A Comparison of ICF and Companding for Impulsive Noise Mitigation in Powerline Communication Systems

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ABSTRACT

In future smart cities, smart grid technologies which are usually enabled by Powerline Communication (PLC) techniques are required. However, data transmission over powerline channel traverses a non-Gaussian media due to the presence of Impulsive Noise (IN) operating at the frequencies of PLC system which can be deployed using the IEEE 1901, that uses Orthogonal Frequency Division Multiplexing (OFDM). These OFDM signals have asymmetric amplitude distribution, which makes it difficult to identify and mitigate the IN presence. Converting the amplitude distribution to a uniform distribution can enhance the ability to mitigate IN when nonlinear IN mitigation techniques such as blanking is applied. In this study, we apply Iterative Clipping and Filtering (ICF) and companding schemes which are Peak-to-Average Power Ratio (PAPR) reduction techniques to enable symmetric amplitude distribution of the OFDM signals. With an optimization search for the optimal blanking amplitude for the two PAPR reduction schemes. Results show that companding scheme achieves 4dB gain in terms of received signal-to-noise ratio better than ICF after the blanking was used to remove the IN.

CCS CONCEPTS

•Security and privacy → Information flow control; •Networks → Link-layer protocols; Wired access networks;

KEYWORDS

Iterative clipping and filtering (ICF), Companding, Impulsive noise (IN), Powerline, Blanking

ACM Reference format:
Kelvin Anoh, Bamidele Adebisi, and Mohammad Hammoudeh. 2017. A Comparison of ICF and Companding for Impulsive Noise Mitigation in Powerline Communication Systems. In *Proceedings of ICFNDS '17, Cambridge, United Kingdom, July 19-20, 2017,* 6 pages.
DOI: 10.1145/3102304.3109815

1 INTRODUCTION

The powerline communication (PLC) system has become prevalent in the modern day communication technologies assisting other forms of communication standards. It finds application in smart-grids and energy Internet [23]. PLC systems such as the IEEE 1901 standard uses Orthogonal Frequency Division Multiplexing (OFDM) [9], which can be deployed using wavelet transform [5, 6] or fast Fourier transform [9]. OFDM multicarrier scheme which divides wide-bandwidths into narrow-bands such that the symbol time increased making the system robust against impulsive channels such as that of the PLC system.

In PLC systems, the periodic additive powerline noise may be categorized as being synchronous or asynchronous to the main powerline frequency [11]. In smart-grid networks in particular, PLC systems are perplexed with uncoordinated interferences emanating from neighbouring PLC devices and these may be grouped into the asynchronous impulsive noise (IN) [11, 13]. These asynchronous interferences occur randomly in time and have high amplitudes. They may be mitigated using co-existence techniques [7, 11] or by applying some memoryless nonlinearity pre-processing at the receiver [10, 21, 22]. In this study, we concentrate on the use of memoryless nonlinearity pre-processing at the receiver which can be enabled by clipping, blanking or their hybrid (blanking-clipping). While clipping induces distortion noise into the system, which further degrades the system output signal-to-noise ratio (SNR) performance, the hybrid blanking-clipping is more complex than either clipping or blanking and only performs marginally better than blanking. In this study, we explore the use of blanking scheme for mitigating IN at the receiver.

Blanking can be performed by determining the OFDM signal amplitudes that exceed a predefined amplitude threshold and setting such amplitude to null. It is possible therefore that the desired OFDM signals may have amplitudes higher than the mean amplitude; these may be erroneously blanked/nulled. This can be further explained from the fact that OFDM signal amplitude distribution is non-uniform and follow the Rayleigh distribution. Thus, if the impulsive noise abound at the frequencies of low amplitude signals (depending on their amplitudes), it follows that resulting signal plus impulsive noise amplitudes (in time) may be in the order of the rest moderately high amplitudes and may not be identified for blanking/nulling mitigation. Consequently, we suggest that the amplitude distributions of the conventional OFDM signal can be converted to assume a symmetrical distribution, in order to enhance the identification and mitigation of any occurring impulsive noise. In other words, reducing the peak-to-average power (PAPR) of OFDM systems can enhance the PLC system impulsive noise mitigation.

In the literature, OFDM system dispensing with constant envelope has been proposed to reduce the PAPR of PLC-OFDM systems and thus enhance the mitigation of IN [15] through the memoryless nonlinearity pre-processing [22]. Also, using partial transmit sequence (PTS) the OFDM signal transmission over powerline channel can enhance the reduction of IN effects [14]. In [2], μ-law companding (MC) technique was proposed to be used with the the memoryless nonlinearity pre-processing to enhance IN mitigation. Unfortunately, while PTS scheme increases system complexity companding scheme is a lightweight method, but was not considered with any other PAPR reduction scheme.

In this study, we evaluate the performance merits of iterative clipping and filtering (ICF) and companding PAPR reduction schemes for reducing the impact of impulsive noise. Through an optimization search, we determine the optimal amplitude for blanking IN presence and achieve optimal SNR. Although both schemes are lightweight on the system, driving the OFDM modulator in the order of clipping iterations expands the processing time and expends the system power [4]. In addition, our results show that ICF scheme depreciates the system performance also in terms of output SNR which leaves the performance of companding scheme better than using ICF. Unlike the study in [2], we will show that the OFDM system provides false impulsive noise presence which leads to poor system performance and thus can be enhanced by any of the PAPR reduction schemes. This is achieved by conducting an optimal search for the best amplitude at which blanking can be performed to realize maximal output SNR. The results show that the true amplitude at which OFDM signal amplitude can be blanked to remove IN is much lower than the one provided by unmodified OFDM system.

In the remaining parts of the paper, we discuss the system model in Section 2, the results and discussions in Section 3 and the conclusion follows. In Section 2, particularly in Sections 2.1 and 2.3, we present the PAPR reduction schemes and the model optimization styles for completeness. The memoryless nonlinear pre-processing is described in Section 2.2.

2 SYSTEM MODEL

We give consideration to an OFDM system that traverses a powerline channel, which is typical of the well-known IEEE 1901 standard [9]. The conventional OFDM modulates some N input data over wide-bandwidth by dividing the bandwidth into many narrowbands making it robust over the powerline fading channel. The narrow-band subcarrier frequencies translates to long symbol time that can combat the IN responses, however, this is only true provided that amplitudes of the IN is not longer than the OFDM symbol time [22]. Since the IN duration is sometimes longer than OFDM symbol time, then a front-end pre-processing is required. Meanwhile, the time domain OFDM signal can be realized from converting the frequency domain signals $X = \left[X_0, X_1, \cdots, X_{N-1}\right]$ as

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi \frac{kn}{N}} \quad \forall n = 0, 1, \cdots, N-1. \tag{1}$$

Being complex, we can separate the output time domain signal into parts such as $x_i(n)$ and $x_r(n)$ which are from $x(n) = x_r + jx_i$, $\forall n = 0, 1, \cdots, N-1$ where $j = \sqrt{-1}$. We can also estimate the amplitude of the signals as

$$|x(n)| = \sqrt{x_r^2(n) + x_i^2(n)}, \forall n = 0, 1, \cdots, N-1 \tag{2}$$

The amplitudes in (2) can further be separated into three parts, namely

$$A_{\dagger} = \frac{1}{N} \sum_{n=0}^{N-1} |x(n)| \tag{3a}$$

$$A_{min} = \arg \min_{x_{n=0,\cdots,N-1}} \{|x(n)|\} \tag{3b}$$

$$A_{max} = \arg \max_{x_{n=0,\cdots,N-1}} \{|x(n)|\} . \tag{3c}$$

Supposing that all OFDM amplitudes obey $|x(n)| \approx A_{\dagger}$, then the distribution of the amplitudes will no longer be asymmetrical but uniformly distributed. Unfortunately, the distribution of $x(n)$ follow $x_0 \sim \left\{\mu_x, \sigma_x^2\right\}$, where x_0 is the discrete envelope of $x(n)$. In other words, if the OFDM signal is sufficiently large, say $N \geq 64$, the knowledge of central theorem provides that the amplitude distribution can be characterized as identically and independent Gaussian random variable and so follows a Rayleigh distribution with probability density function (PDF) of the form

$$f_{|x|}(x; \mu_x, \sigma_x) = \frac{1}{\sqrt{2\pi\sigma_x^2}} \exp\left(-\frac{1}{2}\left(\frac{x_0 - \mu_x}{\sigma_x}\right)^2\right)$$

where $\mu_x = \mathrm{E}\{x(n)\}$, $\mathrm{E}\{\cdot\}$ is the statistical expected mean operator, and $\sigma_x^2 = \frac{1}{2}E\left\{|x(n)|^2\right\} = 1$. The closer $x_0 \rightarrow A_{\dagger}$, then better the PAPR and the easier an occurring IN can be identified and thus mitigated by the nonlinear IN mitigation schemes, such as blanking. We prefer blanking because it is easier to implement and it significantly outperforms clipping in terms of output SNR and consequently the bit error ratio (BER) [22]. Meanwhile, we shall direct our discussion towards the PAPR reduction schemes that can help in the mitigation of IN in the powerline system.

2.1 PAPR Reduction Schemes

In OFDM systems, the amplitudes that exist above the mean amplitude, $A_{\dagger}$, are the major factor for high PAPR performance of the system. This problem drives the OFDM system towards the saturation region which makes the high power amplifier consume high power. To reduce this problem, different PAPR reduction schemes have been reported in literature [16]. Some of these PAPR reduction techniques can be performed before the OFDM modulator at the transmitter of the system while others are performed after the OFDM modulator at the transmitter. Clipping and companding are both simple PAPR reduction schemes usually performed after the OFDM modulator [4, 19]. Both of them distort the amplitude of the signal towards a desired distribution although with different degrees of distortion induced into the signal. Usually, in clipping PAPR reduction style, there exists a threshold T such that all amplitudes above these threshold are clipped off as follows [20]

$$\hat{x}(n) = \begin{cases} T \times \exp(j \times \theta_n), & |x(n)| > T \\ x(n), & |x(n)| \leq T \end{cases}$$

where $\theta_n = \arg\{x(n)\}$ is the phase of $x(n)$ and $\hat{x}(n)$ is the output clipped signal. This is usually followed by frequency domain filtering [3, 24]. The frequency domain filtering leads to peak regrowth which amplifies the PAPR [24] and so must be carried on repetitively. Companding PAPR scheme is an alternative style which does not require the iterative loops involved in ICF. This was introduced in [18] using the μ-law of the form

$$\mathrm{F}(x(n)) = A\,\mathrm{sgn}(x(n))\,\frac{\ln\left(1+\mu\frac{x(n)}{A}\right)}{\ln(1+\mu)} \tag{4}$$

where A is the amplitude output determine parameter which when normalized enables $0 \leq \frac{x(n)}{A} \leq 1$. Conventionally, the power $|\mathrm{F}(x(n))|^2$ of the resulting output signal of the companding transform using the model in (4) is usually well above the power of the original OFDM signal. Thus, the output SNR is usually unduly higher then that of the original signal and exhibit better BER due to the expansion of the lower energy signal [12]. To overcome this limitation, we scale the output companded signal as follows

$$x_c(n) = \alpha \times \mathrm{F}(x(n)) \tag{5a}$$

$$\alpha = \sqrt{\frac{\mathrm{E}\left\{|x(n)|^2\right\}}{\mathrm{E}\left\{|\mathrm{F}(x(n))|^2\right\}}} \tag{5b}$$

before transmitting the signal through the powerline channel. In the next section, we shall describe the memoryless nonlinear scheme for removing the presence of IN. Meanwhile, it worthy to mention that [2] has studied the use of MC transform in mitigating IN, however the study was not compared to any other known companding transform. Other PAPR reduction schemes used are partial transmit sequence and constant envelope OFDM [14, 15] which do not consider companding or ICF techniques.

2.2 Mitigating IN using memoryless nonlinearities

Now, recall the conventional OFDM model in (1). If the IN time becomes larger than OFDM symbol time, then the memoryless nonlinearities such as blanking is required before the OFDM demodulator at the receiver [22]. In this study, we adopt the blanking nonlinearity technique that has been shown to provide better performance than clipping scheme [8, 21, 22]. In general, therefore, the received signal at the destination PLC modem can be expressed as

$$\begin{aligned} r(n) &= x_c(n) + z(n) \\ &= g(x(n)) + z_w(n) + z_i(n)\,. \end{aligned} \tag{6}$$

where $g(x(n))$ represents the PAPR reduction transform that converts the amplitude of the conventional OFDM system to a desired distribution, namely an even distribution. Notice that $z_i(n)$ can be expressed as [17]

$$z_i(n) = b(n) \cdot n_w(n),\ \forall n = 0, 1, \cdots, N-1 \tag{7}$$

where $n_w(n) \sim \mathcal{N}\left(0, \frac{N_0}{2}\Gamma\right)$, $\forall n = 0, 1, \cdots, N-1$ and $b(n)$ is the Bernoulli process that can be expressed as

$$\Pr\{b(n)\} = \begin{cases} p, & b(n) = 1 \\ 0 & b(n) = 0 \end{cases},\ \forall n = 0, 1, \cdots, N-1 \tag{8}$$

where N_0 is the single-sided power spectral density and Γ is the mean power ratio of the IN and additive white Gaussian noise (AWGN) components. The powerline channel has both IN and Gaussian noise. These are respectively characterized by $z_w \sim \mathcal{N}(0, \sigma_w^2)$ and $z_i \sim \mathcal{N}(0, \sigma_i^2)$ with σ_w^2 and σ_i^2 as AWGN and IN noise variances respectively. The PDF of the powerline system can be expressed as [10]

$$f_z(z; \mu_z, \sigma_z) = \sum_{l=\{0,1\}} p_l\,\mathcal{N}\left(z_0(n); 0, \sigma_{z,l}^2\right)\ \forall n = 0, 1, \cdots, N-1 \tag{9}$$

where $\mathcal{N}\left(z_0; 0, \sigma_{z,l}^2\right) = \frac{1}{\sigma_{z,l}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{z_0 - \mu_z}{\sigma_{z,l}}\right)^2\right)$ is the Gaussian PDF of $z(n)$ with z_0 discrete envelope, zero-mean ($\mu_z = 0$), variance $\sigma_{z,l}^2$, and p_l is the l^{th} mixing probability content. For the amplitudes above the threshold, we perform blanking as follows

$$y(n) = \begin{cases} r(n) & |r(n)| \leq T \\ 0 & |r(n)| > T \end{cases} \tag{10}$$

where T is the blanking threshold. From (10), it is clear that the blanking memoryless nonlinear IN mitigation scheme is a nonlinear process. It impacts the amplitude of the OFDM system without phase part.

2.3 Optimization of output SNR and optimal blanking threshold

Traditionally, nonlinear process of signal processing such as the blanking/nulling that mitigates IN presence can be expanded in terms of Bussang theory as $y = K_0 r(n) + D$, where D is the distortion noise. It follows that the output SNR can be found as [22]

$$\begin{aligned} \gamma_{out}^{blank} &= 10\log_{10} \frac{\mathrm{E}\left\{|K_0 g(x(n)|^2\right\}}{\mathrm{E}\left\{|y(n) - K_0 g(x(n)|^2\right\}} && \text{(11a)} \\ &= 10\log_{10} \left(\left(\frac{E_{out}}{2K_0^2} - 1\right)^{-1}\right) && \text{(11b)} \end{aligned}$$

where $g(x(n)$ represents the conversion transform that converts the PDF distribution of the conventional OFDM to a desired distribution, $E_{out} = \mathrm{E}\left\{|y(n)|^2\right\}$ is the output power of the nonlinearly mitigated signal and K_0 is a scaling parameter that compensates the nonlinear distortion. We can maximize the performance of our system through some threshold search for the best amplitude at which blanking/nulling can be performed to achieve maximum received SNR as [1, 2]

$$T_{opt}^{blank} = \arg\max_{0 \leq T \leq A_{max}} \gamma_{out}^{blank}(T, p, \mathrm{SINR}, \mathrm{SNR}) \tag{12a}$$

subject to

$$A_{max} = \arg\max_{0 \leq n \leq N-1} (|x(n)|) \tag{12b}$$

where SINR is the signal-to-interference plus noise ratio which can be found as $\mathrm{SINR} = \sigma_{x_t}^2/\sigma_i^2$, where $\sigma_{x_t}^2$ is transformed signal power. We include the PAPR reduction model in (12) to find the optimal

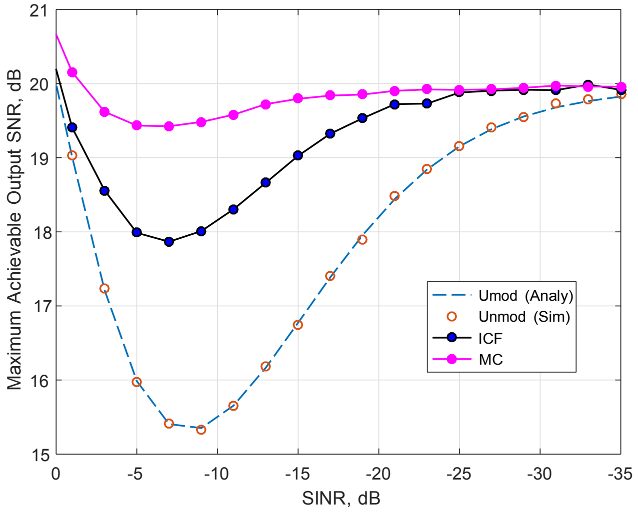

Figure 1: Optimization of the output SNR of the system model under consideration, SNR = 50dB, $p = 0.01$, $N = 4096$, $\mu = 256$

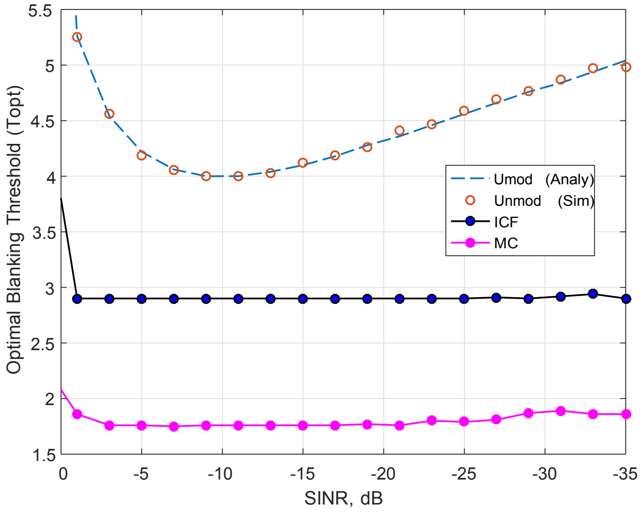

Figure 2: Optimization of the maximal blanking of the system model under consideration, SNR = 50dB, $p = 0.01$, $N = 4096$, $\mu = 256$

blanking threshold which informs the optimal received SNR as

$$T_{opt}^{blank} = \underset{0 \leq T \leq A_{max}}{\arg\max}\, \gamma_{out}^{blank}\left(T, g_m(x(n)), p, \text{SINR}, \text{SNR}\right) \tag{13a}$$

subject to

$$A_{max} = \arg \max_{0 \leq n \leq N-1} \left(|x(n)|\right) \; \forall m = 1, 2 \tag{13b}$$

where $g_m(x(n)) \; \forall m = 1, 2$ represents the PAPR reduction model. From (13), our objective variable is $g_m(x(n))$ which are performed in turns to estimate the respective optimal blanking threshold.

3 RESULTS AND DISCUSSION

The system model is evaluated using simulation performed in MATLAB. It involves transmitting PAPR reduced OFDM system over an IN channel from the foregoing discussion. For reference purposes, we also show analytical model results including the simulation of an unmodified PLC-OFDM system to measure how much improvement has been achieved. Thus, some $N = 4096$ random data are generated and modulated using 16-QAM modulator before passing it through an IFFT block to generate the time domain sequence in (1). The output of the IFFT transform generates the time domain signal which we normalized to ensure that $\sigma_x^2 = \frac{1}{2}\mathrm{E}\left\{|x(n)|\right\} = 1$ $\forall n = 0, 1, \cdots, N-1$.

To enable that the amplitudes of the OFDM signal exists around the mean $A_{\dagger}$, we iteratively clip and filter the OFDM signal twice using a clipping ratio of 6 dB, then pass the signal through the channel. The channel over which the signal is passed consists of AWGN with distribution $z_w \sim \mathcal{N}\left(0, \sigma_w^2\right)$ and has additional noise characteristics of the IN occurring randomly in time with $z_i \sim \mathcal{N}\left(0, \sigma_i^2\right)$ distribution. Since there are only two components (AWGN and IN), the noise PDF model in (9) assumes the probabilities of $p_0 = 1 - p$ and $p_1 = p$ for the AWGN and IN respectively, where p is the probability of IN occurrence in the powerline channel. Using the nonlinear pre-processing model in (10), the IN mitigation is performed to remove IN from the system. Then, the output result is used to compute the SNR required in (13) to estimate the optimal blanking threshold and the corresponding SNR when the PAPR reduction scheme is applied. Afterwards, we repeated these routine for companding PAPR reduction scheme and present our results in Figs. 1 - 4.

In Fig. 1, we compare the output results of the optimization search for the best SNR given the two PAPR schemes under consideration. With ICF, the OFDM signal is iteratively clipped and filtered twice; this is not required in MC. We observe that both clipping and companding significantly increase the output SNR by a minimum of 2.5 dB. However, the companding model clearly outperforms the ICF scheme by a further 1.5 dB. This can be explained on the premise of increased energy in the lower amplitude signal when companding is applied coupled with minimal amplitude distortion compared to ICF. For the ICF, the amplitude distortion coupled with the distortion noise lowers the output power compared to companding scheme. Based on the optimal output SNR, we find the optimal blanking amplitude for which the optimal SNR is maximized is reduced compared to the conventional OFDM performance as shown in Fig. 2. It follows that the companding and optimization schemes correspondingly help to correctly determine the the optimal blanking amplitude for which the signal must blanked to achieve optimal SNR performance. Observe also that the companding scheme find much lower amplitude in Fig. 2 than the ICF due to their corresponding abilities to convert the PDF of the conventional OFDM from asymmetrical to a uniform distribution.

We extended our investigation to a design which involves increased occurrence of the IN by 10%. For example, by varying the previous probability of IN occurrence from $p = 0.01$ to 0.1 we report

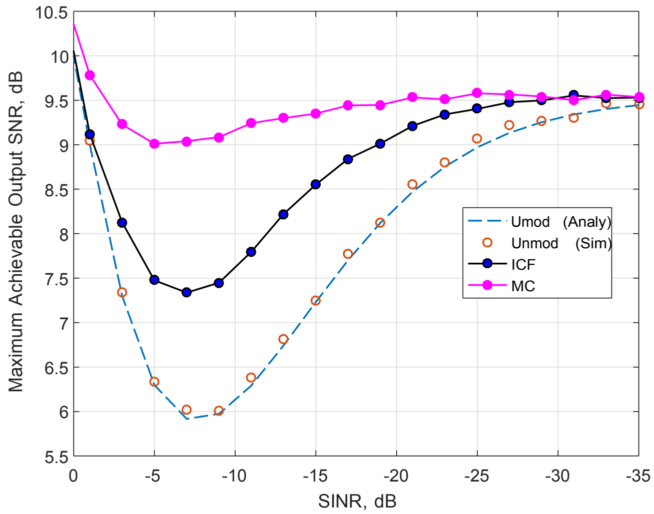

Figure 3: Optimization of the output SNR of the system model under consideration, SNR = 50dB, $p = 0.1$**,** $N = 4096, \mu = 256$

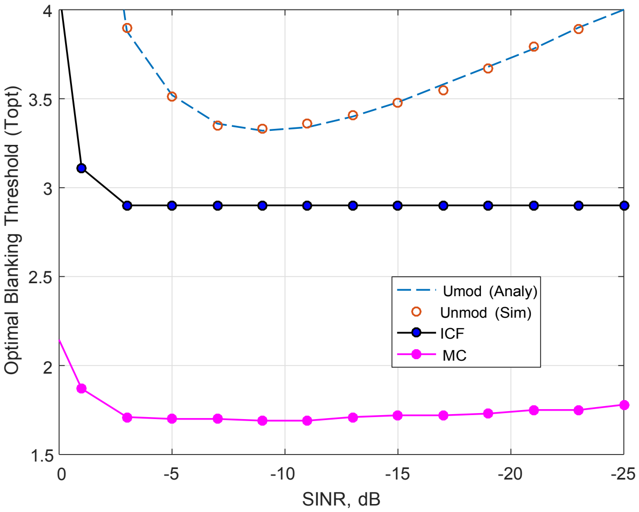

Figure 4: Optimization of the maximal blanking of the system model under consideration, SNR = 50dB, $p = 0.1$**,** $N = 4096, \mu = 256$

in Figs. 3 and 4 the optimal SNR and blanking threshold, respectively. We find that the companding transform transforms the PDF closer to normal distribution availing better better IN removal than the ICF scheme. While both ICF and comapnding transform PAPR reduction techniques outperform the conventional OFDM system whose amplitude distribution is unmodified, it can be observed that increasing the probability of IN occurrence reduces the output SNR as the IN is increased in such situation, thus increasing the overall noise power and reducing the output SNR. This is worst in ICF dues to left-over noise from amplitude clipping.

Lastly, we observe the behavior of the blanking threshold as the IN probability is increased. For example, we have found in Fig. 3 that increasing the percentage of impulsive noise reduces the output SNR, we find also that the optimal blanking threshold becomes lower than in Fig. 2 where $p = 0.01$ than in Fig. 4 where $p = 0.1$ due to the generally reduced signal power. Besides, all the PDF transforming models find lower amplitudes in general that dispense optimal output SNR which can enhance the system BER performance than when OFDM system is operated without modifying the amplitude distribution. However, the companding PAPR reduction scheme finds better threshold in all.It follows therefore from the foregoing discussion that the optimal blanking threshold gives information into the SNR performance and vice versa. In addition, due to the fact that companding transform expands the energy of the low amplitude signals towards the desired symmetrical distribution, it dissipates better/high output power that makes it more stable for mitigating the IN presence in PLC systems than clipping PAPR reduction model.

4 CONCLUSION

In this study, we have presented the idea of reducing the impact of impulsive noise in powerline system to enhance the system performance. For example, the conventional OFDM system has amplitude distribution that are not uniform. The amplitudes above the mean amplitude signals envelope the detection and mitigation of impulsive noise in the system. We proposed using PAPR reduction scheme to modify the PDF distribution of the conventional OFDM system which can enhance the PDF distribution of OFDM system amplitudes towards a uniform distribution. Thus, from the two post-modulated PAPR reduction schemes used namely iterative clipping and filtering and companding, we find that the companding scheme achieves better output SNR. This result is from the fact the companding model achieves a better PDF distribution than the iterative clipping and filtering scheme. By optimizing the received SNR, the two schemes show that the correct blanking amplitude is much lower than the one presented by the conventional OFDM system whose amplitude distribution has not been modified.

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