

Crest Factor Reduction (CFR) for OFDM-based Wireless Systems

An FPGA-based implementation of the CFR algorithm reduces processing latency while maximizing throughput required to support multiple antennas.

CFR for OFDM Systems

OFDM is widely regarded as the key air interface technology for broadband wireless systems. Due to the inherent nature of the technology, OFDM signals exhibit high PAR and CFR techniques are necessary to reduce the PAR and improve PA efficiency. Constrained clipping is a new CFR technique specifically developed for OFDM systems and exhibits good PAR reduction capability while being standards compliant.

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Orthogonal frequency division multiplexing (OFDM) is widely regarded as the key underlying air interface technology for wireless systems such as WiMAX, 3GPP long term evolution (LTE) and 3GPP2 ultra mobile broadband (UMB). Due to the inherent nature of these technologies, OFDM signals have high peak-to-average power ratio (PAR) that adversely impacts the efficiency of power amplifiers (PAs) used in wireless base stations.

Crest factor reduction (CFR) schemes help reduce PAR and have been widely implemented for code division multiple access (CDMA) systems. But CFR schemes developed primarily for CDMA signals exhibit poor performance when used in conjunction with OFDM signals, given the stringent error vector magnitude (EVM) requirements specified in a standard such as WiMAX.

This article introduces a CFR technique developed primarily for OFDM systems and describes how to efficiently implement the CFR algorithm using field programmable gate arrays (FPGAs). The resulting low latency, high performance design significantly reduces the PAR of the output signal while being standards compliant, leading to improved power amplifier efficiency and reduced cost. Although WiMAX is taken as an example, the topic should be of interest to engineers developing future OFDM based wireless system including LTE, UMB and 4G.

Algorithm Overview

The CFR algorithm described is based on a modified version of the algorithm in Constrained Clipping for Crest Factor Reduction in Multiple-user OFDM by G.T. Zhou et al. This algorithm offers these key advantages:

- Needs no receiver side modifications
- Guarantees to never-violate the spectral mask
- Always meets the error vector magnitude specification

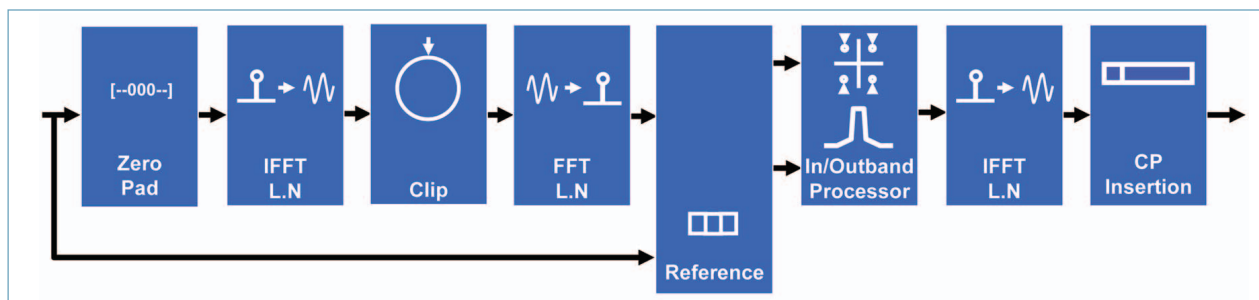


Figure 1. CFR algorithm block diagram of the necessary processing.

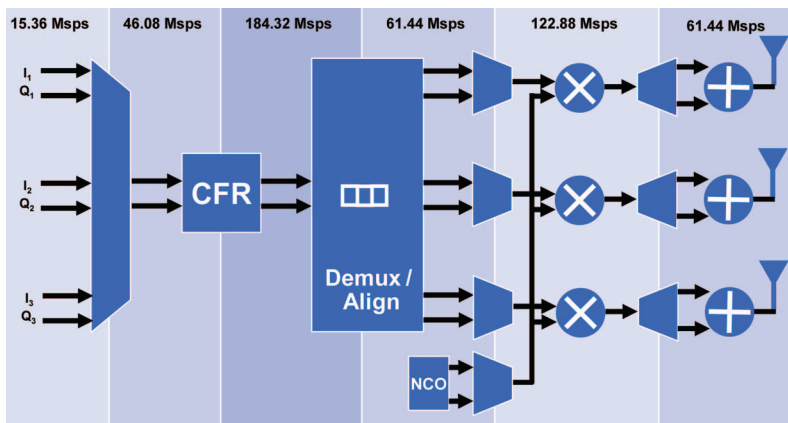


Figure 2. Example system integration of CFR in 10 MHz LTE system.

- Allows good PAR reductions.

The system accepts data at the input as OFDM(A) symbols (of length N carriers) in the frequency domain. The first process is to upconvert the data by a factor $L = 4$ using perfect frequency domain interpolation (zero padding). The technique involves performing CFR at a higher sampling frequency as there is peak growth associated with upconversion. In addition, a higher sampling frequency spreads the non-linear distortions introduced by subsequent blocks across a larger bandwidth.

An inverse Fourier transform (IFT) of length L times N is performed to generate a time domain representation of the OFDM(A) symbol. Next, a clipping operation constrains the envelope of the time domain signal to within the specified bounds. Constraint is achieved by calculating the magnitude of the complex samples. Where the samples exceed the threshold $AMAX$, the magnitude of

the samples is clipped to equal A_{MAX} while maintaining the original sample phase.

This process is known as polar clipping, which minimizes spectral regrowth better than the simpler Cartesian clipping method.

After clipping, the PAR of the signal is reduced, making it possible to transmit the new signal. However, the polar clipping results in distortion (and perhaps unrecoverable errors) in the constellation symbols. In addition, the out of band spectral components can exceed the spectral mask. Correcting distorted constellation symbols and constraining the out of band spectral energy to the spectral mask requires further processing.

To perform this additional processing, the time domain representation is converted back into the frequency domain using a forward Fourier transform (IFFT). Each sample is analyzed. If the sample is associated with a constellation symbol (that is, an inband sample), the sample is compared with the perfect reference sample and corrected if necessary. If the sample is in the outband region, its magnitude is constrained to the spectral mask.

The purpose of the inband processor is to ensure that the overall EVM does not exceed a specified limit. The EVM is defined as the square root of the mean error power divided by the square of the maximum constellation magnitude (S_{MAX}).

$$EVM = \sqrt{\frac{\left(\frac{1}{N}\right) \sum_{k=0}^{N-1} |E_k|^2}{(S_{MAX})^2}}$$

Despite the original algorithm suggesting an optimal method for achieving the target output EVM, the hardware resources and latency required to implement such a large sorting network is not feasible. Instead, a reduced complexity technique that requires minimal resources can be used. Due to the statistical distribution of the errors introduced by the polar clipping block, the output PAR of the reduced complexity technique is almost identical to the output PAR of the original algorithm.

If the calculated error (E_k) power for a sample does not exceed the specified EVM threshold, simply output the clipped sample. If the error power for a sample is greater than or equal to the square of the product of the specified EVM threshold and S_{MAX} , output the reference signal plus a small corrective signal. This corrective signal has a magnitude EVM threshold multiplied by S_{MAX} and a phase that is equal to the phase of the original error signal, namely:

$$EVM_{threshold} \times S_{MAX} \times e^{j\angle E_k}$$

Table 1. SMAX Values for WiMAX and LTE

Highest Order Modulation Scheme	S_{MAX}
QPSK	1
16QAM	$\sqrt{\frac{18}{10}}$
64QAM	$\sqrt{\frac{98}{42}}$

Table 2. Number of Antennas Supported for WiMAX

WiMAX (FFT Size)	$f_{clk} = 182.784 \text{ MHz}$	$f_{clk} = 274.176 \text{ MHz}$
128 ($f_{abb} = 1.428 \text{ Msps}$)	32	48
512 ($f_{abb} = 5.712 \text{ Msps}$)	8	12
1024 ($f_{abb} = 11.424 \text{ Msps}$)	4	6
2048 ($f_{abb} = 22.828 \text{ Msps}$)	2	3

Table 3. Number of Antennas Supported for LTE

LTE (FFT Size)	$f_{clk} = 122.88 \text{ MHz}$	$f_{clk} = 245.76 \text{ MHz}$
128 ($f_{abb} = 1.92 \text{ Msps}$)	16	32
512 ($f_{abb} = 7.68 \text{ Msps}$)	4	8
1024 ($f_{abb} = 15.36 \text{ Msps}$)	2	4
2048 ($f_{abb} = 30.72 \text{ Msps}$)	1	2

Table 4. Main CFR Parameters that determine CFR algorithm performance

Name	Description
A_{MAX}	The lower the number for A_{MAX} , the more aggressive the clipping. As the integrity of the clipping increases, the greater the outband spectral regrowth and distortion introduced to the constellation points.
EVM Threshold	If a high EVM budget is assigned to the CFR algorithm, less of the distorted constellation points need correcting after clipping. This minimizes the peak regrowth associated with the correction applied by the inband processor and in turn increases the PAR reduction capability of the algorithm.
Spectral Mask	An aggressive spectral mask results in a high level of correction required in the out of band region, resulting in greater peak regrowth.

a result, the hardware platform must have a very high throughput processing capability to perform complex functions such as CFR that would be required for each antenna separately. The latest high performance FPGAs have embedded multipliers that provide massive signal processing capability compared to traditional digital signal processors (DSPs). Altera provides a CFR reference design that demonstrates how an FPGA-based implementation reduces processing latency while maximizing throughput.

Figure 2 shows an example of the CFR design integrated into a 10 MHz LTE wireless system. The CFR module processes three baseband channels where each channel has a sampling rate of 15.36 Ms/s. The baseband channels are multiplexed together such that each frequency domain OFDM symbol is presented to the CFR module in a sequential fashion.

At the output of the CFR, the symbols are in the time domain and have been interpolated by a factor of four. The CFR uses an intermedi-

Finally, the corrected frequency domain representation of the symbol is converted back into the time domain for transmission. A cyclic prefix is applied to the stream before calling the digital pre-distortion and digital up conversion blocks.

Hardware Implementation

Existing and emerging wireless technologies such as WiMAX and LTE increasingly employ the use of multiple antennas for techniques such as MIMO. As

ate frequency of 61.44 Ms/s, which requires no further up-conversion. If an IF sampling frequency of 122.88 Ms/s is required, just one single stage of interpolation by two filters is required. As a result of the CFR module processing multiple antennas in a time-multiplexed fashion, the signals need to demultiplexed to be mixed with the appropriate carrier frequency. This demultiplexing requires external buffering to align the three symbols that are all associated with the same time instant.

The number of antennas supported by a design

depends on the baseband sampling frequency (f_{sbb}) and the clock frequency (f_{clk}). The following formula can be used to calculate the number of antennas (where $L = 4$):

$$\text{Antennas} = \frac{f_{clk}}{f_{sbb} \times L}$$

Based on this formula, Table 2 shows the number of antennas supported for WiMAX and Table 3

shows the number of antennas supported for LTE.

Performance Measurement

Generally, the EVM threshold and spectral mask are related to the specification of the system. The optimal value for A_{MAX} can be determined for a given operating mode and data dynamic range with Monte Carlo simulation.

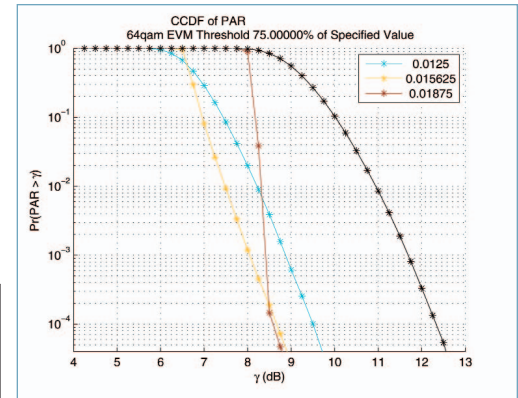


Figure 3. Example of a CCDF performance curve.

Typically the performance of a CFR algorithm is determined by examining a complementary cumulative distribution function (CCDF) curve. The CCDF of the transmit output power is the probability that the signal power is greater than a given PAR. At a given probability level (usually 10^{-4}), the PAR of an OFDM symbol that has been compressed by a CFR algorithm can be compared with the OFDM symbol that has not been compressed.

Figure 3 shows an example CCDF curve for the WiMAX 1K mode where the EVM threshold is equal to 75% of the EVM budget specified in the specification. The black curve shows that the PAR of the input OFDM signal exceeds 12.3 dB for only one out of ten thousand symbols. The other curves on the graph show the output PAR for different values of A_{MAX} . At a probability of 10^{-4} , the output PAR is approximately 3.7 dB less than the OFDM case for the optimal value of A_{MAX} (for this case).

Conclusion

Due to the inherent nature of the technology, OFDM signals exhibit high PAR and CFR techniques are necessary to reduce the PAR and improve PA efficiency. Constrained clipping is a new CFR technique specifically developed for OFDM systems and exhibits good PAR reduction capability while being standards compliant. An FPGA-based implementation of the CFR algorithm reduces processing latency while maximizing throughput required to support multiple antennas.

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