phi(x)$ is the phase of x. While the signal distortion technique guarantees peak reduction, it does however have some drawbacks.

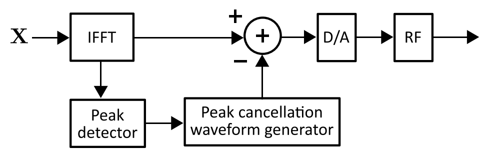


FIGURE 15. Block diagram of peak windowing technique for PAPR reduction [9].

First, clipping causes in-band signal distortion, which produces a degradation in the bit error rate. Also, clipping the OFDM signal envelope causes out-of-band radiation, resulting in interference for the adjacent channels. Several strategies have been developed to reduce these disadvantages. For example, the out-of-band signals generated by clipping can be reduced or removed by filtering, but this can also produce peak regrowth. For this reason, to obtain an appropriate PAPR reduction, iterative clipping and filtering must be used [4]. However, this adds computational complexity to the system [60]–[62].

2) PEAK WINDOWING

In the peak windowing method, the original OFDM signal is multiplied by a correcting function [63] such as Gaussian-shaped, Kaiser, Hamming or cosine window. Ideally, the correcting function frequency spectrum must be close to rectangular in the in-band frequency. Unlike amplitude clipping, peak windowing suppresses out-of-band radiation while reducing the peak signal. When the windowing technique is used, PAPR can be reduced down to about 4 dB, independent of the number of subcarriers, with a loss of SNR, caused by signal distortion, and an increase in out-of-band interference [10].

3) COMPANDING

A companding (compressing and expanding) technique was proposed by [64] to reduce the PAPR of the OFDM signal, based on the speech processing algorithm $\mu-$law. To implement the companding technique in the OFDM signal, the signal is companded and quantized before being converted into an analog waveform. At the receiver, the received signal is first converted into digital form, and expanded. The result in [64] shows that companding is an effective method for reducing the PAPR in OFDM systems, which does not require side information, and hence does not reduce the bit rate. Also, the number of subcarriers does not affect the companding complexity. However, the quantization error for large signals is significant due to companding, which means that this technique can degrade the system BER performance.

There are four classes of companding transforms, namely, linear symmetrical transform (LST), linear asymmetrical transform (LAST), nonlinear symmetrical transform (NLST) and nonlinear asymmetrical transform (NLAST) [9]. An example of nonlinear companding transform is presented in [65] and [66], which show two different types: based on error function [65] and based on exponential function [66].

These techniques provide good system performance, including BER and PAPR reduction, no bandwidth expansion, and low implementation complexity.

D. HYBRID TECHNIQUES

In recent years, some hybrid methods have also been proposed in the literature. These schemes combine two or more methods for PAPR reduction, and can be categorized into: Coding plus Multiple Signaling and Probabilistic techniques (C+MSP), Coding plus Signal Distortion techniques (C+SD), Multiple Signaling and Probabilistic plus Signal Distortion techniques (MSP+SD), and a combination of three methods, i.e., Coding plus Multiple Signaling and Probabilistic plus Signal Distortion techniques (C+MSP+SD). Some examples for each category are summarized in Table 3.

TABLE 3. PAPR reduction hybrid techniques.

	Coding (C)	Multiple Signaling & Probabilistic (MSP)	Signal Distortion (SD)	Ref.
C + MSP	Error-Correcting Code (ECC)	PTS		[68]
	Concatenated low density parity check (LDPC) codes	PTS (low complexity)		[69]
	Error control (EC) (Convolutional, Turbo or LDPC)	SLM		[70]–[72]
	Correction sub-code + Scrambling subcode	SLM		[73]
	Binary cyclic codes	SLM (without SI)		[74]
	Turbo code	SLM (without SI)		[75]
C + SD	FEC coding		Clipping	[76]
	FEC coding		Companding	[77]
MSP + SD		Interleaving	Companding	[78]
		PTS	Clipping	[79]
		Interleaver	Peak windowing	[80]
C + MSP + SD	FEC (Modified repeat accumulate (RA))	SLM (without SI)	Clipping	[81]
	LDPC or RA encoder	SLM (without SI)	Clipping	[82]
	Convolutional Code	SLM	Companding	[83]

Nowadays, hybrid techniques are considered a good option for PAPR reduction as they have the advantages of allowing both or more techniques to be used in hybridization, albeit with slight increases in complexity. Examples of hybrid techniques are the methods that combine a coding-based PAPR reduction scheme with MSP or SD techniques. To date, several studies have examined the combination of the coding peak-to-average power ratio reduction with other PAPR techniques, such as clipping, selected mapping and partial transmit sequence. Probabilistic methods, such as PTS and SLM, achieve significant PAPR reduction with a small data rate loss. On the other hand, coding techniques present good error control properties.

1) PARTIAL TRANSMIT SEQUENCE USING ERROR-CORRECTING CODE (PTS-ECC)

One of the main disadvantages with practically implementing a PTS scheme is the high computational complexity it involves due to the required computation of multiple IFFTs, which is proportional to the number of sub-blocks. Thus, [67] proposed a new PTS sub-block partitioning based on error-correcting codes (ECCs). The PTS-ECC technique presents better PAPR reduction than ordinary PTS (O-PTS), using, for example, pseudo-random sub-blocking partitions, while implementing the PTS with low complexity.

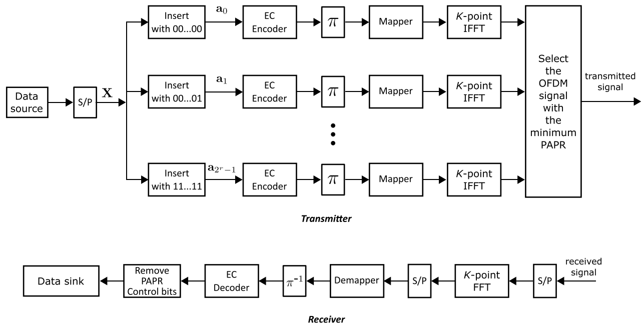


FIGURE 16. Block diagram of an EC-SLM transmitter and receiver [69].

2) ERROR CONTROL SELECTED MAPPING (EC-SLM)

This hybrid technique, which combines coding with a multiple signaling scheme is presented in [69] for a BPSK-OFDM system. This scheme is based on [71], who proposed an extension of SLM (concatenated SLM) that employs a label insertion and scrambling for avoiding the transmission side information. Also, [71] proposed the use of error control and interleaving blocks (π) to improve the BER. The EC-SLM scheme integrates PAPR reduction with error control in OFDM systems, as can be seen in Fig. 16, which shows the structure of an EC-SLM transmitter and receiver. The EC-SLM does not require the transmission of side information, and uses linear block codes and convolutional or turbo codes for error correction. In contrast with the concatenated SLM scheme, EC-SLM coding eliminates error propagation, and results in superior BER performance; however, the PAPR performance of EC-SLM PAPR is slightly worse than that of the concatenated SLM scheme.

Subsequently, Abouda [70] proposed a PAPR reduction technique using turbo coding and selected mapping. Again, they demonstrated that the (Turbo) encoder can be used for error correction and PAPR reduction, and that the turbo code improves the PAPR and BER performance as compared to an OFDM system with uncoded data, which uses SLM for PAPR reduction. Next, [72] extended the EC-SLM technique with the use of cyclic codes with SLM for BPSK, and combining block-coded modulation (BCM) with SLM for 16-QAM OFDM.

3) ERROR CONTROL SELECTED MAPPING WITH CLIPPING (EC-SLM-CP)

A complete hybrid scheme with one technique of each category is given in [80], where a modified repeat accumulate (RA) code, selected mapping, and clipping are combined. The RA code is a repetition code with an accumulator, followed by an interleaver (π) that generates good sequences in relation to PAPR reduction and allows an improvement of BER performance. On the other hand, the EC-SLM-CP uses the modified SLM with label insertion to avoid transmitting side information, followed by a four-stage linear-feedback shift register (LFSR), and the signal is transformed into

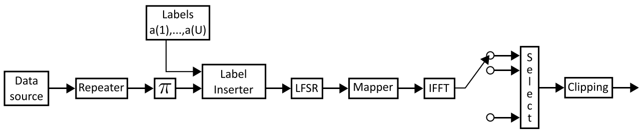


FIGURE 17. Block diagram of EC-SLM-CP technique [80].

orthogonal channels by the IFFT. Finally, in the transmitter the signal is clipped in order to reduce the PAPR. The complete block diagram of the EC-SLM-CP technique is shown in Fig. 17.

A similar technique is applied by [81], who suggests the use of random-like codes, such as turbo codes, low-density parity-check (LDPC) codes, and modified repeat accumulate (RA) codes, combined with a modified SLM. In addition, to avoid transmitting side information, a label insertion scrambler is used, along with a soft amplitude limiter (SAL) for clipping the signal. This technique provides good PAPR reduction and, BER improvement, avoids transmitting side information, and unlike the [80] scheme, [81] does not need an LFSR to implement scrambling.

As has been widely discussed, when different PAPR reduction techniques are considered, all methods show advantages and disadvantages, i.e., each technique must pay a price for peak reduction. A number of authors [10], [11], and [13] suggest that the following important factors must be considered when choosing a specific PAPR reduction: PAPR reduction capability, power increase in transmit signal, BER increase at the receiver, loss in data rate, computational complexity, and bandwidth expansion. For instance, for the technique based on channel coding, although it reduces the PAPR and improves the BER, it produces data rate loss, and sometimes requires extra memory. SLM reduces the PAPR, but results in more computational complexity, and in a loss in data rate from the side information. Finally, the clipping technique is a simple scheme that causes in-band signal distortion and out-of-band radiation.

V. MODIFIED CODE REPETITION, SELECTED MAPPING AND CLIPPING (MCR-SLM-CP)

We now propose a simple hybrid PAPR reduction scheme that combines one technique per category, such as modified code repetition (MCR), selected mapping (SLM), and clipping. This will allow us to compare the different techniques, which we will do in the following section. The structure for the individual schemes were introduced into sections IV-A.2, IV-B.1, and IV-C.1 for MCR, SLM, and in the clipping section, respectively. For the coding category, we use an interleaving in addition to the MCR block. Different types of interleavers are available, depending on how the bits are rearranged, and it is clear that the kind of interleaver used has an impact on the PAPR reduction achieved. In this work, a block interleaver, which writes across rows in the input and reads down columns in the output, is used. Also, the SLM technique requires side information. Fig. 18 shows the complete diagram for the MCR-SLM-CP transmitter.

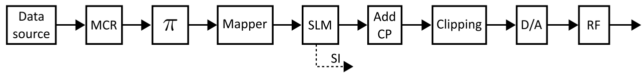


FIGURE 18. Block diagram of MCR-SLM-CP hybrid technique.

A. COMPARISON OF PAPR REDUCTION TECHNIQUES

We will now carry out a comparison of different PAPR reduction techniques in each category. The PAPR reduction techniques chosen to evaluate the performance are modified code repetition (MCR), selected mapping (SLM), and clipping (CP).

In the simulation, we consider an OFDM base-band signal with $K = 512$ subcarriers, a cyclic prefix length of 128 (guard interval percentage equal to 25%), a binary phase shift keying (BPSK), and an oversampling rate $L = 1$. An additive white Gaussian noise (AWGN) channel is assumed, the forward error correction block includes an MCR plus block interleaving, and the MCR decoding is implemented using majority logic detection. For the SLM technique, the rotation factor is defined as $P_v^u \in [\pm 1, \pm j]$, it can be implemented without any multiplications [28].

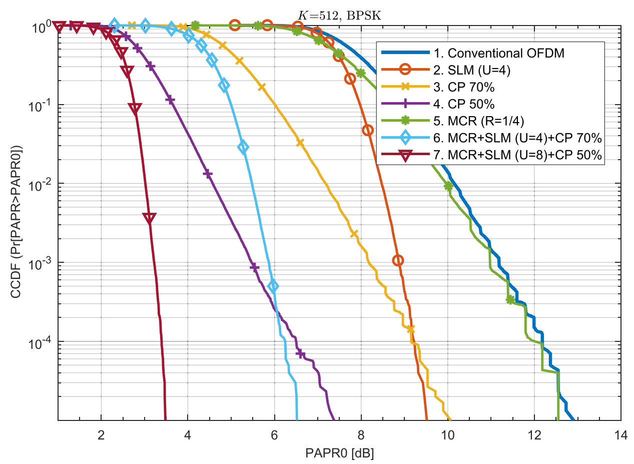


FIGURE 19. Comparisons of CCDF in OFDM-BPSK system for PAPR reduction techniques with $N_S = 3e+5$ for conventional OFDM, CP 70%, CP 50%, and MCR ($R = 1/4$), and $N_S = 1e+5$ for SLM ($U = 4$), MCR+SLM ($U = 4$)+CP 70%, and MCR+SLM ($U = 8$)+CP 50%.

As illustrated in Fig. 19, different curves of the complementary cumulative distribution function (CCDF) of the PAPR are given, and evaluated, for example: the conventional OFDM system without PAPR reduction (reference); the PAPR reduction schemes, namely, clipping with a clipping level equal to 70% and 50% (curves 3 and 4, respectively); the SLM scheme with 4 phase sequences (curve 2); and the MCR scheme with a code rate $R = 1/4$ (curve 5). Also, a hybrid technique is presented, i.e., the MCR-SLM-CP scheme with two variations of parameters: code rate $R = 1/4$, $U = 4$ and clipping level equal to 70% (curve 6) and code rate $R = 1/4$, $U = 8$ and clipping level equal to 50% (curve 7). The algorithm is executed $N_s = 300000$ times for conventional OFDM, CP 70%, CP 50%, and MCR

TABLE 4. Net gain of PAPR reduction techniques.

			Net gain		
	Y_1	Y_2	Γ_1	Γ_2	Γ_3
PAPR Reduction Technique	PAPR Reduction ($\mathrm{CCDF} = 10^{-3}$)	E_bN_0 Reduction ($\mathrm{BER} = 10^{-4}$)	$\alpha_1 = 0.5$ $\alpha_2 = 0.5$	$\alpha_1 = 0.25$ $\alpha_2 = 0.75$	$\alpha_1 = 0.75$ $\alpha_2 = 0.25$
2. SLM ($U = 4$)	2.60	0.00	1.30	0.65	1.95
3. Clipping 70%	3.20	-0.40	1.40	0.50	2.30
4. Clipping 50%	6.20	-3.00	1.60	-0.70	3.90
5. MCR ($R = 1/4$)	0.40	3.40	1.90	2.65	1.15
6. MCR+SLM ($U = 4$)+CP 70%	5.60	3.10	4.35	3.73	4.98
7. MCR+SLM ($U = 8$)+CP 50%	8.20	1.20	4.70	2.95	6.45

($R = 1/4$), and $N_s = 100000$ for SLM ($U = 4$), MCR+SLM ($U = 4$)+CP 70%, and MCR+SLM ($U = 8$)+CP 50%.

After analyzing these curves, it is clear that all the techniques improve the PAPR performance of a conventional OFDM system. To compare the results, we take a reference value of CCDF 10^{-4} for all cases. For instance, the SLM technique ($U = 4$) improves the PAPR performance by 2.96 dB over the conventional OFDM signal. The PAPR performance, for the clipping with clipping level equal to 70% and 50% improves the PAPR performance by 3.02 dB, and 5.68 dB, respectively. In contrast, the PAPR reduction with a coding based technique MCR (code rate $R = 1/4$) is only 0.25 dB better than the reference OFDM signal. On the other hand, the hybrid PAPR reduction technique curves 6 and 7 improve the PAPR performances by 5.93 dB, and 8.78 dB, respectively, over the conventional OFDM signal. That is, the MCR + SLM ($U = 8$)+ CP (50%) technique provides the greatest reduction in the CCDF of the PAPR, while the CCDF provides the greatest reduction with clipping at 50% as compared to the three individual schemes. However, a high percentage of clipping causes in-band signal distortion, and out-of-band radiation, resulting in bit error rate degradation and adjacent channel interference (see Fig. 20), respectively.

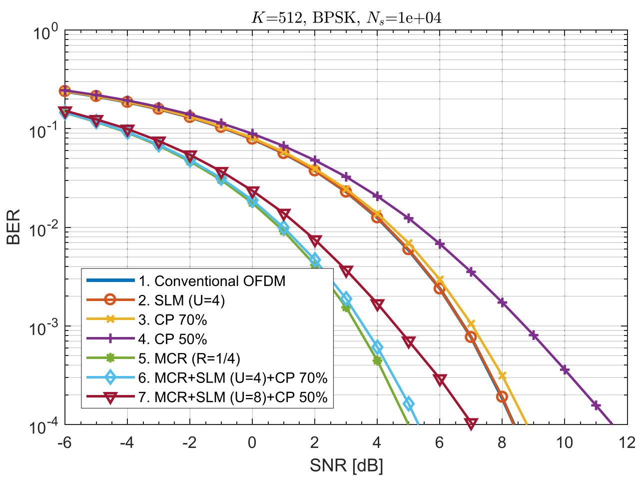


FIGURE 20. Comparisons of BER in OFDM-BPSK system for PAPR reduction techniques.

Figure 20 shows the performance of BER versus SNR for different PAPR reduction techniques and for the conventional OFDM signal (approximately similar BER than SLM ($U = 4$), and close to CP 70 %) when the AWGN channel is considered. It is seen that using a clipping PAPR reduction technique produces a BER degradation compared to the performance bound. For example, when the performance bound is considered, the minimum SNR needed to achieve a BER of 10^{-3} is 6.8 dB. However, in the clipping PAPR reduction technique, with a 50% clipping level, an SNR of 8.6 dB is required. On the other hand, one advantage presented by MCR is the reduction of the BER given a fixed value of SNR when compare with the conventional OFDM signal. For instance, the minimum SNR required for a BER of 10^{-3} is achieved with MCR, and is equal to 3.4 dB.

The net gain defined in the equation (13) is calculated for all case studied.

The results for a net gain are presented in the Table 4. A large value for the Y_1 implies better PAPR reduction. In the same way, a large value for the Y_2 implies better performance (less BER). Additionally, three net gain have been analyzed: first, when $\alpha_1 = \alpha_2 = 0.5$, i.e., equal importance for BER improvement and PAPR reduction; second, when $\alpha_1 = 0.25$ and $\alpha_2 = 0.75$, i.e., it is more important to achieve BER improvement; and third, when $\alpha_1 = 0.75$ and $\alpha_2 = 0.25$, i.e., it is more important to achieve PAPR reduction. In the Table 4, the best net gain for each case (Γ_1, Γ_2 and Γ_3) is highlighted by the gray box.

When we analyzed the net gain for the different techniques in Table 4, we could appreciate the importance of hybrid techniques, which can combine a technique with good PAPR reduction performance and one with BER reduction to provide an improvement in both factors.

Therefore, net gain concept could be considered as a tool to define the technique to be used in a given situation, for this, we must define the priority given to each parameter, i.e. the weights of factors α_k, such as, the PAPR reduction or the degradation in BER, and is possible to add others as the computational complexity of the technique, the increase in transmit power or reduction in goodput [17].

VI. CONCLUSION

Orthogonal frequency division multiplexing is a multi-carrier modulation technique used for both wired and wireless communications, and has a lot of applications in current communications systems. However, a major drawback of the OFDM signal is in the form of its high peaks in the envelope, which cause saturations in the power amplifier at the transmitter. PAPR reductions in OFDM systems could lead to power savings and in great improvements in range and coverage area. Meanwhile, in modern wireless communication many parameters can be changed in an OFDM system and be digitally adapted based on channel status, and traffic type to achieve improvements in PAPR reduction.

In this work, we started by studying theoretical concepts, such as the OFDM system, the PAPR problem, and the motivations for reducing the high peaks in a multi-carrier signal envelope. An extensive literature review for PAPR reduction methods was presented.

Finally, we concluded that a good strategy for reducing the PAPR an OFDM signal involves the use of a hybrid technique because such techniques can take advantage of different individual techniques, while reducing the high peaks in the signal, and can improve the BER performance.

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