Crest Factor Reduction for OFDM-Based Wireless Systems

Introduction

Orthogonal frequency division multiplexing (OFDM) is regarded widely 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 affects the efficiency of power amplifiers (PAs) used in wireless basestations.

Crest factor reduction (CFR) schemes help reduce PAR and have been implemented widely for code division multiple access (CDMA) systems. However, 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.

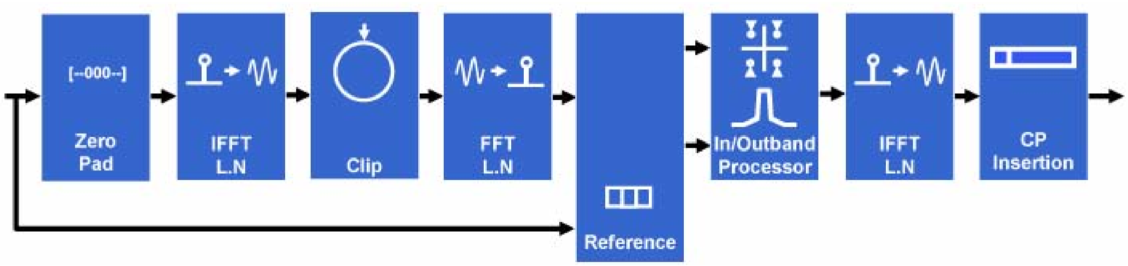
This white paper introduces a CFR algorithm developed primarily for OFDM systems, and describes how to implement it efficiently using FPGAs. The resulting low-latency, high-performance, standard-compliant design significantly reduces the PAR of the output signal, leading to improved PA efficiency and reduced cost. Although this white paper uses WiMAX as an example, the paper should interest anyone developing OFDM-based wireless systems, including LTE, UMB, and 4G.

Algorithm Overview

The CFR algorithm described is based on a modified version of the algorithm discussed in “Constrained Clipping for Crest Factor Reduction in Multiple-User OFDM.” This algorithm, shown in Figure 1, offers these key advantages:

- Needs no receiver-side modifications
- Never violates the spectral mask, guaranteed
- Always meets the EVM specification
- Allows good PAR reductions

Figure 1. CFR Algorithm Block Diagram of the Necessary Processing



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 $L \times N$ generates a time-domain representation of the OFDM(A) symbol. Next, a clipping operation constrains the envelope of the time domain signal within the specified bounds. Constraint is achieved by calculating the magnitude of the complex samples. Where the samples exceed the threshold A_{MAX}, 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.

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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 may exceed the spectral mask. Correcting the 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 to the frequency domain using a fast Fourier transform (FFT), and 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}):

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

Table 1 shows S_{MAX} values for WiMAX and LTE.

Table 1. S_{MAX} Values for WiMAX and LTE

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

Although this algorithm suggests an optimal method for achieving the target output EVM, the hardware resources and latency required to realize 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 error signal. This error signal has a magnitude EVM threshold multiplied by S_{MAX} and a phase that is equal to the phase of the original error, namely:

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

Finally, the corrected frequency domain representation of the symbol is converted back in the time domain for transmission. A cyclic prefix is applied to the stream before calling the digital predistortion and digital upconversion blocks.

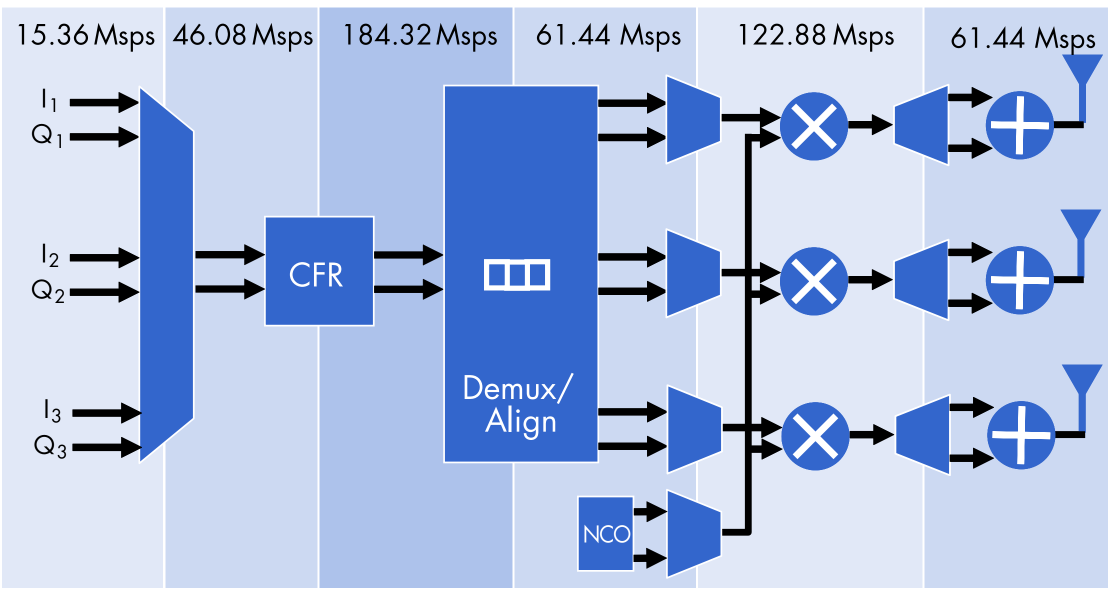
Hardware Implementation

Existing and emerging wireless technologies such as WiMAX and LTE increasingly employ the use of multiple antennas for techniques such as multiple input/multiple output (MIMO). As a result, the hardware platform must be capable of very high throughput processing to perform complex functions such as CFR required for each antenna.

The combination of Altera's high-performance, lowest power Stratix® series FPGAs and HardCopy® ASICs provides a unique opportunity to design for volume from inception, while avoiding time consuming and risky ASIC conversions. Stratix series FPGAs provide an effective mix of on-chip memory and high-performance signal processing capability to achieve the lowest cost-per-channel in next-generation LTE RF card and remote radio head (RRH) designs. With unique low power consumption features such as Programmable Power Technology and Selectable Core Voltage, Stratix series FPGAs meet these allowable power consumption levels. The high density of Stratix series FPGAs also provides unprecedented levels of integration, enabling single-chip solutions for systems with multiple antenna, with further cost, size, and power-consumption reduction via risk-free seamless migration to HardCopy ASICs.

Figure 2 shows an example of the CFR design integrated into a 1- MHz LTE wireless system. The CFR module processes three baseband channels, where each channel has a sampling rate of 15.36 Msps. The baseband channels are multiplexed together such that each frequency domain OFDM symbol is presented to the CFR module in a sequential fashion.

Figure 2. Example System Integration of CFR in 10-MHz LTE System



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 intermediate frequency of 61.44 Msps, which requires no further upconversion. If an IF sampling frequency of 122.88 Msps is required, just one single stage of interpolation by two filters is required. Because of the CFR module processing multiple antennas in a time-multiplexed fashion, the signals must demultiplex to mix with the appropriate carrier frequency. This demultiplexing requires external buffering to align the three symbols 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 $L = 4$):

$$antennas = \frac{f_{CLK}}{f_{SBB} \times L}$$

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.

Table 2. Number of Antennas Supported for WiMAX

WiMAX (FFT Size)	f_{DK} = 182.784 MHz	f_{CLK} = 274.176 MHz
128 (f_{SBB} = 1.428 Msps)	32	48
512 (f_{SBB} = 5.712 Msps)	8	12
1024 (f_{SBB} = 11.424 Msps)	4	6
2048 (f_{SBB} = 22.848 Msps)	2	3

Table 3. Number of Antennas Supported for LTE

LTE (FFT Size)	f_{CLK} = 122.88 MHz	f_{CLK} = 245.76 MHz
128 (f_{SBB} = 1.92 Msps)	16	32
512 (f_{SBB} = 7.68 Msps)	4	8
1024 (f_{SBB} = 15.36 Msps)	2	4
2048 (f_{SBB} = 30.72 Msps)	1	2

Performance Measurement

The main parameters that determine CFR algorithm performance include:

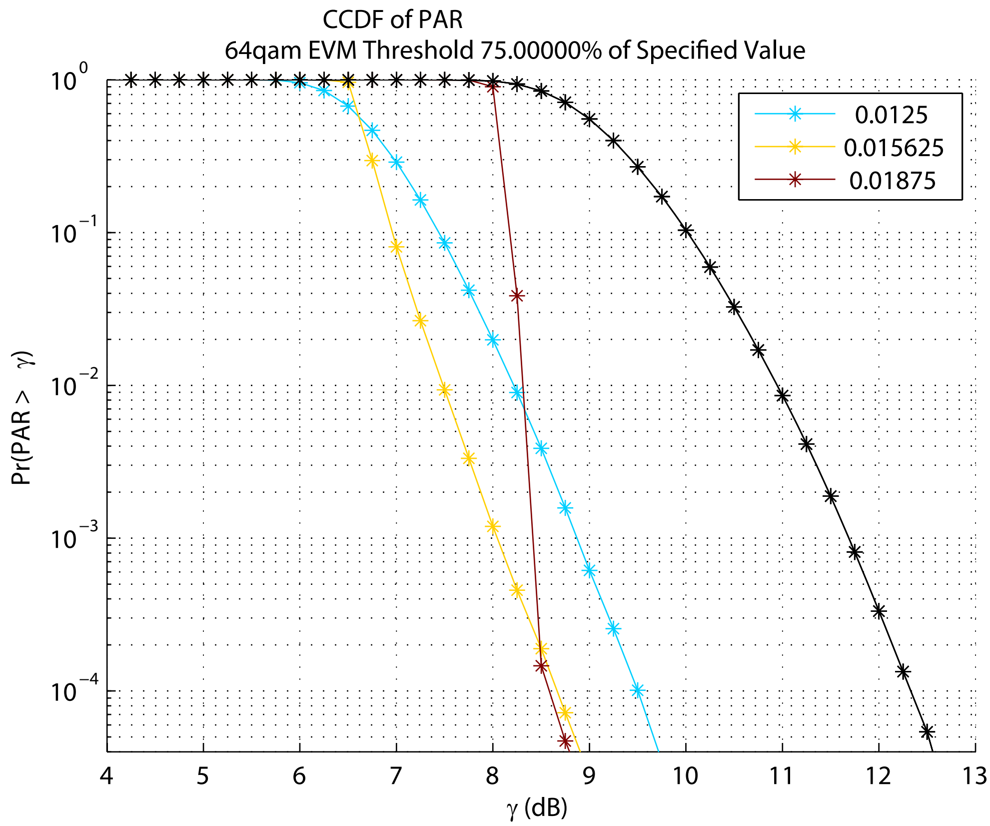
- A_{MAX}: The lower the number for A_{MAX}, the more aggressive the clipping. As the intensity of the clipping increases, the greater the outband spectral regrowth and distortion introduced to the constellation points.
- *EVM threshold:* If a high EVM budget is assigned to the CFR algorithm, less of 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.

Because 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 a Monte Carlo simulation.

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 percent 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).

Figure 3. Example CCDF Performance Curve



Conclusion

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 continuing to be standards compliant. An Altera® FPGA-based implementation of the CFR algorithm reduces processing latency while maximizing the throughput necessary to support multiple antennas.

Further Information

- C. Zhao, R. J. Baxley, G. T. Zhou, D. Boppana and J. S. Kenney, “Constrained Clipping for Crest Factor Reduction in Multiple-User OFDM,” in *Proc. IEEE Radio and Wireless Symposium*, pp. 341-344, Jan. 2007.

- High-performance, lowest power Stratix series FPGAs:
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- High density:
  www.altera.com/products/devices/stratix-fpgas/stratix-iv/overview/density/stxiv-density.html
- *AN 475: Crest Factor Reduction for OFDMA Systems*:
  www.altera.com/literature/an/an475.pdf

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