PEAK TO AVERAGE POWER RATIO REDUCTION IN WIRELESS ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

by

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LIST OF ABBREVIATIONS

AWGN	Additive White Gaussian Noise
ACE	Active Constellation Extension
ACI	Adjacent Channel Interference
ADSL	Asymmetric Digital Subscriber Line
ADC	Analog to Digital Converter
ANE	Adaptive Nonlinear Estimator
APPR	Adaptive Peak Power Reduction
BPSK	Binary Phase Shift Keying
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CDF	Cumulative Distribution Function
CCDF	Complimentary Cumulative Distribution Function
CFO	Carrier Frequency Offset
CR	Clipping ratio
DAB	Digital Audio Broadcasting
DAC	Digital to Analog Converter
DCT	Discrete Cosine Transform
DSP	Digital Signal Processing
dPTS	Direct Approach PTS
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting Terrestrial

DFT	Discrete Fourier Transform
Eb/No	Bit Energy-to-Noise Density Ratio
FEQ	Frequency Domain Equalizers
FFT	Fast Fourier Transform
FDM	Frequency Division Multiplexing
FDMA	Frequency division Multiple Access
FEC	Forward Error Correction
GSM	Global System for Mobile Communication
HDSL	High Bit Rate Digital Subscriber Lines
HDTV	High Definition Television Terrestrial Broadcasting
HF	High Frequency
HPA	High Power Amplifier
HIPERLAN	High Performance Radio LAN
I	Inphase
IMT	International Mobile Telecommunication
IS	Interim Standard
ISI	Inter Symbol Interference
ICI	Inter Carrier Interference
IEEE	Institute of Electrical and Electronic Engineers
IFFT	Inverse Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
LAN	Local Area Network
MCM	Multi-Carrier Modulation

MIMO	Multiple Input Multiple Output
MSE	Mean Square Error
MMSE	Minimum Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDC	Partial Data Circulation
PDF	probability density function
P/S	Parallel-to-Serial Conversion
PRC	Peak Reduction Carriers
PSD	Power Spectral Density
PHY	Physical Layer
PTS	Partial Transmit Sequences
PSK	Phase Shift Keying
PEPs	Peak Envelope Powers
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
Q	Quadrature Phase
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
SC-OFDM	Synchronous Coherent OFDM
SI	Side Information
S/P	Serial-to-Parallel Conversion

SLM	Selective Mapping
SNR	Signal to Noise Ratio
SDR	Software Defined Radio
SDPA	Semi Definite Programming Algorithm
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
TR	Tone Reservation
TI	Tone Injection
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications Systems
UWB	Ultra Wide Band
VHDL	Very High Speed Digital Subscriber Lines
VLSI	Very Large Scale Integration
WiMAX	Worldwide Interoperability for Microwave Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WCDMA	Wide Code Division Multiple Access

PENGURANGAN NISBAH KUASA PUNCAK KE PURATA DALAM PEMULTIPLEKSAN PEMBAHAGIAN FREKUENSI ORTOGON TANPA WAYAR

ABSTRAK

Pemultipleksan Pembahagian Frekuensi Ortogon (OFDM) menawarkan teknik menarik dengan kecekapan spektrum yang tinggi, pelaksanaan yang mudah dan keteguhan terhadap pemudaran berbilang laluan. Trend perkembangan OFDM ialah dengan meningkatkan bilangan subpembawa untuk menambahkan kecekapan. Walaubagaimanapun, apabila bilangan subpembawa meningkat, sebilangan pekali domain masa OFDM akan memerlukan magnitud yang cukup tinggi. Gelombang bagi jalur asas OFDM akan mempunyai nilai PAPR yang tinggi dan mengalami gangguan tidak linear pada tahap kuasa penguat. PAPR yang tinggi boleh menghadkan kecekapan pemancar kuasa, menyebabkan pelebaran spektrum dan mengurangkan prestasi kadar ralat bit (BER). Untuk mengatasi masalah tersebut, tiga teknik novel yang cekap dari segi pengkomputeran dan menjimatkan kos telah dicadangkan. Teknik pertama iaitu kaedah Penjelmaan Diskret Kosinus merupakan satu kaedah alternatif di bahagian pemancar supaya nilai PAPR dapat dikurangkan. Pengurangan perbezaan antara nilai kuasa puncak dan purata kuasa membawa kepada pengurangan PAPR. Teknik ini dapat mengurangkan nilai PAPR sebanyak 2.2 dB. Kaedah pengagihan semula taburan statistik (SRM) yang menggunakan transformasi amplitud isyarat OFDM dari taburan Rayleigh ke taburan Gauss telah digunakan sebagai teknik gabungan dengan kaedah pemetaan terpilih (selected mapping). Keputusan menunjukkan bahawa sebanyak 5 dB pengurangan nilai PAPR dapat dicapai bagi teknik gabungan tersebut.

PEAK TO AVERAGE POWER RATIO REDUCTION IN WIRELESS ORTHOGONAL FREQUENCY DIVISON MULTIPLEXING

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) offers an attractive multicarrier technique with high spectral efficiency, simple implementation and robustness against multipath fading. A trend of OFDM development is to increase the number of subcarriers to enhance efficiency. However, when the number of subcarriers increases, certain time domain OFDM coefficients are likely to acquire excessively large magnitudes. As such, the OFDM baseband waveform is susceptible to high PAPR value and may suffer from non linear distortion at subsequent power amplifier stage. This high PAPR can limit the transmitter power efficiency, cause spectral spreading and reduce the bit-error-rate (BER) performance. To alleviate these potential performance problems, two novel computationally efficient and low cost PAPR reduction methods are proposed. The first method, called DCT-OFDM Method, seeks to apply alternative structure for transmitting the high speed data in the OFDM system. The character of the DCT energy focused is made use of in the frequency domain and it helps to reduce the PAPR engendered by IFFT at the transmitter statistically, avoiding the nonlinear distortion in OFDM systems due to great change of PAPR. It is mathematically verified that this method is potent to reduce PAPR. Simulation results show that about 2.2 dB reduction in PAPR value is achieved by this technique. Statistical Redistribution Method (SRM) which makes use of a non linear companding operation is selected and applied on the OFDM outputs signals has been used as a combination with Selected Mapping Method (SLM). The proposed scheme utilizes Selected Mapping (SLM) followed by the companding SRM technique to further reduce the PAPR of the OFDM signal. Simulation results indicate that about 5 dB reduction in PAPR is achieved compared with the conventional SLM algorithm.

CHAPTER 1

1.0 INTRODUCTION

Mobile communications and wireless networks have experienced massive development in the recent years. As the wireless standards evolved, the access techniques used also exhibited increase in efficiency, capacity and scalability.

A new modulation scheme which has received significant attention over the last few years is a form of multicarrier modulation called Orthogonal Frequency Division Multiplexing (OFDM). Orthogonal Frequency Division Multiplexing (OFDM) is a promising Multicarrier Modulation (MCM) scheme for high-speed communications. The system's operational principal is that the original bandwidth is divided to a high number of narrow sub-bands and it is proved to be a potential candidate for the physical layer of next 4G mobile systems (Wang, 2001).

OFDM has been used for Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) in Europe, and for Asymmetric Digital Subscriber Line (ADSL) high data rate wired links. OFDM has also been standardized as the physical layer for the wireless networking standard 'HIPERLAN2' in Europe and as the IEEE 802.11a, g standard in the US, promising raw data rates of between 6 and 54Mbps.

OFDM is a widely used communication technique that works on combating multipath distortion. OFDM applications have been extended from high frequency (HF) radio communication to telephone networks, digital audio broadcasting and digital television terrestrial broadcasting. The OFDM technique (multicarrier modulation) compared to traditional single carrier modulation scheme has several advantages:

(a) In OFDM system, the subcarriers are orthogonal to each other so that the channel spectrum overlapping and will utilize limited spectrum resources maximally.

(b) In OFDM system, modulation and demodulation can be achieved by FFT and IFFT.

(c) OFDM has the ability to eliminate multi-path interference. In OFDM, high-speed serial data streams are transferred to parallel transmission which increases the duration of data symbols carried by corresponding sub-carriers. This will reduces the channel time dispersion caused by ISI.

(d) A different number of sub-channels is use to provide different transmission rates between uplink and downlink. Currently, downlink channels carry more traffic than uplink channels where the data services are often non-symmetrical. This requires a physical layer that supports non-symmetric high-speed data transmission.

Despite the many advantages of OFDM it still suffers from some limitations such as:

(a) It is more sensitive to frequency offset. OFDM sub-carrier spectrums overlap each other, which require strict orthogonality among them.

Frequency offset impairs orthogonality and will degrade the demodulation performance. Time offset can lead to OFDM symbol interference and amplitude attenuation.

(b) An OFDM signal consists of a number of modulated subcarriers, which can lead to large peak to average power ratio (PAPR). It is known that in OFDM, the output is a superposition of sub-carriers. When the phases of carriers are the same, this could lead to some instantaneous power outputs which are higher than the mean power of the system. This results in a larger Peak-to-Average Power Ratio (PAPR). When the peak power is too high, it could be out of range of linear power amplifiers. This gives rise to non-linear distortion and changes the superposition of the signal spectrum. It also destroys sub-carrier orthogonality and degrades the performance of OFDM.

1.1 Problem Statement

One of the implementation drawbacks of OFDM is that the transmitted signal has a high PAPR, a large dynamic signal range with a very high PAPR. As a result, the OFDM signal will be clipped when passed through a nonlinear power amplifier at the transmitter end. Clipping degrades the bit error rate performance and causes spectral spreading. One way to solve this problem is to force the amplifier to work in its linear region. Unfortunately, such a solution is not powerful efficient. Power efficiency provides adequate area coverage, saves power consumption and allows small size terminals. This can be done through some manipulations of the OFDM signal before transmission.

Several methods such as partial transmit sequences (PTS), selected mapping (SLM), clipping, and coding have been proposed to reduce the high PAPR levels in OFDM systems. A comprehensive comparison between these methods in terms of power loss, distortion, data rate loss, and extra processing can be found in. All these schemes use IFFT and FFT blocks to modulate and demodulate the data symbols. Recently, trigonometric transforms such as the discrete cosine transform (DCT), discrete sine transform (DST), and discrete Hartley transform (DHT) along with their inverses were proposed as replacements for the IFFT/FFT stages in OFDM systems. The main advantage of using such transforms is that they achieve better noise-immunity and hence better BER performance than the standard FFT case while maintaining a low implementation. Although this idea was proposed and analyzed by a number of researchers, a study of PAPR reduction when trigonometric transforms are used was never addressed.

The energy compaction properties of the DCT make it useful in applications, including data communications and DCT concentrates the energy of the original signal into few coefficients. Other than that, the reduction in the autocorrelation between the components of each OFDM signal will result into a reduced PAPR. In terms of orthogonality, IDCT basis functions are orthogonal. Thus, the inverse transformation matrix is equal to its transpose. Therefore, in addition to its decorrelation characteristics, this property renders some reduction in the pre-computation complexity. Compared with the means of conventional FFT OFDM, DCT-OFDM maintains the system orthogonal properties, which will not result in additional noise and need not transmit side information.

Although numerous schemes have been proposed to solve the PAPR problem, no specific PAPR reduction scheme can be considered as the best solution. Signal predistortion techniques such as clipping, peak windowing and peak cancellation aim to reduce the peak amplitudes of the transmitted signals by nonlinearly distorting the OFDM signal at or around the peak values.

Clipping is the most common technique to reduce PAPR, in which the peak amplitude of the input signal is deliberately clipped to a predetermined value. Clipping results in distortion noise, which may fall both in-band or out-of-band depending upon whether clipping is performed on a Nyquist sampled signal, or on an oversampled signal.

Another category of the PAPR reduction schemes transforms the OFDM signals after multicarrier modulation such as companding techniques (Wang *et al.* 2006). Companding outperform clipping method in terms of BER performance. Exponential companding technique offers efficient PAPR reduction with a low bit error rate (BER). However, the exponential companding technique is difficult to implement. In $\mu - law$ companding method, the main disadvantage is that it will increase the average power of the transmitted signal.

Another companding scheme utilizes a nonlinear operation that transform the original OFDM signals into the uniform distribution and efficiently reduce PAPR with a low Bit Error Rate (BER). Similarly, the exponential companding scheme transforms the amplitude of the original OFDM signals into the uniform distribution. The referred uniformly distributed companding schemes can keep the same average power as that of the original signal and significantly outperform the $\mu - law$ companding scheme. However, the uniformly distributed companding scheme cannot perform variably to satisfy the different performance requirements for the systems. Zhu *et al.* (2010) have explored new companding technique that based on transforming the distribution of OFDM signals from Rayleigh distribution into beta distribution. Although it achieves better tradeoff between PAPR reduction and bit error rate performance than the exponential companding scheme, the main disadvantage of this technique is the complexity of the transformation expression.

This study investigates the problem of high PAPR in OFDM systems and focuses on the development of low cost, simple implementation and effective PAPR reduction techniques to enhance the performance of OFDM transceiver implementation.

Firstly, a method for using sinusoidal transforms as an alternative to the DFT for OFDM wireless transmission is presented and it was shown that under certain channel conditions or modulation constellation, throughput is enhanced when sinusoidal transform is used instead of DFT. It is proved that these transforms satisfy the cyclic convolution properties of DFT when used with symmetric extension.

The second method, called Statistical Redistribution Method (SRM) seeks to apply an alternative companding scheme that transforms the amplitude of original OFDM signals from Rayleigh distribution into Gaussian distribution. Only the amplitude values are processed, while the phases of the complex OFDM symbol are kept unchanged. Transforming the distribution of OFDM signals will change the mean and variance values of the signal. This will lead to PAPR reduction.

In this study, the combination of selected mapping scheme with the statistical redistribution method is suggested and its performance to reduce PAPR values is then evaluated. Using these two methods at the same time, the effective PAPR reduction can be achieved with reasonable BER performance and suitable system complexity.

1.2 Objectives

The objectives of this thesis are as follows:

1. To develop a low cost and effective Peak to Average Power Ratio (PAPR) reduction methods on based on new DCT-OFDM method and to reduce the hardware related issues on HPA for the OFDM system.

2. To implement a hybrid scheme by incorporating Selected Mapping Method (SLM) with Statistical Redistribution Method (SRM).

1.3 Scope of Research

The modulation schemes used in this study are based on 16 QAM and 64 QAM modulation scheme. The BER performance is based on AWGN channel and Rician fading with different number of subcarriers. The most frequently used performance measures for PAPR reduction techniques is the cumulative distribution function (CDF). In this research, the complementary CDF or CCDF is used instead of the CDF itself. The CCDF of the PAPR is the probability that the PAPR of a data block exceeds a given threshold. The development of the entire PAPR reduction schemes in this study is based on software implementation and no hardware integration is involved after the results are obtain.

1.4 Dissertation Outline

This thesis is divided into 5 chapters. Chapter 1 covers the introduction of OFDM systems, pros and cons of the systems, problem statements and objectives of the research. Chapter 2 reviews the researches on history and mathematical description of OFDM systems, definition and statistical distribution of peak to average power ratio. The related works on PAPR reduction techniques are then reviewed.

In Chapter 3, the new PAPR reduction method based on DCT-OFDM method is introduced. The hybrid schemes are then explained at the end of this chapter. Consequently, results and discussions are given in Chapter 4 and conclusions of this thesis are summed up in Chapter 5.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

Section 2.2 reports the concept of OFDM system. Section 2.3 gives the advantages and drawbacks of the OFDM system. Section 2.4 gives the statistical distribution of PAPR. Reviews of PAPR reduction technique is reported in Section 2.5. Criteria for selecting PAPR reduction techniques are given in Section 2.6. Section 2.7 and Section 2.8 reports the review of DCT-OFDM method, statistical redistribution method respectively. Section 2.9 provides the review of combination method and finally, the summary is presented in Section 2.10.

2.2 Review of OFDM System

Many research has been carried out to investigate transmission methods that can provide high data rates, can deal with multipath propagation, provide robustness against frequency selective fading or narrowband interference, and require less power and cost. Multicarrier modulation is a technique that can provides the desired demands of high data rates. Orthogonal Frequency Division Multiplexing (OFDM) is a form of multicarrier modulation that can be seen either as modulation technique or a multiplexing scheme. OFDM is considered as a very promising candidate for future mobile communication systems.

Orthogonal frequency division multiplexing (OFDM) is a new digital modulation technique that divides a communications channel into a number of equally spaced frequency bands. In OFDM, a portion of the user information is transmitted in each band. Each subcarrier is orthogonal (independent of each other) with every other subcarrier, differentiating OFDM from the commonly used frequency division multiplexing (FDM) (Nee and Prasad, 2000). The concept of using parallel data transmission and frequency division multiplexing was published in the mid-1960s (Chang, 1996 and Saltzberg, 1967).

In a classical parallel data system, the total signal frequency band is divided into *N* non-overlapping frequency subchannels. Each subchannel is modulated using a separate symbol and then the *N* subchannels are frequency-multiplexed. Figure 2.1 illustrates the difference between the conventional non-overlapping multicarrier technique and the overlapping multicarrier modulation technique. As shown in Figure 2.1, by using the overlapping multicarrier modulation technique, 50% of bandwidth can be saved (Nee and Prasad, 2000).

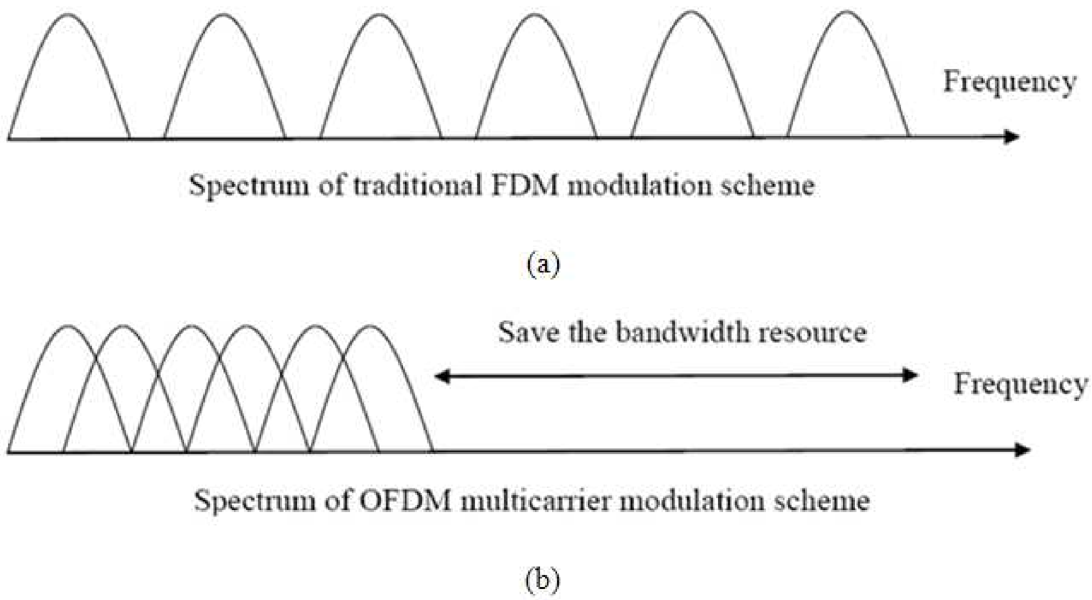

Figure 2.1 Concept of OFDM signal: (a) Conventional multicarrier technique, and (b) orthogonal multicarrier modulation technique (Nee and Prasad, 2000).

2.3 Advantages and Drawbacks of OFDM

As an attractive technology for wireless communications, OFDM has several advantages such as immunity to the frequency selective fading channel, high spectral efficiency as compared to FDM or TDM, multipath delay spread tolerance and provides better system throughput. However, still some challenging issues remain unresolved in the design of OFDM systems. The drawbacks of OFDM system are

(a) More sensitive to carrier frequency offset (CFO) and tone interference than single carrier system. CFO causes number of impairments including phase noise introduced by nonlinear channels, attenuation and rotation of each of the subcarriers and intercarrier interference (ICI).

(b) The effect of eliminating ISI and transmission efficiency by using cyclic prefix guard interval.

(c) Another challenging issue is the effect of phase noise (Armada, 2001). The effect of both frequency offsets and phase noise is worse in OFDM than in single carrier systems.

(d) High peak to average power ratio (PAPR) of the transmitted OFDM signal which due to the summation of sinusoid waves and non-constant envelope. Therefore, the OFDM receiver's detection efficiency is very sensitive to the nonlinear devices used in its signal processing loop, such as Digital-to-Analog Converter (DAC) and High Power Amplifier (HPA).

2.4 Statistical Distribution of PAPR

The most frequently used performance measures for PAPR reduction techniques is the cumulative distribution function (CDF). From literature, the complementary CDF or CCDF is widely used instead of the CDF itself. The CCDF of the PAPR is the probability that the PAPR of a data block exceeds a given threshold (Nee and Prasad, 2000).

Central limit theorem stated that for large values of *N* (*N*>64), the real and imaginary values of $x(t)$ become Gaussian distributed with a mean of zero and variance of 0.5. Therefore the amplitude of the OFDM signal has a Rayleigh distribution while the power distribution becomes a central chi-square distribution with two degrees of freedom. The CDF of the amplitude of a signal sample can be expressed as

$$F(z) = 1 - e^{z} \quad (2.1)$$

The CCDF of the PAPR of a data block with Nyquist rate sampling can be derived as

$$Prob(PAPR > z) = 1 - Prob(PAPR \leq z)$$

$$= 1 - F(z)^{N} = 1 - (1 - e^{-z})^{N} \quad (2.2)$$

There have been many efforts to derive more accurate distribution of PAPR .(Ochiai and Imai, 2001; Wei *et al*. 2002; Sharif *et al*. 2003; Wunder and Boche, 2003).

2.5 Review of Existing PAPR Reduction Techniques

Several schemes have been proposed to reduce the PAPR in OFDM system. These techniques can mainly be categorized into signal scrambling techniques and signal distortion techniques. Figure 2.2 gives some overview of PAPR reduction techniques. The signal distortion techniques introduce both in band and out of band interference and complexity to the system.

The signal scrambling technique, are all variations on how to scramble the codes to reduce the PAPR and can further be classified into

- Schemes with explicit side information
- Schemes without explicit side information

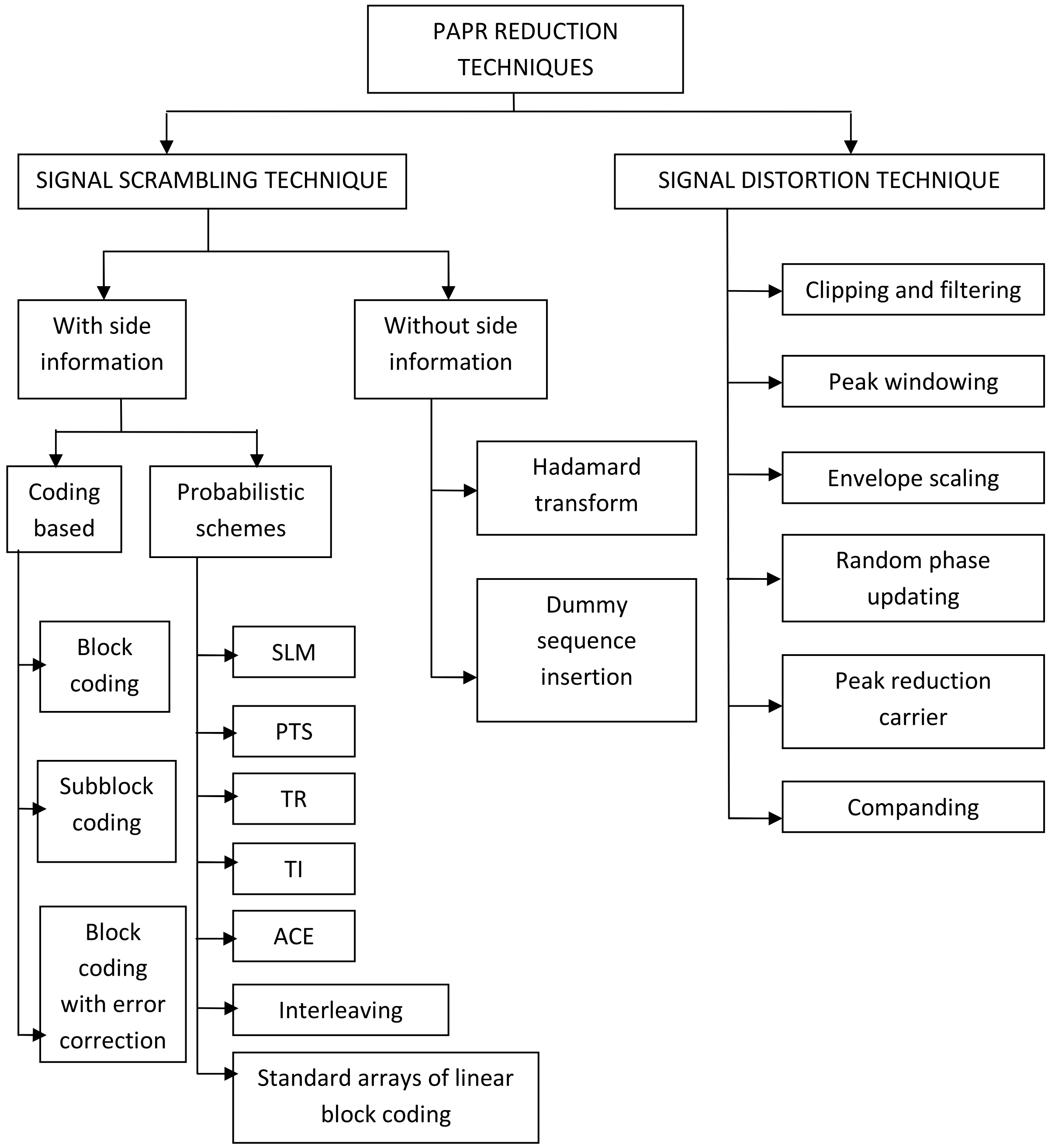

Figure 2.2 PAPR Reduction Technique

A more sophisticated approach can be found in Eltholth *et al*. (2008). This study has presented the use of Huffman coding to reduce the PAPR of an OFDM system as a distortion-less scrambling technique. The idea is to assign frequently used signal sample values fewer bits, and seldom used sample values more bits to make an appropriate compression for the signal to be transmitted.

Partial transmit sequence (PTS) is a technique based on combining signal subblocks which are phase-shifted by constant phase factors (Muller and Huber, 1997a). The main idea of PTS is to partition the original data block into U pair wise disjoint subblocks $X_u,\ u = 1,2,\cdots U$ as shown in Figure 2.3. Each subcarrier in an OFDM symbol is represented in exactly one of those subblocks. Although each sub-block can include an arbitrary number of subcarriers, the carrier positions represented in other subblocks need to be set to zero.

PTS needs U IDFT operations for each data block, and the amount of PAPR reduction depends on the number of subblocks U and the number of allowed phase factors.

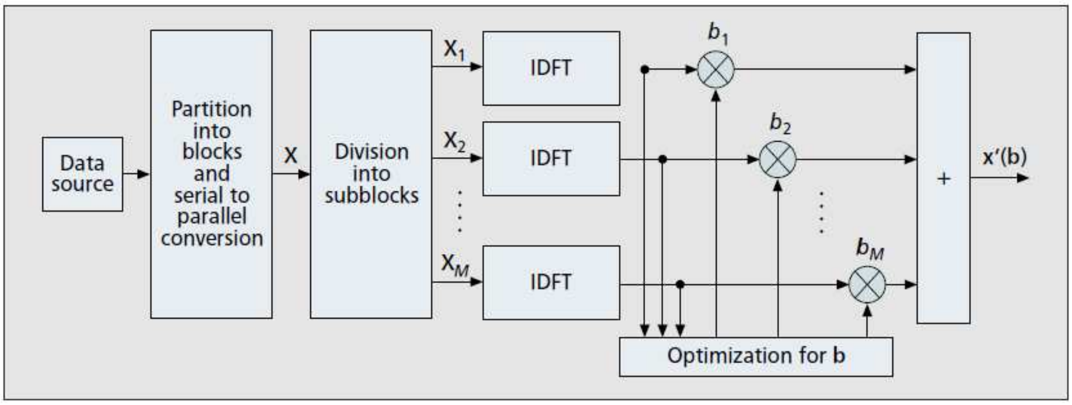

Figure 2.3 Block Diagram of PTS Technique (Jiang and Wu, 2008).

Factor that may affect the PAPR reduction performance in PTS is the subblock partitioning, which is the method of division of the subcarriers into multiple disjoint subblocks (Han and Lee, 2005).

Therefore, there are two important issues should be solve in PTS: high computational complexity for searching the optimal phase factors and the overhead of the optimal phase factors as side information needed to be transmitted to receiver for the correct decoding of the transmitted bit sequence (Jiang and Wu, 2008).

Tu and Chiu (2007) have proposed a novel PTS technique with reduced complexity that each level inverts twice of phase factor bits from previous level. They also study the usage of initial random phase sequence to find the better search way of PAPR reduction and the results show that the new scheme can achieve significant reduction in complexity with little performance degradation.

In another experiment, Siegl and Fischer (2008) have studied the application of partial transmit sequences for peak to average power ratio reduction in multiantenna point to point OFDM. The main idea is to use the directed approach to PTS (dPTS) that is able to utilize the multiple antennas and employing more transmit antennas and better PAPR reduction.

Baxley and Zhou (2007) have compared selected mapping (SLM) and partial transmit sequence (PTS) for PAPR reduction. In this study, it shows that the overall computational complexity of PTS is only lower than that of SLM in certain cases, and that SLM always has better PAPR reduction performance. The idea is to make comparison between the two schemes using three different performance metrics by assuming a given amount of computational complexity that can be afforded. Using the metrics, the results show that SLM outperforms PTS for a given amount of complexity.

A new PAPR reduction in OFDM systems using the combination of PTS with adaptive peak power reduction (APPR) has been proposed by Pradabpet and Dejhan (2008). The main idea is to rearrange the input data by PTS and then fed into the APPR process. The APPR method controls the peak level of the signal by an adaptive algorithm and the proposed scheme shows improvement on PAPR and on the high performance on bit error rate (BER) of an OFDM system.

The objective for the tone reservation (TR) technique is to reserve a small set of tones for PAPR reduction. The basic idea is to find the time domain signal to be added to the original time domain signal $\boldsymbol{x}$ such that the PAPR is reduced. Factors that will affect the amount of PAPR reduction depends on the numbers of reserved tones, their location within the frequency vector and the amount of complexity (Tellado, 2000).

Tone injection (TI) is an additive scheme, which performs PAPR reduction of multicarrier signals with no bandwidth expansion or data rate loss. The main idea is to increase the constellation size so that each of the points in the original basic constellation can be mapped into several equivalent points in the expanded constellation (Han and Lee, 2005).

Active constellation extension (ACE) technique has been proposed by Krongold and Jones (2003). The main idea is that some of the outer signal constellation points in the data block will be extended toward the outside of the original constellation such that the PAPR of the data block is reduced. This technique simultaneously decreases the BER slightly while substantially reducing the peak magnitude of a data block. In this technique, no side information is required and these modifications increase the transmit signal power for the data block.

Jayalath and Tellambura (2000) have demonstrated interleave based technique for improving the peak to average power ratio of an OFDM signal. An interleaver is a device that operates on a block of N symbols and recorders or permutes them; thus, data block $X = [X_0, X_1, \cdots X_{N-1}]^T$ becomes $X' = \left[X_{\pi(0)}, X_{\pi(1)}, \cdots X_{\pi(N-1)}\right]^T$ where $\{n\} \leftrightarrow \{\pi(n)\}$ is one to one mapping $\pi(n) \in \{0,1, \dots N-1\}$ and for all *n*. To make K modified data blocks, interleavers are used to produced permuted data blocks from the same data block. The PAPR of (*K-1*) permuted data blocks and that of the original data block are computed using K IDFT operations; the data block with the lowest PAPR is then chosen for transmission. To recover the original data block, the receiver need only know which interleaver is used at the transmitter; thus, the number of required side information bits is [$\log_2 K$].

The most important aspect of this method is that it is less complex than the PTS method but achieves comparable results. The amount of PAPR reduction depends on the number of interleavers (K-1) and the design of the interleavers.

Yang and Chang (2003) have proposed a method to reduce the PAPR by using the standard arrays of linear block codes. In this scheme, a signal with a minimum PAPR from U distinct signals is chosen as the transmit signal. The main idea is that the U distinct signals are constructed by scrambling a codeword with the properly selected co-set leaders. In this scheme, there is no side information is needed to be transmitted and the received signals can be easily decoded by syndrome decoding.

The simplest approach to reduce PAPR of any multicarrier (MC) signal is to clip it before amplification. Clipping is a non-linear process and may cause significant in-band distortion, which degrades BER performance and out-of-band noise, which reduces the spectral efficiency.

Amstrong (2002) has proposed a method based on K-times repetition of the clipping and frequency domain filtering process. The successive repetition of clipping and filtering produces signals with reduced PAPR, while the out-of band distortions are completely eliminated. The main drawback of this technique is its high complexity. For each frequency domain filtering operation, two FFT calculations are needed.

Armstrong and Feramez (2002) and Chen and Haimovich (2003) have proposed an iterative method of clipping and filtering. The effect of amplitude limiting and scaling on PAPR performance have been studied by Wulich and Goldfeld (1999), Chow *et al*. (1997) and Wulich (1996).

PAPR reduction of OFDM signals using deliberate clipping and pre-scrambling technique has been proposed by Wang *et al*. (2007). The main idea is to combine SLM technique and deliberate clipping technique. The effect of symbol selection scheme on the deliberate clipping was analyzed by deriving the probability distribution function of the samples amplitude of the adaptively-selected OFDM symbol.

Nakamura *et al*. (2007) have proposed a novel low complexity clipping method for OFDM signals. In this study, the proposed clipping method exploits the conventional square clipping, which clips signal according to the amplitude in I/Q channels separately, to avoid obtaining a real amplitude of each sample which costs relatively high computational complexity. By combining the square clipping and the phase rotations of signals, the proposed octagon clipping achieves close clipping performances to the amplitude based normal clipping with a small amount of computations.

In another experiment, Abdul Malik *et al*. (2006) have investigated the effectiveness of the clipping technique by focusing on the performance of PAPR value with different values of CR and the relationship between PAPR value and BER. The range of CR level from -6 dB to 6 dB had been analyzed with variety of SNR value and the optimum BER performance of OFDM signal can be improved by increasing the CR level and the SNR value.

Combination of interleaving method with peak windowing has been proposed by Sakran *et al*. (2008). The main advantages of the proposed combination are PAPR reduction, decrease BER over conventional techniques and improve the spectrum efficiency, where the proposed technique is evaluated in presence of nonlinear power amplifier.

Kohandani and Khandani (2008) have proposed a new PAPR reduction method called MMSE-Threshold in OFDM systems. This technique is a combination of the constellation shaping with peak energy reduction algorithm. Peak reduction is based on extra flexibilities provided by dummy bits. The constellation sets with minimum PAPR are selected by MMSE-Threshold and this selection is formulated in terms of zero-one quadratic problem which subsequently optimized by semidefinite programming algorithm (SDPA)

Another experiment using modification of the modulation constellation in active subcarriers and the modulation symbols in unused subcarriers has been done by Kou *et al*. (2004). This study proposes two new PAPR reduction algorithms that jointly optimize the constellation points in active subchannels and the unused subsymbols. For real-baseband multicarrier systems, the proposed algorithm is based on linear programming (LP) approach where all the subsymbols in unsused subchannels and the exterior constellation points in active subchannles are optimize simultaneously. For passband multicarrier systems where all subchannels are active, a new algorithm has been proposed using an accelerated least-*p*th approach.

Implementation of hybrid QAM-FSK OFDM transceiver has also been reported by Latif and Gohar (2008). This study proposes a hybrid modulator that reduces PAPR. The result show that the scheme can work with arbitrary number of subcarriers and no side information required to be transmitted with the signal. The receiver complexity is slightly increased as it detects coherently the FSK carriers and QAM symbols to decode the information bits properly.

Another experiment using combination of Golay complimentary sequences and SLM has been done by Bakhshi and Shirvani (2009). By using this scheme, the PAPR improves by 3 dB at CCDF = 10^{-3} over original system.

2.6 Criteria of the PAPR reduction in OFDM system

There are several techniques has been proposed in literature. Thus, it is possible to reduce the large PAPR by using the different techniques. Note that the PAPR reduction technique should be chosen with awareness according to various system requirements.

There are many issues to be considered before using the PAPR reduction techniques in a digital communication system. According to Han and Lee (2005), these issues include PAPR reduction capability, power increase in transmit signal, BER increase at the receiver, loss in data rate, computational complexity increase and so on. Simultaneously most of the techniques are not proficient to obtain a large reduction in PAPR with low coding overhead, with low complexity and without performance degradation

2.6.1 PAPR reduction capability

The most primary factor to be considered in choosing a PAPR reduction technique is the PAPR reduction capability. More emphasize toward to the fact that some techniques will result in other harmful effects such as in-band distortion and out-of-band radiation.

2.6.2 BER worsen in the receiver

The main goal of PAPR reduction is to avoid HPA saturation. Some technique may have worsen the BER at the receiver if the transmit signal power is fixed or equivalently may require large transmit power to maintain the same BER after applying the PAPR reduction techniques. Therefore, all the methods which have worsen the BER should be paid careful attention in practice such as SLM, PTS and interleaving where the entire data block may be lost if the side information is received in error (Jiang and Wu, 2008).

2.6.3 Power increase in transmit signal

Tone reservation (TR) requires more additional signal power because some of its power must be used for the peak reduction carriers (PRC). A set of equivalent constellation point for an original constellation point are used in TI to reduce PAPR. All the equivalent constellation points require more power than the original constellation points, therefore the transmit signal will have more power after applying Tone injection (TI). If operations of the technique which decrease the PAPR require a power increase in the transmitted signal, it will affect the BER performance. When the transmitted signals are normalized back to the original signals, it will result in BER performance degradation (Han and Lee, 2005).