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A Survey & Taxonomy of PAPR Reduction Techniques In MIMO-OFDM

Malleswari Akurati,
Department Of ECE, Senior Assistant Professor, CVR College Of Engineering, Hyderabad, Telangana, India.
Research Scholar, Jntuk, Kakinada.

Satish Kumar Pentamsetty,
Department Of ECE, ACE College Of Engineering, Hyderabad, Telangana, India.

Satya Prasad Kodati,
Department Of ECE, Retd. Professor, Jntuk, Kakinada, India.

Abstract-
The purpose of this survey is to give industry practitioners and readers a deeper comprehension of the high peak-to-average power ratio (PAPR) issue in create a taxonomy of the various ways to alleviate the issue with orthogonal frequency division multiplexing (OFDM) systems. After providing an overview of OFDM systems, the survey goes on to discuss the most frequent obstacle to OFDM systems, the PAPR issue, and how it affects power amplifiers, causing nonlinear distortion. The measures that can be used to assess the effectiveness of PAPR reduction plans are defined in detail in this survey. A taxonomy of PAPR reduction strategies divides them into three categories: coding approaches, signalling and probabilistic, and signal distortion. Within each group, there is further classification. In order to illustrate the variations in complexity requirements across various approaches, we also present complexity studies for a few PAPR reduction techniques. Furthermore, the work sheds light on the transmitted power constraint by demonstrating how companding transformations with carefully selected companding parameters can be used to satisfy the constraint without adding further complexity. There is a greater need for OFDM-based wireless systems that can handle high data rates and high mobility as a result of the explosive rise of multimedia-based applications, which has stoked an insatiable desire for high data rates. The number of subcarriers rises along with the data rates and mobility that the OFDM system supports, which ultimately results in high PAPR. It will also be necessary to reduce the high PAPR that occurs when future OFDM-based systems may increase the number of subcarriers to satisfy the increased data rates and mobility demands. This will probably lead to more research efforts. According to the authors, this study will be an invaluable educational tool for comprehending the most recent advancements in the field of PAPR reduction in OFDM research. In particular, for future research in PAPR reduction schemes for high data rate OFDM systems, the authors believe that this survey will be an invaluable educational tool for understanding the current research contributions in the area of PAPR reduction in OFDM systems, the various techniques that are available for designers, and their trade-offs towards developing more effective and practical solutions.

Keywords:*OFDM, PAPR, Power Amplifiers*

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I. Introduction

The contemporary trend of heightened information consumption coupled with the rapid expansion of novel multimedia wireless applications has led to a surge in the requirement for technologies that facilitate ultrafast transmission speeds, mobility, and the effective utilisation of available spectrum and network resources. One of the most effective ways to accomplish this is through OFDM, which also presents a viable option for upcoming high-speed data rate systems [1], [2]. IEEE 802.11a and IEEE 802.11g both include OFDM as a standard for high bit rate data transfer across wireless LANs [3].In the physical layer of the long-term evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) standards, OFDM is the preferred transmission technique. Other standards and applications that use it include the Japanese multimedia mobile access communications (MMAC), the European HIPERLAN/2, and digital audio video broadcasting (DAVB) [4], [5]. Numerous commercial applications have also made use of it, including MediaFLO, DSL, and DVB-H (digital video broadcast-handheld) [6]. The late 1950s saw the introduction of

OFDM, which became fully realised in the mid-1960s [7], [8]. Several carriers modulate several data bits concurrently in the OFDM modulation method. The transmission frequency band is divided into several smaller subbands by this process, with the spectrum of each data symbol occupying one of these subbands. By using overlapped subbands, OFDM improves spectral efficiency in contrast to traditional frequency division multiplexing (FDM), where such subbands are non-overlapping (Fig. 1). Subbands are mutually independent because they are positioned orthogonally to one another to prevent interference between them. Through the division of the broad transmission band into smaller, numerous subbands, OFDM methods successfully counteract the impact of frequency-selective fading, which is typically present in wireless channels. The phenomenon known as multipath propagation, in which multiple copies of the transmitted signal travelling along separate routes mix at the receiver, is the cause of frequency-selective fading [2]. Inter-symbol interference (ISI) and inter-carrier interference (ICI), however, are introduced by OFDM. By adding a guard gap between OFDM signals, both of these issues can be greatly mitigated. This interval, known as the cyclic prefix (CP), is a cyclic extension of the signal concatenated at the start of the OFDM symbol. A thorough examination of the issues surrounding ISI and ICI, as well as the strategies employed to mitigate them, is outside the purview of this survey and will not be covered in this one. It is anticipated that OFDM systems will become more significant in fixed and mobile high-speed wireless telecommunications systems in the future. Such high-speed networks' physical layer growth suggests the usage of OFDM systems with plenty of subcarriers and possibly high PAPR. Therefore, it is anticipated that interest in mitigation strategies will grow and that more study will be conducted. Although the topic of PAPR reduction has been surveyed in the literature [9]–[12], this survey, in comparison to all the prior studies, has both deeper and larger coverage and contains the most recent literature relating to the topic.Through simulation results, complexity studies, and insights into the transmitted power constraint, the research also makes a number of innovative contributions. As a result, this survey is ideally equipped to act as a comprehensive information source on the subject of OFDM system PAPR reduction. The paper's detailed and comprehensive presentation of the subject makes it a useful resource for novice researchers seeking to learn a wide range of topics. It also serves as a well-organized guide to extensive contributions found in the literature. The remaining portions of the survey are arranged as follows: Section II goes over the fundamental ideas of the traditional OFDM system. The PAPR metric and additional variables taken into account when assessing the effectiveness of PAPR reduction techniques are presented in Section III. The main body of this review, Section IV, classifies and briefly presents PAPR reduction techniques that have been found in the literature along with the most recent relevant. This survey is finally summarised and concluded in Section V.

II. Notation of OFDM System

OFDM

It is possible to create OFDM by sending several modulated carriers in tandem. However, this approach increases the complexity and cost of transmitters and presents implementation challenges. The discrete Fourier transform (DFT) method can be used to get around this issue [13].Examine a data stream with a rate of R bps in which a digital modulation such as quadrature amplitude modulation (QAM) is used to map bits to specific constellation points. For the OFDM symbol interval, let N of these constellation points be kept for a time interval of Ts = N/R. Currently, one of the subcarriers is modulated for each of the N constellation points, and all of the modulated subcarriers are transmitted concurrently across the symbol interval Ts [3]. The expression for the OFDM signal y(t) is:

$$y(r) = \frac{1}{\sqrt{V}} \sum_{k=0}^{V-1} Y(k) e^{j2\pi} \frac{k}{PV} r \qquad (1)$$

Where, $r = 0, 1, \dots \dots \dots V - 1$

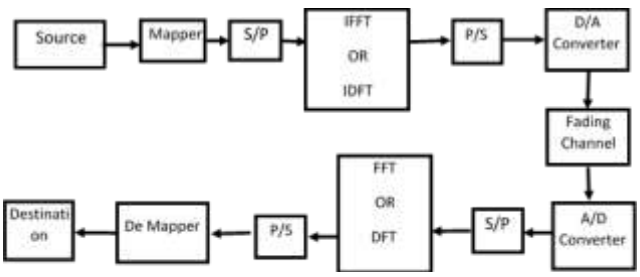

Fig.1 Block diagram of OFDM System

An example of a traditional FFT-based OFDM system is seen in Figure 1, where the transmitter and receiver use IFFT and FFT, respectively. Wavelet filter banks present an intriguing substitute for the OFDM scheme, albeit one that is not as well-liked as the IFFT method. Certain wavelet bases have the orthogonality property, which makes them appropriate for use as coefficients in a group of orthogonal digital filter banks.However, there is a high PAPR issue with this implementation as well, so mitigation strategies for these issues must be incorporated. Numerous sources discuss the challenges associated with designing OFDMsystems utilising wavelet filter banks, contrast wavelets with IFFT techniques, and suggest ways to lower high PAPR in wavelet-based OFDM systems.

PERFORMANCE of PAPR

The ensuing non-constant envelope with large peaks in multicarrier systems such as OFDM is a significant drawback [14]. The instantaneous power will exceed the average power when the independently modulated subcarriers are combined coherently.Examine the OFDM signal x(t), which is defined in (2) and consists of the sum of N subcarriers. Based on the central-limit theorem (CLT), the resulting signal x(t) will resemble a complex Gaussian process if N is large enough [15]. This indicates that its envelope and power follow Rayleigh and exponential distributions, respectively, and that both of its real and imaginary components have Gaussian distributions.In the temporal domain, PAPR can be phrasedas:

$$PAPR(y[n]) = \max_{0 \leq n \leq V-1} \frac{|y[n]|^2}{E[|y(n)|^2]} \qquad (2)$$

with the expectation operator denoted by E[.]. It is important to note that PAPR is calculated according to each OFDM symbol. Four sinusoidal signals with distinct frequencies and phase shifts are coherently added to produce a high peak. When the instantaneous amplitudes of the several signals have high peaks aligned simultaneously, the final signal's envelope displays high peaks. High peaks like these will cause the transmitter to build a power amplifier (PA), which will cause spectral spreading and nonlinear distortions [16]. The discrete-time OFDM signal samples that are produced are at the Nyquist-rate since the OFDM signal is generated via IFFT. It's possible that the peak value calculated with these samples will differ from the continuous-time OFDM signal's peak value [17]. Therefore, the accuracy is increased by oversampling by a factor larger than 1. It has been discovered that, provided the oversampling factor is at least 4, the PAPR of the over-sampled discrete-time signal provides an accurate estimate of the PAPR of the continuous-time OFDM signal [18]. The link between the PAPR of the continuous signal and the oversampled OFDM signal is discussed in length in References [19] and [20].The third generation partnership project (3GPP) has developed and approved the cubic metric (CM) as an alternative to the classical and commonly used PAPR metric for quantifying envelope variations [21], [22]. A few recent contributions [23]–[25] took this statistic into consideration. The third order intermodulation product, which is the convolution of the signal and the third order nonlinearity of the PA model, is primarily responsible for the distortion caused by the nonlinearity of the PA, which is the driving force behind the CM.

III. PAPR Reduction Techniques

A high PAPR would overwhelm the transmitter's PAs, causing subcarrier interference that tampers with the signal's spectrum and reduces BER performance. The average power of the signal may be decreased to prevent the PA from being saturated. But this approach lowers the signal-to-noise ratio and BER performance as a result. Also, it is better to lower the signal's peak power in order to address the high PAPR issue. Numerous methods for reducing PAPR have been put forth in the literary works. These methods can be divided roughly into three primary groups: strategies for signal distortion, several strategies for signallingprobability, and coding. Under each heading, we will go over a few important techniques and highlight the benefits and drawbacks of each.

Signal distortion schemes:

By altering the transmitted OFDM signal before it enters the PA, signal distortion techniques lower the PAPR. The most popular methods for distorting signals include peak windowing [26], companding [27]–[33], peak cancellation [34], and clipping and filtering [35]–[44].

These methods dramatically lower the PAPR but raise BER by introducing in-band and out-of-band distortion.

Clipping and Filtering:

Cutting the high peaks out of the OFDM signal before sending it through the PA is one of the most basic ways to distort signals. In this method, a clipper is used, which, if the signal exceeds a predefined clipping level (CL), limits the signal envelope to that level; if not, the clipper passes the signal unchanged. Nonlinear processes like clipping can cause distortions that are both in- and out-of-band. The former can impair BER performance and cannot be lessened by filtering, but the latter results in spectral spreading and can be removed

by filtering the signal following clipping. Oversampling, however, can lessen the influence of in-band distortion since a portion of the noise is reshaped outside of the signal range and can be filtered out later. This is achieved by taking longer IFFTs. By removing out-of-band distortion, filtering the clipped OFDM signal can maintain spectral efficiency and improve BER performance, but it can also cause peak power regrowth.The authors of [41] look into how clipping affects how well OFDM systems operate in a frequency-selective fading channel. In [42], the effects of clipping on channel capacity and PAPR reduction are examined. A modified repetitive clipping and filtering approach was provided in Reference [45] to limit the distortion on each OFDM tone and achieve low PAPR and low BER with quick convergence. The authors of [46] created an improved repeated clipping and filtering technique that uses convex optimisation to identify the best frequency response filter for each iteration.The filter's goal is to reduce signal distortion to the point that the PAPR falls below a given threshold. The standard clipping and filtering method takes approximately 8 to 16 iterations to obtain a similar PAPR decrease, according to the authors, whereas the method achieves the appropriate PAPR reduction after just 1 or 2 cycles.Simulations for the OFDM signal with no clipping and with clipping applied at 1dB and 5dB clipping ratios (CR) are carried out starting with [47]. The BER is rising and the empirical CCDF is falling as a result of the CR being lowered, the CL being lowered, and more OFDM signal components being clipped.
Peak Windowing: Maximum height peaks are restricted by multiplying them by a weighting function known as a window function in peak windowing, as opposed to peak clipping, which hard-limits peaks that beyond a preset threshold. Given that they possess good spectral qualities, a multitude of window functions can be employed in this procedure [26]. Hanning, Kaiser, and Hamming windows are the most often utilised window functions. The process of reducing PAPR involves aligning a window function with the signal samples so that the signal peaks double its valley, and the lower amplitude signal samples surrounding the peaks multiply its higher amplitudes. Reduced distortion is the outcome of this process, which attenuates signal peaks considerably more smoothly than harsh clipping.

***Companding Transforms*:**

To minimise the amount of bits needed for each sample, speech signals are usually subjected to expanding transforms. The speech signal and OFDM signal behave similarly in that high peaks which appear frequently, hence the PAPR of the OFDM signal can also be decreased using the same companding transforms [27], [28]. Companding complexity is independent of the number of subcarriers, in addition to having a comparatively low computational complexity when compared to other PAPR reduction strategies. Furthermore, companding does not lower bit rate because it does not require side information. The authors of [29] examine how companding affects the OFDM system's BER performance when AWGN is present and show that a satisfactory symbol error rate is achieved.

***Peak Cancellation*:**

This method involves creating a peak cancellation waveform, scaling it, shifting it, and subtracting it from the OFDM signal at the segments that show high peaks. Certain peak cancellation tones that are not used for data transmission are the only ones that the resulting waveform is band limited to [48], [49]. When a possible peak larger than a predetermined threshold is detected, peak cancellation can be performed by subtracting the peak cancellation waveform from the OFDM signal, which can be done after the IFFT block of the OFDM transmitter. As the peak cancellation waveform, a randomly selected sinc function is employed. It is important to exercise caution while cancelling peaks so as not to create new ones.

ProbabilisticSigalling techniques

There are two ways in which these methods function. One method is to create several OFDM signal permutations and send the one with the lowest PAPR. Altering constellation points, adding peak reduction carriers, or introducing phase shifts are some alternative methods of modifying the OFDM signal. In order to reduce PAPR, the modification parameters are optimised.

***Selective Mapping*:**

One somewhat easy way to lower PAPR is through selective mapping (SLM). The fundamental concept is to produce a sufficient number of distinct OFDM signals, each of length N, that convey the same information as the original OFDM symbol x. The least PAPR symbol is subsequently transmitted [50], [51]. Numerous blind SLM techniques have been researched in order to eliminate the requirement to broadcast side information [52]–[58]. Among these, the maximum likelihood decoder is derived for the system in [57], which, under the assumption of perfect side information recovery, exhibits the same BER performance as the traditional SLM scheme but results in a high decoding complexity at the receiver. The side information is embedded into each phase sequence by providing the phase offset to the phase sequence components, which are determined by the biorthogonal vectors for the partitioned subblocks, according to a blind SLM approach with low decoding complexity that was suggested in [57].Furthermore, it was demonstrated in [54] that the BER of the scheme is nearly identical to the traditional blind PTS for QPSK and 16-QAM. A low complexity decoding algorithm and a pilot phase sequence that allows data recovery without side information are proposed in [59]. The suggested technique's BER performance is significantly better than the Maximum Likelihood decoding scheme and roughly equal to that of the traditional SLM scheme with side information. Furthermore, as compared to the maximum likelihood decoding strategy, the computational complexity of the suggested decoding scheme is significantly lower.Using multiple all-pass filters to rotate the symbol phase instead of the many complex multiplication modules and IFFT modules used in the typical SLM system, the authors of [60] devised a scheme that generates OFDM sequences. This approach lowers the computational complexity by avoiding the need of several IFFT modules, which place a significant computational load at the transmitter. Nonetheless, a minor deterioration in PAPR reduction performance results from the reduction in complexity. For instance, compared to the traditional SLM technique with 8 IFFT modules, the suggested scheme with 8 first order all-pass filters for 2048 subcarriers OFDM system reduces the number of needed multiplications by 69.2% and adds by 63.1% at a cost of just 0.25 dB PAPR increase.

***Partial Transmmit Sequence*:**

An input data block of length N is divided into several discontinuous sub-blocks in partial transmit sequence (PTS). Each of these sub-blocks has its IDFT calculated independently, and it is then phase factored. In order to minimise the PAPR of the combined signal of all the sub-blocks, the phase factors are chosen [61]–[66].In order to reduce the computing complexity, the authors of [67] presented a PTS scheme based on listing the phase factors into several subgroups table and using the correlation among phase factors in each subset. In order to considerably lower the PAPR statistics for OFDM signals, a collection of subcarrier signs is chosen according to the sign selection technique provided in Reference [68]. The use of the quantum-inspired evolutionary algorithm (QEA) was suggested as a way to find a decent set of subcarrier signs with enhanced PAPR statistics while lowering the computational burden of an exhaustive search across all possibilities of sign patterns.In order to reduce the complexity of the PTS scheme, other combinatorial optimisation techniques have been employed, such as the parallel tabu search algorithm [69] and the artificial bee colony algorithm [70], to effectively search a decent subset of phase rotating vectors. A better search strategy has been put out in [71], wherein the sphere decoding method is used to limit the search among the alternate sequences inside a sphere, hence reducing the computational cost of the traditional PTS technique.The authors of [72] present a low-complexity PTS scheme based on a W-way tree, in which layers represent subblocks and nodes in the tree correlate to phase factors. By combining layers and weighting factors on the paths from the tree, the computation of candidate signals make use of the tree's structure.By adding layers and weighting factors on the paths from the root to the leaves, the computation of candidate signals makes use of the tree's structure. While the PAPR reduction capability is maintained at the level of the standard PTS, the approach drastically decreases complexity.

***Tone Injection*:**

This method enlarges the constellation so that, before IDFT processing, every point in the initial complex plane constellation is mapped onto many additional points in the expanded constellation [73]–[76]. This additional degree of freedom makes a decrease in PAPR possible. The method's name comes from the fact that replacing a point in the original constellation with one in the extended one is akin to injecting a tone into the OFDM signal with the correct frequency and phase. In contrast to the QAM constellation, references [77] and [78] suggest a tone injection technique with a hexagonal constellation to reduce PAPR with only a slight power increase.

Tone Rejection:

Using the tone reservation (TR) strategy, a portion of the tones are set aside for the lowering of PAPR. As a result of their poor SNR, these tones don't convey any information. The OFDM signal x is given a structured time domain vector c to alter its statistical distribution in an effort to lower PAPR [9], [73]–[75]. In the TR approach, the amount of reserved tones, their positions in the frequency domain vector C, and the optimisation difficulty all affect how much PAPR is reduced. Reference [76] demonstrates that the same performance as the general LP may be achieved with a decreased complexity of O (N) by optimising the signal-to-clipping noise ratio rather than PAPR and by employing a gradient algorithm with optimisation done on the time domain vector c. A straightforward and computationally effective TR technique is proposed in Reference [79], wherein a small number of frequency domain tones are set aside to produce a time domain Gaussian pulse that will act as a peak cancellation signal while reducing the likelihood of secondary peaks. A computationally efficient PAPR reduction approach was proposed in Reference [80]. It uses the truncated kernel signal generated from the IFFT of the shaped PRC set to lower the peak sample of each parabolic pulse.

Coding Methodologies:

Certain coding schemes are a good option for performing PAPR reduction because of their inherent capacity to provide error detection and correction. These coding schemes can be modified to provide both functionalities with an acceptable extra complexity. Here, we go over a few of the PAPR reduction coding methods that have been documented in the literature.

Linear block Coding:

Certain codeword bits are now allocated to lower PAPR rather than improving BER performance. Selecting codewords for transmission with a low PAPR is the aim of these codes. In [81], a straightforward linear block coding (LBC) scheme was presented, in which a parity bit is added to transfer three bits to four bits. To lower PAPR by more than 3 dB, [82] uses a basic rate-3/4 cyclic code for any number of subcarriers that is a multiple of 4. Using the suggested sub-block coding (SBC) technique, which divides large information sequences into sub-blocks and adds an odd parity bit to each sub-block, similar performance was achieved with less complexity in [83]. To further minimise PAPR, the extra parity bit's location is optimised. Furthermore, each sub-block can be encoded using two different coding schemes in place of one, and the arrangement of the coded sub-blocks can be optimised to reduce PAPR. In order to create a codeword with a lower PAPR, a low complexity complement block coding (CBC) method is proposed in [84], [85]. Standard arrays of linear block codes are employed in [86] to reduce the PAPR. This system can be thought of as a modified version of SLM, wherein the received signal can be decoded via syndrome decoding and no side information needs to be provided because the coset leaders of a linear code are utilised for scrambling.

Golay Complementary Sequences:

In order to modulate the OFDM system's subcarriers and produce a PAPR signal with an upper bound of 2, one can employ Golay Complementary Sequences [87] as codewords [88], [89]. Golay Complementary Sequences meet the requirement of having a zero out-of-phase autocorrelation function. In [90], a constellation known as the Asterisk 16-QAM is put out to lower PAPR when data encoding is done with Golay sequences. A new constellation family controlled by a single parameter is proposed in [91], which presents a generalised paradigm for the Asterisk 16-QAM constellation. In [92], a novel family of 64-QAM sequences that aren't always Golay sequences are created using Golay sequences as the building blocks.

Turbo Coding:

Applying the SLM technique to data produced by a turbo encoder with different interleavers is one technique to take advantage of turbo codes for PAPR reduction [93]. This solution avoids the BER performance reduction caused by improper side information recovery in conventional SLM systems, since no side information is needed. In addition to the benefit of PAPR reduction, Turbo coding's error correction features can be used.A different strategy based on the dual bose-ray-chaudhuri (BCH) codes was put out in [94]. There are several desirable PAPR features in dual BCH coding [95]. In particular, [96] demonstrates that this code's codewords' IFFT displays low envelope fluctuations and, thus, low PAPR. However, the wide performance gap to the Shannon limit and the lack of a workable decoder limit the promise of this code for PAPR reduction.

IV. Conclusions

Because of its high data rates, resilience to multipath fading, and spectral efficiency, OFDM is a successful multicarrier modulation technology for future wireless applications. Notwithstanding these benefits, its primary disadvantage is that it produces high PAPR, which saturates the transmitter's PA and results in spectrum spreading and nonlinear aberrations. There are numerous PAPR reduction approaches available in literature that significantly lower PAPR at the price of higher BER, more transmitted power, lower bit rates, or higher complexity. Numerous significant facets of PAPR reduction strategies and their effects on several crucial design elements have been covered in this survey. The distribution of the OFDM signal and the statistics of PAPR were two of the most important mathematical formulations that were given. For instance, signal distortion techniques, particularly clipping and filtering, are the least computationally intensive while still delivering good PAPR reduction in OFDM systems with a large number of subcarriers ($N<256$). Because future wireless systems are probably going to use OFDM structures with more subcarriers than current ones in order to achieve better data rates and mobility, the topic of PAPR reduction assumes increased importance. This suggests that there are many interesting avenues for future research on the topic of creating PAPR reduction strategies for OFDM systems that can mitigate the issue with the optimum performance trade-offs, including the least amount of complexity and expense. This survey offers a comprehensive collection of references on the topic of PAPR reduction techniques. In addition, it updates earlier surveys by covering the latest research and includes unique contributions such as simulations, complexity analyses, and a treatment of the subject under transmitted power constraints. The survey's authors firmly think that by giving academics, OFDM system architects, designers, and developers an awareness of the most recent research contributions in the field, it will be a useful educational tool.

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