Constrained Clipping for Crest Factor Reduction in OFDM

Robert J. Baxley, Chunming Zhao, and G. Tong Zhou

***Abstract*—In this paper, we propose a constrained clipping method for reducing the peak to average power ratio (PAR) or crest factor of an orthogonal frequency division multiplexing (OFDM) signal. This is a transmitter-side processing technique that does not impose any modification at the receiver. Specifically, constrained clipping achieves PAR reduction while simultaneously satisfying spectral mask and error vector magnitude (EVM) constraints which are specified by most modern communications standards. Our proposed constrained clipping method consists of two independent processing units, one to satisfy the in-band EVM constraint and the other to satisfy the out-of-band spectral constraint. Achievable PAR reduction results vary depending on the particular standards' requirements, but we show that by using constrained clipping on a QPSK WiMax signal with 256 subcarriers, a 4.5 dB PAR reduction at the 10^{-2} complementary cumulative distribution function (CCDF) level can be obtained.**

***Index Terms*—Clipping, crest factor reduction (CFR), orthogonal frequency division multiplexing (OFDM), peak-to-average power ratio (PAR).**

I. Introduction

ORTHOGONAL frequency division multiplexing (OFDM) is a popular method in high-speed communications schemes. For example, the IEEE 802.11 wireless standard has an OFDM option and WiMax (IEEE 802.16) also uses OFDM or multiuser OFDM [1]. Additionally, OFDM has been adopted by digital audio broadcasting (DAB), digital video broadcasting (DVB) and high performance radio metropolitan area network (HIPERMAN).

Despite its popularity, OFDM has the drawback of large peak-to-average power ratios (PARs) or equivalently, crest factors. There have been a number of proposals to solve this problem, many of which require receiver side modifications that may be difficult to deploy in existing communications systems. Such approaches include selected mapping [7], [8], companding [12], [13], [24], partial transmit sequence [11], [15], [17], [19], [25], tone injection, tone reservation, coding (see [23] and references therein). Additionally, there have been several methods proposed that do not require receiver side modification such as the clipping-based methods that we review in Section II, active constellation extension (ACE) [14], [26] and an ACE-like method proposed in [9]. Crest factor reduction (CFR) techniques have also been applied to other OFDM-based systems such as coded OFDM [10], MIMO-OFDM [6], OFDM-CDMA [27], and uplink of the OFDMA systems [28].

In this paper, we will propose an OFDM CFR algorithm that does not require receiver side modification to the typical OFDM system. By not requiring any receiver side modification, it is possible, for instance, to implement our proposed CFR algorithm at the base station of an existing mobile communications network without requiring modifications to individual handsets.

Our proposed constrained clipping algorithm is meant to work in OFDM systems which require that both in-band and out-of-band distortions be kept below certain specified values. In this paper, we consider the case where the out-of-band distortion must not exceed a given spectral mask, which specifies the allowed amount of out-of-band radiation. In-band distortion is quantified with a metric called the error vector magnitude (EVM); most standards specify an EVM threshold that the transmitted signal is not to exceed. The novelty in our proposed constrained clipping algorithm is that it can guarantee that the EVM and spectral mask are met for each transmitted symbol. Constrained clipping is not an iterative technique; thus its computational complexity is relatively low.

II. Overview of Clipping Techniques

Let $\{X_k\}_{k=-N/2}^{N/2-1}$ be the frequency domain sequence of an OFDM symbol where N is the number of subcarriers. Since Nyquist rate samples might not represent the peaks of the continuous-time signal, it is desirable to show CFR performance on over-sampled discrete-time signals [4], [5], [16], [18], [20]. It is typical to use an over-sampling factor of $L \geq 4$ so that the PAR before the digital to analog (D/A) conversion can accurately describe the PAR after the D/A conversion [22]. For CFR methods with distortion, over-sampling is also necessary in order to examine the out-of-band spectral characteristics of the signal after CFR.

Let us define the out-of-band indices to be the set $\mathcal{O} : [-LN/2, -N/2-1] \cup [N/2, LN/2-1]$ and the in-band indices to be the set $\mathcal{I} : [-N/2, N/2-1]$. We will denote the zero-padded version of X_k by $\{X_k^{(L)}\}_{k=-LN/2}^{LN/2-1}$ where

$$X_k^{(L)} = \begin{cases} X_k, & k \in \mathcal{I}, \\ 0, & k \in \mathcal{O}. \end{cases} \tag{1}$$

The over-sampled discrete-time domain symbol $x_n^{(L)}$ can be calculated as follows:

$$x_n^{(L)} = \frac{1}{\sqrt{LN}} \sum_{k=-LN/2}^{LN/2-1} X_k^{(L)} e^{j\frac{2\pi kn}{LN}}, \quad 0 \leq n \leq LN-1. \tag{2}$$

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Clipping is the simplest CFR method. Polar clipping $x_n^{(L)}$ with threshold A_{max} yields

$$\bar{x}_n^{(L)} = \begin{cases} x_n^{(L)}, & \left|x_n^{(L)}\right| \leq A_{max}, \\ A_{max} e^{j\angle x_n^{(L)}}, & \left|x_n^{(L)}\right| > A_{max}. \end{cases} \quad (3)$$

The corresponding frequency domain signal is

$$\bar{X}_k^{(L)} = \frac{1}{\sqrt{LN}} \sum_{n=0}^{LN-1} \bar{x}_n^{(L)} e^{-j\frac{2\pi kn}{LN}}, \quad -\frac{LN}{2} \leq k \leq \frac{LN}{2} - 1. \quad (4)$$

The clipping operation in (3) generates distortions in $\bar{X}_k^{(L)}$ both in-band and out-of-band. In-band distortion is observed when $\bar{X}_k^{(L)} \neq X_k$ for $k \in \mathcal{I}$. Out-of-band spectral regrowth is revealed since $\bar{X}_k^{(L)} \neq 0$ for $k \in \mathcal{O}$. These are in contrast to the unclipped signal $X_k^{(L)}$ described in (1).

Denote by

$$\begin{aligned} E_k &= \bar{X}_k^{(L)} - X_k^{(L)}, \quad k \in \mathcal{I} \\ &= \bar{X}_k^{(L)} - X_k, \quad k \in \mathcal{I} \end{aligned} \quad (5)$$

the error vector at the kth subcarrier in-band. The formula for calculating the so-called EVM varies depending on the communication standard [1]–[3]. As an example, let us use the EVM metric defined in the WiMax standard,

$$EVM\left\{\bar{x}_n^{(L)}\right\} = \frac{1}{S_{max}} \sqrt{\frac{1}{N} \sum_{k\in\mathcal{I}} |E_k|^2}, \quad (6)$$

where S_{max} is the maximum amplitude of the constellation [1]. In other words, EVM is a scaled root-mean-squared (rms) distance between the desired constellation points X_k and the positions of the signal $\bar{X}_k^{(L)}$, $k \in \mathcal{I}$.

The EVM calculated according to (6) is only for one symbol period. However, in some OFDM standards the measured period may contain several OFDM symbols and the EVM is taken as the average. When N is large, the per symbol EVM will be very close to the average EVM over several symbols according to the law of large numbers.

Recall that $\bar{x}_n^{(L)}$ is the result of simple clipping. Suppose that $\widetilde{x}_n^{(L)}$ is the signal that actually gets transmitted, which may be obtained after certain operations on $\bar{x}_n^{(L)}$. The standard usually specifies a threshold Th for the EVM and a spectral mask $P(\omega)$ for the power spectral density (PSD) of the transmitted signal $\widetilde{x}_n^{(L)}$. The objective of our research can be described as follows: Obtain $\widetilde{x}_n^{(L)}$, or equivalently, $\widetilde{X}_k^{(L)}$, such that:

(i) $\mathrm{PAR}\{\widetilde{x}_n^{(L)}\} \ll \mathrm{PAR}\{x_n^{(L)}\}$;
(ii) $\mathrm{EVM}\{\widetilde{x}_n^{(L)}\} \leq Th$;
(iii) $\mathrm{PSD}\{\widetilde{x}_n^{(L)}\} \leq P(\omega)$, for $(\pi/L) < |\omega| < \pi$.

In calculating $\mathrm{EVM}\{\widetilde{x}_n^{(L)}\}$, we replace the E_k in (6) by

$$\widetilde{E}_k = \widetilde{X}_k^{(L)} - X_k, \quad k \in \mathcal{I}. \quad (7)$$

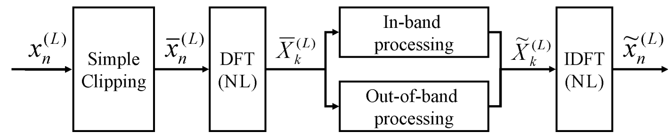

Fig. 1. Block diagram of the proposed constrained clipping method.

One well-known method to contain the out-of-band spectral regrowth (c.f. objective (iii) above) is to set $\widetilde{X}_k^{(L)} = 0, \forall k \in \mathcal{O}$; this is the so-called frequency domain filtering method proposed by J. Armstrong [4]. With the Armstrong method, nothing is done to control the in-band EVM (c.f. \ objective (ii) above). The out-of-band spectral regrowth stays far below the spectrum mask $(0 \ll P(\omega))$, which essentially wastes energy that is allotted by the standard that could be used for CFR (c.f. objective (i) above). After filtering, the PAR is always larger than that of the simple clipping method; i.e., $\mathrm{PAR}\{\widetilde{x}_k^{(L)}\} > \mathrm{PAR}\{\bar{x}_k^{(L)}\}$. Our proposed constrained clipping technique expands on Armstrong's work by incorporating the EVM constraint and by being more efficient with out-of-band energy allocation.

III. Proposed In-Band and Out-of-Band Processing Algorithm

The overall structure of the proposed constrained clipping scheme is shown in Fig. 1. Assume that the incoming signal is a standard OFDM signal before any CFR has been applied. First, the signal $x_n^{(L)}$ is simply clipped at some optimized clipping level A_{max} to create $\bar{x}_n^{(L)}$ as in (3). Next, the signal is transformed to the frequency domain with an LN-point discrete Fourier transform (DFT) which outputs the signal $\bar{X}_k^{(L)}$ as in (4). Afterwards, separate in-band and out-of-band processing modules follow to generate $\widetilde{X}_k^{(L)}$ from $\bar{X}_k^{(L)}$ to ensure that the EVM and spectral mask requirements are met. Finally, the outgoing low-PAR symbol, $\widetilde{x}_n^{(L)}$, is created with an LN-point inverse DFT operation (replace $X_k^{(L)}$ by $\widetilde{X}_k^{(L)}$ and $x_n^{(L)}$ by $\widetilde{x}_n^{(L)}$ in (2)). In the following subsections, we will detail the three components of our algorithm: in-band processing, out-of-band processing and clipping level optimization.

A. In-Band Processing Algorithm

If the clipping is so light that the EVM requirement is already met by the simple clipping signal; i.e., $EVM\{\bar{x}_n^{(L)}\} \leq Th$, then no in-band processing is necessary and we simply set $\widetilde{X}_k^{(L)} = \bar{X}_k^{(L)}, k \in \mathcal{I}$. If on the other hand, $EVM\{\bar{x}_n^{(L)}\} > Th$, our proposed in-band processing algorithm strives to obtain a $\widetilde{x}_n^{(L)}$ whose EVM is below the threshold Th and whose PAR is at a low level.

One way to ensure that the EVM is met is to set

$$\widetilde{X}_k^{(L)} = X_k + E_k \frac{Th}{EVM\left\{\bar{x}_n^{(L)}\right\}}, \quad \forall k \in \mathcal{I}, \quad (8)$$

i.e., scale down each E_k to reduce the EVM in $\widetilde{x}_n^{(L)}$. Substituting (8) into (7) and then into (6), we can show that the corresponding $\mathrm{EVM}\{\widetilde{x}_n^{(L)}\} = Th$. However, through extensive computer simulations we found that excessive peak regrowth occurs in $\widetilde{x}_n^{(L)}$

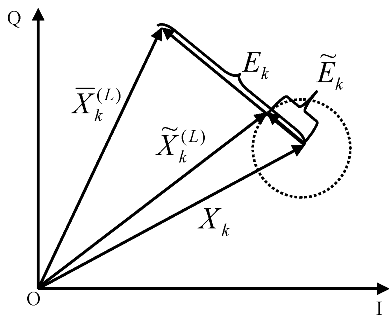

Fig. 2. Vector diagram to illustrate the in-band processing algorithm, $k \in (\mathcal{I} \setminus \mathcal{M})$.

as the result of the above scaling operation. We propose next a sorting-based method which can yield significantly better CFR performance.

In our in-band processing algorithm, we first sort $|E_k|$, calculated according to (5), in ascending order. If the rms average of the smallest $M|E_k|$ values is less than or equal to $Th \cdot S_{max}$, but the rms average of the smallest $M+1|E_k|$ values is greater than $Th \cdot S_{max}$, we record the value M and collect the subcarrier indices k that correspond to the M smallest $|E_k|$ values in a set $\mathcal{M}$. In other words, $\mathcal{M}$ is the largest set such that

$$\frac{1}{S_{max}} \sqrt{\frac{1}{M} \sum_{k \in \mathcal{M}} |E_k|^2} \leq Th. \tag{9}$$

We assign

$$\widetilde{X}_k^{(L)} = \bar{X}_k^{(L)}, \quad k \in \mathcal{M} \subseteq \mathcal{I}. \tag{10}$$

This implies that

$$\frac{1}{S_{max}} \sqrt{\frac{1}{M} \sum_{k \in \mathcal{M}} |\widetilde{E}_k|^2} \leq Th \tag{11}$$

as well.

For $k \in \mathcal{I}$ but $k \notin \mathcal{M}$; i.e., $k \in (\mathcal{I} \setminus \mathcal{M})$, the process of obtaining $\widetilde{X}_k^{(L)}$ from $\bar{X}_k^{(L)}$ is explained next. If we make

$$|\widetilde{E}_k| = Th \cdot S_{max}, \quad \forall k \in (\mathcal{I} \setminus \mathcal{M}), \tag{12}$$

we infer from (11) and (12) that

$$\begin{aligned} &EVM\left\{\widetilde{x}_n^{(L)}\right\} \\ &= \frac{1}{S_{max}} \sqrt{\frac{1}{N} \sum_{k \in \mathcal{M}} |\widetilde{E}_k|^2 + \frac{1}{N} \sum_{k \in (\mathcal{I} \setminus \mathcal{M})} |\widetilde{E}_k|^2} \\ &\leq \frac{1}{S_{max}} \sqrt{\frac{M \cdot Th^2 \cdot S_{max}^2}{N} + \frac{(N-M) \cdot Th^2 \cdot S_{max}^2}{N}} \\ &= Th. \end{aligned}$$

Thus (12) ensures that the EVM requirement will be met. This means that the vector $\widetilde{X}_k^{(L)}$ should end on the circle that is centered at X_k and that has radius $Th \cdot S_{max}$ (Fig. 2).

The next consideration is the PAR. Since $\bar{x}_n^{(L)}$ has low PAR, we should make $\widetilde{x}_n^{(L)}$ closely resemble $\bar{x}_n^{(L)}$ so the PAR of $\widetilde{x}_n^{(L)}$ is likely to be low as well. Recalling the Parseval's Theorem and (10), we infer that

$$\begin{aligned} &\sum_{n=0}^{LN-1} \left| \widetilde{x}_n^{(L)} - \bar{x}_n^{(L)} \right|^2 \\ &\quad = \sum_{k \in (\mathcal{I} \setminus \mathcal{M})} \left| \widetilde{X}_k^{(L)} - \bar{X}_k^{(L)} \right|^2 + \sum_{k \in \mathcal{O}} \left| \widetilde{X}_k^{(L)} - \bar{X}_k^{(L)} \right|^2. \end{aligned}$$

Therefore, we should make $|\widetilde{X}_k^{(L)} - \bar{X}_k^{(L)}|$ as small as possible to ensure a low PAR value in $\widetilde{x}_n^{(L)}$. Jointly considering this and (12), we conclude that $\widetilde{X}_k^{(L)}$ should lie at the intersection of the circle and the line connecting vectors X_k and $\bar{X}_k^{(L)}$. In other words,

$$\widetilde{X}_k^{(L)} = X_k + Th \cdot S_{max} e^{j\angle E_k}, \quad k \in (\mathcal{I} \setminus \mathcal{M}). \tag{13}$$

B. Out-of-Band Processing Algorithm

For the out-of-band part of the algorithm, we are concerned with meeting a spectral mask requirement. The most commonly cited method involves filtering the baseband clipped signal with a low-pass filter [5], [16], [18]. In filtering, the out-of-band $|\bar{X}_k^{(L)}|^2$ values are scaled by various constants at each frequency bin k. Since $\bar{X}_k^{(L)}$ is random, the resulting filtered spectrum is random as well so it is difficult to ensure that the spectral mask requirement is always met. Moreover, filtering causes peak regrowth in $\widetilde{x}_n^{(L)}$.

Denote by P_k the spectral mask $P(\omega)$ sampled at $\omega = 2\pi k/(LN)$. Our proposed method, called spectral clipping, entails the following:

$$\widetilde{X}_k^{(L)} = \begin{cases} \bar{X}_k^{(L)}, & \left|\bar{X}_k^{(L)}\right|^2 \leq P_k,\ k \in \mathcal{O}, \\ \sqrt{P_k} e^{j\angle \bar{X}_k^{(L)}}, & \left|\bar{X}_k^{(L)}\right|^2 > P_k,\ k \in \mathcal{O}. \end{cases} \tag{14}$$

Note that (14) is a deterministic operation that is performed on the out-of-band frequency bins of each symbol $\bar{X}_k^{(L)}$; therefore, $\mathrm{PSD}\{\widetilde{x}_n^{(L)}\} \leq P(\omega)$ can be guaranteed for each $\omega = 2\pi k/(LN)$, $k \in \mathcal{O}$.

Spectral clipping resembles the method proposed in [21]; the difference is that with spectral clipping, the out of band components that are clipped retain their pre-clipped phases. Similar to time-domain clipping, spectral clipping works by clipping in the frequency domain, the out-of-band parts of the signal that exceed the spectral mask back down to the spectral mask.

In summary, our proposed in-band and out-of-band processing algorithm transforms $\bar{X}_k^{(L)}$ into $\widetilde{X}_k^{(L)}$ according to (10), (13) and (14). Finally, $\widetilde{X}_k^{(L)}$ is transformed back to the time domain to yield the transmitted signal $\widetilde{x}_n^{(L)}$. The PAR of $\widetilde{x}_n^{(L)}$ will be larger than that of $\bar{x}_n^{(L)}$ but it will still be much lower than the PAR of the original signal $x_n^{(L)}$.

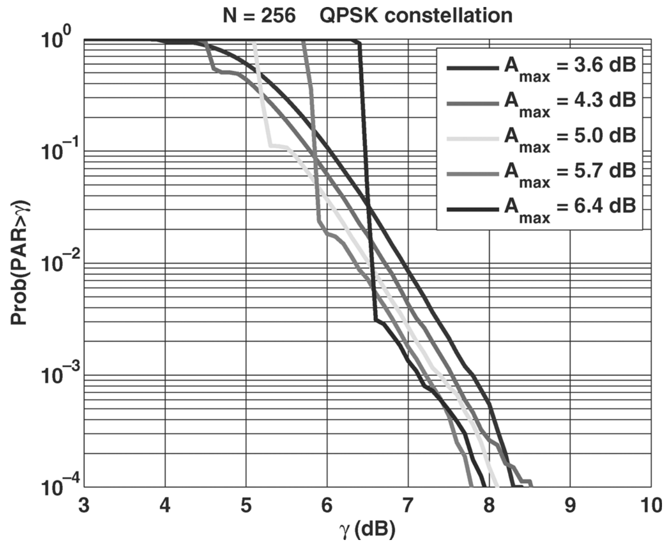

Fig. 3. CCDF plot of constrained clipping with different initial clipping levels A_{max}. $N = 256$ with a WiMax spectral mask and $\mathrm{EVM} = 6\%$.

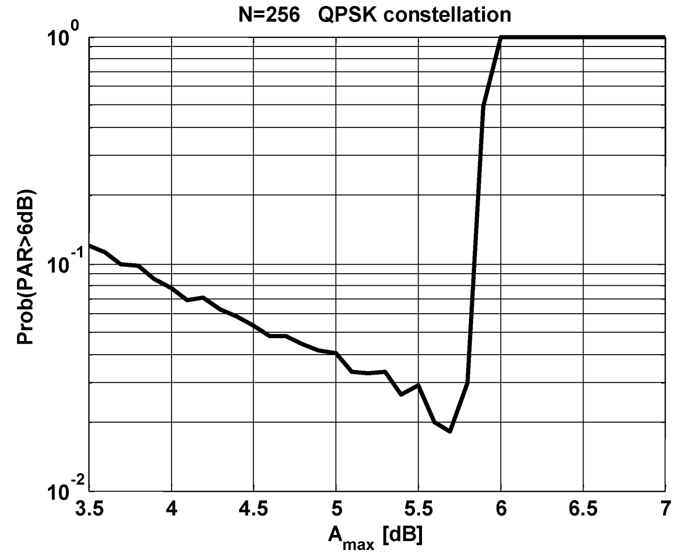

Fig. 4. Plot of the probability that an OFDM symbol will exceed 6 dB in PAR versus the initial clipping level A_{max}. $N = 256$ with a WiMax spectral mask and $\mathrm{EVM} = 6\%$.

C. Clipping Level Optimization

Based on empirical studies, we have found that the PAR of $\widetilde{x}_n^{(L)}$ has a complex relationship with the initial clipping level, A_{max}. If A_{max} is set too low then large peak regrowths occur when generating $\widetilde{x}_n^{(L)}$ from $\bar{x}_n^{(L)}$, but if A_{max} is set too high then the output signal has a larger PAR than is necessary. Stated more precisely, the complementary cumulative distribution function (CCDF) of the final PAR is convex in the clipping level A_{max}. Naturally, we want to find the A_{max} that minimizes the output PAR; but because the constrained clipping algorithm is very difficult to theoretically analyse we have to perform the minimization empirically.

To demonstrate this, we plot the CCDF curves for five different clipping levels in Fig. 3. In the plot, $N = 256$, $\mathrm{EVM} = 6\%$, the constellation is QPSK and the spectral mask is taken from the 802.16 standard [1]. Assume that the system calls for an output PAR of 6 dB. That is, any signal with a peak 6 dB above its mean will be clipped by the power amplifier, for instance. If we try to meet the output PAR of 6 dB by clipping at a low level of $A_{max} = 3.6$ dB then 10 percent of the processed symbols $\widetilde{x}_n^{(L)}$ will have a PAR above 6 dB. However, if we clip at a moderate $A_{max} = 5.7$ dB then only about two percent of the processed symbols $\widetilde{x}_n^{(L)}$ will exceed a PAR of 6 dB. Finally, if we set the clipping level to $A_{max} = 6.4$ dB, we can observe from the plot that virtually every symbol will have an output PAR above 6 dB, which is very undesirable because all symbols with PAR above 6 dB are clipped.

Fig. 4 is a plot of the probability that the final output PAR of $\widetilde{x}_n^{(L)}$ is above 6 dB for different initial clipping levels A_{max} for $x_n^{(L)}$. From Fig. 3, we determined that the optimal clipping level was 5.7 dB for this particular example. Fig. 4 confirms that the optimal clipping level is 5.7 dB, with about two percent of the output symbols having a PAR above 6 dB.

Fig. 4 demonstrates that it is possible to select the clipping level A_{max} so that the probability of the symbol PAR exceeding 6 dB is minimized. In order to create a PAR CCDF for our proposed method, it is necessary to find the optimal A_{max} for every possible output PAR. Accordingly, creating a CCDF via Monte Carlo runs will require a great deal of simulation time. However, in a practical system, the optimization only needs to be performed once, offline, for each set of system parameters (system parameters include the spectral mask, number of subcarriers, EVM threshold and the type of constellation). For each set of parameters, the offline optimization will return a clipping level A_{max}, that will be used in the constrained clipping algorithm. Hence, while the simulation computational complexity is high, the actually complexity when constrained clipping is implemented is very low.

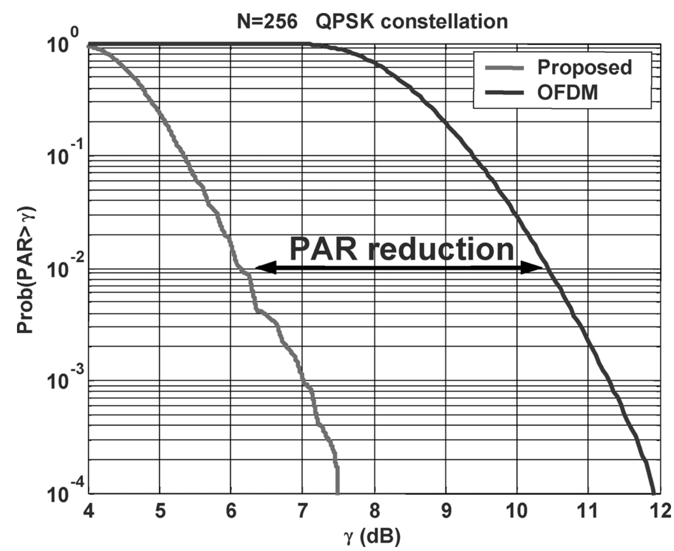

Fig. 5. CCDF plot for the proposed method after clipping level optimization. $N = 256$ with a WiMax spectral mask and $\mathrm{EVM} = 6\%$.

Fig. 5 is a plot of the CCDF of our proposed method after the initial clipping level A_{max} has been optimized for every output PAR from 4 dB to 8 dB in increments of 0.1 dB. As we can see, an impressive PAR reduction of close to 4.5 dB at

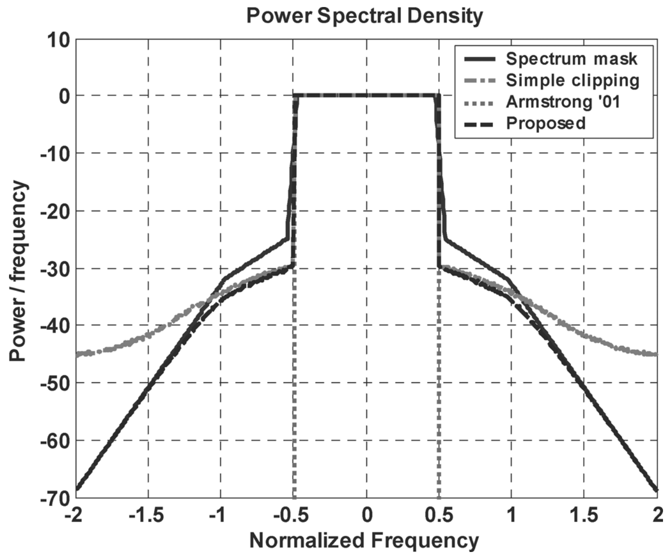

Fig. 6. Power spectral densities from various clipping methods. The spectral mask is also shown.

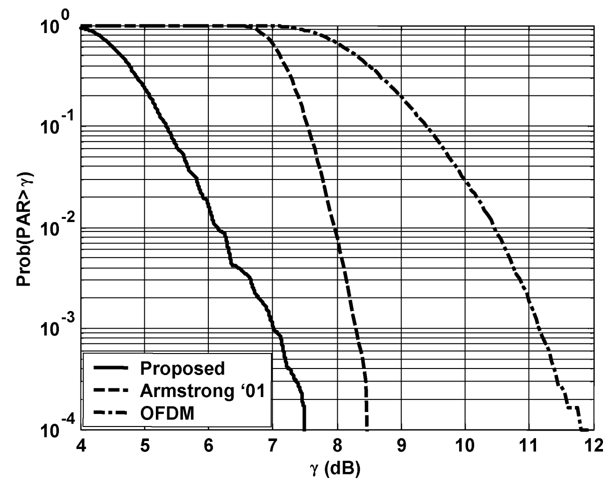

Fig. 7. CCDF comparison between Armstrong's method and the proposed algorithm.

the 10^{-2} CCDF level is possible while still meeting the spectral mask and EVM constraints. Our simulations have shown that even larger PAR reduction results can be achieved for larger N values with the same EVM and spectral constraints (plots are not shown here due to space limitations).

IV. Simulated Spectrum and EVM Characteristics

For simulation purposes we have adopted the spectral mask from the 802.16 standard [1]. Also, in all simulations we used a QPSK constellation, $\mathrm{N} = 256$, and $\mathrm{EVM} = 6\%$.

A. Spectral Characteristics

Ideally, an OFDM symbol after being processed by our algorithm will meet the spectrum mask exactly. This is in contrast to the method presented in [4], where all of the out-of-band subcarriers are set to zero. Fig. 6 is a simulated PSD plot of the proposed algorithm, Armstrong's algorithm, the spectral mask, and the PSD of the signal after simple clipping. For the plot $N = 256$, $\mathrm{EVM} = 6\%$, $A_{max} = 5.7\ \mathrm{dB}$, and the constellation is QPSK. In the plot we can see that the spectrum of the signal processed by our algorithm closely follows that of the simple clipping signal for frequencies where the latter does not exceed the spectral mask. For frequencies where the spectrum of the simple clipping signal does exceed the spectral mask, the spectrum of the signal processed by our algorithm closely follows the spectral mask. This is to be expected as we intentionally clipped the signal in the frequency domain to exactly meet the spectral mask.

B. EVM Characteristics

The EVM of the proposed algorithm is designed to never exceed the specified maximum EVM, so it is difficult to compare the proposed method with a CFR method like Armstrong's that does not take EVM into account.

In order to compare the CFR capability of Armstrong's method to our proposed algorithm, we had to accept a certain probability of EVM-threshold violation from Armstrong's method. In Fig. 7 we plot the CCDF of the proposed method along with the CCDF of Armstrong's method. For the plot we chose a clipping level of 5.7 dB for Armstrong's method. At this clipping level, symbols processed by Armstrong's method will exceed the EVM threshold about 1.5% of the time, whereas symbols processed by our method are guaranteed to never exceed the threshold. Despite this handicap, the proposed method still significantly outperforms Armstrong's method in CFR capability.

V. Conclusions

In this paper we have proposed constrained clipping, a CFR method that is designed to drastically reduce the PAR while satisfying any given EVM and spectral mask constraints. Constrained clipping accomplishes these guarantees by using separate operations for the in-band and out-of-band portions of the signal. With the in-band processing algorithm, the largest error vectors are modified to achieve the desired EVM. In the out-of band processing algorithm, spectral clipping is implemented where the out-of-band signal frequencies that contain more energy than is allowed by the mask are "clipped" down to the mask level. Through extensive simulations we have shown that even for tight EVM and spectral constraints, PAR reductions of some 4.5 dB can be achieved for an OFDM signal with 256 subcarriers. The distinct advantage of our proposed algorithm is that all processing is done at the transmitter side so no receiver side modification is necessary.

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