This chapter presents a detailed literature survey on signal distortion techniques, Partial Transmit Sequence (PTS) schemes, companding schemes and time domain based methods to limit PAPR of an OFDM signal.

2.1 SURVEY ON SIGNAL DISTORTION TECHNIQUES

The basic signal distortion method to reduce PAPR of OFDM signals is clipping the high amplitude peaks, however repeated clip and filter operation can reduce the overall peak regrowth. Li & Cimini (1998) introduced a post filtering operation to reduce the effects of out of band radiation and spectral regrowth due to the clipping process, however the possibility of spectral regrowth in the time domain is not addressed.

Based on the survey performed, the clipping process based PAPR reduction involves different strategies like iterative clipping followed by filtering in frequency domain, non-iterative clipping methods, peak cancellation and peak windowing method for suppressing large signals to reduce PAPR of an OFDM signal.

2.1.1 Iterative Clipping Methods

The repeated clipping followed by an FFT - based frequency domain filtering of an oversampled time domain OFDM signal achieves the PAPR reduction with only moderate level of clipping noise and no increase in out-of-band power (Armstrong 2002). This method distorts the in band
spectral components to shrink the signal constellation and adds noise. While Leung et al (2002) proposed an Iterative Clipping and Filtering (ICF) technique in time domain with reduced complexity requires no FFT/IFFT operation and achieves similar PAPR reduction performance as that of the Armstrong’s method.

Deng & Lin (2007) introduced a Repeated Clipping and Filtering (RCF) method, where the number of recursions is reduced by employing Smart Gradient Projection (SGP) algorithm and also bounds or limits the distortion on each tone after every iteration to reduce the PAPR of an OFDM signal. However the iterative clipping process makes it difficult to estimate the Bit Error Rate (BER) performance.

Table 2.1 Computational complexity of Armstrong’s RCF and Leung’s RCF technique.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Armstrong’s RCF technique</th>
<th>Leung’s RCF technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational Complexity for K iterations</td>
<td>( O(2^N K L \log_2 N L) )</td>
<td>( O\left(\sum_{i=0}^{L-1} M_i^2 + (N L - M_0) M_0\right) )</td>
</tr>
<tr>
<td>Computation time in seconds</td>
<td>169</td>
<td>10</td>
</tr>
</tbody>
</table>

Where \( L \) – oversampling rate

Bae et al (2010) based on a noise enhancement factor suggested analytical expressions for the estimation of attenuation factor, BER and Error Vector Magnitude (EVM). The work also characterizes the clipping noise for iterative processes. The filtering process suppresses the out of band radiation but results in peak regrowth. Their work based on iterative clipping and filtering technique was the first to report an effective tradeoff between PAPR reduction and BER performance in OFDM systems.
Wang & Luo (2011) proposed an iterative clipping and filtering technique where each iteration is expressed as a convex optimization technique and the optimal frequency response filter is designed to minimize the signal distortion so that PAPR is reduced for each of the OFDM symbol. This method achieves a PAPR reduction in just one or two iterations while the same performance in a conventional technique requires eight to sixteen iterations. Even though the ICF process reduces spectral expansion and eliminates peak re-growth, it is time consuming and also increases the complexity of the transmitter (Wang & Tellambura 2005).

Recently Al-Safadi & Al-Naffouri (2012) achieved PAPR reduction in OFDM system by employing sparse clipping operation to the OFDM signal at the transmitter and Compressive Sensing to observe the clipping noise at the receiver.

2.1.2 Non-Iterative Clipping Methods

A computationally efficient single iteration clipping-filtering technique is proposed by Wang & Tellambura (2005) exploits the fact that the clipping noise obtained after several iterations of clipping and filtering is approximately equal to that generated in the first iteration. The observation is made by analyzing the conventional clipping and filtering method by using a parabolic approximation of the clipping pulse. The simplified technique scales the clipping noise generated during the first iteration and with just three FFT/IFFT operations it achieves the same PAPR reduction as that of the existing iterative techniques with (2K+1) FFT/IFFT operations where K is the number of iterations.

Baxley et al (2006) Suggested a non-iterative constrained clipping technique which satisfies the in-band metric called Error Vector Magnitude (EVM) and the maximum permissible out-of-band spectral constraints, so that PAPR of an OFDM signal is reduced.
2.1.3 Peak Cancellation Methods

An active set approach is employed by Krongold & Jones (2003) to effectively construct a peak cancelling signal in order to limit PAPR of OFDM signal. The convergence rate of this approach slows down after several iterations while an effective tradeoff between complexity and performance is achieved. Wang & Tellambura (2008) constructed a peak cancelling signal using the clipping noise generated during the clipping of an OFDM signal at a pre defined threshold to achieve better PAPR reduction performance than the active set approach. While Jeon et al (2012) employed the IFFT of the shaped Peak Reduction Tones (PRTs) to generate a truncated kernel signal to perform parabolic peak cancellation of the OFDM signal in time domain so that PAPR reduction is achieved with reduced computational complexity. By proper selection of shaping parameters of PRTs leads to reduction of the out-of-band radiation and improvement in BER performance.

2.1.4 Peak Windowing Methods

Cha et al (2008) introduced an advanced peak windowing method that computes new weighting coefficients based on Matrix inversion process for suppressing the successive peaks to a certain threshold level within half the window length. The windowing method preserves the Complementary Cumulative Distribution Function (CCDF), BER and the spectral characteristics of the OFDM signal.

2.2 SURVEY ON PTS METHODS

The following survey discusses the PTS approach in PAPR reduction by employing cyclically shifted PTS, DFT property, autocorrelation function of PTS and algorithm – assisted PTS approach to generate partial transmit sequences. The optimal combination of the candidates with reduced computational complexity are generated based on cross – entropy method,
Quantum Inspired Evolutionary Algorithm, Artificial Bee Colony Algorithm, Parallel Tabu search Algorithm and Greedy Algorithm to produce better PAPR statistics of an OFDM signal.

2.2.1 PTS Based on Phase Optimization Methods

Muller & Huber (1997) introduced an effective PAPR reduction scheme called Optimal Binary Phase Sequence (OBPS) for OFDM systems with arbitrary number of subcarriers and unconstrained signal set by optimally combining the partial transmit sequences.

Subcarrier block $A_{\mu}$ is subdivided into $V$ pair wise disjoint carrier sub blocks $A_{\mu}^{(i)}$ where $i = 1, 2, \ldots V$. An optimization parameter called rotation factor or phase factor $b_{\mu}^{(i)} = e^{j\phi_{\mu}^{(i)}}$, $\phi_{\mu}^{(i)} \in \{0, 2\pi\}$ is introduced to each subblock $i$ and the peak power optimized PTS in time domain is

$$\bar{a}_{\mu} = \sum_{i=1}^{V} b_{\mu}^{(i)} \cdot a_{\mu}^{(i)} \tag{2.1}$$

This scheme works with almost vanishing redundancy and has a transmitter complexity which increases exponentially with the number of subcarriers.

Tellumbura (1998) proposed a phase optimization criterion for several block phase factor in PTS approach for PAPR reduction in OFDM system with increase in complexity. The new optimized criterion is expressed in Equation (2.2) as

$$[\Phi_2, \Phi_3, \ldots, \Phi_v] = \arg\min \sum_{k=0}^{N-1} |\rho(k)| \tag{2.2}$$

where $\rho(k)$ is the aperiodic autocorrelation of the information vector.

While Hill et al (2000) made an adaptation to OBPS to reduce PAPR by combining the cyclically shifted version of the IFFT sub block output with the Partial Transmit Sequences.
Cyclically shifted PTS increases the number of alternative transmit sequences with trivial operations by cyclically shifting the data before or after they are phase rotated

\[
\tilde{a}_k = \sum_{i=1}^{V} a_k^{(i)} \cdot e^{j\phi(i)}
\]  

(2.3)

Cyclic shift in Time Domain is performed as

\[
\tilde{a}_\mu = \sum_{i=1}^{V} a_{\mu + \delta(v)}^{(i)} \cdot e^{j\phi(i)}
\]  

(2.4)

Where \(\delta(v)\) is cyclic shift in time domain.

Cimini & Sollenberger (2000) introduced sub-optimal Iterative Flipping Algorithm (IFA) for combining PTS to reduce PAPR but it has a performance gap with ordinary PTS technique in other words the algorithm performs worse than conventional PTS with reduced complexity.

Tellambura (2001) introduced an optimal set of quantized phase factors which when employed with the conventional PTS scheme achieves better performance than the exhaustive search process of PTS approach. For small number of sub blocks the proposed algorithm performs better than OBPS and when the number of sub blocks is large it performs similar to OBPS. While Han & Lee (2004) suggested a gradient descent search algorithm to compute the phase factors which leads to reduced PAPR statistics than the IFA with reduced search complexity and a slight degradation in BER performance.

Recently Cho et al (2012) proposed Low-Complexity PTS (LC-PTS) scheme which performs successive local search to achieve PAPR reduction. In the first step, the initial phase factors with low correlation are generated and in the second step, local search is performed within the selected
phase rotation factors to identify the candidate signals with better PAPR value. While Qi et al (2012) proposed a W-way tree based PTS approach in which the nodes corresponds to phase rotation vectors and layers represent the sub blocks. The candidate signal with reduced PAPR is determined by combining the layers and phase factors by traversing the tree from the root to the leaves.

2.2.2 Extended PTS Scheme

Kang et al (1999) proposed a concatenated pseudo-random Sub-block Partition Scheme (SPS) for PTS such that it achieves the same PAPR reduction performance as that of the conventional pseudorandom SPS with extensively reduced computational complexity.

Chen & Pottie (2002) proposed a novel orthogonal projection based on PTS approach that achieves significant PAR reduction with low redundancy.

Equation (2.1) can be rewritten in matrix form as

\[ \bar{a} = b^T M = [b^T m_1, b^T m_2, \ldots, b^T m_N] \]  \hspace{1cm} (2.5)

Where \( m_n \) - nth column of Matrix M,

\[ b = [b_1, b_2, \ldots, b_N] \]

This geometrical interpretation forms the basis for finding the optimal phase rotation vector ‘b’ based on orthogonal vector function of the columns \( m_n, 1 \leq n \leq N \).

Schenk et al (2005) proposed a Spatial shifting based PTS scheme to transmit the partial transmit sequences of the OFDM signal on the
transmission branches with minimum PAPR, so that significant PAPR reduction with limited complexity and signaling overhead is achieved.

Xiao et al (2007) presented a LC-PTS scheme to reduce the PAPR by exploiting the correlation among the candidate signals by dividing the candidate signal into multiple subsets. The method outperforms the conventional PTS scheme by not compromising on the number of candidate signals but significantly reducing the computational complexity. A comprehensive analysis of computational complexity involved in PTS and the LC-PTS is given in Table 2.2.

**Table 2.2  Computational complexity of PTS and LC-PTS**

<table>
<thead>
<tr>
<th>Operation</th>
<th>PTS</th>
<th>LC-PTS</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex Addition</td>
<td>LN(M−1)</td>
<td>L(M−1)</td>
<td>(N−P)/W + P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L(M−1)</td>
<td>N</td>
</tr>
<tr>
<td>Complex</td>
<td>LN(M+1)</td>
<td>L(M+1)</td>
<td>(N−P)/W + P</td>
</tr>
<tr>
<td>Multiplication</td>
<td></td>
<td>L(M+1)</td>
<td>N</td>
</tr>
<tr>
<td>Computations</td>
<td>LN − 1</td>
<td>L(N−1)</td>
<td>L(N−1)/W + P - 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L(N−1)</td>
<td>LN − 1</td>
</tr>
</tbody>
</table>

where M is the Number of sub blocks, N is the Number of subcarriers, W is the Number of phase factors and P is the Number of highest amplitude positions.

Ghassemi & Gulliver (2010) employed the Autocorrelation function of PTS sub blocks to develop a new PTS sub blocking technique using error-correcting codes to reduce PAPR reduction in OFDM systems. This method minimizes the number of repeated subcarriers within a sub block and provides better PAPR reduction than the m-sequence sub blocking with reduced complexity. The multiplicative complexity involved in Decimation in Time (DIT) inorder to compute the FFT is reduced by employing Decimation in Frequency (DIF) algorithm.
2.2.3 PTS Approach Based on DFT Property

Generation of candidates based on transformation of OFDM signals by employing DFT properties for PAPR reduction of an OFDM signal has been proposed.

Lu et al (2006) suggested to apply certain transformations on PTS (T-PTS) of a OFDM signal to generate alternate frequency domain signals and transmit the signal which has a reduced PAPR than that of the actual signal. Basic operations like complex conjugation, frequency reversal, circular shift and their combinations are used either individually or jointly on different sub blocks to perform transformation. The equivalent frequency domain signal is rewritten from Equation (2.1) as

\[ \tilde{X}_k = \sum_{i=1}^{V} b^{(i)}_\mu \, T^{(i)}[A^{(i)}_\mu] \quad (2.6) \]

Where \( T^{(i)}[A^{(i)}_\mu] \) is a certain pre-defined transformation made on \( A^{(i)}_\mu \). The alternative time domain signal is given as

\[ \tilde{x}_\mu = \sum_{i=1}^{V} b^{(i)}_\mu \, \text{IDFT}\{T^{(i)}[A^{(i)}_\mu]\} \quad (2.7) \]

T-PTS outperforms OBPS method for the same number of sub blocks and exhibits similar performance for the same number of carriers with reduced complexity.

Wang & Cao (2008) introduced a sub-optimum PTS scheme that combines an alternate optimization method to reduce the computational complexity by avoiding the need to perform exhaustive search overall possible phase factors and the linearity property of IDFT to increase the number of candidate signals so that PAPR reduction performance of OPTS is attained with dramatically reduced computational complexity.
Zhu et al (2008) suggested five novel transformations namely (a) circular time shift of $a_\mu^{(i)}$ (b) circular frequency shift of $A_\mu^{(i)}$ (c) time reversal of $a_\mu^{(i)}$ (d) complex conjugate of $a_\mu^{(i)}$ (e) complex conjugate of $A_\mu^{(i)}$ are proposed using DFT property on PTS in an iterative manner to reduce PAPR. For small number of sub blocks, some of the proposed transformations achieve better performance than the Iterative Flipping Algorithm (IFA).

A PTS with simple detector suggested by Yang et al (2011) recursively combines the cyclically shifted sub block sequences based on the linearity property of IFFT to generate a set of candidate signals in the time domain with different phase constellation without employing multiplication while the phase detector recovers the OFDM signal at the receiver. This method achieves PAPR reduction and maintains BER performance as that of the conventional PTS over both AWGN and Rayleigh fading channel.

2.2.4 Algorithm Assisted PTS Approach

Nguyen & Lampe (2008) preprocessed the data stream ahead of PAPR reduction so that side information is embedded with minimal possible redundancy, maintaining the BER without causing peak regrowth. The complexity in the search process of phase factor is formulated as a combinatorial optimization problem enabling us to (a) unify different search strategies proposed in the PTS literature (b) adapt different optimization algorithms known from the literature to achieve PAPR reduction based on PTS method.

Chen (2009) reduced the search complexity of PTS approach by combining the PTS with cross-entropy method to reduce both the PAPR and the computational load to be the same as that of Exhaustive Search Algorithm (ESA). The PAPR problem is rewritten as a score or fitness function that is further translated to a stochastic approximation problem which is effectely solved using a stochastic optimization technique called cross-entropy method.
PAPR reduction problem is rewritten as a combinatorial optimization problem which is effectively solved using Quantum Inspired Evolutionary Algorithm by Chen (2010a) to find the optimal phase factors that achieves significant PAPR statistics. While search for optimal phase factors in a PTS scheme is rewritten as a global optimization problem and is solved using a population based search method called Electromagnetism-like (EM) Algorithm. The EM based PTS scheme proposed by Chen (2010b) follows a stochastic optimization approach and employs attraction-repulsion mechanism to search the optimal phase rotation factor so that the desired PAPR statistics is achieved with reduced complexity.

Wang et al (2010) proposed a sub optimal method with three control parameters by combining a numeric function optimization algorithm called Artificial Bee Colony (ABC) Algorithm with PTS to reduce the search complexity of the allowable phase factors, such that PAPR reduction is achieved.

The optimal phase rotation factors are selected based on an iterative heuristic search method which eliminates the iterations to visit the solution obtained recently called Parallel Tabu search Algorithm is used in conjunction with PTS to optimize the PAPR statistics was introduced by Taspinar et al (2011). The parallel information exchange between Tabu search algorithm is based on crossover operator used in Genetic Algorithm (GA) which combines the good features of the parent to achieve better performance.

Since Genetic Algorithm converges rapidly in changing channel conditions and provides solution for Gradient based search method, it is used along with PTS approach to reduce PAPR in MCM systems by Lixia & Murroni (2011). Based on the comparative study on OFDM and Wavelet packets MultiCarrier Modulation (WP-MCM) in Additive White Gaussian Noise (AWGN) channel, GA applied to PTS reduces PAPR more effectively in OFDM when compared to WP-MCM.
2.3 SURVEY ON COMPANDING SCHEMES

The companding scheme which is used for reducing PAPR of an OFDM signal is basically classified into non linear companding and linear companding scheme.

2.3.1 Non Linear Companding Schemes

Wang et al (1999) introduced a $\mu$-Law companding technique to generate optimal companding coefficients to limit PAPR of a OFDM signal and improves the BER performance. A companded signal increases the transmit signal power while the noise power remains constant and makes the High Power Amplifier (HPA) to operate in the non linear region. Mattsson et al (1999) commented on their work that companding leads to spectral regrowth and raised a question whether the improvement in BER is due to companding or increase in the transmit signal power. Later Wang et al (1999) compared the performance of a companded signal with that of the non companded signal with constant transmission power to justify that in the region of high SWR the SER of a companded signal achieves better results than that of an uncompanded signal. The work elaborated that the spectral regrowth due to companding is minimal and is insensitive to the variations of companding coefficients. The companding scheme of Wang et al (1999) shows better performance than clipping, but ignored the non-linear operation of power amplifiers which resulted in growth of spectral side lobes.

Huang et al (2001) suggested that the increase in the average input power of $\mu$-Law companding technique can be avoided and maintained constant by transforming the OFDM signal based on their power distribution, so that the HPA operates in linear region. In $\mu$-law companding transform, by the proper selection of the companding form and its corresponding inflexion point the PAPR can be reduced with reduced complexity and moderate degradation.
Jiang & Zhu (2004) introduced a non-linear companding transform described by a single valued function exploits the statistical characteristics of the OFDM signal to limit PAPR and exhibits good BER performance over an AWGN channel. The analytical expression to calculate the companding noise due to the non-linear companding operation is also suggested.

Huang et al (2004) proposed the design criteria of Companding Transform (CT) based on the statistical characteristics of OFDM signal to enable an effective tradeoff between PAPR reduction and BER performance. The work also discussed about the performance of four companding schemes namely Linear Symmetrical Transform (LST), Linear Nonsymmetrical Transform, Nonlinear Symmetrical Transform (NLST) and Nonlinear nonsymmetrical Transform (NLNST). The inflexion point in NLST treats the large and small amplitude signals on different scales and achieves better performance than the other three schemes and the clipping method.

Jiang et al (2005) proposed an Exponential Companding (EC) scheme that converts the amplitude statistics of an OFDM signal into a uniformly distributed signal to limit the PAPR while maintaining the average signal power unchanged.

The exponential companding function is given by

$$h(x) = \text{sgn}(x) \sqrt[\alpha]{\left[1 - \exp\left(-\frac{x^2}{\sigma^2}\right)\right]}$$

(2.8)

In Equation (2.8), $\text{sgn}(x)$ is sign function

$$\alpha = \left(\frac{E[|s_n|^2]}{E\left[|1-\exp\left(-\frac{|s_n|^2}{\sigma^2}\right)|^2\right]}\right)^{\frac{d}{2}},$$

a positive value to maintain the average power constant.
The de-compressing function $h^{-1}(x)$ at the receiver side is given by

$$
h^{-1}(x) = \text{sgn}(x) \sqrt{-\sigma^2 \log \left( 1 - \frac{x}{\alpha} \right)} \quad (2.9)$$

The non-linear companding functions mentioned above enhances the small signals and compresses the large signals at the same time which is desirable when compared to that of the $\mu$-law companding scheme which enlarges the small signal and ignores the signal peaks. Hence the non-linear companding scheme attains better PAPR reduction, BER, Power Spectrum and Phase error than the $\mu$-law companding scheme. The main liability of exponential companding scheme is that its performance remains unchanged for different levels of companding i.e. for $d > 4$.

Jiang et al (2006) inferred that at the receiver side, a companded signal when undergoes only Inverse Companding Transform (ICT) the resultant spectrum exhibits severe out of band, in-band distortion and peak regrowth due to excessive channel noise. Hence they proposed an iterative receiver with slight increase in complexity to cancel out the channel noise and companding noise. The companding scheme suggested are

$$C_1(x) = h_1 \cdot \text{erf} \left( \frac{x}{\sqrt{2}\sigma} \right) \quad (2.10)$$

$$C_2(x) = \text{sgn}(x) \cdot \sqrt{h_2 \cdot \text{erf} \left( \frac{|x|}{\sqrt{2}\sigma} \right)} \quad (2.11)$$

where erf() is error function and $h_1$ and $h_2$ are parameters to maintain the average power constant.

Later Jiang et al (2007) introduced two novel nonlinear companding transforms for MCM signals which maintains the average signal power constant. It transforms the Gaussian-distributed OFDM signal to a Trapezoidal-distributed signal and with proper selection of parameters it provides an effective PAPR reduction.
The two novel companding functions introduced by Jiang et al are

\[ C_1(x) = \sqrt{3} \sigma \text{erf} \left( \frac{x}{\sqrt{2\sigma}} \right), \quad 0 \leq x \leq 1 \text{ is a LNST} \quad (2.12) \]

\[ C_2(x) = \text{sgn}(x) \sqrt{2\sigma \text{erf} \left( \frac{|x|}{\sqrt{2\sigma}} \right)} \text{ is a NLNST} \quad (2.13) \]

where \( \sigma^2 = \int_{-b_1}^{b_1} (t_n)^2 p(t_n) dt_n \), maintains average power constant.

The LNST scheme \( C_1(x) \) achieves better tradeoff between BER and PAPR reduction while the NLNST scheme \( C_2(x) \) provides result consistent with non linear companding scheme for PAPR reduction.

Pratt et al (2006) investigated the performance of companding techniques in OFDM system involving non-linear transmit power amplifier to conclude that only proper selection of the companding parameter and amplifier back off, a compounded OFDM system can perform better than a system without companding. The investigation revealed that at low back off, impairment due to non linear amplification is significant i.e., increasing the compression reduces the non linear distortion but at the cost of noise amplification during expansion at the receiver whose effect almost negates any performance gain of OFDM system. Recently Wang et al (2013) proposed a non linear companding scheme where the OFDM signal is transformed into a Probability Density Function (PDF) by employing a linear piecewise function. By introducing variable slopes and inflexion points in the target PDF, the companding form is more flexible to achieve an effective trade-off between PAPR and BER performance.

### 2.3.2 Linear Companding Schemes

Aburakhia et al (2009) proposed a Linear Companding Transform (LCT) with two inflexion points to scale different signal levels independent of one another. Based on the simulation results of the proposed LST and NLST over an AWGN channel it was manifested that LCT performs better in terms of PAPR reduction and BER performance. The average value of PAPR reduction is 50% for LNST and 70% for the proposed LCT.
Hou et al. (2009) introduced a companding scheme based on transformation of a Gaussian-distributed OFDM signal to a Trapezoidal-distributed signal with proper selection of parameters provides a better PAPR reduction and BER performance than that of the EC scheme.

Jiang (2010) proposed a new companding transform based on a smooth function called airy special function which is given by

\[ f(x) = \beta \cdot \text{sign}(x) \cdot [\text{airy}(0) - \text{airy}(\alpha \cdot |x|)] \]  

In equation (2.12), airy(.) is an airy function of first kind, \( \alpha \) is a parameter to control the degree of companding and \( \beta \) maintains average power

\[ \beta = \frac{\mathbb{E}[|x|^2]}{\mathbb{E}[|\text{airy}(0) - \text{airy}(\alpha \cdot |x|)|^2]} \]

\( \mathbb{E}[\cdot] \) denotes Expectation

The decompanding function is given by

\[ f^{-1}(x) = \frac{1}{x} \cdot \text{sign}(x) \cdot \text{airy}^{-1}\left[\frac{|x|}{\beta}\right] \]  

which is computed based on Look-up table.

The airy function based Transform is flexible, the degree of companding is varied by changing \( \alpha \) which is reflected in the performance and this feature overcomes the liability of EC scheme.

Hou et al. (2010) suggested a non-linear companding method which mainly compresses only the large signals and even without decompanding function it maintains a good BER performance. The PAPR reduction capability and Power spectrum achieved based on this method is superior to that of EC scheme.
2.4 SURVEY ON TIME DOMAIN BASED PAPR REDUCTION METHODS

PAPR reduction is performed by employing some properties or methods in time domain to the original OFDM signal so that the alternate candidate signals are generated and the candidate with lowest PAPR is selected for transmission.

Lu et al (2007) proposed a PAPR reduction method in which the candidate signals are generated in time domain directly by computing the product of circular convolution of the OFDM data and IFFT of Optimized Cyclically Shifted Phase Sequences (OCSPS).

A LC time domain-based PAPR reduction technique introduced by Alsusa & Yang (2008) uses a linear symbol combining technique to consecutive OFDM symbols to create several time domain representation of each OFDM symbol at the transmitter. The scheme requires one IFFT block per OFDM symbol while PTS requires N IFFT blocks per OFDM symbol where N is the number of sub sets. But Forward Error Correction (FEC) coding has to be performed on side information to overcome the noise in the channel, and to improve the BER performance at low SNR values, which demands additional processing at the receiver. The BER performance is slightly reduced due to its dependency on side information, symbols and multiblock combination.

A LC-SLM scheme using Time Domain Sequence Superposition (TDSS) needs two IFFT blocks is proposed by Yang et al (2008) to limit PAPR of OFDM signal. Here two phase sequences generated are multiplied with the input symbol, one time domain sequence is fixed and linearly combined with the cyclically shifted version of the second sequence to produce new alternate sequences. The Table 2.3 below compares the computational requirements of conventional SLM scheme and the LC-SLM TDSS scheme.
Table 2.3 Computational complexity of SLM scheme and LC-SLM TDSS scheme

<table>
<thead>
<tr>
<th>Operation</th>
<th>Conventional SLM Scheme</th>
<th>LC-SLM TDSS scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiplications</td>
<td>(\frac{\log_2LN}{M})</td>
<td>(\frac{1}{\log_2LN})</td>
</tr>
<tr>
<td>Number of Additions</td>
<td>(\frac{\log_2LN}{M(\log_2LN)})</td>
<td>(\frac{2}{\log_2LN(\log_2LN + M)})</td>
</tr>
<tr>
<td>When M = 4, 8, 16</td>
<td>PAPR reduction</td>
<td>PAPR is 0.2 dB less than the</td>
</tr>
<tr>
<td>and 32</td>
<td>better than LC-SLM TDSS</td>
<td>conventional SLM scheme</td>
</tr>
<tr>
<td></td>
<td>scheme</td>
<td></td>
</tr>
</tbody>
</table>

Where M refers to the number of phase sequences.

Du et al (2009) proposed a selective time domain filtering technique which employs a filter bank to generate candidate signals with different PAPR. Since scrambling is performed in time domain, the need for additional IFFT block is eliminated. Data recovery in an OFDM system demands use of both pilot tone channel estimation and demodulation techniques. This method has reduced complexity but slightly poor PAPR reduction performance than that of SLM technique.

Wang et al (2010) introduced a PAPR reduction scheme in time domain in which the OFDM signal is linearly combined with its cyclically shifted version with various allowable phase and time delays to produce candidate signals. The scheme has reduced complexity than that of SLM scheme with some degradation in BER performance.

2.5 OBJECTIVE OF THE RESEARCH

Advent of ubiquitous and highly enhanced wireless devices supporting multimedia applications is a product of advancements in the field
of wireless communication and emergence of wireless standards in order to ensure their quality. To maintain the quality of wireless devices it is desired to employ MCM techniques which can perform both modulation and demodulation effectively. Moreover use of MCM techniques with orthogonal subcarriers (SCs) demands the need for positioning highly directional antennas at a specific height so that Line of Sight (LoS) link is established between the base station and user. Bandwidth efficient modulation schemes which can perform wireless transmission effectively under non-LoS condition are preferred for broadband mobile applications. Likewise to provide broadband services to large number of subscribers it is mandatory to use minimum bandwidth in the physical layer of a shared radio channel. OFDM is one such modulation scheme which is widely preferred in broadband wireless systems due to its ability to combat the effects of multipath fading and need for simple equalizers at the receiver. Among the modulation techniques OFDM is the forerunner for third Generation (3G) and fourth generation (4G) wireless communication systems, it elevated the Wireless Local Area Network (WLAN) to be operated in the 5GHz band. But the main impediment in using OFDM is the large Peak-to-Average Power Ratio (PAPR) value which can demean the overall transmission process. The issue of high PAPR has generated interest widely among the researchers and various solutions were proposed by them to address the problem. Since the PAPR reduction in OFDM systems is a potential problem that needs to be addressed, the same has been investigated by means of five schemes that are proposed in this thesis.

Most of the work discussed in the literature concentrates on parameters like PAPR reduction, computational complexity, in band radiation, out of band radiation, peak regrowth, BER performance and EVM in OFDM systems individually but an effective tradeoff between PAPR reduction and BER performance over different communication channels
which evaluates the effectiveness of the system is rarely addressed. This research work investigates the importance of PAPR reduction in OFDM system and proposes novel schemes based on non-iterative clipping and filtering method, companding scheme, an algorithm assisted PTS scheme and linear combination of cyclically delayed sequences.