FPGA Implementation of PAPR Reduction Technique using Polar Clipping

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Abstract: *Modern spectral efficient signals suffer from the problem of high peak to average power ratio (PAPR). High PAPR results in in-band and out-band distortion. Various PAPR reduction techniques are available in literature. But due to its less hardware complexity, polar clipping is widely used. This paper presents the FPGA implementation of polar clipping technique.*
Key Words: *Crest Factor, FPGA, Peak to Average Power Ratio, Polar Clipping*

I.   Introduction

To date, 3G wireless networks are rolling out almost all over the world. Interest in streaming media and other high-speed wireless data applications are growing. To ensure wireless networks can meet future users demand, operators and manufacturers plan for the fourth generation (4G) mobile communication systems. These systems which are expected to have a wider bandwidth with bit rates of up to 100 Mbps able to support interactive multimedia services, global mobility, teleconferencing and wireless [1].The spectral efficient modulation techniques such as Wideband-Code Division Multiple Access system (W-CDMA) and Orthogonal Frequency Division Multiplexing (OFDM) used in 3G and 4G suffer from a high Peak-to Average Power Ratio (PAPR).This means that there is a large variation between the average signal power and the maximum signal power. The PAPR is defined as [2].

$$PAPR = \frac{\max\left(x^2\left(t\right)\right)}{mean\left(x^2\left(t\right)\right)} \qquad (1)$$

Where $x(t)$ is the amplitude of the signal. PAPR is also directly related to Crest Factor (CF) as [2]

$$CF = \sqrt{PAPR} \qquad (2)$$

To transmit the signal through the antenna, it is first converted to analog time domain by means of a D/A converter and then amplified with an RF power amplifier.
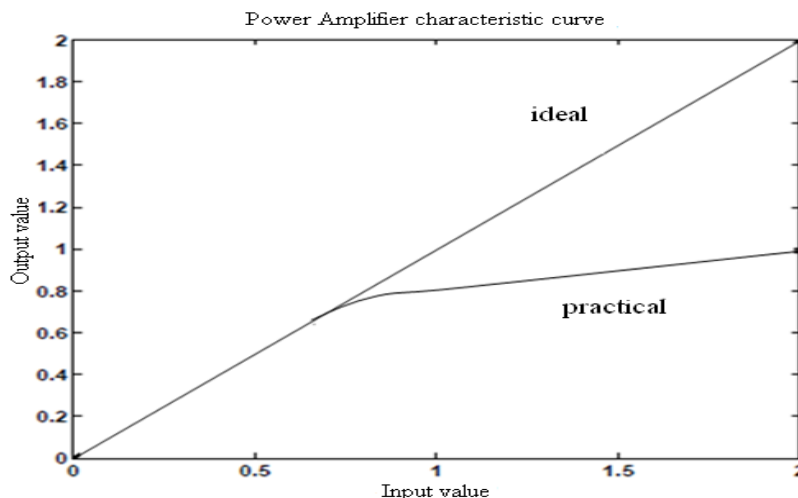

Fig 1 Non-linear amplifier characteristic curve

High PAPR causes nonlinear distortion because of the nonlinear component in the transmitter i.e. Power Amplifier (PA). Taking a deeper look into the PA, actually into its characteristic curve which has been shown in Fig 1.

It clearly shows two operating regions, the linear and the saturation ones. When the amplifier operates in the linear region, as its name indicates, signals are linearly amplified. However, when it operates in the saturation region, signals are not amplified anymore; they are flattened at the maximum output power of the amplifier.

In order to limit the Adjacent Channel Leakage Ratio (ACLR), which is defined as the ratio between the transmitted power (power inside the BW) to the power measured in the adjacent channel (power outside the BW) and in order not to distort the data, it is desirable for the PA to operate in its linear region. The better performance can be achieved for an Input Back-Off (IBO) = 0 dB. An IBO= 0 dB means that the amplifier is working at the upper limit of the linear region. The problem appears when the peaks of the signal are too large and do not fit in the linear region. In this case they are treated by the saturation region and so they are non-linearly modified, causing Inter Modulation (IMD) among subcarriers and out-of-band radiation.

To be able to hold these peaks, PA of the transmitter needs a very large dynamic range. Increasing the linear region of a PA is very expensive and it is inefficient in this case. Besides, the larger the PA's dynamic range is, the more battery it consumes and since most of the systems are power limited, an PA with a large linear region would consume most of the battery of the system, which is another reason why increasing the dynamic range of the PA is not a good solution. A high PAPR causes saturation in power amplifiers, leading IMD products among the sub carriers and disturbing out of band energy. Therefore, it is desirable to reduce the PAPR by means of PAPR reduction schemes [3].

II.   Papr Reduction Using Polar Clipping

Among all other techniques clipping has been identified as the most efficient and simplest technique. Clipping too large peaks is a simple solution to the PAPR problem. Clipping reduces large peaks but also introduces distortion in the signal. But due to low probability of occurrence of too large peaks this nonlinear distortion is generally small. The maximum peak power allowed is determined by the system specifications. A maximum peak amplitude *A* is chosen so that the signal does not exceed the limits of this region, symbols that exceed this maximum amplitude, will be clipped. The clipping function is performed in digital time domain, before the D/A conversion as shown in Figure 2.8 and the process is described by the following expression:

$$x_k^c = \begin{cases} x_k & |x_k| \le A \quad ,0 \le k \le N-1 \\ Ae^{j\phi k} & |x_k| > A \end{cases} \tag{3}$$
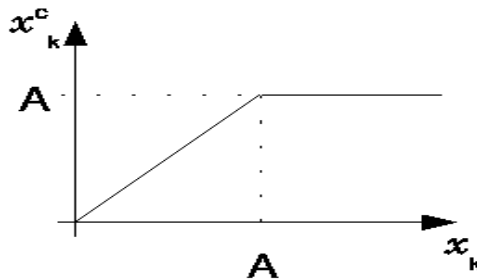

Fig 2 Clipping function

Where x_k^c is the clipped signal, x_k is the transmitted signal, is the clipping amplitude and f(x_k) is the phase of the transmitted signal x_k. The graphical expression of this function is shown in Fig 2.
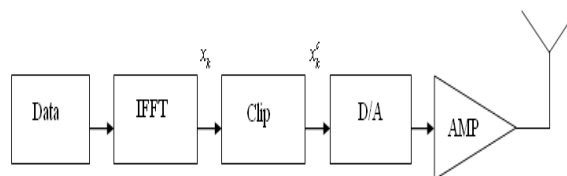

Fig 3Clipping in the transmitter

The Clipping Ratio (CR) is defined as

$$CR = \frac{A}{\sigma} \tag{4}$$

And the Clip Ratio in dB is given by

$$CR_{[dB]} = 20\log\frac{A}{\sigma} \tag{5}$$

Where σ is the root mean squared value of the unclipped OFDM signal and its mathematical expression is

$$\sigma^2 = \frac{1}{N}\sum_{k=1}^{N}x_k^2 \tag{6}$$

The simplest way to remove the peaks is by clipping the signal such that the peak amplitude becomes limited to some predefined maximum level. By defining the highest accepted peak value as the Clipping Threshold, any peak above this value can be clipped appropriately. Clipping Threshold is defined as

$$\text{Clipping Threshold} = \sqrt{10^{0.1*clip\_ratio} * avg\_power} \tag{7}$$

Clipping is a non-linear process so it introduces in-band distortion, also called clipping noise, out-of-band radiation and inter-carrier interference shown in Fig 2.9, which degrade the system performance and the spectral efficiency [4].

In-band distortion: This distortion occupies the same bandwidth as the desired signal. It can be seen as additive noise and it reduces BER performance of a communication system.

Out-of-band distortion: The inter-modulation products produce undesired frequency components at frequencies that are not occupied by signal of interest. This can cause high out-of-band radiation, which can interfere with other signals and can render a system unable to comply with spectral regulations.
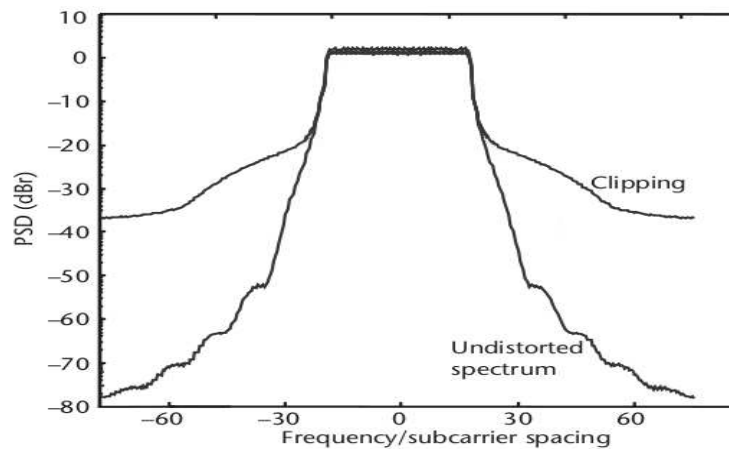

Fig 4 Out-of-band radiation due to clipping [5]

With a complex waveform, either Cartesian or polar clipping can be used. With polar clipping, the magnitude of the signal is clipped while preserving the phase. From the literature [6], [7]. it has been concluded that polar clipping gives better performance in terms of overall signal distortion i.e. lower Error Vector Magnitude (EVM),which is defined as the ratio of the RMS value of the error signal to the RMS value of the reference signal. Polar clipping quantizes the magnitude of the resultant complex signal. Filtering after clipping can reduce out-of-band radiation but may also cause some peak re-growth. To reduce overall peak re-growth, a repeated clipping and filtering operation can be used. Noise shaping is a method that limits the spectral content of the clipping noise through filtering. The noise-shaping method reduces the PAPR of a signal by subtracting a spectrally shaped clipping error, where the clipping error (or clipping noise) is the difference between the clipped signal and the original signal. The noise shaping filter can be defined to eliminate any unwanted out-of-band energy.

III. Fpga Implementation Of Papr Reduction Technique

Fig.5 and Fig.6 shows a top level and internal structure Register Transfer Level (RTL) schematic diagrams of proposed Crest Factor Reduction technique. In this design, RTL is a level of abstraction used in describing the operation of a synchronous digital circuit.
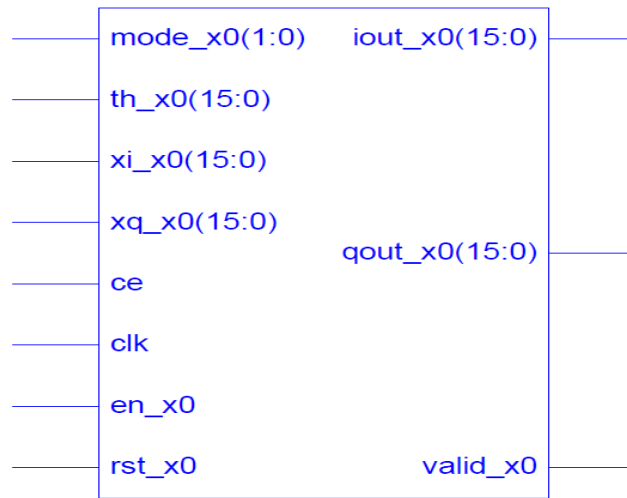

Fig 5 Top level RTL Schematic diagram of CFR Module

In RTL design, a circuit's behaviour is defined in terms of the flow of signals (or transfer of data) between hardware registers, and the logical operations performed on those signals. Register transfer level abstraction is used in Hardware Description Languages (HDLs) like Verilog and VHDL to create high-level representations of a circuit, from which lower-level representations and ultimately actual wiring can be derived.
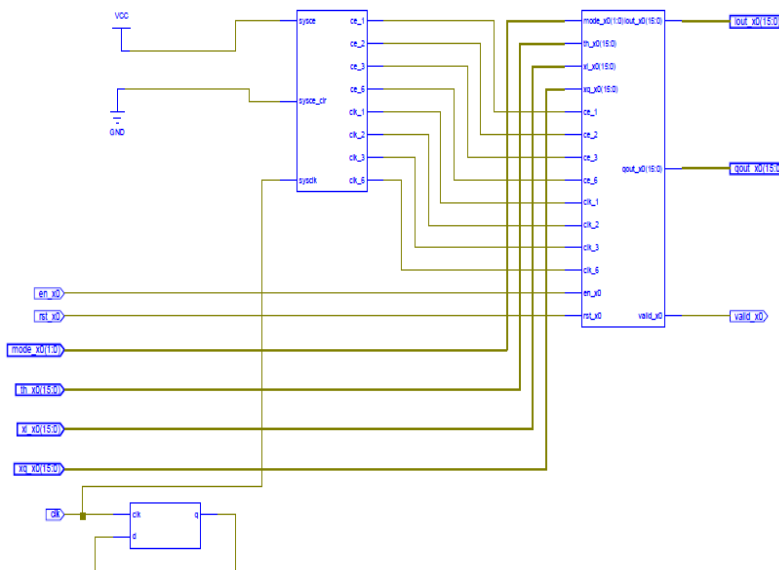

Fig. 6 Internal Structure of RTL Schematic diagram of CFR Module

Using an EDA tool for synthesis, VHDL code of the circuit can usually be directly translated to an equivalent hardware implementation file for an FPGA. The synthesis tool also performs logic optimization. Table 1 show the resources used in this model which just takes a small part in Xilinx Virtex-4 Kit for CFR and Noise Shaping Filter respectively.

Table1 Device Utilization Summary of Xilinx FPGA for Polar Clipping

Device Utilization Summary (Estimated values)			
Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slices	2431	10240	23%
Number of Slice Flip Flops	3158	20480	15%
Number of 4 input LUTs	1334	20480	6%
Number of bonded IOBs	145	320	45%
Number of GCLKs	1	32	3%
Number of DSP48s	28	128	21%

IV.   Conclusion

The implementation of the proposed clipping technique is done using Virtex-4 FPGA; it shows an efficient utilization of internal resources. The resource utilization for polar clipping and noise-shaping filter shows that almost every item is below 40%. The FPGA implementation has been done for 10 MHz bandwidth. The comparison shows that FPGA implemented model has almost same performance as given by the simulated model.

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