A Low Complexity PTS Technique using Threshold for PAPR Reduction in OFDM Systems

Dai hwan.Lim[1], Byung Ho.Rhee[2]
[1] graduate school, of Hanyang University
Seoul, South Korea
[2] Professor, of Hanyang University
Seoul, South Korea
[e-mail: jpeace1226@gmail.com, bhrhee@hanyang.ac.kr]
**Corresponding author: Byung Ho.Rhee*

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Abstract

Traffic classification seeks to assign packet flows to an appropriate quality of service (QoS) class based on flow statistics without the need to examine packet payloads. Classification proceeds in two steps. Classification rules are first built by analyzing traffic traces, and then the classification rules are evaluated using test data. In this paper, we use self-organizing map and K-means clustering as unsupervised machine learning methods to identify the inherent classes in traffic traces. Three clusters were discovered, corresponding to transactional, bulk data transfer, and interactive applications. The K-nearest neighbor classifier was found to be highly accurate for the traffic data and significantly better compared to a minimum mean distance classifier.

Keywords: Traffic classification, unsupervised learning, k-nearest neighbor, clustering

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1. Introduction

The orthogonal frequency division multiplexing (OFDM) is an attractive multicarrier modulation technique for broadband wireless access due to its strong immunity to multipath fading and high spectral efficiency. Because of these advantages, the OFDM technique has been adopted in many wireless standards. Recently the OFDM technique is also a standard for the fourth generation (4G) mobile wireless system [1]. However, one major drawback of OFDM systems is the high peak-to-average power ratio (PAPR) which causes OFDM signal distortion in the nonlinear region of the high power amplifier (HPA). Since this nonlinear distortion generates inter-symbol interference and inter-modulation, a compensation algorithm is required.

There are several celebrated techniques used for PAPR reduction. These techniques can be divided into two groups, including those with distortion and those without distortion. The typical distortion techniques are amplitude clipping [2] and clipping and filtering [3]. In contrast, coding [4], partial transmit sequence (PTS) [5][6] and selected mapping (SLM) [7] are distortionless techniques. Among these techniques, the Selected Mapping (SLM) is the most promising one because it is simple to implement, and it introduces no distortion in the transmitted signal. Most important, it can achieve significant PAPR reduction [10][11][12][13][14].

In this paper, we present the phase factor selection algorithm, which applies to the preset threshold, with reduced computational complexity. This algorithm employs a stepwise process to obtain phase factors with low complexity. As an optimum set of phase factors is selected, the peak value of time domain vector will be minimized. Therefore, PAPR can be reduced.

This paper is organized as follows: In Section 2, OFDM system, PAPR and C-PTS, suboptimal PTS technique are briefly described. Section 3 introduces the proposed PTS technique and discusses the computational complexity. The simulation results are shown in Section IV and are followed by a conclusion in Section V.

2. OFDM System and PTS Techniques

2.1 OFDM Systems

OFDM is a special form of multicarrier modulation which is particularly suited for transmission over a dispersive channel. **Fig.1** shows the OFDM spectrum in frequency domain. As show in **Fig.1**, the different carriers are orthogonal to each other, that is, they are totally independent of one another.

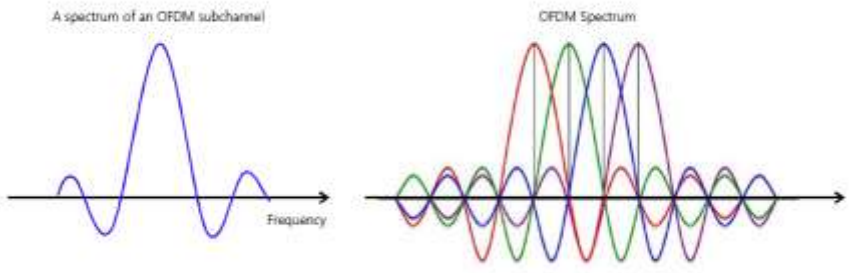

Fig. 1. OFDM spectrum

This is achieved by placing the carrier exactly at the nulls in the modulation spectra of each other. Unlike single carrier systems described above, OFDM communication systems do not rely on increased symbol rates in order to achieve higher data rates. This makes the task of managing ISI much simpler. OFDM systems break the available bandwidth into many narrower sub-carriers and transmit the data in parallel streams. Each subcarrier is modulated using varying levels of QAM modulation, e.g. QPSK, QAM, 64QAM or possibly higher orders depending on signal quality.

Each OFDM symbol is therefore a linear combination of the instantaneous signals on each of the sub-carriers in the channel. Because data is transmitted in parallel rather than serially, OFDM symbols are generally MUCH longer than symbols on single carrier systems of equivalent data rate.

There are two truly remarkable aspects of OFDM. First, each OFDM symbol is preceded by a cyclic prefix (CP), which is used to effectively eliminate ISI. Second, the sub-carriers are very tightly spaced to make efficient use of available bandwidth, yet there is virtually no interference among adjacent sub-carriers (Inter Carrier Interference, or ICI).

These two unique features are actually closely related. In order to understand how OFDM deals with multipath distortion, it's useful to consider the signal in both the time and frequency domains. The OFDM symbol consists of two major components: the CP and an FFT period (FFT). The duration of the CP is determined by the highest anticipated degree of delay spread for the targeted application. When transmitted signals arrive at the receiver by two paths of differing length, they are staggered in time as shown in **Fig. 2**.

Within the CP, it is possible to have distortion from the preceding symbol. However, with a CP of sufficient duration, preceding symbols do not spill over into the FFT period; there is only interference caused by time-staggered "copies" of the current symbol. Once the channel impulse response is determined (by periodic transmission of known reference signals), distortion can be corrected by applying an amplitude and phase shift on a subcarrier-by-subcarrier basis.

Note that all of the information of relevance to the receiver is contained within the FFT period. Once the signal is received and digitized, the receiver simply throws away the CP. The result is a rectangular pulse that, within each subcarrier, is of constant amplitude over the FFT period.

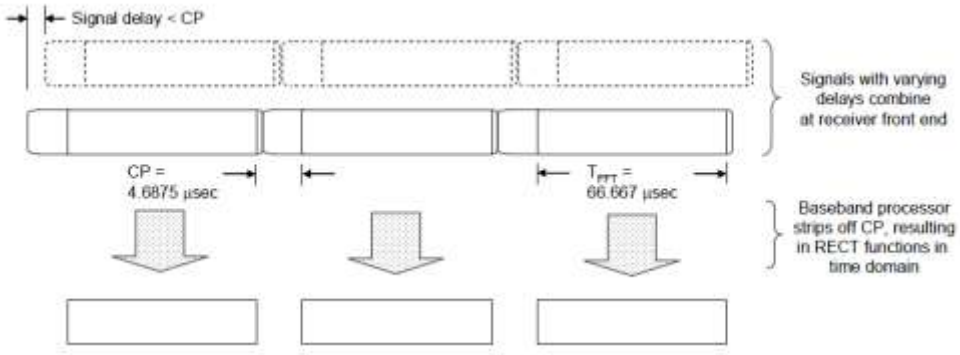

Fig. 2. OFDM Eliminates ISI via Longer Symbol Periods and a Cyclic Prefix

The rectangular pulses resulting from decimation of the CP are central to the ability to space subcarriers very closely in frequency without creating ICI. Readers may recall that a uniform rectangular pulse in the time domain results in a SINC function (sin(x) / x) in the frequency domain as shown in **Fig.3**.

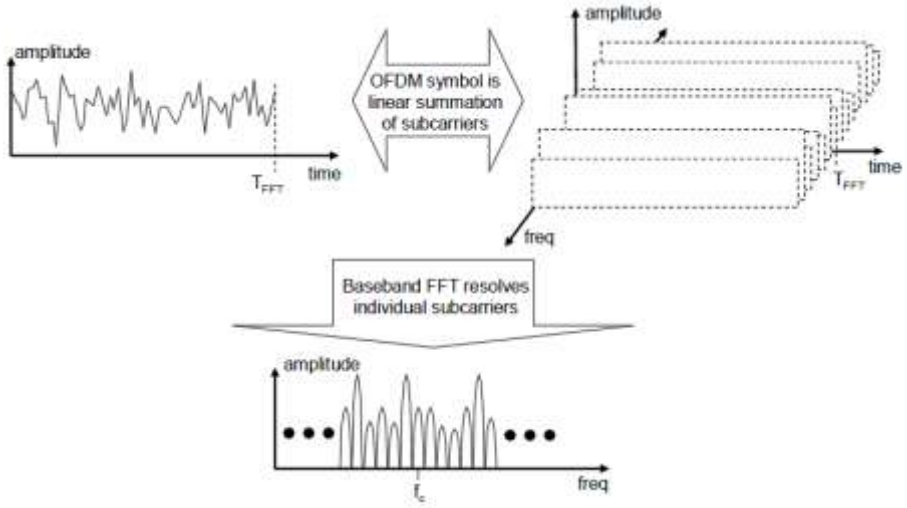

Fig. 3. FFT of OFDM Symbol Reveals Distinct Subcarriers

Then within the time interval the following signal of the m-th OFDM block period can be described by equation (1) as: An OFDM symbol can be generated as the sum of many independent symbols modulated onto sub-channels of equal bandwidth. Let $\mathbf{X}=\{X_k,\ k=0,1,\cdots,N-1\}$ denote the input data symbol vector with period T. Then, the resulting time domain signals of an OFDM symbol are expressed as[15][16]

$$x(t)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}X_k\cdot e^{j2\pi k\Delta ft},0\le t<T \qquad (1)$$

where N is the number of subcarriers, which is typically a large number, and $\Delta f=1/T$ is the subcarrier spacing.

The PAPR is defined as the ratio of the peak to the average power during an OFDM symbol period, that is

$$\mathrm{PAPR}\{x(t)\}=\frac{\max\limits_{t\in[0,T]}\left[|x(t)|^2\right]}{E\left[|x(t)|^2\right]}, \qquad (2)$$

where $\max[\cdot]$ is the maximum power of the OFDM signal, and $E[\cdot]$ is the average power. [15][16] The complementary cumulative distribution functions (CCDFs) of PAPR, i.e., the probability that PAPR exceeds a certain threshold PAPR_0, can be calculated as

$$\Pr(\mathrm{PAPR}>\mathrm{PAPR}_0)=1-(1-e^{-\mathrm{PAPR}_0})^N. \qquad (3)$$

2.2 Advantages & Disadvantages of OFDM system

Advantages : Flexible in meeting various design requirements, such as complexity,bandwidth efficiency with its multicarrier modulation. OFDM converts a wide band frequency selective fading channels into a series of narrowband frequency non-selective fading subchannels by using the parallel multicarrier transmission. Resistance against multipath fading using guard

interval and cyclic prefix. Makes single frequency network possible, which is especially attractive for broadcasting applications.

Disadvantages : More sensitive to carrier frequency offset and tone interference than that of a single carrier system. Trade-off between eliminating ISI and transmission efficiency by using the cyclic prefixed guard interval. Higher transmitter output back off is required because of the high peak-to average power ratio of an OFDM system. This may reduce the power efficiency of the RF power amplifier.

2.3 PAPR Problem

An OFDM signal consists of a number of independently modulated Sub carriers, which can give a large peak-to-average power (PAP) ratio when added up coherently. When *N* signals are added with the same phase, they produce a peak power that is N times the average power.
High PAPR of the transmitted signals results in Clipping noise (Limited quantization levels, rounding and truncation during IDFT and FFT computation), non–linear distortions of power amplifiers, BER performance degradation, energy spilling into adjacent channels, intermodulation effects on the sub carriers, warping of the signal constellation in each sub channel, increased complexity in the analog to digital and digital to analog converter.

Let the data block of length *N* be represented by a vector X=[X_0, X_1, X_2,……., X_{N-1}]T. Duration of any symbol Xk in the set 'X' is 'T' and represents one of the subcarriers {fn ,n=0,1,…..,N-1} set. As the *N* sub–carriers chosen to transmit the signal are orthogonal to each other, so we can have fn= n_f, where n_f = 1/*N*T and NT is the duration of the OFDM data block 'X'. The PAPR of the transmitted signal is defined as (2)

PAPR is defined as a ratio of peak instantaneous power to the average power. Reducing the $max|x(t)|$ is the principle goal of PAPR technique.

2.4 Conventional Partial Transmit Sequence Technique

In the conventional PTS (C-PTS) technique, an input OFDM frame of N subcarriers is partitioned into M sub-blocks. The sub-blocks are multiplied by phase factors and then added together to produce alternative transmit signals containing the same information. To obtain the optimal phase factors for each input data frame, all possible combinations are searched in order to obtain the minimum PAPR. Because the search complexity of the C-PTS technique increases exponentially with the number of sub-blocks, it is not practically realizable for a large number of sub-blocks.
Fig. 4, shows the block diagram of the C-PTS technique, where the input data block is partitioned into disjoint sub-blocks. Each sub-block is multiplied by the phase factors, which are obtained using the optimization algorithm to minimize the PAPR value.
The input data block $\mathbf{X}$ is partitioned into *M* disjoint sub-blocks, which are represented by the vectors $\{\mathbf{X}^{(m)},\ m=0,1,\cdots,M-1\}$ [5][14][15] such that

$$\mathbf{X}=\sum_{m=0}^{M-1}\mathbf{X}^{(m)}. \qquad (4)$$

The sub-blocks $\mathbf{X}^{(m)}$ are transformed into time domain sequences through IFFT operation.

$$\mathbf{x}=\sum_{m=0}^{M-1}\mathrm{IFFT}\{\mathbf{X}^{(m)}\}, \qquad (5)$$

where $\mathbf{x}^{(m)}=\mathrm{IFFT}\{\mathbf{X}^{(m)}\}$ is called partial transmit sequence. The set of phase factors can be

represented as

$$\mathbf{b} = \{b_m = e^{j2\pi\omega/W} \mid \omega = 0,1,\cdots,W-1\}, \quad (6)$$

where W is the number of allowed phase factors for the rotating signal which commonly consists of $b_m \in \{1, -1\}$ or $b_m \in \{\pm 1, \pm j\}$. A weighted sum combination of the M sub-blocks is then written as

$$\mathbf{x} = \sum_{m=0}^{M-1} b_m \cdot \mathbf{x}^{(m)}. \quad (7)$$

The optimal phase factors $\bar{b}_m$ can be obtained from an exhaustive search of all possible combinations that minimize the PAPR. With the optimized phase factors $\bar{b}_m$, the optimized transmit sequence vector $\bar{\mathbf{x}}$ can be generated as

$$\bar{\mathbf{x}} = \sum_{m=0}^{M-1} \bar{b}_m \cdot \mathbf{x}^{(m)}. \quad (8)$$

Thus, the W^{M-1} sets of phase factors are searched to find the optimum set of phase factors. The phase factor search complexity increase exponentially with the number of sub-blocks M.

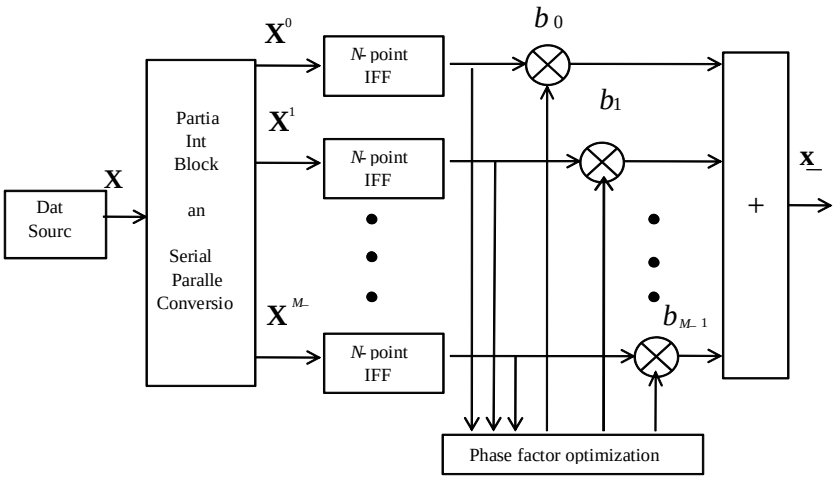

Fig. 4. Block diagram of the **C-PTS** technique

2.5 Suboptimal PTS Techniques

The I-PTS technique was developed by Cimini and Sollenberger [8] as a suboptimal technique for PTS. In the I-PTS technique, after the input data block is divided into M disjoint sub-blocks, $b_m = 1$, (m = 0, 1,…, $M-1$) is assumed for all of the sub-blocks, and the PAPR of the OFDM signal is computed. The sign of the first sub-block phase factor is changed from 1 to – 1 and the PAPR of the signal is recomputed. If PAPR of the previously computed signal is larger than that of the current signal, keep $b_0 = -1$. Otherwise, the phase factor reverts o its previous value, $b_0 = 1$. The computational complexity of the technique is linearly proportional to the number of sub-blocks M and the number of allowed phase factors W.

Jayalath and Tellambura's A-PTS technique is similar to I-PTS technique. To reduce complexity, the flipping can be stopped at the middle of the procedure if one gets the desired PAPR signal during the procedure [9].

Like I-PTS and A-PTS techniques, the suboptimal PTS approaches which have reduced sub-block combining complexity and little performance degradation.

3. Proposed PTS Technique in OFDM System

3.1 Phase factor selection algorithm

In this section, a phase factor selection algorithm is introduced to achieve a significantly low computational complexity to obtain the optimal phase factors.

In the proposed PTS technique, the input data block is partitioned into disjoint sub-blocks as in the C-PTS technique. The difference in the proposed PTS technique as compared with the conventional technique is that this algorithm uses only the peak value in the time domain sequences to determine the phase factors. To reduce the peak value, the subsequences of the peak value should be separated by four independent quadrants using optimal phase factors that are searched by the phase factor selection algorithm. In order to further reduce the computational complexity, a preset threshold (P_{th}) is used, where the search of phase factors is stopped once the minimum PAPR drops below the P_{th}, then take the phase factors $\bar{\mathbf{b}}$ as the output.

A flow chart of the proposed algorithm is depicted in **Fig. 5**. The whole process of the proposed algorithm in practical operations is summarized as follows:

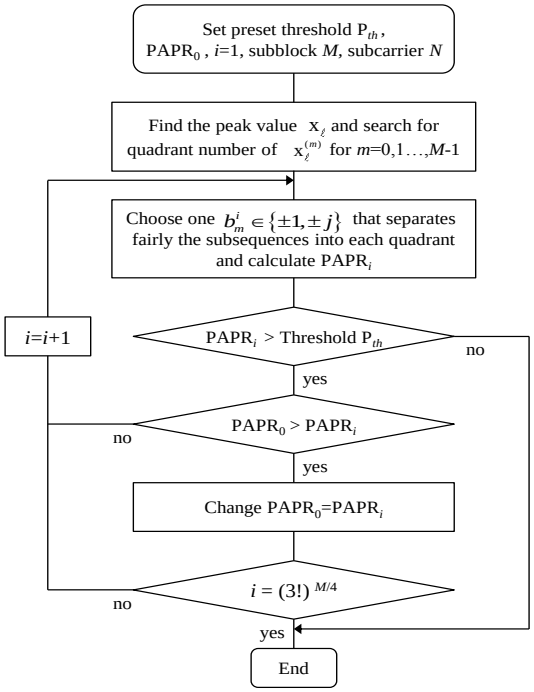

Fig. 5. Flow chart of the phase factor selection algorithm.

1) Partition data into M sub-block.
2) Determine the number of N subcarriers, $PAPR_0$ value, preset threshold P_{th}, and iteration count i=1.
3) After the N-IFFT operation, the time domain sequence vector $\mathbf{x}^m = [x_0^{(m)}\ x_1^{(m)} \cdots x_{N-1}^{(m)}]$ for m=0, $1, \cdots, M-1$ can be obtained. Then, find only the peak value of $\mathbf{x}$, where ℓ implies the ℓ-*th*

row of $\mathbf{x}$, which can be defined as follows:
Therefore, x_ℓ becomes a peak value of $\mathbf{x}$.

4) Analyze the signs of both $\mathrm{Re}(x_\ell^{(m)})$ and $\mathrm{Im}(x_\ell^{(m)})$ for m=0, 1, $\cdots$, $M-1$, quadrant in which the subsequences are located.
5) Among the phase factors $\{\pm 1, \pm j\}$, find $\bar{\mathbf{b}}^i$ for rotating original subsequences $\mathbf{x}^{(m)}$. Hence, the subsequences of peak value x_ℓ are rotated by the selected phase factors, such that

$$\begin{aligned}
&1 \text{ quadrant: } \mathrm{Re}(\bar{b}_m^i \cdot x_\ell^{(m)}) \geq 0, \mathrm{Im}(\bar{b}_m^i \cdot x_\ell^{(m)}) > 0 \\
&2 \text{ quadrant: } \mathrm{Re}(\bar{b}_m^i \cdot x_\ell^{(m)}) < 0, \mathrm{Im}(\bar{b}_m^i \cdot x_\ell^{(m)}) \geq 0 \\
&3 \text{ quadrant: } \mathrm{Re}(\bar{b}_m^i \cdot x_\ell^{(m)}) \leq 0, \mathrm{Im}(\bar{b}_m^i \cdot x_\ell^{(m)}) < 0 \\
&4 \text{ quadrant: } \mathrm{Re}(\bar{b}_m^i \cdot x_\ell^{(m)}) > 0, \mathrm{Im}(\bar{b}_m^i \cdot x_\ell^{(m)}) \leq 0
\end{aligned} \qquad (10)$$

In (10), the subsequences of the peak value are separated by the four independent quadrants. Next, compute the PAPR_i of the combined subsequences.
6) If PAPR_i is less than PAPR_0, change PAPR_0 to PAPR_i and proceed to the next step.
7) The search of phase factors is terminated as soon as the drops less than the preset threshold P_{th}, i.e. in the case of M=8, 1~36 combinations are searched to obtain a set of phase factors.

By combining the selected phase factors $\bar{\mathbf{b}}^i$, the improved partial transmit sequences $\bar{\mathbf{x}}$ can be generated as

$$\bar{\mathbf{x}} = \sum_{m=0}^{M-1} \bar{b}_m^i \cdot \mathbf{x}^{(m)} . \qquad (11)$$

This algorithm finds the optimum set of phase factors, which has a low computational complexity and the required side information is the same when compared to that of C-PTS technique.

Table 1. Computational Complexities of the C-PTS, I-PTS, and the proposed PTS (W=4)

PTS Technique	Phase factor search complexity
C-PTS	W^{M-1}
I-PTS	$W*M$
Proposed PTS	$1 \sim (3!)^{M/4}$, $M \geq 4$

3.2 Computational Complexity

Like the other PTS techniques, the proposed PTS technique requires only several IFFT blocks in parallel per OFDM symbol. Hence, the main complexity factor for these PTS techniques is the number of iterations required to search the optimized phase factors.
Table 1 compares the computational complexities of C-PTS, I-PTS, and the proposed PTS technique, assuming that the number of allowed phase factors is four (W=4). For example, the maximum computational complexity using eight sub-blocks (M=8) is 16,384 for the C-PTS technique, 32 for the I-PTS technique per an OFDM frame. If the preset threshold value P_{th} is used, the iteration counts can be ranged from 1 to 36 for the proposed PTS technique.

4. Simulation Results

To evaluate and compare the performance of the proposed PTS technique to those of the others, a computer simulation is performed.

The number of subcarriers is assumed to be 128 (N=128) per OFDM frame, 100,000 random OFDM symbols are generated, and 16 QAM data symbols are applied for symbol mapping. The input data block was partitioned into eight (M=8) disjointed sub-blocks. The transmitted signal is oversampled by a factor of 4 (L=4), and it is assumed that the number of allowed phase factors is four (W=4) $\{\pm 1, \pm j\}$.

To compare the relative computational complexity of the proposed PTS technique with those of I-PTS and C-PTS, the computational complexity reduction ratio (CCRR) is defined as

$$\text{CCRR} = \left(1 - \frac{\text{Complexity of proposed PTS}}{\text{Complexity of CPTS or IPTS}}\right) \times 100\%. \quad (12)$$

Fig. 6 shows the CCDF of the PAPR for the original OFDM, C-PTS, I-PTS, and the proposed PTS techniques without the preset threshold. As shown in **Fig. 3**, when M=8 at CCDF=10^{-4}, PAPR=6.4dB for the C-PTS technique,

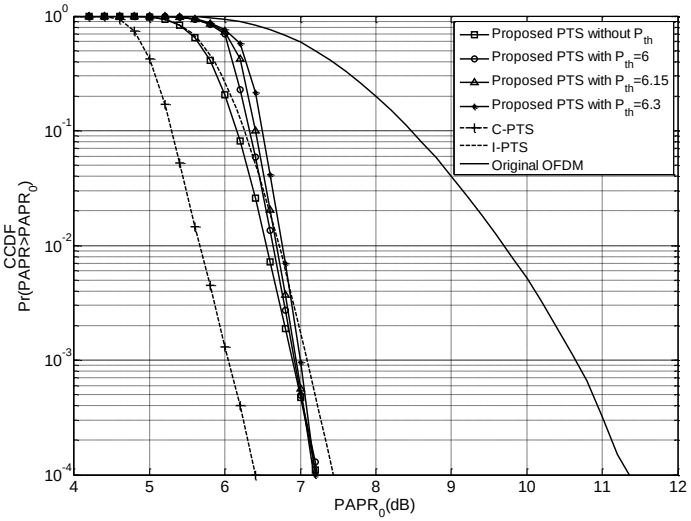

Fig. 6. The CCDF of the PAPR of the original OFDM, **C-PTS**, I-PTS, and the proposed PTS (M=8, W=4).

PAPR=7.4dB for the I-PTS technique, PAPR=7.1dB for the proposed PTS technique, and PAPR=11.3dB for the original OFDM signals. Although there is a gap of 0.7dB between the PAPR performance of the proposed PTS technique and that of the C-PTS technique, the CCRR of the proposed PTS technique without the preset threshold is 99.8% lower than that of the C-PTS technique. When compared with the I-PTS technique, the proposed PTS technique has an approximately about 0.3dB improved PAPR performance. However, the CCRR of the proposed PTS technique without the preset threshold is 12.5% higher than that of the I-PTS technique.

The iteration numbers of these PTS techniques are shown in **Table 2**. For eight (M=8) sub-blocks without the preset threshold, the C-PTS technique requires 16,384 iterations per OFDM frame, while I-PTS technique requires 32 iterations per OFDM frame. In order to

further reduce the computational complexity of the proposed PTS technique, the preset thresholds P_{th} of 6dB, 6.15dB, and 6.3 dB are applied, respectively. The complexity of the proposed PTS technique required 36 iterations per OFDM frame without a threshold, yet with the preset thresholds P_{th} of 6dB, 6.15dB, and 6.3 dB exhibits the lower complexities than the I-PTS technique with only 31.317, 29.159, and 26.684 iterations on average per OFDM frame, respectively. Therefore, the CCRR of the proposed PTS technique are 2.14%, 8.88%, and 16.61% lower than that of the I-PTS technique.

Table 2. Comparison of the phase factor search complexities

(M=8, W=4, 100,000 OFDM frames)

	CPTS	IPTS	Proposed combine SLM and PTS			
			P_{th}=0	P_{th}=6.0	P_{th}=6.15	P_{th}=6.3
Average iteration	16,384	32	36	31.317	29.159	26.684
Min. to Max. iteration	-	-	-	7~36	6~36	5~36

5. Conclusion

This paper has presented a phase factor selection algorithm, which finds the optimum phase factors with a low computational complexity and without increased side information. In the proposed algorithm, a stepwise process is performed to obtain the phase factors. Since the peak value of the time domain sequences is minimized by the selected optimum phase factors, the PAPR can be reduced. By applying the reasonable preset threshold, the computational complexity of the proposed technique can be further reduced without PAPR performance degradation.

As an alternative solution for reducing the complexity of the C-PTS technique, the proposed PTS is more suitable when low complexity system implementations are required.

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Dai Hwan LIM received B.S. degree in informaition from Hong-ik University, Seoul, Korea in 1999. Received Master's degree in information processing engineering at Hanyang Univercity in seoul, Korea. Currently Ph.D. degree course in electronic and computer engineering at Hanyang Univercity in seoul, Korea. Research interests include Mobile VoIP, IP Multimedia Subsystem, Mobile communication and network security.

Byung Ho Rhee received the B.S. and M.S. degrees in electronics engineering from Hanyang University, Seoul, Korea in 1975 and 1977, respectively, and the Ph.D. degree in electric and electronics engineering from National Chiba University, Chiba, Japan in 1993. Since 1981, he has been a Professor in the College of Information and Communications at Hanyang University, Seoul, Korea. From 2006 to 2008, he was the Dean of the college. Since 2004, he has been the President and Member of Committee, IT personnel, Cultivating and Policy Council, MKE, Korea. His primary research interests include network management, software defined radio, session initiation protocol, NGN, and security in wireless network.