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A Survey on OFDM PAPR Reduction Techniques for 60 GHz Wireless CMOS Radio

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Abstract

Multi-giga-bit-per-second 60 GHz transceivers are being developed and implemented on CMOS. OFDM is being considered as the modulation scheme. High Peak-to-Average Power Ratio (PAPR) is a major problem for OFDM. This paper reviews and discusses the advantages and limitations of several important PAPR reduction techniques such as Coding, Partial Transmit Sequence, Clipping, Selective Mapping, Tone Reservation, Tone Injection, and Active Constellation Extension. It concludes that Clipping and Partial Transmit Sequence are more practical than other techniques for implementation of multi-giga-bit-per-second 60 GHz wireless communication systems.

Index

OFDM, Peak-to-Average Power Ratio (PAPR), 60 GHz, multi-carrier, IEEE 802.15.3, Coding, Partial Transmit Sequence, Clipping, Selective Mapping, Tone Reservation, Tone Injection, Active Constellation Extension

I. Introduction

The unlicensed spectrum around 60 GHz became available in recent years in the US, Europe, Japan and Australia. This availability has unlocked significant opportunities for developing ubiquitous gigabit wireless connectivity. Significant research activity is now being undertaken to design next generation high-speed wireless communication systems in this millimeter wave band. Because of the relatively low cost of CMOS manufacturing, CMOS will become one of the dominant 60 GHz wireless technologies in the near future. The IEEE 802.15.3c (60 GHz baseband) working group is considering using Orthogonal Frequency-Division Multiplexing (OFDM) as its modulation scheme.

60 GHz indoor wireless channel is a highly reflective environment with a long impulse response[1], [2]. An important reason why OFDM is a good candidate for 60 GHz is that it provides great immunity to multi-path fading [3]. But the high Peak-to-Average Power Ratio (PAPR) is a major problem for 60GHz CMOS radios, especially Power Amplifiers. High frequency Power Amplifiers on CMOS have limited Dynamic Range, a significant AM-AM and AM-PM distortion and low efficiency.

Many PAPR reduction techniques have been investigated in the past [4], [5], [6]. However, many of them are computationally expensive and others provide minimal PAPR reduction. In this paper we compare several important PAPR reduction techniques for implementation of multi-giga-bit-per-second 60 GHz wireless communication systems.

The paper is organized as follows. In Section II we review the OFDM PAPR problem. In Section III we introduce 60 GHz CMOS radios. In Section III we examine seven different PAPR reduction techniques, namely, Coding, Partial Transmit Sequence, Clipping, Selective Mapping, Tone Reservation, Tone Injection, and Active Constellation Extension. Section V concludes the paper.

II. OFDM PAPR Problem

OFDM is a popular scheme for wireless digital communication systems such as IEEE 802.11a/g Wireless LANs, IEEE 802.16 (WiMax Wireless MAN), and IEEE 802.20 (Mobile Broadband Wireless Access) standards. The IEEE 802.15.3c (60 GHz) standard committee is considering using OFDM as its modulation schemes.

Multi-carrier transmission systems have an inherent problem: high PAPR. PAPR is the ratio of the instantaneous peak signal power to its time-averaged value. It can be expressed by (1)

$$PAPR = \frac{(|x|_\infty)^2}{E[(|x|_2)^2]} \quad (1)$$

For 60 GHz radios built on CMOS, the transistors used to build the fundamental components are operated near the transistor transit frequency. Dynamic Range, Noise Figure and other characteristics such as AM-AM and AM-PM distortion of Power Amplifiers is worse than those designed to operate at lower frequencies. Signals with high PAPR suffer from nonlinear distortion which impairs the orthogonality between sub-carriers when passing through a Power Amplifier (PA) at the transmitter side and a Low Noise Amplifier (LNA) at the receiver side. High instantaneous peaks introduce significant inband noise and also drive the PA into compression generating out-of-band spectrum content. Out-of-band emissions are strictly restricted by regulatory authorities. In order to ensure low distortion, high voltage power rails are required. But this leads to high power consumption which results in reduction of battery life.

III. 60 GHz CMOS Radio And Our Selection Criteria

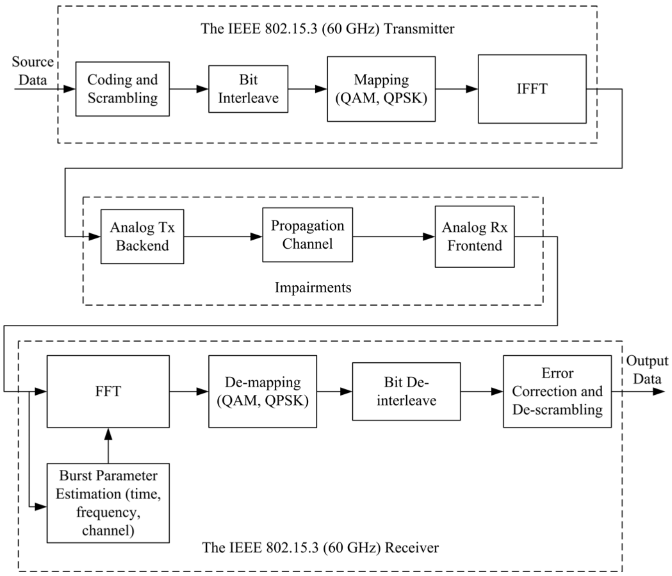

Fig. 1. The IEEE 802.15.3 (60 GHz) Transmitter and Receiver Chain

The 60 GHz radio architecture is shown in Fig.1. On the transmitter side of an OFDM wireless system, data symbols are converted from the frequency domain to the time domain using an Inverse Fast Fourier transform (IFFT). Filtered, amplified and upconverted, the time domain symbols are then sent over the wireless channel. On the receiver side the inverse process is undertaken.

For 60 GHz CMOS baseband, an FFT/IFFT block consumes almost ten to fifteen percent of the baseband die size and five to seven percent of the overall system die size. In addition, in the 60GHz baseband, because of the required 5 Gbps data rates, the IFFT block cannot be reused during the same OFDM symbol. This places practical limitations on PAPR reduction techniques.

IV. PAPR Reduction Techniques

A. Coding

PAPR reduction researchers have investigated coding [6], [7], [8], [9], [10]. The main idea is to select those codewords that minimize or reduce the PAPR for transmission. For example, Complementary Golay Sequences have peak-to-average power ratios less then 2 [11].

These methods are not practical for a 60 GHz system because their complexity increases exponentially with the subcarrier number and requires very significant computation capability to successfully operate at 5 Gbps.

B. Clipping

In Clipping, the amplitudes of the input signal are clipped to a predetermined value [12]. A comparison of the histograms

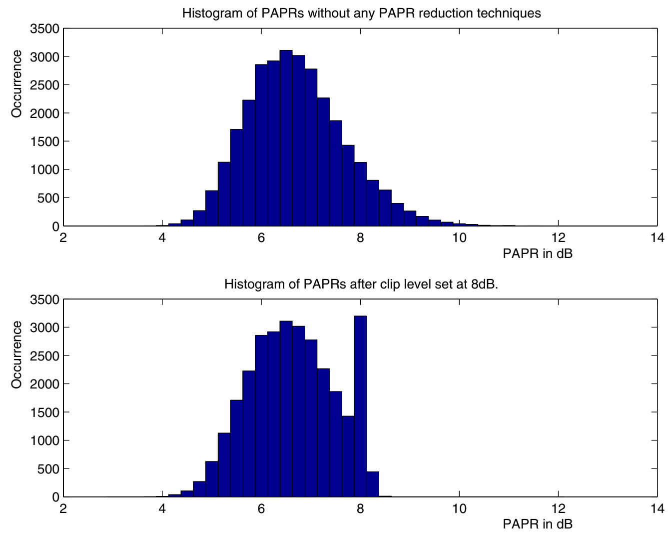

Fig. 2. The comparison of the histogram of PAPRs with and without Clipping. Here the hard clip level is set to 8 dB for 64 sub-carriers. The simulation has run over randomly generated QAM4 data for 30,000 iterations.

of the PAPRS of unclipped and clipped signals is shown in Fig.2.

Another method is to shape all time domain signals with a logarithm function before transmission and to restore them with an exponential function at the receiver side. However, through simulation we have found that the performance of Clipping is comparable to the logarithm shaping method for the same average PAPR reduction effect and the corresponding average Error Vector Magnitude (EVM) of the received data symbols. We compares these two methods in a realistic situation with a 60 GHz wireless channel model which is measured on a highly reflective desktop environment. Gaussian noise was added with a 20 dB SNR. Two BPSK OFDM preambles are used for both the frequency domain channel compensation and power estimation. Three groups of simulations on typical situations such as slightly clipped, moderately clipped and heavily clipped are conducted over random QAM4 data, with 256-point OFDM schemes, for 200,000 iterations. The simulation results are shown in Fig. 3, 4 and Table I. We find that if slightly clipped or moderately clipped, the performance of the two methods in terms of average EVM are very close. But heavy clipping causes about 1 dB lower average EVM than for the logarithm shaping method.

The reason for this is that Clipping only changes the signals which exceed a certain threshold, however, logarithm shaping effects all signals. Another approach is to use a window function to shape the peak signals [5], [13]. Peak windowing decreases out-of-band noise and increases in-band noise.

Clipping introduces inband distortion and out-of-band signals, which can be controlled by proper filtering. A repeated Clipping-and-filtering method requires duplicating IFFT and FFT blocks [4], [14]. This increases fabrication cost as well as slowing the system.

TABLE I

THE PERFORMANCE COMPARISON OF CLIPPING AND LOGARITHM SHAPING

	Original	*Clipping*	*Logarithm Shaping*
Heavily clipped		clip at 5.1 dB	log(1+20x)
avg PAPR	7.81 dB	5.27 dB	5.33 dB
avg EVM	-18.40 dB	-17.53 dB	-16.51 dB
Slightly clipped		clip at 8.5 dB	log(1+0.3x)
avg PAPR	7.81 dB	7.71 dB	7.72 dB
avg EVM	-18.40 dB	-18.39 dB	-18.39 dB
Moderately clipped		clip at 7.15 dB	log(1+3x)
avg PAPR	7.81 dB	7.09 dB	7.07 dB
avg EVM	-18.40 dB	-18.30 dB	-18.24 dB

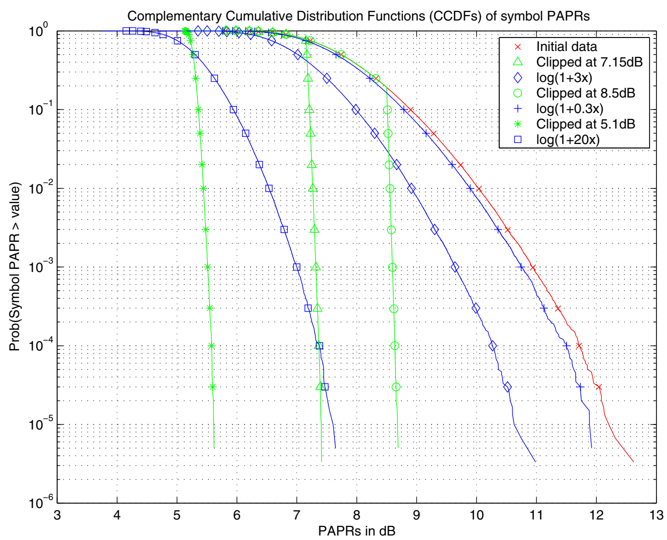

Fig. 3. Comparison of the Complementary Cumulative Distribution Functions (CCDFs) of symbol PAPRs. The hard clip level is set to three different typical levels. The logarithm function is adjusted according to similar average PAPR reduction effects. The SNR is 20 dB. The simulations have run over randomly generated QAM4 data for 200,000 iterations.

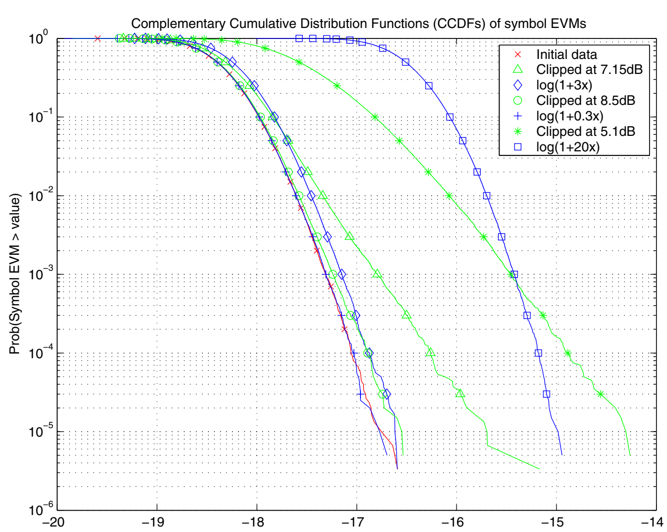

Fig. 4. Comparison of the Complementary Cumulative Distribution Functions (CCDFs) of received symbol EVMs as shown in Fig. 3.

C. Partial Transmit Sequence (PTS)

As a PAPR reduction technique, Partial Transmit Sequence (PTS) [15], [16], [17] is simple, fast, and requires a relatively small amount of side information and introduces no distortion. However it requires duplicating hardware IFFT blocks.

In a PTS scheme, all N subcarriers are partitioned into M disjoint sub-blocks, and each sub-block is weighted by one phase factor. Each sub-block is calculated by IFFT of size N (not N/M), while treating all other subcarriers as zero. As shown in Fig. 5, the selection of a best PAPR is performed after M parallel IFFTs, by weighting M Partial Transmit Sequences with M phase factors and adding them together.

Parallel calculation of IFFTs means there is no sacrifice of system speed. The optimization of the phase factors is performed after all IFFT operations. So there is no need to repeat IFFT calculations, as required by many other PAPR reduction techniques. A simulation result for PTS is shown in Fig.6. Here sixty-four sub-carriers are grouped in four adjacent sub-blocks, the phase factor can be selected from 0, 45, 90 or 135 degrees. The simulation has run over randomly generated QAM4 data for 30,000 iterations. Results show that PTS has stable control over PAPR. PTS has better PAPR reduction performance than Clipping but it is computationally more expensive.

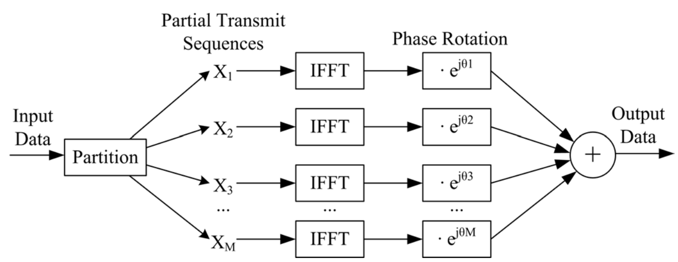

Fig. 5. A block diagram of PTS. Notice that the optimization of phase factors is performed after M parallel IFFTs.

D. Selective Mapping (SLM)

As shown in Fig. 7, Selective Mapping (SLM) uses M different sets of phase factors as the candidates and passes the rotated frequency domain data symbols through an IFFT [18]. The result with the lowest PAPR is selected and sent out. The side information of which phase factor set is used is transmitted over the wireless channel.

The idea of SLM sounds similar with PTS, but it is less flexible. With the same sub-block number M, PTS (in case of L different phase factors) can do a flexible combination in the order of L^M but SLM has only M selections. In another words, with the same number of duplicated IFFT blocks, PTS is more efficient than SLM.

E. Tone Reservation(TR)

Tone Reservation reserves a set of frequency domain sub-carriers (tones), (for example, 20% of the subcarrier), for PAPR reduction [19], [20], [21]. Proper tone values are calculated in an iterative manner to cancel the peaks generated

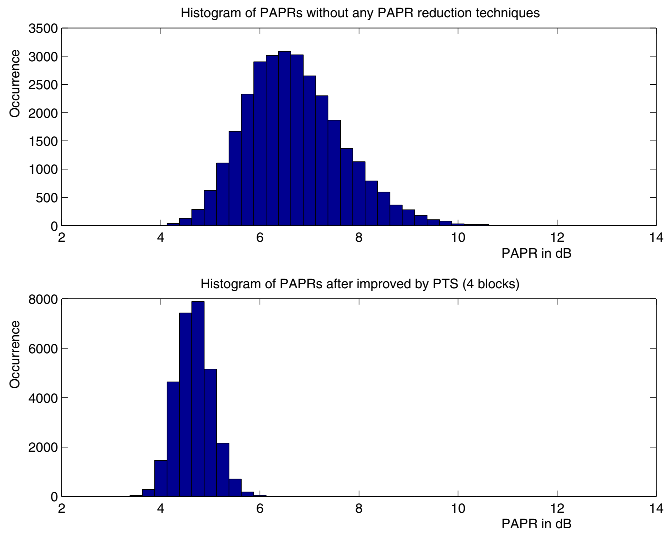

Fig. 6. Comparison of the histogram of PAPRs with and without Partial Transmit Sequence. Here 64 sub-carriers are grouped in 4 adjacent sub-blocks, phase factor can be selected from 0, 45, 90 or 135 degrees. The simulation has run over randomly generated QAM4 data for 30,000 iterations.

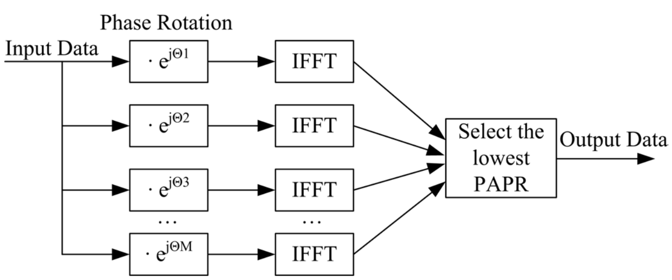

Fig. 7. A block diagram of SLM.

by the remaining 80% tones which carry information. Such optimization requires IFFT operations several times until the predeterminate PAPR reduction threshold is achieved, which inevitably reduces the system speed. It also leads to bandwidth sacrifice.

F. Tone Injection (TI)

In Tone Injection, the original basic constellation can be mapped into several equivalent points in the expanded constellation [22]. Tone Injection needs an IFFT operation for each iteration. In addition, because of the method to increase the constellation size, it leads to unavoidable power increase.

G. Active Constellation Extension (ACE)

We see Active Constellation Extension (ACE) as an improvement to Tone Injection. In ACE, some of the outer signal constellation points in the data block can be extended toward the outside of the original constellation. Such freedom is used to reduce the PAPR of the data block[23]. The EVM will not be increased because of the unique design of the constellation range. In addition, no side information is needed. However, it needs an IFFT operation for each iteration. Similar to TR and TI, ACE requires significant computational resources.

V. Conclusion

Comparisons of various PAPR reduction techniques have been given in [4], [5], [24]. Here we compare several important PAPR reduction techniques using a different approach specially for 60 GHz CMOS transceivers.

Due to the fabrication costs and the throughput requirement, the most practical PAPR techniques are Clipping and PTS. In this application, coding, SLM, and the iterative optimization methods such as TI, TR and ACE, which need several iterations of IFFT calculations, are of limited utility because of computational requirement.

In a multi Gbps 60 GHz CMOS transceiver design, it is recommended to implement PTS, which has no reduction in EVM, if the silicon area is available. Otherwise Clipping is also suitable.

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