Selective Clipping and Filtering: A Low-EVM PAPR Reduction Scheme for OFDM Standards

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***Abstract*—OFDM transmit signals typically have high PAPR (Peak to Average Power Ratio). This requires high back off operation of the power amplifier in the transmitter, resulting in higher hardware costs and/or low power efficiency for the overall transceiver system. Clipping and Filtering (CF) is a popular technique for reducing PAPR, because of its low complexity and its backward compatibility with existing standards. However, clipping and filtering distorts the OFDM signal, thus increasing the Error Vector Magnitude (EVM). When applying CF, some of the clipped peaks have very little contribution to PAPR, but the resulting distortion adds up in frequency domain causing a higher overall EVM value. To avoid this effect, we propose a modified form of clipping and filtering where fewer peaks are clipped, but where those peaks are clipped at a lower value. Our method, which we call Selective Clipping and Filtering (SCF), has been tested in simulations based on IEEE802.11a waveform. Results show that SCF achieves 0.9dB lower PAPR than CF for a similar EVM value. Alternatively, when considering Frame Error Rate (FER) at the receiver, we achieve 4.6 dB PAPR reduction with no increase in FER.**

***Index Terms*—OFDM, PAPR reduction, Crest factor reduction, Wireless LAN, IEEE802.11, clipping and filtering.**

I. Introduction

OFDM (Orthogonal Frequency Division Multiplexing) is a digital transmission method where data bits are transmitted in orthogonal subcarriers. This provides important benefits such as simple and high performance equalization in case of selective fading channels, high spectral efficiency and good overall performance when combined with error correcting codes. Consequently, many industry standards choose OFDM for wireless communication and networking, e.g. LTE and LTE-A standards for cellular communication, IEEE802.11a/g/n/ac standards for wireless local area networks, IEEE802.11p standard for the emerging area of vehicular networks, and many video/audio broadcast standards such as DVB, DAB, CMMB, DMB-T, ISDB-T, etc.

Due to the many independent modulated carriers in OFDM modulation, the transmitted time-domain signal has a high peak-to-average power ratio (PAPR). A high PAPR complicates the design of transmitter circuitry: for high efficiency, the power amplifier needs to operate close to saturation region. When that is the case for a high PAPR signal, the signal will undergo nonlinear distortion due to power amplifier nonlinearity [2]. Furthermore, due to high PAPR, the dynamic range required by the D/A converter will be higher so the digital precision and thus the complexity of the D/A converter will increase. For these reasons, modifying the transmitted OFDM signal to decrease the PAPR can be advantageous for the overall system design in terms of power consumption and cost. However, since these PAPR reduction methods are essentially a modification of the OFDM waveform, applying them often result in increased error vector magnitude (EVM), increased bandwidth, decreased data throughput, increased bit error rate (BER) at the receiver, or a combination of these [1][2][3].

In industrial applications, backwards compatibility is an important aspect of PAPR reduction methods. Some standards such as DVB-T2 have defined PAPR reduction methods in the standards, where certain parts of frames are reserved for PAPR reduction usage [6][7][8][9]. This enables PAPR reduction at some reduced throughput, which is by definition taken into account in the standard. However, many communication and networking standards, e.g. the IEEE802.11 family of networking standards, do not include PAPR reduction. For these standards, the techniques must be fully backward compatible and therefore invisible to the receiver.

In this paper, we introduce a new standard compatible PAPR reduction method and show its effectiveness for IEEE802.11 wireless local area network (WLAN) standards. In section II, we define the problem and give a summary of the state of the art. In section III, we explain the requirements for the IEEE802.11 standards family. In section IV, we describe our method, selective clipping and filtering (SCF). In section V, we present our simulation results and finally in section VI we discuss the conclusions and future work.

II. Problem Definition and State of the Art

A simple block diagram of an OFDM transmitter is shown in Figure 1. For the complete baseband, the OFDM modulation is augmented by interleaving and error correction coding. We focus here on the OFDM modulation and the associated effect on the PAPR of the transmit signal.

Let $\{X_k\}_{k=0}^{N-1}$ be a block of N frequency-domain complex data symbols modulated with PSK or QAM. In OFDM, each of those N symbols modulate one of N equally spaced subcarriers $\{f_k\}_{k=0}^{N-1}$ where $f_k = k\Delta f$ and the useful symbol duration T_s is $T_s = 1/\Delta f$. The OFDM signal is thus defined as:

$$x(t) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_k e^{j2\pi kt/T_s}, \text{ for } 0 \leq t \leq T_s$$

In the discrete time, an inverse discrete Fourier transform (IDFT) generates the time domain OFDM signal efficiently:

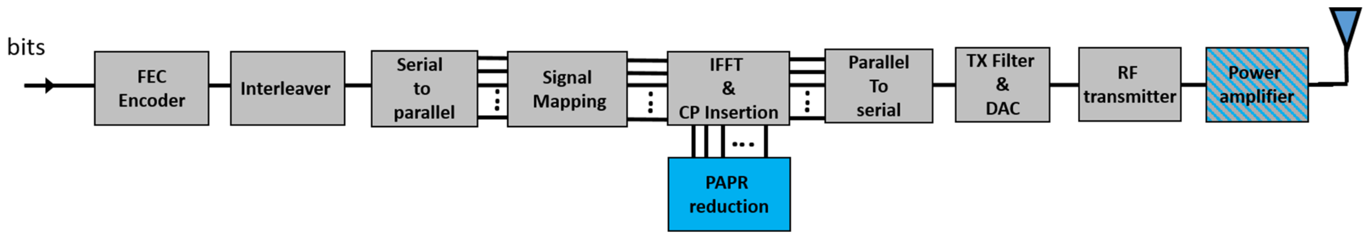

Figure 1: OFDM transmitter block diagram

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N} = IDFT\{X_k\}$$

The PAPR of this signal is defined as the ratio of the power in the largest OFDM waveform sample divided by the average power of all samples, and is often expressed in dB:

$$PAPR_{dB}(x[n]) = 10\log_{10}\frac{\max\limits_{0\le n\le N-1}|x[n]|^2}{\mathbb{E}\{|x[n]|^2\}}$$

The high PAPR value for OFDM symbols is created by the conversion from frequency to time domain. From the central limit theorem, the IDFT transformation causes the magnitudes of an OFDM symbol to have a Gaussian distribution, creating a time-domain symbol with high PAPR.

Theoretically, an OFDM generated by N-point IFFT will have a worst-case PAPR value of $10\log N$, based on the case where there is only one peak and the rest of the time-domain subcarrier values are zero. PAPR for most signal frames are, however, much lower. This can be seen in Figure 2, where the distribution of PAPR values for randomly generated frames is given for a 64-point OFDM signal modulated with QPSK (having a theoretical maximum of 18dB PAPR).

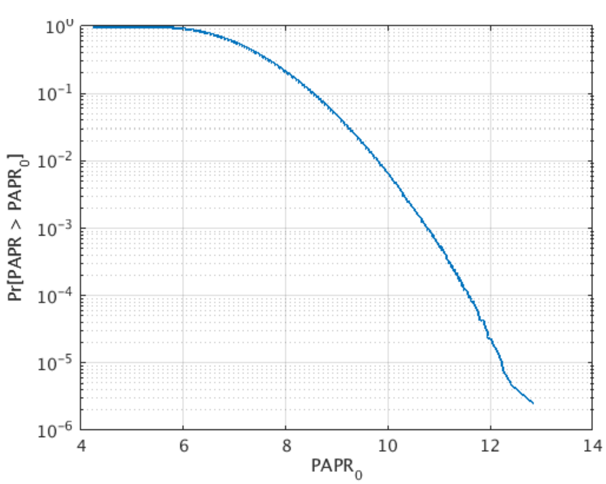

Figure 2: CCDF (Complementary Cumulative Distributive Function) of the PAPR of an OFDM signal consisting of QPSK subcarriers modulated with 64-point FFT. A point (x,y) denotes that y is the probability that PAPR value of the signal is above x (dB).

Due to the disadvantages of high PAPR for system design, past research has focused on designing/modifying OFDM transmit signals such that the PAPR value is decreased [1][2][3]. In general, techniques can be either standardized or compliant to already existing standards. In the standardized case, different techniques exist that reserve bits in a frame for PAPR reduction [6][7][8][9], modify the values of points in QAM constellation [10][11][12][13] or add coding [1][2][3]. These methods make tradeoffs between bandwidth usage, processing complexity, and PAPR level.

In practice, we often need a PAPR reduction method that can be applied to any existing standard by modifying the transmitter design only. In this case, the receiver does not know about the added functionality, so the frame structure cannot be changed. Therefore, the time-domain signal is distorted in a controlled manner in order to decrease the peaks above a certain threshold. However, the overall distortion in the signal needs to be limited because distortions to the transmitted signal can affect the EVM (error vector magnitude) at the transmitter and consequently the BER (bit error rate) at the receiver.

A. Clipping and filtering

The most used way to achieve standard-compliant PAPR reduction is the so-called clip-and-filter method [4] [5], where the highest peaks in the time-domain signal are clipped and then low-pass filtered to obtain a transmit signal with lower PAPR. The clipping method limits the peaks of the time domain signal to a predetermined threshold level, while keeping the remaining signal unchanged. If we define a clipping level C, the clipped signal will be

$$\tilde{x}[n] = \begin{cases} Ce^{j\phi_n}, & |x[n]| > C \\ x[n], & |x[n]| \le C \end{cases}$$

where $x[n] = |x[n]|e^{j\phi_n}$.

Furthermore the clip signal, representing the clipped peaks of the signal, is defined as

$$x_c[n] = x[n] - \tilde{x}[n] = \begin{cases} (|x[n]| - C)e^{j\phi_n}, & |x[n]| > C \\ 0, & |x[n]| \le C \end{cases}$$

Since the average signal power changes with the number of subcarriers N we define a metric called the clipping ratio:

$$CR = 20\log_{10}\left(\frac{C}{\sqrt{P_{avg}}}\right)$$

where P_{avg} is the average power of one OFDM symbol.

Clipping introduces distortions in the signal both in-band and out-of-band (OOB). The former is unavoidable and therefore results in an increase in EVM at transmitter and BER at the receiver. OOB distortions result in spectral spread but it can be reduced by filtering either the frequency- or time- domain. Armstrong proposed a method in which the clipped signal is transformed back to frequency domain by DFT, then the OOB components can be set to their original value and the modified signal is transformed back to the time-domain with an IDFT [4]. However, as a consequence to filtering, the signal may experience peak regrowth. To limit the regrowth, an iterative clipping and filtering (ICF) method can be used, where the process of clipping and filtering is performed a predefined number of times or several times until a certain PAPR reduction is achieved [5]. PAPR reduction performance of ICF method with 64-point FFT, QPSK modulation and $CR = 6dB$ is shown in Figure 3.

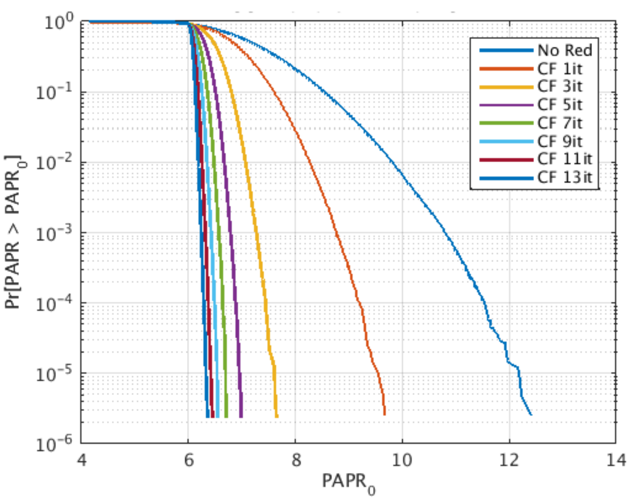

Figure 3: Iterative clipping and filtering (ICF) PAPR reduction with 64-point FFT, QPSK modulation and $CR = 6dB$. Rightmost curve shows the reference case without PAPR reduction.

We consider clipping and filtering the reference case for our method, as it is the most widely used standard compatible PAPR reduction method. In what follows, we shall show how to improve on this method in terms of added distortion for a desired PAPR reduction.

III. PAPR REDUCTION FOR IEEE802.11 STANDARDS

In this paper, we focus on IEEE802.11 wireless local area network (WLAN) standards [14] for demonstrating our method. Specifically, we show simulation results on IEEE802.11a standard, where N=64 subcarriers are modulated with BPSK, QPSK, 16- or 64-QAM and are protected using convolutional coding with various rates $R = {}^1/_2, {}^2/_3, {}^3/_4$.

A. Error Vector Magnitude (EVM)

The IEEE802.11 standards do not include a PAPR reduction strategy, although this is valuable, for both cost and power consumption reasons [15]. On the other hand, PAPR reduction also comes with disadvantages such as increase in EVM (error vector magnitude), in BER (bit error rate) or in average power and it is necessary to limit those in order to achieve a reasonable performance. The IEEE802.11 standards specify maximum EVM values for transmitters so the measured values need to be under the specified levels for certification. For this reason, we need to consider EVM in any backward compatible PAPR reduction method for IEEE802.11 standards.

The EVM represents the distance between the distorted complex point and the ideal constellation point. It is calculated as a root-mean square value over a burst of symbols:

$$EVM_{rms} = \frac{\sum_{i=1}^{N_f}\sqrt{\frac{\sum_{j=1}^{L_p}\left[\sum_{k=1}^{N}\{\left(I(i,j,k)-I_0(i,j,k)\right)^2+(Q(i,j,k)-Q_0(i,j,k)^2\}\right]}{NL_pP_o}}}{N_f}$$

where N is the number of subcarriers, L_p is the number of OFDM symbols within one frame and N_f is the number of frames. $(I_0(i,j,k), Q_0(i,j,k))$ are the real and imaginary part of the closest ideal constellation point of the i[th] frame, j[th] OFDM symbol in that frame and k[th] subcarrier inside that symbol. $(I(i,j,k), Q(i,j,k))$ is, similarly, the observed point.

B. EVM increase due to clipping and filtering

The error vector magnitude (EVM) is a good measure for the distortions introduced by clipping and filtering (CF) methods. Clipping one value in the time-domain translates to small distortions in all the frequency components in the frequency domain. Thus, when a larger number of peaks are included in $x_c[n]$, the distortions increase on every subcarriers as well. Consequently, it is better, in terms of EVM, to clip fewer peaks, thereby introducing less distortion and keeping the EVM value low.

Since the EVM is a measure of distortion, a high EVM will have a direct impact on the performance of the system and thus on the BER. Convolutional coding will allow correcting some of the errors that are introduced, but uncorrected errors can impact BER when distortion is sufficiently large. Hence, the EVM is a good source of information for the impact of the PAPR reduction method on the BER at the receiver.

IV. SELECTIVE CLIPPING AND FILTERING

We propose a modified clipping and filtering algorithm we call selective clipping and filtering (SCF). With this new method we minimize the impact on the EVM while achieving a given PAPR reduction.

As explained, to reduce the impact on the EVM it is best to clip only a few peaks. Furthermore, to decrease the PAPR, we want to decrease the peak power, without decreasing the average power significantly. In order to do that it is best to clip the highest peaks and not include any other smaller peaks. Therefore, in proposed scheme we define a higher clipping level $C > C_{CF}$ where C_{CF} is the clipping level in classical CF method.

Our method starts by clipping the time-domain signal at a clipping level C and obtain the clip signal $x_c[n]$ as defined earlier. This peak selection yields a signal that contains only the highest peaks in the signal and just subtracting this signal from the original time-domain transmit waveform would yield a waveform clipped at clipping level. However, instead of straightforward clipping, we transform this signal to frequency domain by means of a DFT, to obtain the frequency-domain signal $X_c(f)$. Next, this signal is scaled by a frequency-dependent signal $S(f)$ and the resulting signal is

$$\tilde{X}_c(f) = S(f) \times X_c(f)$$

The scaling signal $S(f)$ is a real-valued signal and takes values in a predefined range, where $S(f)$>1 so that we are clipping at least the amount dictated by clipping value C. $S(f)$ can be defined in different ways, for example a constant value for all f or random values. If certain subcarriers are desired to be preserved more, or certain subcarriers are less important, either due to known or estimated channel function or due to the mapping of data bits, those factors can be taken into account in determining $S(f)$.

The out of band (OOB) components are then filtered out to form the signal $\tilde{X}_{c,filtered}(f)$ and by IFFT the signal $\tilde{x}_{c,filtered}[n]$. Lastly, the scaled, filtered clip signal is subtracted from the original signal:

$$x_{lowPAPR}[n] = x[n] - \tilde{x}_{c,filtered}[n].$$

This process is shown in Figure 4.

In our method, only the highest peaks are clipped and by adding the scaling step, these peaks are suppressed further than the clipping level C. Consequently, the PAPR is reduced significantly while the distortions and regrowth are minimized.

In order for CF to achieve a similar PAPR reduction as SCF, the algorithm should operate at a lower clipping level which in turns results in including new peaks in $x_c[n]$. This causes the maximum peak power to become smaller but the mean power does as well. Furthermore, the new included peaks introduces more distortions and the EVM increases.

The difference between CF and SCF signals can be observed in Figure 5. The first two columns ((a), (d), (g) and (b), (e), (h)) represent the process of firstly CF and secondly SCF for the same clipping ratio $CR = 4.9dB$, while column 3 ((c), (f) and (i)) illustrates CF with a clipping ratio $CR = 1dB$ such that we achieve the same PAPR reduction as SCF with $CR = 4.9dB$. The first row ((a), (b) and (c)) is $x_c[n]$, the second ((d), (e) and (f)) is $\tilde{x}_{c,filtered}$ and the third ((g), (h) and (i)) represent $x[n]$ in blue and $x_{lowPAPR}[n]$ in green.

Comparing (a) and (b) or (c) and (e) shows that filtering indeed introduces regrowth. From (d) to (e) we observe how scaling accounts for the regrowth and allows to clip the peaks that we selected further. In addition, it can be seen in (b) and (c) that more peaks need to be included in $x_c[n]$ for CF in order to have the same PAPR reduction than with SCF, hence increasing the EVM. Finally, on the last row, it is clear that the peaks are lower for (h) than (g) and that much more distortions have been introduced in (i) than in (g).

In conclusion, in order to obtain the same PAPR reduction, the clipping level with CF needs to be consequently lower than with SCF, thus, including new peaks in $x_c[n]$ and resulting in more distortion and a larger EVM.

V. RESULTS

The proposed SCF method has been tested using a Matlab simulation chain for the IEEE802.11a standard. The chain is a simplified model of the physical layer functions assuming perfect acquisition, synchronization and channel equalization. The OFDM symbol is made of $N = 64$ subcarriers, with QPSK modulation, a code rate of $R = 3/4$, a guard interval ratio of $1/4$ and an oversampling factor of $L = 4$. We scale the $x_c[n]$ with a scaling factor higher than 1. It was found, through our simulations, that values between 1.6 and 2 gave the best results for our target case. However, the method yields good results for any value above 1.

The IEEE802.11 standard allows a maximum EVM of -13dB at the transmitter. We compare the PAPR reduction for this EVM value. The results show that CF achieves a PAPR reduction of 2.9dB whereas SCF achieves 3.8dB, hence an additional 0.9 dB of PAPR reduction. This is shown in the CCDF curves of the PAPR on Figure 6. Note that in a real system including other distortion sources such as mixer, power amplifier, etc. a lower EVM target will be required for PAPR reduction algorithm, however, similar results apply also at lower EVM targets.

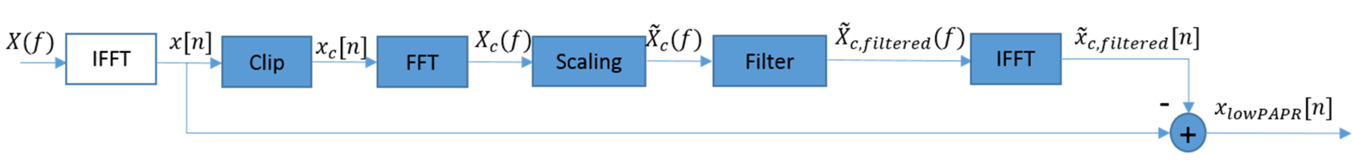

Figure 4: Block Diagram of SCF method.

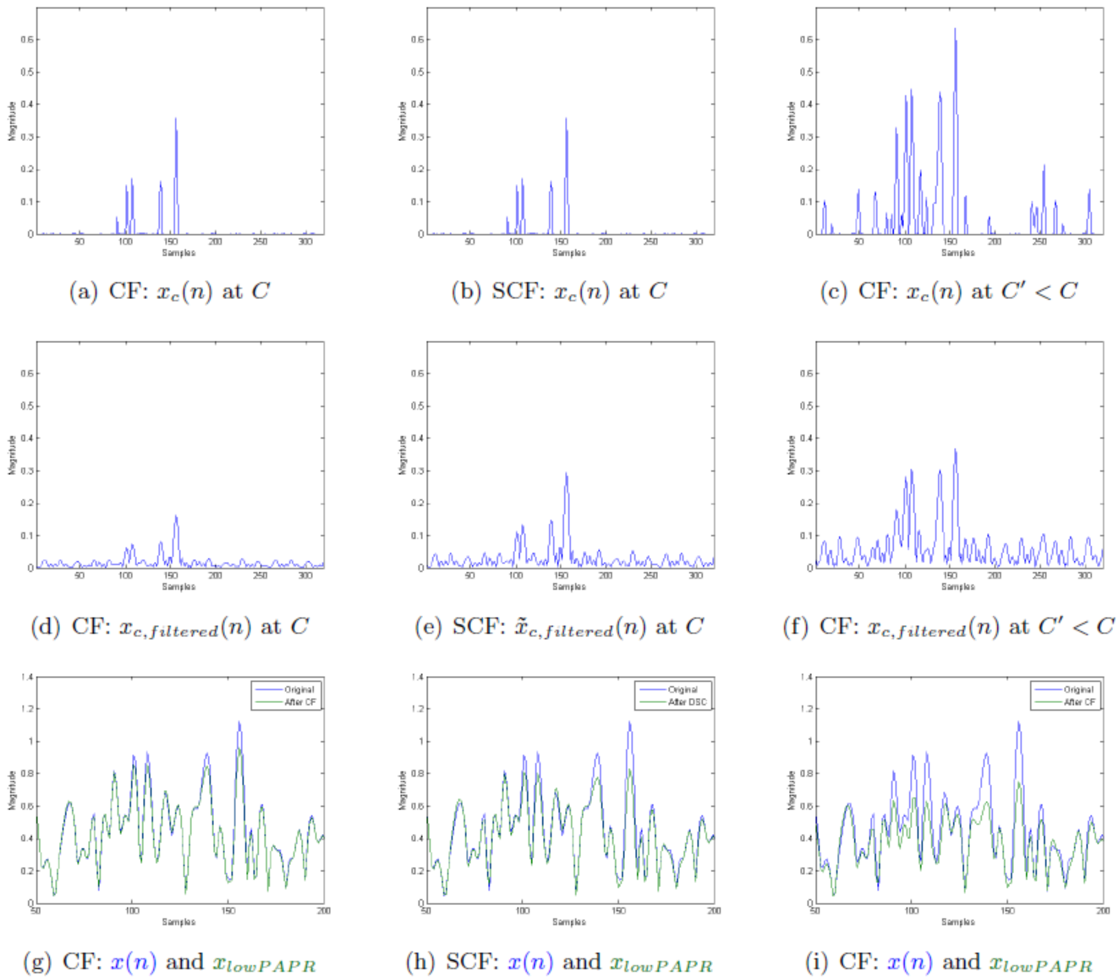

Figure 5: CF and SCF process example. The first column (a), (d) and (g) represent CF at $CR = 4.9\ dB$; The second column (b), (e) and (h) represent SCF at $CR = 4.9dB$ with random value ranging from 1.6 to 2 for $S(f)$; The last column, (c), (f) and (i) represent CF at $CR = 1dB$ and for the same PAPR reduction as (b), (e) and (h). The first row (a), (b), (c) is the clip signal $x_c[n]$, the second row (d), (e) and (f) is the clipped (scaled for (e)) and filtered signal $\tilde{x}_{c,filtered}[n]$ and the last row (g),(h) and (i) represent a magnified version of the original signal $x[n]$ in blue and the final signal $x_{lowPAPR}[n]$ in green.

Another way of evaluating our method is comparing EVM degradation caused by PAPR reduction. We found that for a similar PAPR reduction the selective clipping and filtering achieves an EVM which is 4dB lower than that of CF.

When a specific EVM requirement is not dictated by a (proprietary) standard, the degradation can also be measured by the bit or frame error rate (BER of FER) at the receiver. To check this, we simulated the transmitter and receiver including a wireless channel model. Resulting FER curves show that there is no significant difference at high clipping level. This is due to the error correction from convolutional code. However, as seen on Figure 7, at low clipping level and a similar PAPR reduction of 4.6dB there is 1.2dB SNR loss for CF, while our method SCF yields no significant SNR loss compared to the original waveform.

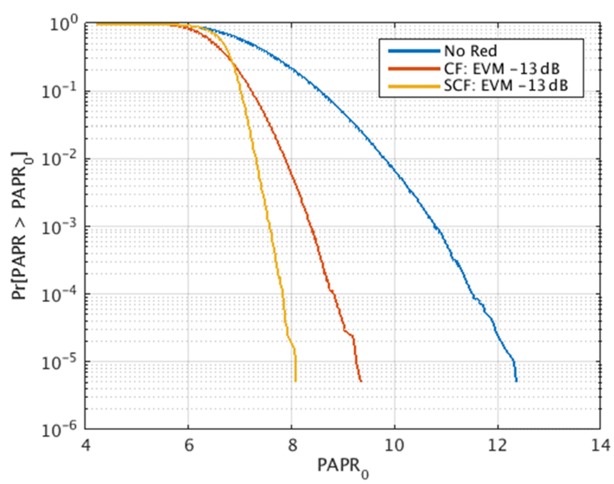

Figure 6: SCF achieves up to 3.8dB PAPR reduction at target EVM -13dB, 0.9dB lower PAPR than the CF method.

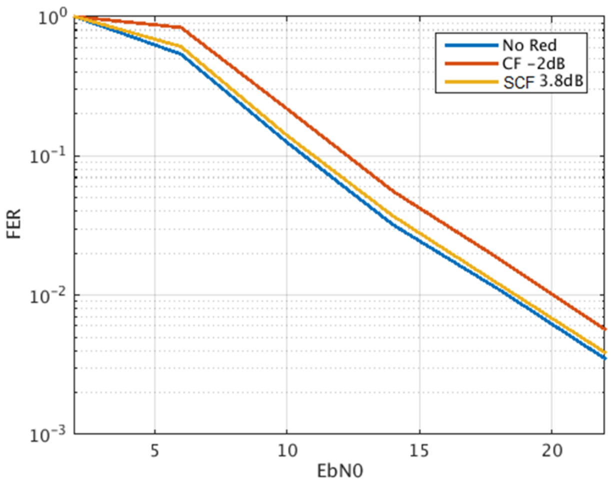

Figure 7: Comparison of FER at the receiver for 4.6dB PAPR reduction. $CR = 3.8dB$ for SCF and $CR = -2dB$ for CF

VI. Conclusions and Future Work

In this paper we have proposed an improved version of Clipping and Filtering (CF) algorithm for standard compliant reduction of the PAPR of an OFDM signal. Our algorithm, called Selective Clipping and Filtering (SCF), is generic for different OFDM waveforms, so it can be applied to diverse existing standards. The SCF method allows fewer peaks than CF to be clipped, hence decreasing the PAPR while keeping the EVM in reasonable ranges.

Through extensive simulations with the help of a Matlab chain for the IEEE802.11a standard, we compared the performance of both algorithms. We have shown that we can achieve an additional 0.9dB PAPR reduction with SCF compared to CF and still meet -13dB EVM requirement. When considering the complete transmit and receive chain, we have shown that a 4.6dB PAPR reduction can be achieved with no significant increase in FER.

Similar to the CF algorithm, SCF can be applied in an iterative manner, although this has not been covered in this paper. As future work, we plan to define a cost function reflecting distortions (e.g. EVM) and to use this function to fine tune the PAPR decrease in an iterative manner.

Our proposed SCF requires frequency domain filtering and an iterative approach is desired, thus, two FFT's per iteration are required which, depending on the hardware platform, can be costly in terms of computation. Filtering in the time domain could also be a possibility, but it would require a rather long filter. The scaling is then reduced to a constant value and cannot be adapted to different frequency requirements. Hence, developing a low complexity algorithm for SCF is an important next step.

Furthermore, if standard compliancy is not a requirement, SCF could be combined with methods such as Tone Reservation [ref 6-9] which reserves subcarriers for PAPR reduction. In this case, the scaling function would be designed accordingly, putting more or all weight on the selected subcarriers.

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