Investigations on Nonlinearity Effects in Communication Systems and their Compensation Techniques

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Investigations on Nonlinearity Effects in Communication Systems and their Compensation Techniques

Abstract

Nonlinearity effect is one of the most undesirable phenomena in the modern communication systems which appear in the form of harmonic distortion, gain compression, intermodulation distortion, phase distortion, adjacent channel interference, etc. Modern communication systems use orthogonal frequency division multiplexing (OFDM) which has high data rate transmission capability in addition to robustness to channel impairments. One of its major disadvantages is having high peak-to-average power ratio (PAPR). High PAPR drives power amplifier into saturation region and causes it to operate in the nonlinear region. In the present research work mathematical modeling and Matlab simulations have been carried out on the transceiver of multicarrier OFDM communication systems. Its PAPR have been calculated using QAM baseband modulated signal with different number of subcarriers. Linearization of the class B solid state power amplifier using feedback, feed forward and pre-distortion techniques have been investigated. Among power amplifier linearization techniques digital pre-distortion outperforms when compared with other linearization techniques. In order to reduce PAPR of OFDM systems different PAPR reduction techniques such as clipping and filtering, selective mapping method (SLM), partial transmit sequence (PTS) and single carrier frequency division multiple access (SCFDMA) have been analyzed. Among different PAPR reduction techniques, SCFDMA results in the lowest PAPR. The effect of raised-cosine pulse shaping filter has also been investigated in order to reduce the out-of-band signal energy of SCFDMA system. From the result obtained it can be observed that effect of pulse shaping is more on interleaved frequency division multiple access (IFDMA) than that on localized frequency division multiple access (LFDMA) technique.

1. Brief Description of the State of the Art of the Research Topic

Modern communication systems use multicarrier OFDM for high data rate transmission capability. OFDM is desirable because of several advantages associated with it, such as tolerance to inter-symbol interference, good spectral efficiency, best performance of frequency selective fading in a multipath environment, robustness to channel impairments etc. OFDM systems have many applications and are widely used in high-bit-rate digital subscriber lines (HDSL), digital audio broadcasting (DAB), digital video broadcasting (DVB) along with high-definition television (HDTV), terrestrial broadcasting. Third generation partnership project (3GPP) for long term evolution (LTE) and LTE advanced (LTE-A) uses orthogonal frequency division multiple accessing

(OFDMA) for the downlink and SCFDMA technique for the uplink transmission. OFDM is widely used in 4th generation mobile communications and is also being considered for the 5th generation mobile communication applications.

2. Literature Review

Investigation on nonlinear compensation techniques has been done by Ralph Hall [1]. He has observed that in order to reduce the effect of nonlinearity a biased semiconductor diode can be used in the emitter feedback impedance at the output stage of each repeater. Pedro and Carbalho [2] have reviewed major techniques for evaluating nonlinear distortion in communication systems and discussed their major limitations. They have shown that the theoretical value obtained with a third order nonlinear system, the multitone test characteristics is directly related to two- tone test figures and noise power ratio gives an optimistic measure of co-channel interference. Roblin et al [3] have presented a review on modeling and linearization of multiband power amplifiers used for the amplification of signals with noncontiguous spectra. They have presented supportive theories, simulation, and experimental results to demonstrate the concept and practical implementation of multiband digital pre-distortion (DPD) systems. With the increase in the number of noncontiguous bands, the algorithm complexity also increases. Frederick Raab et al, [4] in their classic paper have investigated power amplifiers for radio frequency (RF) and microwave. They have observed that incorporation of power amplifiers in transmitters are done in a wide variety of architectures such as linear, Kahn, envelope tracking, out phasing and Doherty. They have also investigated and suggested different power amplifier linearization techniques which include feedback, feedforward, and pre-distortion.

Han and Lee [5], have described some important PAPR reduction techniques for multicarrier OFDM transmission. They have emphasized that the PAPR reduction technique should be carefully selected as per the system requirement. Jiang and Wu [6] have observed that although OFDM is an attractive technique owing to its spectrum efficiency and channel robustness for wireless communications. It has one of the serious drawbacks of high PAPR when the input sequences are highly correlated. They have described many aspects and have provided a mathematical analysis, which included the distribution of the PAPR, in the multicarrier OFDM systems. Ai Bo, et al [7] have observed that PAPR reduction may improve the high power amplifier (HPA) power efficiency, but, very few have attempted to analyze the relation between PAPR reduction and HPA linearization. In their paper, based on Saleh's travelling wave tube amplifier (TWTA) model, found that all those data with amplitudes larger than $A_{sat}/2$ can not be compensated for with a pre-distorter. Armstrong [8] in his letter emphasized that the reduction of PAPR for an OFDM signal can be achieved without increasing the out-of-band power first by clipping the oversampled time domain signal and then followed by filtering the clipped signal using an fast Fourier transform (FFT)-based, frequency domain filter which is designed to reject the out-of-band discrete frequency components. Wang and Tellambura [9] have proposed a new clipping and filtering technique with reduced computational complexity that, in one iteration, obtains the same PAPR reduction as that of the iterative clipping and filtering technique with several iterations. The computational complexity is, therefore, significantly reduced. Li and Cimini [10] in their letter have investigated the effects of clipping and filtering on the performance of OFDM. In order to better characterize the peakiness of an OFDM signal, they have used the CF's at various percentiles of the cumulative distribution function (CDF) instead of using an absolute crest factor (CF). Le Goff, et al [11] have proposed a quite simple SLM technique for PAPR reduction in OFDM system which does not require the transmission of additional side information bits. Their investigations, based on quadrature phase shift keying (QPSK) and 16 quadrature amplitude modulation (QAM) baseband modulations, have revealed that their technique is most suitable for systems having a large number of subcarriers. FPGA implementation of SLM technique have been investigated by Bansode, Mishra & Temrikar [12] and by Kamdar, Shah and Sorathia [13] and the result obtained have shown a similar trend with as that of obtained by mathematical modeling and simulations with additional advantages of reduced hardware resource consumption and system complexity.

Varahram and Mohd Ali [14] have investigated on a new phase sequence of PTS scheme wherein a matrix of possible random phase factors are first generated which is multiplied point-wise with the input signal. In this new technique, the number of inverse fast Fourier transform (IFFT) operation has been reduced to 50 % so that the system complexity has been reduced when compared with continuous PTS at the cost of a slight decrease in PAPR. Yang, Chen, Siu, and Soo [15] have proposed a reduced complexity PTS method and have given a derivation taking into account the relationship between the transmitted signals and the weighting factors. They have demonstrated that the computational complexity of their proposed method is only about the one (N-1)th of the conventional PTS method, where N is the number of sub-blocks. Myung, Lim, and Goodman [16] have investigated the effects of subcarrier mapping on throughput and PAPR. Among different subcarrier mapping approaches, they observed that localized FDMA (LFDMA) with channel-dependent scheduling gives higher throughput than interleaved FDMA (IFDMA). But, the PAPR performance of IFDMA is better than that of LFDMA by 4 to 7 dB. Lin, Xiao, Vucetic, and Sellathurai [17] derived frequency domain receiver algorithm for the SCFDMA based uplink multiple input multiple output (MIMO) systems with the improper signal constellation. They also derived mathematical expressions of the received signal-to-interference-plus-noise ratio (SINR) for the considered MIMO systems. In order to reduce the PAPR of the SCFDMA uplink systems, Feng et al [18] have investigated a novel piece-wise linear pulse shaping filter. They have considered the optimal values of the design parameters that produce the minimum value of PAPR through simulation as a function of the roll-off factor for the SCFDMA system. Using a spline construction in the frequency domain Beaulieu and Damen [19] have investigated a new parametric approach to construct families of ISI-free pulses. When compared with raised-cosine pulses with the same value of excess bandwidth, their proposed technique has more open pulse-sequence eye, smaller distortion, and a smaller average probability of error with symbol-timing error.

3. Research Gap

Powerful techniques have been developed to mitigate the harmful effects of nonlinearity, but are not effective when applied alone. There is a need to address this issue at the transmitter and receiver simultaneously. At the transmitter, there is a need to use the efficient modulation technique such as multicarrier OFDM system with effective PAPR reduction techniques and utilization of effective power amplifier linearization techniques. Similarly, effective pulse shaping filter and demodulation technique are required to be used at the receiver.

4. Definition of the Problem

- Mathematically modeling and simulation of the transceiver of multicarrier OFDM systems.
- Calculate its PAPR with QAM baseband signal with different number of subcarriers.
- Perform linearization of the class B solid state power amplifier using feedback, feed forward and pre-distortion techniques.
- Perform PAPR reduction using clipping and filtering, SLM, PTS and SCFDMA techniques.
- Investigate effect of raised cosine pulse shaping filter on SCFDMA signal.

5. Objective of the Work

To apply multilevel approach at the transmitter and receiver simultaneously by mathematically modeling and analyzing the transceiver of multicarrier OFDM systems. Calculate its PAPR with a different number of subcarriers. Perform linearization of the class B solid state power amplifier using feedback, feed forward and pre-distortion techniques. Perform PAPR reduction using clipping and filtering, SLM, PTS and SCFDMA techniques. Investigate effect of raised cosine pulse shaping filter on SCFDMA signal.

6. Research Methodology

Following research methodology has been adopted for investigation on the nonlinearity effects in multicarrier OFDM communication systems and their compensation techniques:

- Mathematical modeling and Matlab simulation of the transceiver of multicarrier OFDM communication systems and evaluation of its PAPR.
- Linearization of class B solid state power amplifiers using feedback, feedforward and digital pre-distortion technique using student evaluation copy of visual system simulator of National Instrument's AWR version 12.0 commercial software.
- Clipping and filtering technique for PAPR reduction with (a) Matlab software simulation (b) National Instrument's AWR software (c) FPGA implementation using Xilinx Spartan 3 Protoboard XC 3S 400 board and (d) performance comparison with the above three mentioned techniques.
- Selective mapping method of PAPR reduction using (a) Matlab software simulation (b) FPGA implementation using Xilinx Spartan 3 Protoboard XC 3S 400 board and (c) performance comparison with Matlab and FPGA implementation.
- Mathematical modeling and Matlab simulation of partial transmit sequence (PTS) technique.
- PAPR reduction with SCFDMA or DFT-spread techniques for IFDMA, DFDMA, and LFDMA subcarrier mapping.
- Reduction of PAPR and spectral growth on SCFDMA signal using raised-cosine pulse shaping filter.

7. Original Contribution by the Thesis

In order to compensate the effect of nonlinearity in multicarrier OFDM communication systems multilevel approach at the transmitter and receiver have been applied simultaneously. Mathematical modeling and Matlab simulations have been carried out on the transceiver of multicarrier OFDM communication systems. Its PAPR have been calculated using QAM baseband modulated signal with different number of subcarriers. Linearization of the class B solid state power amplifier using feedback, feed forward and pre-distortion techniques have been investigated. In order to reduce PAPR of OFDM system different reduction techniques such as clipping and filtering, SLM, PTS and SCFDMA have been analyzed. The effect of raised-cosine pulse shaping filter has also been investigated to reduce the PAPR of SCFDMA system.

7.1 Multicarrier OFDM Communication Systems

OFDM has become an attractive technique and gained more popularity in the wireless communication systems [20-22]. On the other hand, OFDM systems are vulnerable to power amplifier nonlinearities due to its high PAPR and for low-cost applications, the disadvantage of high PAPR may outweigh all its major advantages. Peak to average power ratio (PAPR) is used to quantify the fluctuations in the envelope of the signal.

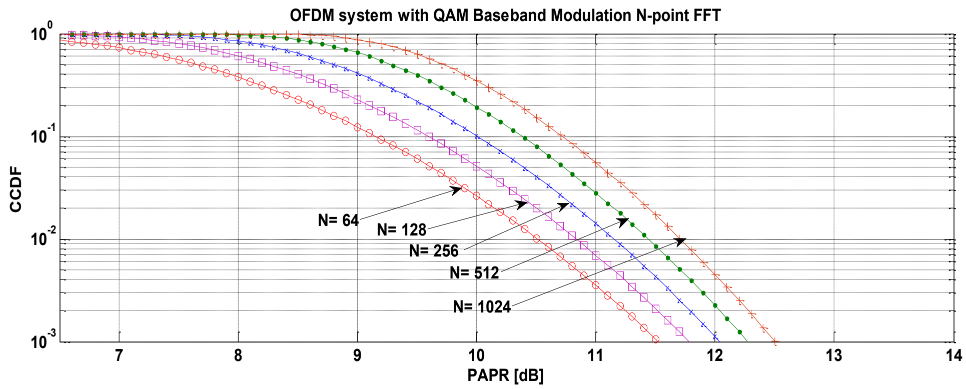

FIGURE 1. PAPR of the OFDM signal with Matlab simulation

PAPR is defined as the ratio of maximum (peak) power to average power of the complex passband discrete time signal [23]. Complementary cumulative distribution function (CCDF) is used to measure PAPR of the OFDM signal. In order to calculate PAPR of the OFDM signal mathematical modeling and Matlab simulations have been carried out. Figure 1 shows PAPR value for 4 QAM baseband signal with different number of subcarriers. At 10^{-3} of CCDF, PAPR values for QAM modulation are 11.5, 11.7, 12.0, 12.2, and 12.6 dB for 64, 128, 256, 512 and 1024 number of subcarriers respectively. It is evident from the figure 1 that with an increase in the number of subcarriers PAPR also increases.

7.2. Linearization of Power Amplifier

Feedback, feedforward, and pre-distortion are three different linearization techniques used to improve the linearity of power amplifiers. Feedback is one of the simplest technique to implement but suitable for low frequency operation [24]. Feed forward technique is mostly used for wide bandwidths applications where feedback technique is impractical. This technique is comparatively costly due to the use of couplers, delay lines, error power amplifier, etc. On the other hand, the digital pre-distortion technique does not use these RF components and improves linearity with higher efficiency. All the above three mentioned techniques have been modeled and simulated using visual system simulator of National Instrument's AWR commercial software at 2 GHz operating frequency.

7.2.1 Feedback Technique

It is simple to implement and can be applied either directly to the RF amplifier or indirectly to the modulator. In this, a portion of the output signal from the amplifier is subtracted from the input signal. Simulation has been performed at 2 GHz operating frequency which has resulted in 5 dBm reductions in amplitude and 30 dB reductions in adjacent channel power ratio (ACPR) with 10 MHz bandwidth.

7.2.2 Feed Forward Technique

Feed forward linearization is mostly stable because of unavailability of the feedback path. Nonlinear distortions are corrected at the output level in the feed forward, whereas it was done at input level in the feedback systems. It requires highly linear and efficient error amplifier and precise analog RF-components. In order to maintain accuracy, overloading, time, and temperature highly precise analog components are required. At 2 GHz of operating frequency performance of the PA using feed forward loop has been improved compared to feedback technique with operating bandwidth of 1.2 GHz. When simulated it has resulted in 20 dBm reductions in amplitude with 25 dB reductions in ACPR.

7.2.3 Digital Pre-distortion Technique

In the digital pre-distortion technique only the data symbols are distorted, not the transmit signal and pulse-shaping are performed after the pre-distortion stage.

TABLE 1 Comparative Result of Power Amplifier Linearization Techniques

Parameters/ Linearization Techniques	Feedback			Feed Forward			Digital pre-distortion		
	Without Feed back	With Feed back	Reduction	Without Feed Forward	With Feed Forward	Reduction	Without DPD	With DPD	Reduction
Amplitude (dBm)	25	20	-5	0	-20	-20	-24	-24	0
ACPR (dB)	0	-30	-30	-60	-85	-25	-52	- 72	-20

In this technique, the reduction in amplitude and ACPR is 0 dBm and 20 dB respectively with 3dB bandwidth of 10 MHz. DPD has lowest spectral regrowth with the highest gain compared to feedback and feed forward correction techniques. Table 1 gives the comparative performance of different power amplifier linearization techniques.

7.3 PAPR Reduction Techniques

Different techniques are used for PAPR reduction of OFDM signals. In this paper, we have investigated clipping and filtering, selective mapping method (SLM), partial transmits sequence (PTS) and SCFDMA technique.

7.3.1 Clipping and Filtering Technique

It is the simplest technique where PAPR can be reduced by clipping the amplitude of the transmitted signal and passing it through a low-pass filter. Low pass filter used after clipping operation moderately enlarges the PAPR. PAPR also depends upon the clipping ratio (CR) which is defined as the clipping level normalized by the RMS value σ of OFDM signal.

A. Clipping and Filtering with Matlab Simulation: Figure 2 gives values of PAPR with Matlab simulation for 4 QAM baseband OFDM signal with 1024 number of subcarriers. The PAPR values obtained are 10.7, 11.0, 11.2, 11.4 and 11.7 dB with 0.8, 1.0, 1.2, 1.4 and 1.6 clipping ratio respectively.

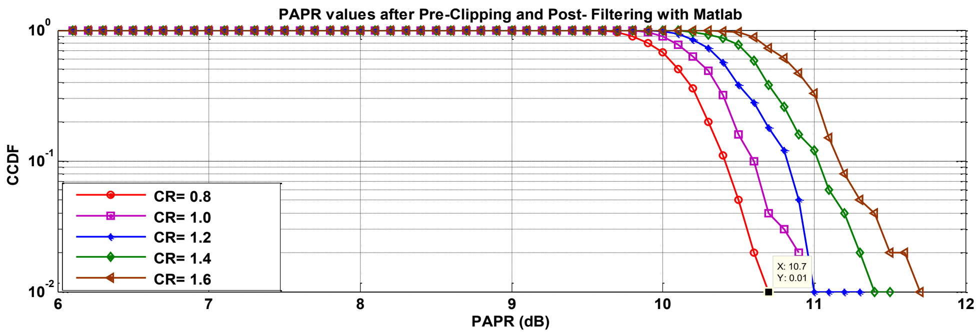

FIGURE 2. PAPR of clipped and filtered signal with Matlab simulation

B. Clipping and Filtering with NI'S AWR Visual System Simulator Software simulation: The clipping and filtering operation have also been simulated using student evaluation license of National Instrument's AWR visual system simulator commercial software.

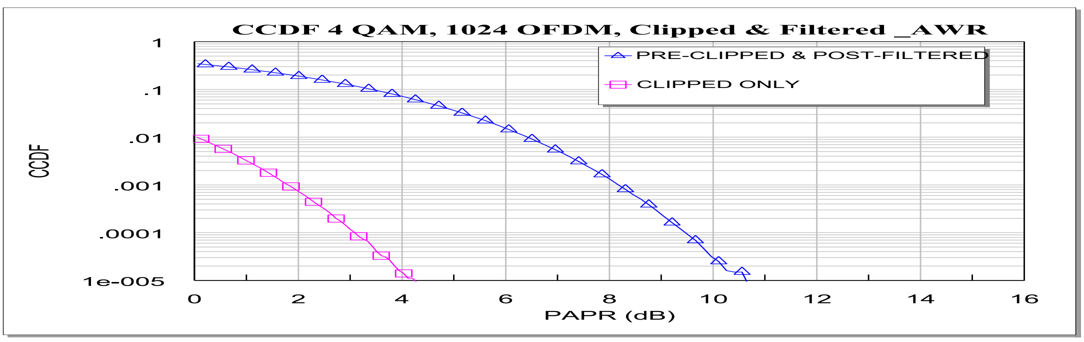

FIGURE 3. PAPR using NI's AWR visual system simulator

As observed from figure 3, at CCDF of 10^{-5} the PAPR value obtained are 4.2 and 10.6 for clipped only and clipped and filtered signals respectively at 0.8 clipping ratio.

C. FPGA Implementation of Clipping and Filtering Technique: Clipping and filtering technique has been implemented on FPGA and tested on hardware co-simulation using Xilinx Spartan 3 Protoboard XC 3S 400 development board. Figure 4 depicts the values of PAPR for pre-clipping and post filtering with FPGA implementation of 4 QAM baseband OFDM signal with 1024 number of subcarriers. For clipping ratio of 0.8, 1.0, 1.2, 1.4 and 1.6 corresponding PAPR values are 10.9, 11.2, 11.5, 11.8 and 12.1 dB respectively.

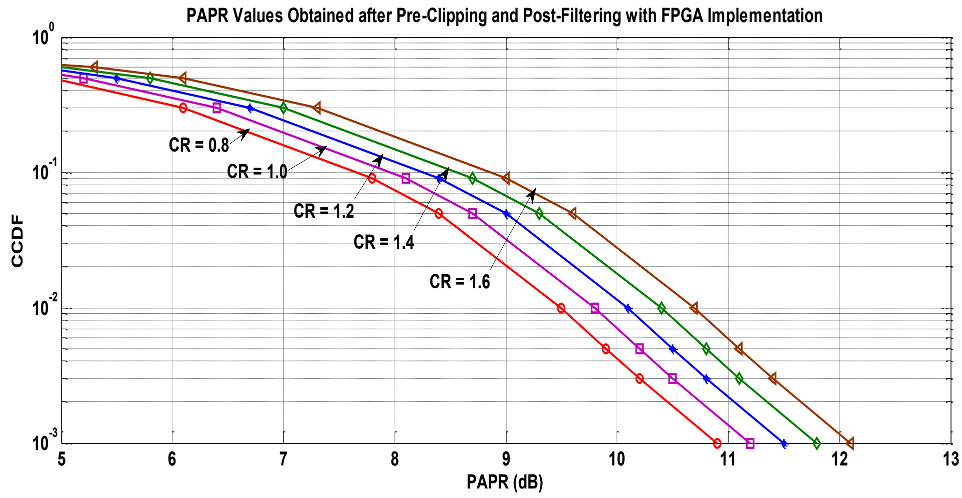

FIGURE 4. PAPR of Clipping and Filtering with FPGA implementation

D. Comparative values of PAPR with clipping and filtering: Figure 5 depicts the comparative values of PAPR obtained through simulation with Matlab, NI's AWR software and FPGA implementations.

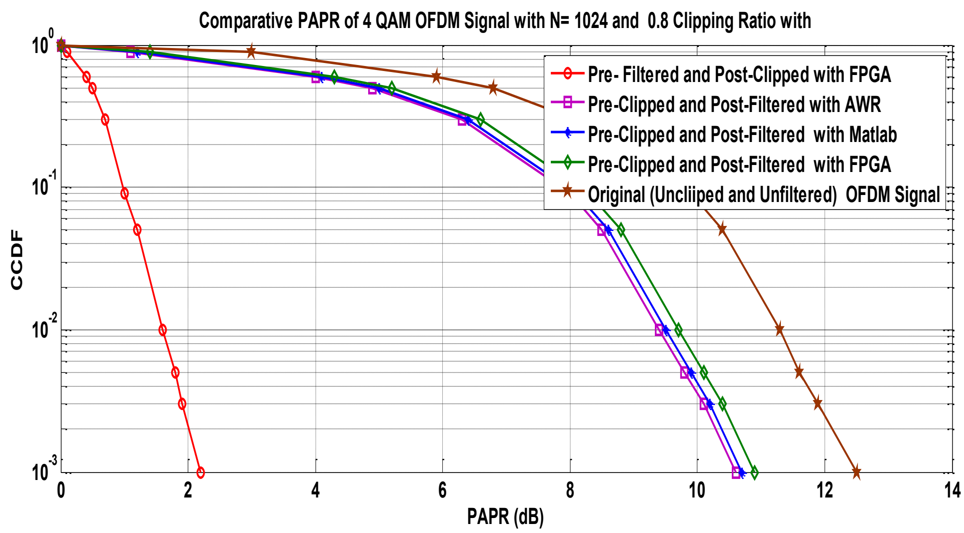

FIGURE 5. PAPR of Clipping and Filtering with different methods

PAPR with FPGA implementation of pre-filtering and post-clipping with clipping ratio = 0.8 is 2.2 dB. Whereas PAPR values obtained in the case of the pre-clipping and post-filtering method with clipping ratio = 0.8, are 10.6, 10.7 and 10.9 dB with NI's AWR software, Matlab and FPGA implementations respectively. Although pre-filtering and post-clipping gives lowest PAPR but is not used practically because of worst BER performance.

7.3.2 Selective Mapping Method

SLM is one of the most important methods for reducing PAPR of OFDM signals. It is simple in implementation, has an absence of distortions in the transmitted signal, and results in a significant reduction in PAPR. In the SLM method, the original data block is converted into several independent signals. Different phase rotations are applied to parallel baseband modulated signals. The phase rotation which gives minimum PAPR is selected.

A. Matlab Simulation of SLM Technique: As shown in figure 6 at 10^{-2} of CCDF, PAPR obtained with phase vectors, V = 16, 8, 4, 2 and 1 are 8.2, 8.4, 8.9, 9.7 and 10.6 dB respectively for 1024 number of subcarriers. It can be observed from the figure that PAPR value is low when the number of phase vector is high (V= 16) and increases with either increase in the number of subcarriers or reduction in the number of phase rotations.

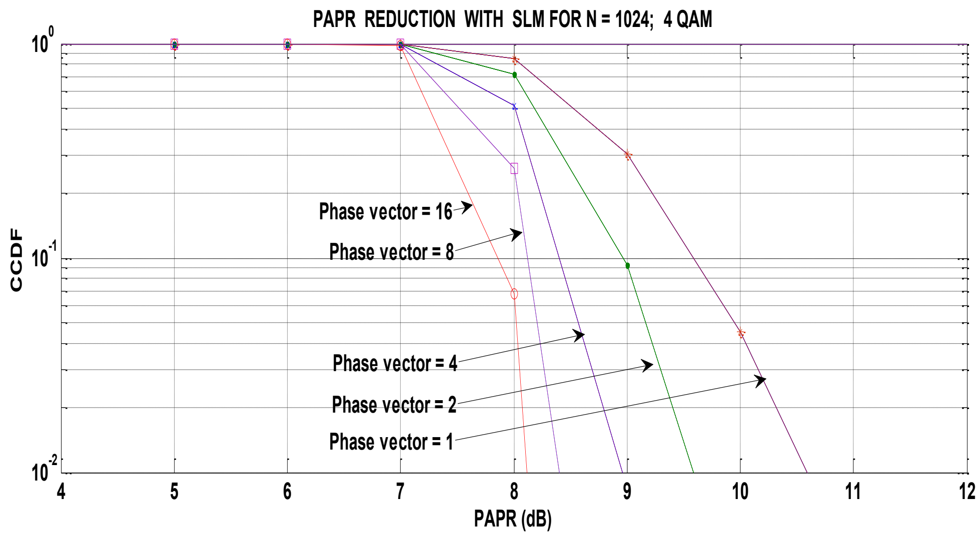

FIGURE 6. PAPR reduction with SLM

B. FPGA implementation of SLM Technique: Complete system design has been implemented on FPGA and tested on hardware co-simulation using Xilinx Spartan 3 Protoboard XC 3S 400 development board. Table 2 gives the PAPR with different number of subcarriers and number of phase vector, V = 4. The phase sequence which gives minimum PAPR is selected for transmission.

TABLE 2 Value of PAPR of SLM with different Methods

Phase Sequence / No of carriers	N=64 (dB)	N=128 (dB)	N=256 (dB)	N=512 (dB)	N=1024 (dB)
p^0	11.3	11.5	8.9	9.7	10.8
p^1	9.4	10.9	11.6	11.2	12.1
p^2	7.8	10.9	9.6	10.9	9.8
p^3	9.1	8.4	11.0	9.2	11.5
Minimum PAPR with FPGA implementation	7.8	8.4	8.9	9.2	9.8
PAPR with Matlab simulation	7.5	8.1	8.5	8.8	8.9
PAPR without SLM (original OFDM signal)	11.5	11.7	12.0	12.2	12.6

C. Comparative values of PAPR with SLM: As shown in figure 7 the PAPR of the FPGA implementation for the case of 4 QAM OFDM signal with 1024 number of subcarriers is 9.8 dB which is 2.8 dB less from the original OFDM signal obtained without applying SLM technique but 0.9 dB higher than the Matlab simulated value.

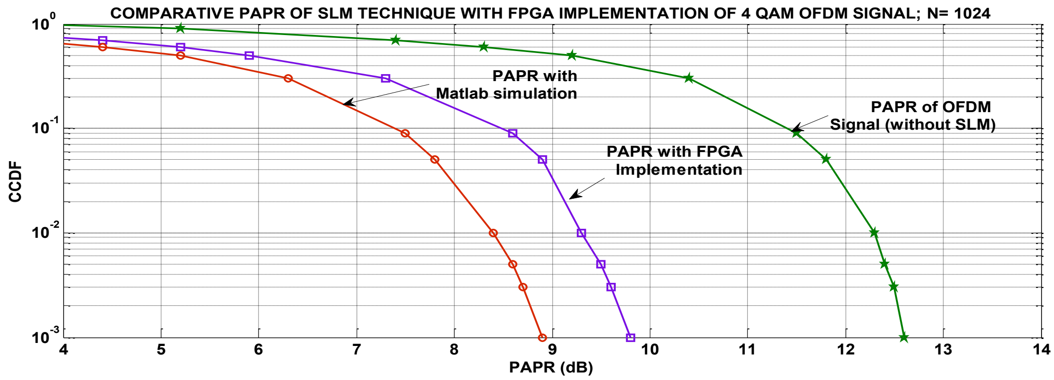

FIGURE 7. Comparative value of PAPR reduction with SLM technique

7.3.3 Partial Transmit Sequence

PTS technique, partitions an input data block of N symbols into M disjoint Subblock of equal size that is consecutively located. In PTS technique scrambling is applied to each subblock, whereas in the SLM technique scrambling is applied to all subcarriers. Each partitioned subblock is multiplied by a corresponding complex phase factor $b^n = e^{jbn}$ where, n =1, 2, …N and its IFFT is taken and phase vector is chosen such that the PAPR can be minimized. Selection of the phase factors $\{b^m\}_{N-1}^{N}$ is limited to a set of elements to reduce the search complexity.

The mathematical modeling and Matlab simulations using the pseudo-random method of block partitioning has been carried out. 4 QAM OFDM signal constellation has been taken into consideration with 8000 blocks with 64, 128, 256, 512 and 1024 number of subcarriers. Table 3 shows the PAPR values for the number of sub-blocks, M = 16, 8, 4, 2 and 1 respectively. From the table it is clear that PAPR value is least when a number of sub-blocks are large (M= 16).

TABLE 3 PAPR Value with PTS Technique

Number of Subcarrier (N)	M= 16 (dB)	M= 8 (dB)	M= 4 (dB)	M= 2 (dB)	M= 1 (dB)
64	6.0	6.6	7.5	8.3	9.3
128	6.7	7.3	7.9	8.8	9.6
256	7.3	7.8	8.3	9.2	10.0
512	7.6	8.1	8.5	9.4	10.4
1024	8.3	8.6	9.1	9.8	10.6

7.3.4 DFT-Spread Technique

DFT-spread is also known as single carrier frequency division multiple accessing (SCFDMA) technique. It gives the lowest PAPR value and has been used for upward transmission in the fourth generation mobile communication which has been recommended by 3 GPP group for LTE systems [25].

TABLE 4 PAPR value of SC-FDMA signal

Mod Type	**DFT- spread mapping**	**PAPR with N=64 (dB)**	**PAPR with N=128 (dB)**	**PAPR with N=256 (dB)**	**PAPR with N=512 (dB)**	**PAPR with N=1024 (dB)**
4-QAM	OFDMA	9.3	9.7	10.1	10.3	10.5
	LFDMA	0.0	6.9	6.9	6.9	6.9
	IFDMA	0.0	0.0	0.0	0.0	0.4
16-QAM	OFDMA	9.2	9.7	10.1	10.3	10.6
	LFDMA	3.3	7.7	7.7	7.7	7.8
	IFDMA	3.3	3.3	3.3	3.3	3.4
64-QAM	OFDMA	9.3	9.7	10.1	10.3	10.6
	LFDMA	4.5	7.9	7.9	7.9	7.9
	IFDMA	4.5	4.5	4.5	4.5	4.5

Table 4 gives the comparative values of PAPR for SCFDMA signals for 4 QAM, 16 QAM and 64 QAM modulation format with the number of subcarriers, N=64, 128, 256, 512 and 1024 at 10^{-2} of CCDF value. It is clearly indicated that PAPR is lowest for IFDMA and highest for OFDMA. Its value increases with an increase in the number of subcarriers and modulation format from 4 QAM to 64 QAM.

7.4 Comparative Performance of all the four PAPR Reduction Techniques

Comparative performance of all the PAPR reduction techniques discussed above is illustrated in figure 8 for 4 QAM modulation format with 1024 number of subcarriers.

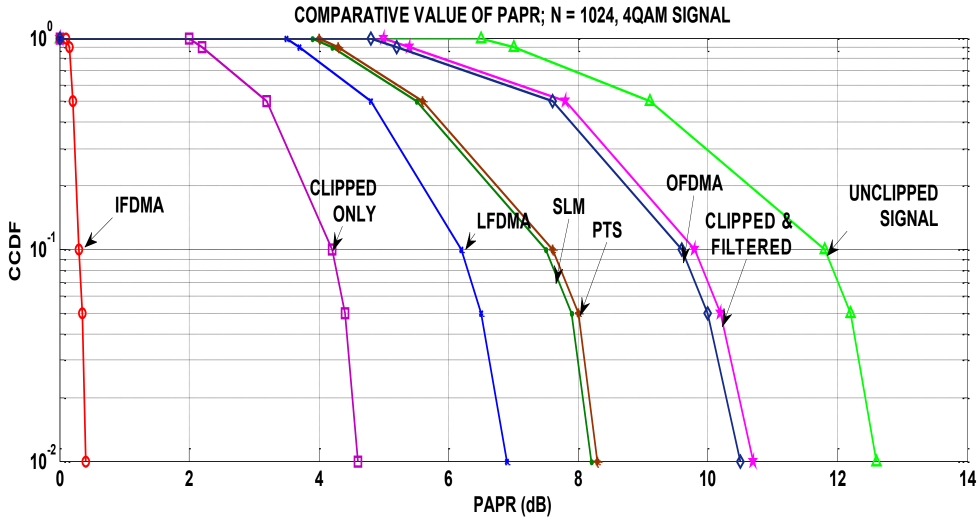

FIGURE 8 Comparative value of PAPR with different reduction techniques for N= 1024

The observed PAPR values at 10^{-2} of CCDF with IFDMA technique is 0.4 dB, clipped only at CR = 0.8 has 4.6 dB, LFDMA has 6.9 dB, SLM with number of phase vector, V = 16 has 8.2 dB, PTS with No. of sub-blocks, M = 16 has 8.3 dB, OFDMA has 10.5 dB, clipped and filtered at CR = 0.8 has 10.7 dB and unclipped signal has PAPR value of 12.6 dB. Reduction in PAPR value of 12.2, 4.4, 4.3 and 1.9 dB have been obtained with SCFDMA, SLM, PTS and CF techniques respectively. It can be observed from figure 8 that IFDMA gives the lowest PAPR of 0.4 dB obtained so far in the literature at the cost of marginal implementation complexity.

7.5 PAPR of SCFDMA Signal using Pulse Shaping Filter

A linear filtering operation known as pulse shaping, which is used to reduce the out-of-band signal energy, is performed in the transmitter through convolution between the modulated subcarriers and the filter's impulse response. Mathematical modeling and Matlab simulations of the SCFDMA signal have been carried out for 4 QAM, baseband modulation format with 1024 number of subcarriers and 2048 FFT size. 5000 number of blocks have been taken for iteration with an oversampling factor of 8 and 0.0, 0.3, 0.6 and 0.9 roll-off factors of the RC filter.

Table 5 shows the Matlab simulated result on the effect of raised cosine pulse shaping filter on 4 QAM, 16 QAM, and 64 QAM baseband modulated IFDMA and LFDMA signal with 0.0, 0.3, 0.6

and 0.9 roll- off factor. It can be observed that with 4 QAM baseband signal the value of PAPR is 2.4 dB for IFDMA and 7.7 dB for LFDMA with roll- off factor 0.9. It increases to 7.2 and 8.7 dB when the roll- off factor is reduced to 0.0 for the case of IFDMA and LFDMA respectively.

TABLE 5 Effect of Roll - off Factor on PAPR Performance

SC - FDMA	IFDMA			LFDMA		
Roll- off factor	4 QAM (dB)	16 QAM (dB)	64 QAM (dB)	4 QAM (dB)	16 QAM (dB)	64 QAM (dB)
Without Pulse Shaping	0.4	2.8	3.9	7.6	8.6	8.7
α= 0.0	7.2	8.4	8.6	8.7	9.7	9.9
α= 0.3	5.6	7.4	7.8	8.4	9.3	9.5
α= 0.6	3.8	5.9	6.7	8.0	8.9	9.2
α= 0.9	2.4	4.7	5.7	7.7	8.7	8.9

8. Achievements with Respect to Objectives

The present work gives emphasis to optimize the performance of the proposed techniques with emphasis on reduction in computational complexity and hardware utilization. In the case of linearization of power amplifiers with digital pre-distortion technique, 20 dB reduction in adjacent channel power ratio (ACPR) has been achieved without (0 dBm) reduction in amplitude while ensuring the best AM to AM and AM to PM characteristics. The result obtained with this technique has not increased computational complexity and hardware resources because of the exploitations of digital signal processing power. For the case of PAPR reduction with clipping and filtering technique, while maintaining better bit error rate (BER) performance, a significant reduction in PAPR has been achieved with minimum hardware and computational complexity. Further, the result obtained with mathematical modeling and Matlab simulations have been further verified with National Instrument's AWR commercial software and through FPGA implementation. When compared with original OFDM signal PAPR with FPGA implementation of pre-filtering and post-clipping reduces by 10.4 dB, whereas the reduction is 1.7 dB with FPGA implementation of pre-clipping and post-filtering. On the other hand, these reductions are 2.0 and 1.9 dB with AWR and Matlab software simulations.

The result obtained with the proposed SLM technique with mathematical modeling and Matlab simulations have been further verified with FPGA implementation and tested on hardware co-simulation using Xilinx Spartan 3 Protoboard XC 3S 400 development board. The PAPR of the SLM technique with Matlab simulation is 8.9 dB and it is 9.8 dB with FPGA implementation for the case of 4 QAM OFDM signal with 1024 number of subcarriers and number of phase vector, V=4. The investigations in PTS technique have resulted with the PAPR of 9.1, dB for 4 number of sub-blocks with 1024 number of subcarriers. The PAPR obtained is lowest with very low computational complexity as the number of IFFT operations has been reduced. When the performance of the SCFDMA techniques are considered, IFDMA gives the lowest PAPR of 0.4 dB at 10^{-2} of CCDF with 4 QAM baseband modulation and 1024 number of subcarriers. The observed value is lowest as compared to other PAPR reduction techniques discussed. Among many Nyquist pulses used for the distortionless transmission without the presence of intersymbol interference, raised-cosine (RC) pulse is the most popular Nyquist pulse. From the result obtained it can be observed that effect of pulse shaping is more on IFDMA than that of LFDMA. Further, the PAPR value decreases with increase in the roll - off factor. For IFDMA system the PAPR at 10^{-2} of CCDF with 1024 number of subcarriers with a change in the roll- off factor from 0.0 to 0.9, the reductions in PAPR value obtained is 4.8 dB for 4 QAM modulation format. But it is only 1.0 dB for the case of LFDMA system.

9. Conclusion

OFDM is one of the spectral efficient modulation technique for modern communication systems. It is spectrally efficient but suffers from high PAPR. Mathematical modeling and Matlab simulations have been carried out on the transceiver of multicarrier OFDM communication systems. Its PAPR have been calculated using QAM baseband modulated signal with different number of subcarriers. Nonlinearity is one of the undesirable behavior shown by power amplifiers which causes signal degradation and spectral regrowth. With high PAPR the power amplifiers are further driven into saturation region. Linearization of the class B solid state power amplifier using feedback, feed forward and pre-distortion techniques have been investigated. The feedback loop is simple to implement and 30 dB reduction in ACPR has been achieved with 5 dBm reduction in amplitude at 10 MHz bandwidth. Feed forward technique has resulted in 25 dB reduction in ACPR with 20 dBm reduction in amplitude at 1.2 GHz of 3 dB bandwidth. On the other hand, at 10 MHz of bandwidth, digital pre-distortion is the most efficient technique which has resulted in 20 dB reduction in ACPR without reduction (0 dBm) in amplitude. In order to reduce PAPR of OFDM system different reduction techniques such as clipping and filtering, SLM, PTS and SCFDMA have been analyzed. Among the techniques investigated, SCFDMA with IFDMA results with lowest PAPR of 0.4 dB. Investigation on the effect of raised cosine pulse shaping filter on the SCFDMA system reveals that effect of pulse shaping is more on IFDMA than that of LFDMA. Further, the PAPR value decreases with increase in the roll-off factor.

10. Scope of Future Work

- The problem of resolving inter-carrier interference (ICI) has not been addressed in the present work and can be undertaken as future work.
- The power amplifier linearization using other behavioral models such as Saleh model, Volterra model, Wiener model, Hammerstein model, etc. can be undertaken as future work.
- PAPR reduction techniques like coding scheme, nonlinear companding transforms, tone reservation and tone injection schemes, etc. can be taken for further study.
- Nyquist pulse shaping filters such as piece-wise linear Nyquist filter, flipped-exponential, flipped-hyperbolic secant, flipped-inverse hyperbolic secant, parametric linear combination pulses, etc. can be undertaken as future work.

11. List of all Publications Arising from the Thesis

11.1 Journal Papers

1. Yadav Shatrughna Prasad, Bera Subhash Chandra (2016), “Hardware Implementation of PAPR Reduction with Clipping and Filtering Technique for Mobile Applications”, International Journal of Engineering and Technology (IJET), Vol. 8 , No. 5, pp. 2018-2033, ISSN: 0975-4024 (online), ISSN: 2319-8613 (print), DOI : 10.21817/ijet/2016/v8i5/160805420 (SCOPUS Indexed).
2. Yadav Shatrughna Prasad, Bera Subhash Chandra (2016), “PAPR Reduction for Improved Efficiency of OFDM Modulation for Next Generation Communication Systems”, International Journal of Electrical and Computer Engineering (IJECE), Vol 6, No 5, pp. 2310-2321, ISSN: 2088-8708. DOI: 10.11591/ijece.v6i5.10878. (SCOPUS Indexed).
3. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), “Reduction of PAPR in SC-FDMA System using Pulse Shaping Technique", International Journal of Applied Engineering Research (IJAER), Volume 10, Number 23, pp. 43509-43513 ISSN 0973-4562. http://www.journalindex.net/visit.php?j=3560 (SCOPUS Indexed).
4. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), “PAPR Reduction using Selective Mapping Method for OFDM Communication Systems”, STM Journal of Communication Engineering & Systems; Volume 5, Issue 3, pp. 50-57. ISSN: 2249-8613 (Online); 2321-5151 (Print) http://stmjournals.com/index.php?journal=JoCES&page=article&op=view&path%5B%5D=6632
5. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), “Investigations on PAPR Reduction using PTS Technique for OFDM Communication Systems”, STM Journal of Communication Engineering & Systems; Volume 5, Issue 3, pp. 19-26. ISSN: 2249-8613 (Online); 2321-5151 (Print). http://stmjournals.com/index.php?journal=JoCES&page=article&op=view&path%5B%5D=6505
6. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), “OFDM Transceiver for Nonlinear Communication Systems”, International Journal of Engineering Science and Innovative Technology (IJESIT), Volume 4, Issue 1, pp. 185- 194, ISSN: 2319-5967.

http://www.ijesit.com/archive/20/volume-4issue-1january-2015.html

7. Yadav Shatrughna Prasad, Bera Subhash Chandra (2014), "PAPR Reduction using DFT-Spread Technique for Nonlinear Communication Systems", International Journal of Engineering and Innovative Technology (IJEIT) Volume 4, Issue 6, pp - 178- 184, ISSN: 2277-3754. http://www.ijeit.com/Vol%204/Issue%206/IJEIT1412201412_33.pdf
8. Yadav Shatrughna Prasad, Bera Subhash Chandra, "Power Amplifier Linearization with PAPR reduction for OFDM Communication", (Springer's) Sadhana - Academy Proceedings in Engineering Science (Under Review).
9. Yadav Shatrughna Prasad, Bera Subhash Chandra, "FPGA Implementation of SLM technique for OFDM Communication Systems", Indian Journal of Science and Technology (Under Review).

11.2 Conference Papers

1. Yadav Shatrughna Prasad, Bera Subhash Chandra (2016), "Linearity Improvement of Microwave Power Amplifiers", 13th IEEE India International Conference, 2016 (INDICON 2016), Indian Institute of Science, Bengaluru. (Paper Accepted for oral presentation).
2. Yadav Shatrughna Prasad, Bera Subhash Chandra (2016), "Hardware implementation of SLM technique for OFDM Communication Systems", IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES 2016), Delhi Technological University, New Delhi. (To be Published in IEEE Xplore) ISBN: 978-1-4673-8586-2.
3. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "Single Carrier FDMA for Wireless Communication System", 12th IEEE India International Conference, 2015 (INDICON 2015), Jamia Millia Islamia, New Delhi, pp. 1-6. (Published in IEEE Xplore, DOI:10.1109/INDICON.2015.7443655), ISBN: 978-1-4673-7399-9.
4. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "PAPR Analysis of Single Carrier FDMA System for Uplink Wireless Transmission", 10th IEEE International Conference on Information, Communications and Signal Processing (ICICS 2015), Singapore, PP. 1-5 (Published in IEEE Xplore, DOI: 10.1109/ICICS.2015.7459941), ISBN: 978-1-4673-7217-6.
5. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "PAPR Reduction using Clipping and Filtering Technique for Nonlinear Communication Systems", IEEE International Conference on Computing, Communication and Automation (ICCCA-2015), pp.1220-1225, Galgotias University, Greater Noida, Uttar Pradesh. (Published in IEEE Xplore, DOI: 10.1109/CCAA.2015.7148590), ISBN: 978-1-4799-8890-7.
6. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "Selective Mapping and Partial Transmit Sequence Techniques for PAPR Reduction in OFDM for Spectrum Efficient Multimedia Communication Systems", International Conference on Telecommunication Technology & Management (ICTTM 2015), pp.4, IIT Delhi, ISBN: 978-0-9926800-5-3.
7. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "Multicarrier OFDM Communication for High Power Amplifiers", IEEE International Conference on Computing, Communication, Control and Automation (ICCUBEA-2015), pp. 78- 82, Pune, Maharashtra (Received best paper award). (Published in IEEE Xplore, DOI: 10.1109/ICCUBEA.2015.22), ISBN: 978-1-4799-6893-0.

8. Yadav Shatrughna Prasad, Bera Subhash Chandra (2015), "PAPR Reduction techniques for OFDM Communication Systems", National Conference on Emerging Trends in Engineering, Technology & Management (NCEETM), pp.37-38, Ahmedabad, Gujarat, ISBN: 978-93-80867-75-5.
9. Yadav Shatrughna Prasad, Bera Subhash Chandra (2014), "Nonlinearity Effects of Power Amplifiers in Wireless Communication Systems", IEEE International Conference on Electronics, Communication and Computational Engineering (ICECCE 2014), pp.12-17, Hosur, Tamilnadu (Published in IEEE Xplore, DOI: 10.1109/ICECCE.2014.7086613), ISBN: 978-1-4799-5747-7.
10. Yadav Shatrughna Prasad, Bera Subhash Chandra (2014), "Nonlinearity Effect of High Power Amplifiers in Communication Systems", IEEE International Conference on Advances in Communication and Computing Technologies (ICACACT-14), pp.1-6, Mumbai, Maharashtra. (Published in IEEE Xplore, DOI: 10.1109/EIC.2015.7230741), ISBN: 978-1-4799-7319-4.

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