Preprocessing Based Impulsive Noise Reduction for Power-Line Communications

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***Abstract*—Signal blanking is a common technique for mitigating impulsive noise (IN) in power-line communications. When signal samples unaffected by IN are erroneously blanked, part of the useful signal will be lost and performance will degrade. In this paper, we show that the performance of this technique is sensitive not only to the blanking threshold but also to the signal's peak-to-average power ratio (PAPR). We thus propose to enhance the capability of the conventional blanking technique by preprocessing the signal at the transmitter. With this in mind, a closed-form analytical expression for the probability of blanking error is then derived and the problem of blanking threshold optimization is addressed. The results reveal that the proposed is able to minimize the probability of blanking error dramatically and can provide up to 3.5dB SNR improvement relative to the conventional technique. Furthermore, it will be shown that if the transmitted signal's PAPR is maintained below a certain threshold then not only a considerable SNR enhancement can be achieved but also it is possible to completely alleviate the need for any prior knowledge about the IN characteristics.**

***Index Terms*—Blanking, impulsive noise, peak-to-average power ratio (PAPR), power-line communications (PLC), probability of blanking error, selective mapping (SLM), signal-to-noise ratio (SNR).**

I. Introduction

POWER-LINE communication (PLC) is attractive for the realization of smart grid since it utilizes an existing infrastructure of wiring networks which can be easily accessed through electricity outlets in the home. This technology becomes even more appealing in harsh wireless environments where radio spectrum is scarce or/and propagation loss is high such as in underground structures and buildings with metal walls [1]. Power-line networks however are not well suited for communication signals [2]. Thus in order to improve the reliability of PLC, it is essential to overcome a number of inherent challenges such as the varying impedance of the wiring, high levels of frequency-dependent attenuation [3], [4] and the noise. Noise over power-lines is divided into two categories colored background noise and impulsive noise (IN) [5]–[7]. The latter, however, is the most dominant factor that degrades the PLC signals and its power spectral density (PSD) always exceeds the PSD of the background noise by at least 10–15dB and occasionally may reach as much as 50dB [8]. To analyze and evaluate the system performance in the presence of IN, Middleton class-A noise model, [5], [9], has been widely accepted and therefore it will be adopted in this paper.

A number of methods with different degrees of complexity have been reported in the literature to improve the performance of orthogonal frequency division multiplexing (OFDM) based receivers in IN channels [10], [11]. The simplest of such methods is to precede the conventional OFDM demodulator with a nonlinear preprocessor such as a blanking device to zero the received signal when it exceeds a certain threshold [12], [13]. This method is widely used in practice because of its simplicity and ease of implementation [14]–[16]. Theoretical performance analysis to find closed-form expressions for the signal-to-noise ratio (SNR) at the output of the blanker and optimization of the blanking threshold first appeared in [17], [18]. The main disadvantage of this method, however, is the fact that in order to optimally suppress IN, the noise characteristics must be accurately known apriori in the form of signal-to-impulsive noise ratio (SINR) and the IN probability of occurrence. In this paper we refer to this method as the unmodified method. Imperfect recognition of the IN signal may lead to nulling uncorrupted signal samples leading to blanking errors and hence performance deterioration [19].

To date, all studies on IN mitigation are based on entirely countering IN at the receiver side. In this paper, it is proposed that the OFDM signal is preprocessed at the transmitter in such a way to minimize the probability of blanking error at the receiver. This could be done simply by applying a peak-to-average power ratio (PAPR) reduction technique such as amplitude clipping [20], tone reservation (TR) [21], coding [22] and selective mapping (SLM) [23]. In this paper, we exploit the SLM technique as it is well known for its robustness, and combine it with blanking at the receiver to reduce IN. Therefore, the contribution of this paper is twofold. First we derive a closed-form expression for the probability of blanking error and demonstrate how it can be reduced considerably. For more quantitative characterization, the corresponding output SNR is also considered. The second contribution resides in addressing the problem of blanking threshold optimization under various IN and PAPR scenarios. The results reveal that minimizing the PAPR can also minimize the probability of blanking error significantly and provide up to 3.5dB SNR enhancement relative to the unmodified method. Furthermore and most importantly, it will be shown that if the PAPR is maintained below a certain threshold the optimal blanking threshold (OBT) becomes independent of the IN parameters. In such scenario we refer to the proposed as the blind blanking technique. In contrast to previous studies, this implies that the blind blanking technique can completely eliminate the need for any prior knowledge about the IN characteristics as well as achieving a gain between $1.5-3.5$dB relative to the in modified technique.

The rest of the paper is organized as follows. In Section II, the system model is presented. The proposed technique is described in Section III and the SLM scheme is reviewed in Section IV. In Section V, a theoretical expression for the probability of blanking error is derived and some simulation results are presented whereas the probability of miss and successful

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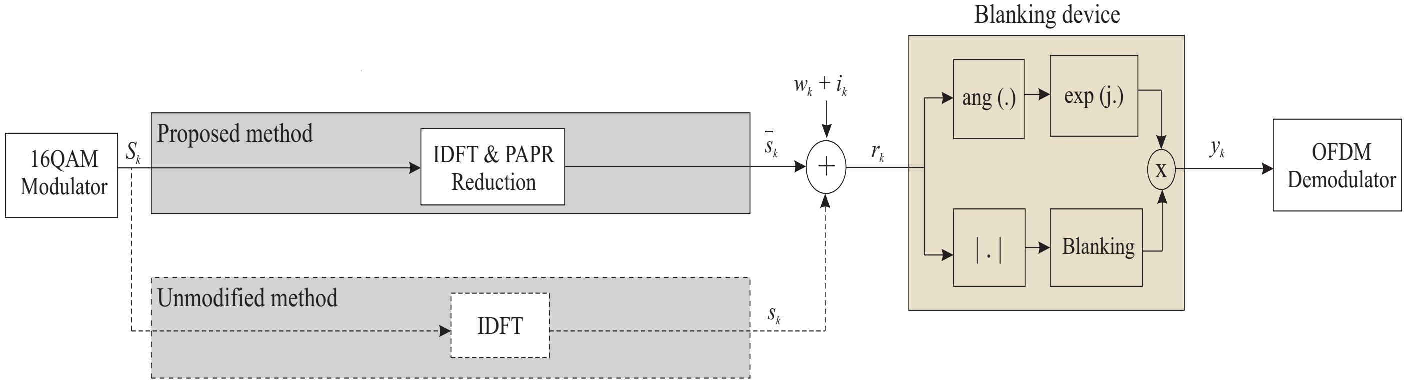


Fig. 1: Block diagram of OFDM system with PAPR reduction at the transmitter and blanking at the receiver

detection are analyzed in Section VI. Section VII outlines the simulation results including output SNR performance and blanking threshold optimization with and without multipath effect. Finally conclusions are drawn in Section VIII.

II. System Model Overview

Fig. 1 illustrates the basic system diagram used in this study. This figure presents the two methods considered in this paper which differ only in the transmitting side. These techniques are the unmodified method (dashed lines) and the proposed method (solid lines). In both systems, the information bits are first mapped into 16QAM symbols which are then passed through either an IDFT or IDFT/PAPR reduction to produce a time domain signal, $s(t)$ or $\bar{s}\,(t)$, respectively. $s(t)$ is expressed as in (1) whereas $\bar{s}\,(t)$ is defined in section IV.

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{\frac{j2\pi kt}{T_s}}, \quad 0 < t < T_s \tag{1}$$

where S_k is the complex constellations of the data symbols, N is number of sub-carriers and T_s is the active symbol interval. In general, the PAPR of the transmitted signal is given by

$$\text{PAPR} = \frac{\max |s(t)|^2}{\mathbb{E}\left[|s(t)|^2\right]}, \quad 0 < t < T_s \tag{2}$$

where $\mathbb{E}[.]$ is the expectation function. In order to get accurate estimates of the actual PAPR, oversampling by 4 times is deployed in all our investigations since such oversampling rate was shown to be sufficient to approximate the true PAPR [24]. Such process, however, would significantly increase the computational complexity as more processing is performed [25]. In this paper we consider a special case of Middleton class-A noise model in which IN is modeled as a Bernoulli-Gaussian random process [26] and is given as

$$n_k = w_k + i_k, \quad k = 0, 1, 2, \ldots, N-1 \tag{3}$$

where

$$i_k = b_k g_k, \quad k = 0, 1, 2, \ldots, N-1 \tag{4}$$

n_k is the total noise component, w_k is the additive white Gaussian noise (AWGN), i_k is the IN, g_k is complex white Gaussian noise with mean zero and b_k is the Bernoulli process with probability mass function

$$\Pr(b_k) = \begin{cases} p, & b_k = 1 \\ 0, & b_k = 0 \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{5}$$

The probability density function (PDF) of the total noise can be expressed as

$$P_{n_k}(n_k) = (1-p)\,\mathcal{G}\left(n_k, 0, \sigma_w^2\right) + p\,\mathcal{G}\left(n_k, 0, \sigma_w^2 + \sigma_i^2\right) \tag{6}$$

where $\mathcal{G}\,(.)$ is the Gaussian PDF and is given by (7), σ_w^2 and σ_i^2 are the AWGN and IN variances which are related to the input SNR and SINR as in (8) and (9), respectively.

$$\mathcal{G}\left(x, \mu, \sigma_x^2\right) = \frac{1}{\sqrt{2\pi\sigma_x^2}}\, e^{-\frac{(x-\mu)^2}{2\sigma_x^2}} \tag{7}$$

$$\text{SNR} = 10 \log_{10}\left(\frac{\sigma_s^2}{\sigma_w^2}\right) \tag{8}$$

$$\text{SINR} = 10 \log_{10}\left(\frac{\sigma_s^2}{\sigma_i^2}\right) \tag{9}$$

Under perfect synchronization condition and depending on which method is applied, the received signal has the following form

$$r_k = \begin{cases} s_k/\bar{s}\,(t) + w_k, & \mathcal{H}_0 \\ s_k/\bar{s}\,(t) + w_k + i_k, & \mathcal{H}_1 \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{10}$$

where $s_k/\bar{s}\,(t)$, w_k and i_k are assumed to be mutually independent. The null hypothesis $\mathcal{H}_0$ implies the absence of IN, $P\left(\mathcal{H}_0\right) = (1-p)$, whereas the alternative hypothesis $\mathcal{H}_1$ implies the presence of IN, $P\left(\mathcal{H}_1\right) = p$.

At the receiver, before the OFDM demodulator, the received signal is fed into the blanking device as shown in Fig. 1. The output of this device is

$$y_k = \begin{cases} r_k, & |r_k| \le T \\ 0, & |r_k| > T \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{11}$$

where T is the blanking threshold. r_k and y_k are the input and output of the blanker, respectively. It is obvious that the device only processes the amplitude of the received signal leaving its phase unmodified. The threshold T should be carefully

$$\alpha = 1 - \left(1 + \frac{T^2}{2\left(1+\sigma_w^2\right)}\right)(1-p)\, e^{-\frac{T^2}{2\left(1+\sigma_w^2\right)}} - \left(1 + \frac{T^2}{2\left(1+\sigma_w^2+\sigma_i^2\right)}\right) p\, e^{-\frac{T^2}{2\left(1+\sigma_w^2+\sigma_i^2\right)}} \tag{12}$$

$$\mathbb{E}\left[|y_k|^2\right] = 2+2\,\left(1+\sigma_w^2+p\sigma_i^2\right) - (1-p)\left\{T^2+2\left(1+\sigma_w^2\right)\right\} e^{-\frac{T^2}{2\left(1+\sigma_w^2\right)}} - p\left\{T^2+2\left(1+\sigma_w^2+\sigma_i^2\right)\right\} e^{-\frac{T^2}{2\left(1+\sigma_w^2+\sigma_i^2\right)}} \tag{13}$$

selected to optimize the system performance. For instance, if the threshold is too small, many unaffected samples of the OFDM signal will be blanked resulting in poor bit error rate performance; whereas for very large threshold, IN will be overlooked and will become part of the detected signal hence will degrade performance. In [18], it is presented that the output of the blanking device is given as $y_k = \alpha s_k + d_k$ where α is the appropriately selected scaling factor and d_k is the cumulative noise term. This decomposition is justified by the application of Bussgang's theorem [27]. It is also shown that when α is chosen as $\alpha = (1/2)\,\mathbb{E}\left[|y_k s_k^*|^2\right]$, a theoretical expression for the output SNR of the unmodified method can be expressed as

$$\mathrm{SNR}_{unmod} = \left(\frac{\mathbb{E}\left[|y_k|^2\right]}{2\alpha^2} - 1\right)^{-1} \tag{14}$$

where $\mathbb{E}\left[|y_k|^2\right]$ and α are defined by (12) and (13), respectively. These expressions will be used to provide a comparative analysis to show the superiority of the proposed and also to verify the accuracy of our simulation model.

III. The Proposed Method

Unlike other studies which focus on mitigating the IN at the receiver side only, in this paper we propose preprocessing the OFDM signal at the transmitter to improve the noise cancellation process at the receiver. It is intuitive to think that if the average PAPR of the OFDM symbols is small, then this will make IN more distinguishable from the useful transmitted signal and therefore can be blanked more effectively at the receiver. This can be accomplished simply by deploying a well-known PAPR reduction method such as the SLM scheme. For further clarity, an illustrative example is presented in Fig. 2 showing plots of an unmodified OFDM signal, an SLM-OFDM signal and IN pulses. This presents two different scenarios. First, in the case of the unmodified system it can be seen that when the blanking threshold T_1 is considered, two IN pulses will be recognized {IN2, IN3} whereas IN1 remains undetected which then becomes part of the signal fed to the OFDM demodulator. Whereas if T_2 is used, the blanker will be able to identify {IN1, IN2, IN3}; however, the unaffected samples {S1, S2, S3} will also trigger the blanker and consequently will be set to zero causing a blanking error. On the other hand the SLM-OFDM system allows using T_2 without any blanking error (leaving the unaffected samples untouched) in addition to eliminating {IN1, IN2, IN3}. The amount of reduction in blanking threshold is referred to as blanking threshold gain ($\mathrm{BTG} = T_2 - T_1$). It will be shown later that the higher the BTG, the more performance enhancement is achieved in term of the output SNR. For better realization of the proposed technique, it is important to briefly review the operation of the SLM scheme.

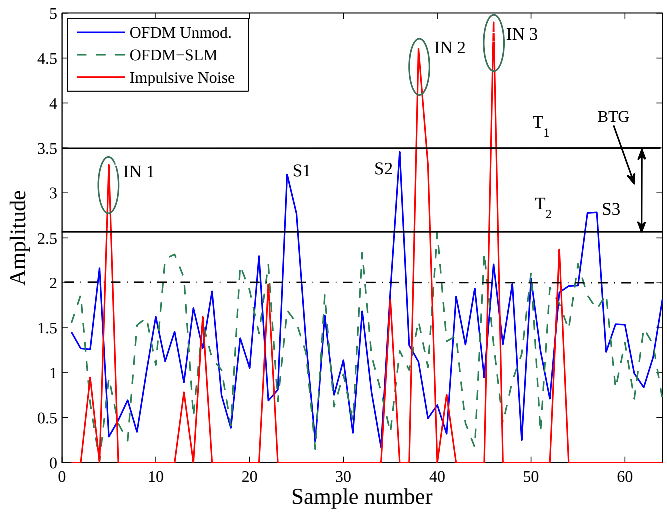


Fig. 2: Improved blanking threshold for 16QAM-SLM-OFDM system with $(N = 64)$ and $(U = 32)$

IV. Selective Mapping (SLM)

The SLM scheme is based on phase rotations in which the transmitter generates a set of different data blocks representing the same information as the original data block and then selects the one with the minimum PAPR for transmission. Assuming that the data stream is defined as $S = [S_0, S_1, \ldots, S_{N-1}]^T$, then each data block S is multiplied by U different phase sequence vectors W of length N

$$W^{(u)} = \left[W_0^{(u)}, W_1^{(u)}, \ldots, W_{N-1}^{(u)}\right]^T \quad u = 1, 2, \ldots, U \tag{15}$$

This multiplication yields U modified data blocks

$$\bar{S}^{(u)} = \left[S_0^{(u)} W_0^{(u)}, W_1^{(u)} W_1^{(u)}, \ldots, S_{N-1}^{(u)} W_{N-1}^{(u)}\right]^T \tag{16}$$

The modified blocks are then passed through the IDFT and the SLM-OFDM signal with N sub-carriers is given as

$$s^{(u)}(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \bar{S}_k^{(u)} e^{\frac{j2\pi kt}{T_s}}, \quad 0 < t < T_s \tag{17}$$

The modified data block with the minimum PAPR is selected for transmission, $\bar{s}(t)$. The amount of PAPR reduction is measured in terms of the complementary cumulative distribution

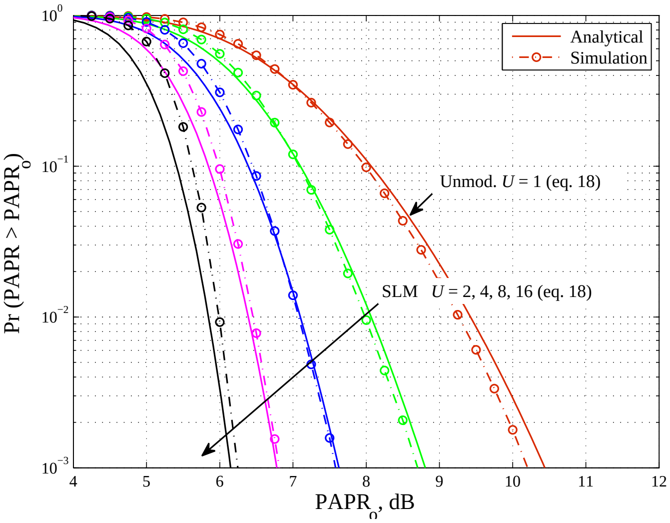


Fig. 3: CCDF plot for 16QAM-SLM-OFDM system for various values of U when $(N = 64)$

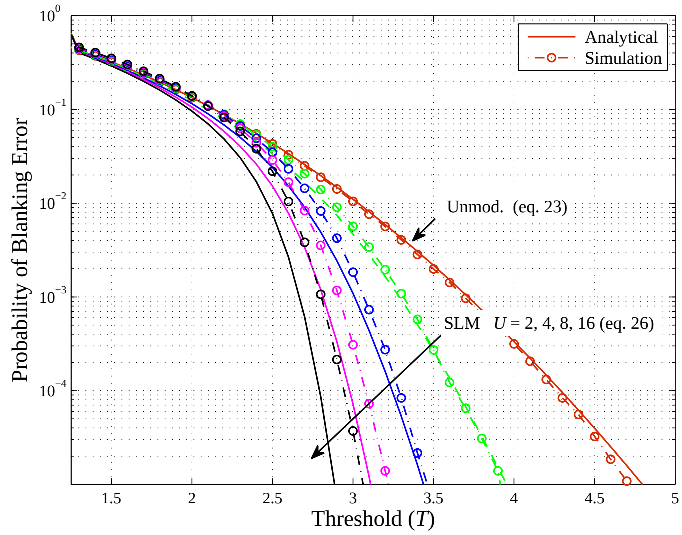


Figure 4: Probability of blanking error for the unmodified system and the SLM system for various values of U when $(N = 64)$

function (CCDF) which provides the probability that the PAPR of a data block exceeds a given threshold (PAPR_o). The CCDF of an SLM-OFDM system with U statistically independent frames is expressed as [28]

$$\text{CCDF} = \left(1 - \Pr\left\{\text{PAPR} \leq \text{PAPR}_o\right\}\right)^U$$

$$= \left(1 - \left(1 - e^{(-\text{PAPR}_o)}\right)^N\right)^U \tag{18}$$

It is worthwhile mentioning the fact that a more accurate expression for the CCDF of PAPR can be found in [29]. The amount of PAPR reduction depends on the number of phase sequences U and the design of the phase sequences, in this study $W \epsilon \{\pm 1, \pm j\}$. A plot of (18) is illustrated in Fig. 3 along with simulation results for 16QAM-OFDM signal with $N = 64$ sub-carriers for different values of U. It can be seen that the PAPR reduction improves as U increases and can be as high as 5dB at CCDF $= 10^{-3}$ when $\{U = 64\}$. However, it is evident that this enhancement becomes less significant as U goes beyond 8 sequences. This reduction in the PAPR implies that more of the transmitted signal energy is contained close to the average value and hence larger BTG value can be obtained.

V. Probability of Blanking Error

The probability of blanking error (P_b) is the probability that the amplitude of the received sample, $A_r = |r_k|$, exceeds the blanking threshold when it is unaffected by IN. P_b is defined by the joint probability $P(B, \mathcal{H}_0)$, where B is the event of blanking the received signal exceeding T, and can also be expressed as

$$P_b = P\left(A_r > T \,|\, \mathcal{H}_0\right) \, P\left(\mathcal{H}_0\right) \tag{19}$$

Equation (19) can also be rewritten as

$$P_b = \left[1 - F_{A_r}\left(T \,|\, \mathcal{H}_0\right)\right] \, P\left(\mathcal{H}_0\right) \tag{20}$$

$F_{A_r}(T \,|\, \mathcal{H}_0)$ is the conditional cumulative distribution function (CDF) and is related to the PDF as

$$F_{A_r}\left(T \,|\, \mathcal{H}_0\right) = \int_{-\infty}^{T} f_{A_r}\left(r \,|\, \mathcal{H}_0\right) \mathrm{d}r \tag{21}$$

A. Unmodified Method

In the absence of IN, the amplitude of the unmodified received signal has Rayleigh distribution with parameter $\sigma^2 = \sigma_s^2 + \sigma_w^2$

$$f_{A_r}^{unmod}\left(r \,|\, \mathcal{H}_0\right) = \frac{r}{\left(\sigma_s^2 + \sigma_w^2\right)} \, e^{-\left(\frac{r^2}{2\left(\sigma_s^2 + \sigma_w^2\right)}\right)} \tag{22}$$

By substituting (22) into (21) and then (21) into (20), P_b is found as

$$P_b^{unmod} = e^{-\left(\frac{T^2}{2\left(\sigma_s^2 + \sigma_w^2\right)}\right)} \left(1 - p\right) \tag{23}$$

B. Proposed Method

In the case of the SLM-OFDM system, the PDF of the transmitted signal as a function of N and U is derived in [30]. This expression is reproduced for the received signal, in the absence of IN, as in (24) (at the top of the next page). Similar to the unmodified method, the conditional CDF of the received SLM-OFDM signal is determined as

$$F_{A_r}^{SLM}\left(T \,|\, \mathcal{H}_0\right) = \int_{-\infty}^{T} f_{A_r}^{SLM}\left(r \,|\, \mathcal{H}_0\right) \mathrm{d}r$$

$$= \left[1 - \left[1 - \left(1 - e^{-\frac{T^2}{2\left(\sigma_s^2 + \sigma_w^2\right)}}\right)^N\right]^U\right]^{\frac{1}{N}} \tag{25}$$

$$f_{A_r}^{SLM}\left(r\,|\,\mathcal{H}_0\right) = U\, f_{A_r}^{unmod}\left(r\,|\,\mathcal{H}_0\right) \left(\left(\left(1 - e^{-\frac{r^2}{2\left(\sigma_s^2+\sigma_w^2\right)}}\right)^N \right)^{U-1} \left(1 - \left(1 - \left(1 - e^{-\frac{r^2}{2\left(\sigma_s^2+\sigma_w^2\right)}}\right)^N\right)^U\right) \right)^{\frac{1}{N}} \tag{24}$$

$$P_b^{SLM} = \left(1 - F_{A_r}^{SLM}\left(T\,|\,\mathcal{H}_0\right)\right)\, P\left(\mathcal{H}_0\right) = \left[1 - \left(1 - \left(1 - \left(1 - e^{\left(-\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2\right)}\right)}\right)^N\right)^U\right)^{\frac{1}{N}}\right] (1-p) \tag{26}$$

Using the definition of P_{b_e} in (20) we can write the probability of blanking error for the SLM-OFDM system $\left(P_b^{SLM}\right)$ as in (26). Some numerical results obtained from (23) and (26) are shown in Fig. 4 along with simulation results for the unmodified and SLM systems with $\{N = 64\}$ and input SNR $=$ 40dB for various values of U. It is clear that the simulation results closely match the analytical ones when U is small and deviate slightly for large values of U. This deviation is due to the fact that the PDF of the SLM signal (24), used to derive P_b^{SLM}, utilizes the *approximate* CCDF expression of the PAPR (18). This phenomena can also be observed in Fig. 3.

From Fig. 4, it is obvious that the behavior of the probability of blanking error can be divided into two regions. The first region is when $\{T \lesssim 2\}$ during which the proposed system does not provide any probability reduction compared to that of the unmodified method. It is clear that when $\{T = 2\}$, about $\{\simeq 10\%\}$ of the signal samples will exceed this threshold regardless of the number of phase sequences being used. This can also be clearly observed from Fig. 2 where about 7 samples out of 64 for each system exceed 2 (dashed line), which represents about 10% of the total samples. In the second region $\{T > 2\}$ it is noticeable that the proposed technique minimizes the probability of blanking error in comparison with the unmodified method. It is also evident that the probability is inversely proportional to U and T. For instance when $\{U = 16\}$ and at blanking threshold of 2.5, the probability is reduced by about 0.5 order of magnitude whereas for blanking threshold of 3, the probability is minimized by about 3 orders of magnitude. This implies that the system performance will improve for higher values of U as will be further discussed in the next section.

VI. Probability of Miss and Successful Detection

The probability of blanking error is useful to observe the distribution of the signals after the PAPR reduction, so that the blanker does not zero the uncontaminated signals. However, after the OFDM signal is passed to the IN channel two other measures of the system performance, which highly depend on the SINR, should be used instead, namely, the probability of missed blanking (P_m) and the probability of successful detection (P_s). P_m is the probability that the affected signals are not blanked and is expressed as

$$P\left(\bar{B}\,,\,\mathcal{H}_1\right) = P\left(A_r < T\,|\,\mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right)$$

$$= p\left(1 - e^{-\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2+\sigma_i^2\right)}}\right) \tag{27}$$

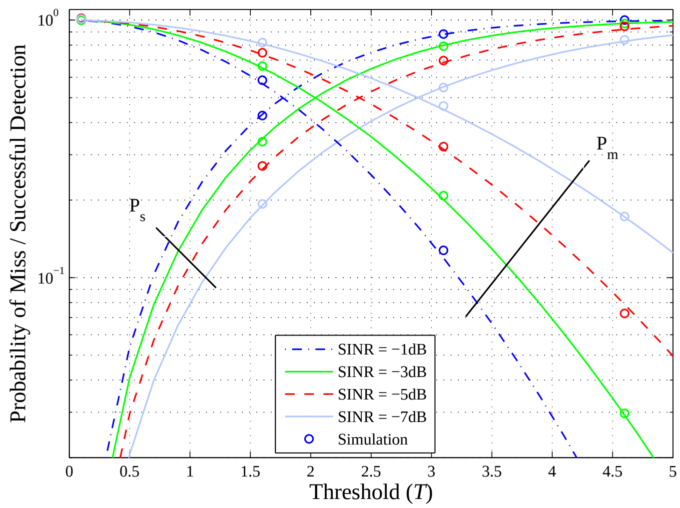


Fig. 5: Probability of missed blanking and successful detection for various values of SINR

where $\bar{B}$ denotes the absence of blanking. On the other hand, P_s is defined as the probability of correctly blanking the affected samples and is given by the joint probability

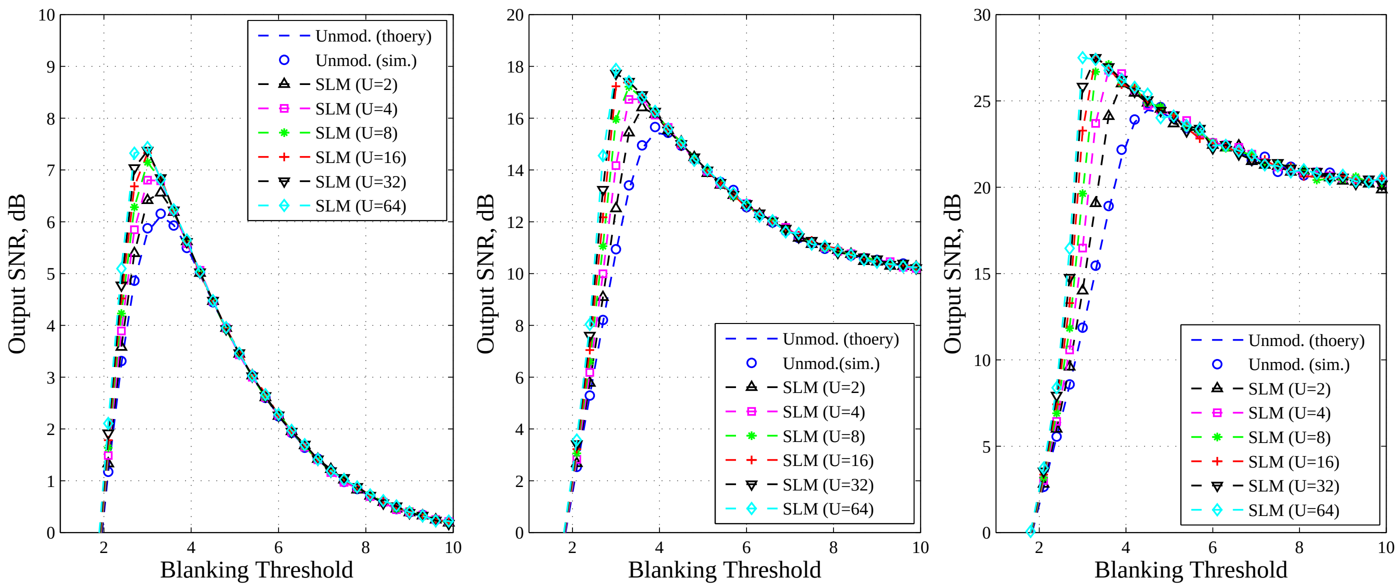
$$P\left(B\,,\,\mathcal{H}_1\right) = P\left(A_r > T\,|\,\mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right)$$

$$= p\, e^{-\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2+\sigma_i^2\right)}} \tag{28}$$

Fig. 5 depicts some numerical results of (27) and (28) along with simulation results for different values of SINR. It can be observed that these probabilities are inversely proportional. It can also be seen that as IN becomes smaller, for example SINR = -1dB or -3dB, the probability of missed blanking worsens whereas the probability of successful detection improves. At the other extreme, however, when IN is higher for instance SINR = -7dB, P_m is minimized and P_s increases. This is justified by the fact that when SINR becomes closer to zero, the amplitude of the OFDM and IN signals become more comparable leading to inaccurate blanking and consequently causing performance degradation.

VII. Simulation Results

In this section the performance of the proposed technique in terms of the output SNR is examined. In addition, the OBT



(a) $p = 0.1$ (b) $p = 0.01$ (c) $p = 0.001$

Figure 6: The output SNR versus blanking threshold for different values of U and p

that maximizes the output SNR is investigated. The simulation parameters used are: $N = 64$ sub-carriers, 16QAM modulation, $\sigma_s^2 = (1/2)\,\mathbb{E}[|s_k|^2] = 1$, $\sigma_w^2 = (1/2)\,\mathbb{E}[|w_k|^2]$ and $\sigma_i^2 = (1/2)\,\mathbb{E}[|i_k|^2]$.

The output SNR is found by (29) with $\bar{s_k} = \bar{s}\,(kT_s/N)$ and $\alpha = (1/2)\,\mathbb{E}\left[|y_k s_k^*|^2\right]$. In our investigations we set SNR $=$ 50dB and SINR $= -10$dB.

$$\text{SNR}_{SLM}^{U} = \frac{\mathbb{E}\left[|\alpha\,\bar{s_k}|^2\right]}{\mathbb{E}\left[|y_k - \alpha\,\bar{s_k}|^2\right]} \tag{29}$$

A. The Output SNR versus Blanking Threshold

The output SNR as a function of the blanking threshold for an SLM-OFDM system with $U = \{1, 2, 4, 8, 16, 32, 64\}$ is plotted in Fig. 6(a), (b) and (c) for $p = 0.1, 0.01$ and 0.001, respectively. It is seen that when $U = 1$ (unmodified method) the theoretical results, obtained from (14), and simulation results are matching. It is obvious from theses figures that as U increases, the output SNR is improved and this gain becomes less significant as U goes beyond 8 as anticipated in section III. This improvement is inversely proportional to p. For instance, it can be observed that when $\{p = 0.1\}$ the gain in the output SNR when $\{U = 64\}$ is about 1.5dB whereas when $\{p = 0.001\}$ the gain becomes about 3dB for the same value of U.

For the three IN probabilities, there is a general trend that when T is too small $\{T \lesssim 2\}$ the system performance degrades dramatically due to the fact that a great amount of the useful signal energy is lost. On the other hand, if T is too high $\{T \to \infty\}$ no blanking takes place and this allows all the IN energy to be part of the detected signal. In such scenario, it is clear that the output SNR approaches 0dB, 10dB and 20dB when $p = 0.1, 0.01$ and 0.001, respectively and this can be mathematically expressed as (30).

$$\text{SNR}_{SLM}^{U}\,(T \to \infty) = 10\log_{10}\left(\frac{\sigma_s^2}{\sigma_w^2 + p\,\sigma_i^2}\right) \tag{30}$$

when $p\,\sigma_i^2 \gg \sigma_w^2$, (30) can be approximated to

$$\simeq 10\log_{10}\left(\frac{1}{p\,\sigma_i^2}\right) \tag{31}$$

Furthermore, it can be noticed that for each value of U there exists an OBT at which the output SNR is maximized. Besides, as U increases the OBT is deceased and higher SNR is achieved. The optimization of the blanking threshold of the SLM-OFDM system is investigated next.

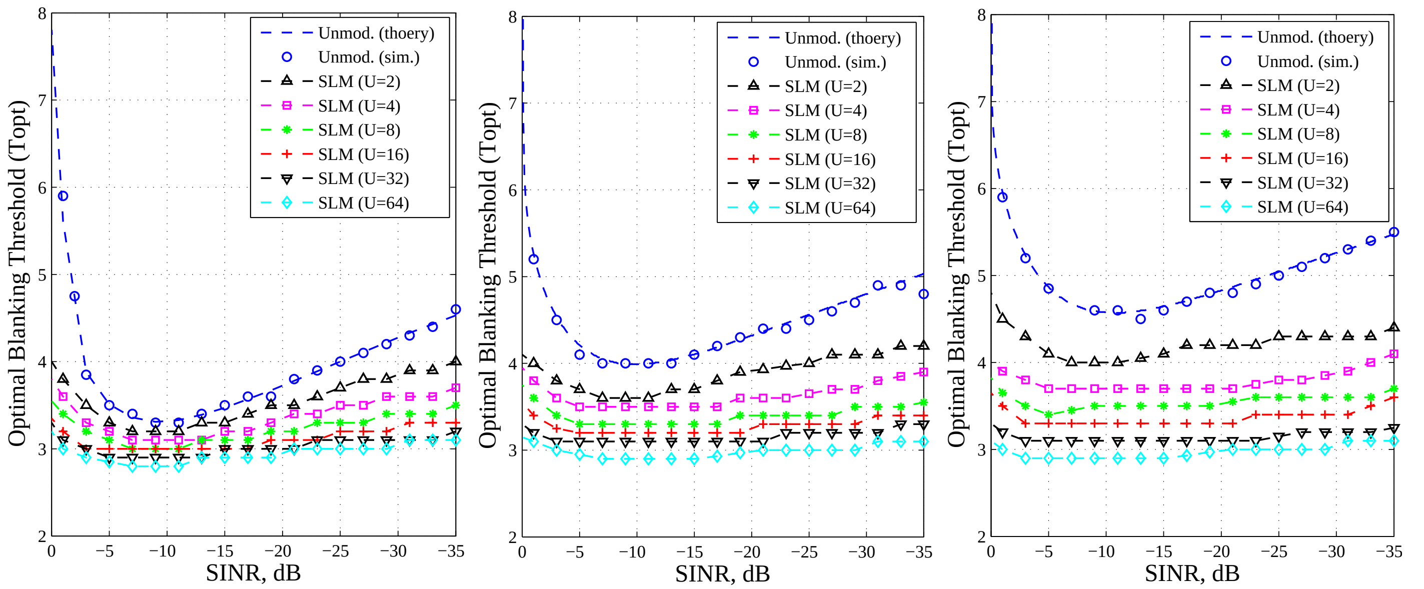
B. The Blanking Threshold Optimization

In this subsection we have carried out an extensive search for the OBT under various IN conditions and for different values of U

$$T_{opt}^{U} = \arg \max_{0 \le T < \infty} \left\{\text{SNR}_{SLM}^{U}\,(T,\, p,\, \text{SINR},\, \text{SNR})\right\} \tag{32}$$

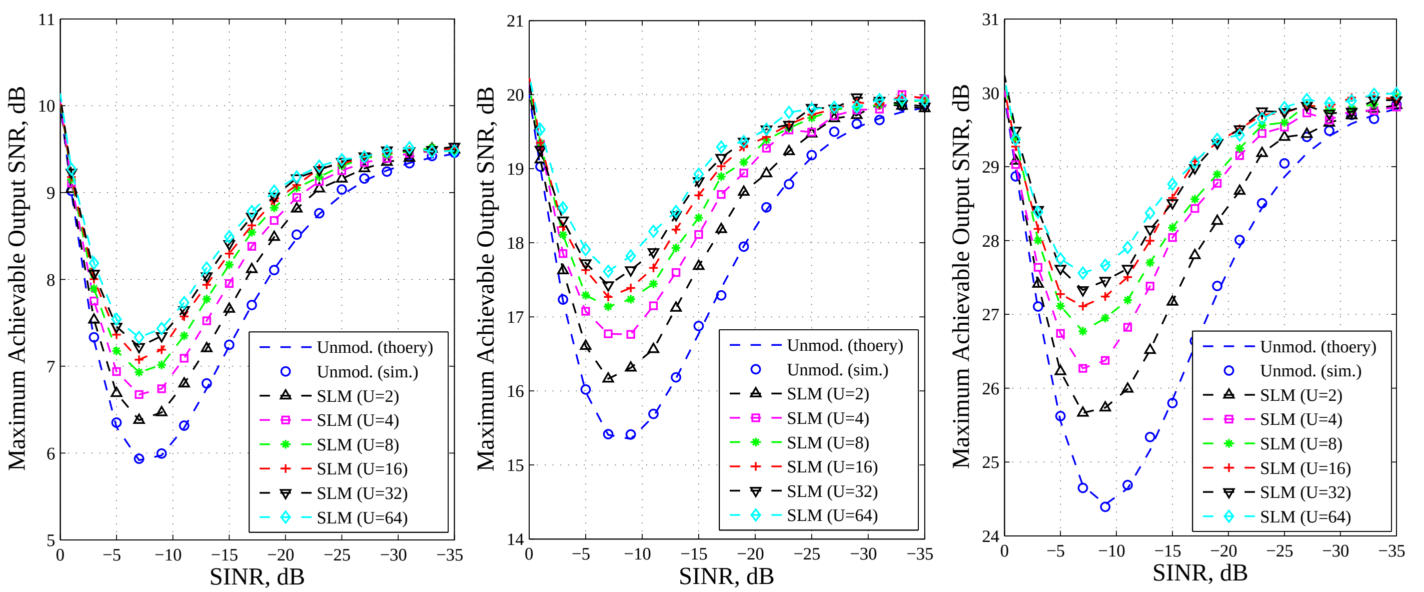
This expression finds the OBT of the SLM system with U phase sequences that maximizes the output SNR for given p, SINR and SNR values. Fig. 7(a), (b) and (c) depict the OBT versus SINR for $p = 0.1, 0.01$ and 0.001, respectively, when $U = \{1, 2, 4, 8, 16, 32, 64\}$. It is observed that, for the unmodified method and the proposed technique when $\{U \lesssim 8\}$, the OBT is larger for small IN probabilities compared to the OBT when p is high. One common observation one can clearly see for all p values is that when U is increased, the OBT decreases. The intuitive explanation of this is that when U increases, the useful signal energy will be contained within lower level and hence smaller blanking threshold will allow more effective blanking of the IN.

Furthermore, it is interesting to note that when $\{U \lesssim 8\}$ the OBT tends to be very large when the IN amplitude is either



(a) $p = 0.1$ (b) $p = 0.01$ (c) $p = 0.001$

Figure 7: Optimal blanking threshold versus SINR for different values of U and p



(a) $p = 0.1$ (b) $p = 0.01$ (c) $p = 0.001$

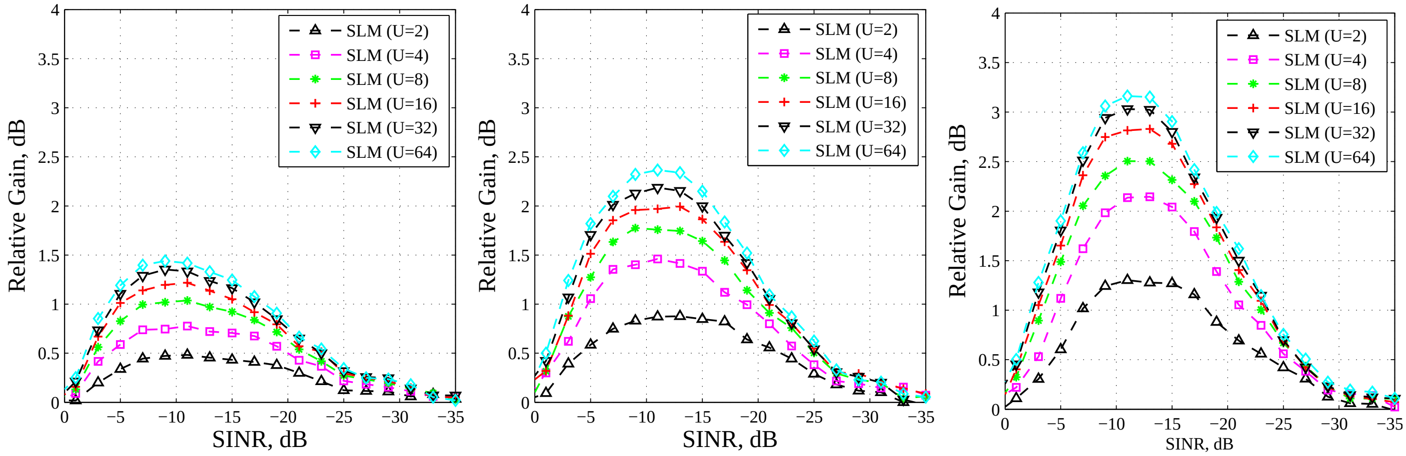
Figure 8: Maximum achievable output SNR versus SINR for different values of U and p

extremely low $(\text{SINR} \rightarrow 0)$ or extremely high $(\text{SINR} \rightarrow -\infty)$. This can be justified as follows: in the first scenario when the SINR approaches zero this implies that IN becomes comparable to the useful signal variance; as a result blanking does not provide any enhancement. On the other hand, for extremely high IN amplitudes $(\text{SINR} \rightarrow -\infty)$ IN becomes easily identifiable and therefore large blanking threshold can still provide optimal performance.

It is important to point out that for large values of U $\{U \geq 16\}$ the OBT levels off, i.e the OBT becomes independent of SINR, and this applies to all IN probabilities. Interestingly enough it can also be seen that when $\{U = 64\}$ the OBT is almost equal for all the SINR and p values which means if we deploy an SLM-OFDM system with a large number of phase sequences, it will be possible to optimally blank the IN independently of the noise characteristics. This phenomena will be investigated thoroughly in subsection D.

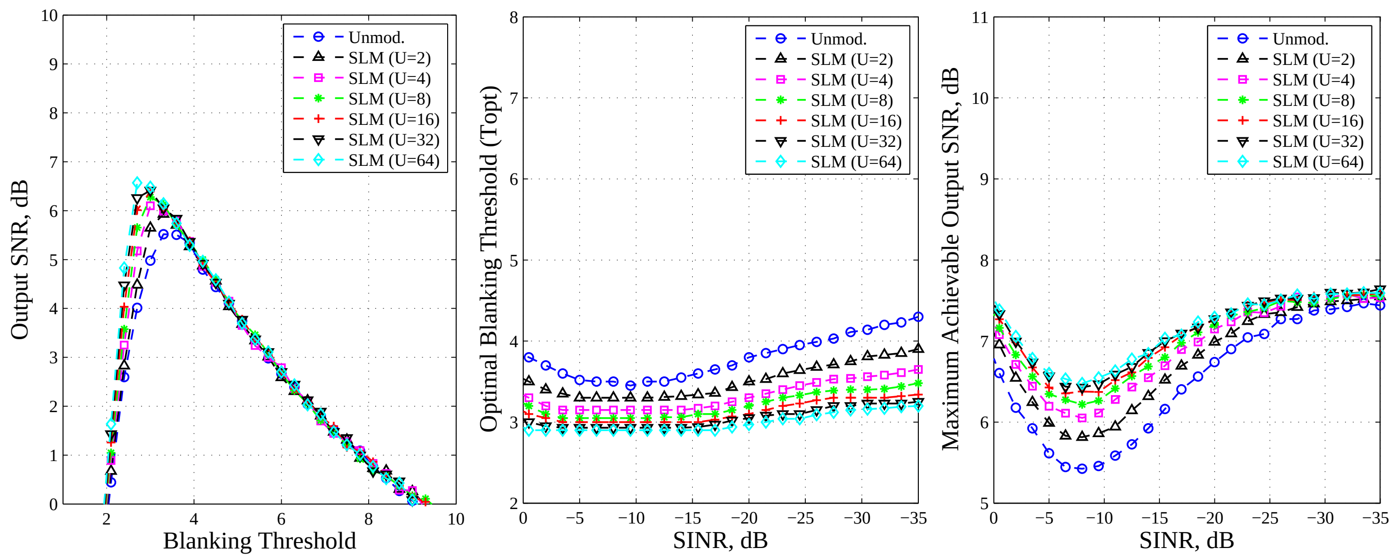
C. Maximum Achievable Output SNR

The maximum achievable SNR at the output of the blanker corresponding to the OBT found in the previous subsection is demonstrated in Fig. 8 versus SINR for different values of p and U. It is clear that the proposed technique always outperforms the unmodified method and this enhancement is proportional to U for all values of p. It is also evident that this improvement becomes more significant for low IN probabilities $\{p = 0.001\}$



(a) $p = 0.1$ (b) $p = 0.01$ (c) $p = 0.001$

Figure 9: Relative gain versus SINR for different values of U and p



(a) The output SNR versus blanking threshold (b) Optimal blanking threshold versus SINR (c) Maximum achievable output SNR

Figure 10: Output SNR, OBT and maximum achievable output SNR with multipath when $p = 0.1$ for different values of U

as shown in Fig. 8(c). To highlight this phenomena, we have plotted the relative gain (G_R), given by (33), versus SINR in Fig. 9.

$$G_R = 10\log_{10}\left(\frac{\text{SNR}_{SLM}\left(T = T_{opt}^{U}\right)}{\text{SNR}_{unmod}\left(T = T_{opt}^{(U=1)}\right)}\right) \tag{33}$$

It can be seen that, for the three IN probabilities, the largest improvement is reached in the intermediate SINR region (-5dB $\rightarrow -15$dB) where gains of up to 1.6dB, 2.75dB and 3.6dB are achieved in the output SNR over the unmodified method when $\{U = 64\}$, for $p = 0.1$, 0.01 and 0.001, respectively. It is worthwhile mentioning that even for small number of phase sequences $\{U = 2\}$ the proposed technique still can provide 0.5dB, 1dB and 1.5dB SNR enhancement when $p = 0.1$, 0.01 and 0.001, respectively. Furthermore, it is noticed that this gain becomes negligible in the low SINR region (SINR $\rightarrow -\infty$). This is due to the fact that in this region IN amplitude is extremely high and can easily be recognized and hence can be completely eliminated even with the unmodified method.

It is important to stress the fact that recovering the side information of the SLM scheme is crucial and in order to achieve best performance such information must be protected by using powerful channel codes. However, other schemes, which eliminate the requirement for the use of side information such as the blind approaches [31], can be an attractive candidate in practice. In addition, single-carrier frequency division multiple access (SC-FDMA) systems [32], [33], which are well-known for their low PAPR property, can also be utilized in conjunction with blanking to improve the IN mitigation.

D. *Performance Evaluation with Multipath*

In this section we examine the impact of multipath on both the unmodified and proposed methods in which the received

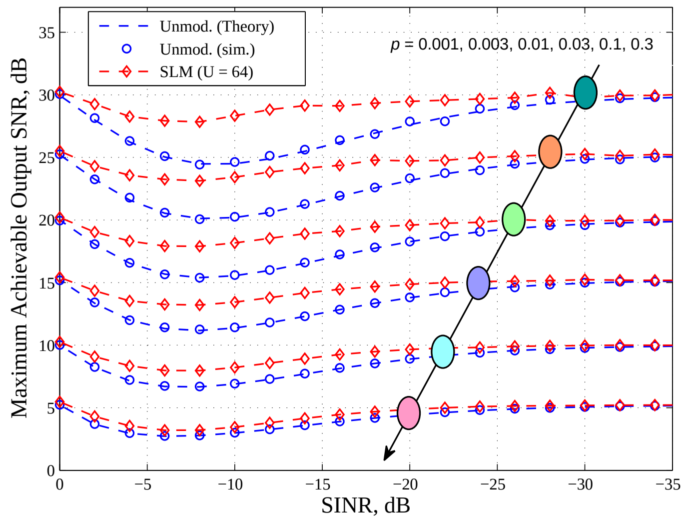


Figure 11: The output SNR versus SINR for the blind blanking technique and the unmodified method for various values of p

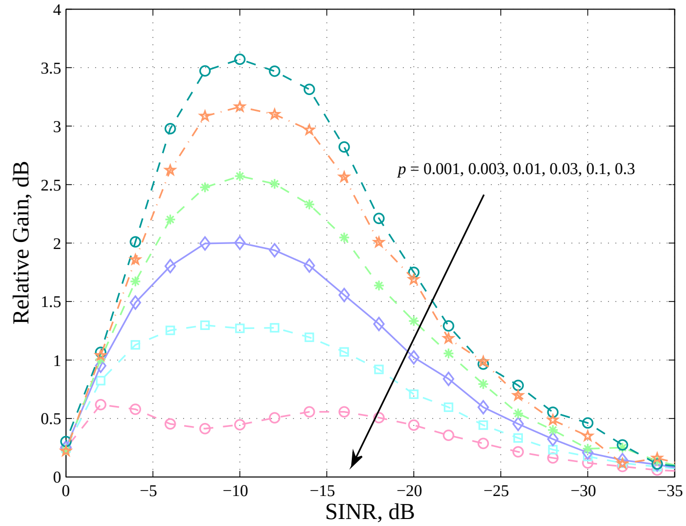


Figure 12: Output SNR gain of the blind system relative to the unmodified method versus SINR for different values of p

signal is given as

$$r_k = h_k * s_k + w_k + i_k, \quad k = 0, 1, \ldots, N-1 \tag{34}$$

where h_k is the impulse response of multipath fading channel. In this investigation we assumed perfect channel estimation and that orthogonality is maintained by the cyclic prefix [34]. Figs. 10(a), (b) and (c) show the output SNR versus blanking threshold, OBT and maximum achievable SNR versus SINR with multipath fading, respectively. By comparing Fig. 10(a) and Fig. 6(a) it can be observed that the presence of multipath fading degrades the performance slightly. However, this degradation affects both the unmodified and the proposed techniques.

E. The Blind Blanking Technique (Fixed Threshold)

Similar to the unmodified method and although it maintains better performance, our proposed approach assumes perfect estimation of IN parameters at the receiver in order to achieve best performance. However, in practice the fulfillment of such assumption can be difficult due to the dynamic nature of the PLC channel. As presented previously, see Fig. 7, the OBT reaches a plateau when U is very large irrespective of the IN characteristics. It can be noticed from this figure that when $\{U = 64\}$ the OBT stays constant at about 2.9 for all the given IN probabilities and SINR values.

In this subsection we assign a predetermined and fixed blanking threshold value $\{T = 2.9\}$ for the SLM-OFDM system with $\{U = 64\}$. The output SNR of a such scenario is plotted versus SINR for various pulse probabilities ranging from highly to weakly disturbed IN $p = \{0.3, 0.1, 0.03, 0.01, 0.003, 0.001\}$ as illustrated in Fig. 11. This method is referred to as the blind blanking technique. In order to provide comparative figures, the output SNR of the unmodified method is also included on the same plot. It is clearly seen that the blind technique always outperforms the unmodified method in addition to the fact that no previous knowledge about the IN is required at the receiver in order to optimally blank the noise. To make this enhancement clearer, the relative gain obtained by this technique over the unmodified method versus SINR is presented in Fig. 12 for the aforementioned values of p. It is evident that the gain can be as high as 3.75dB in a weakly disturbed IN environment $\{p = 0.001\}$ and about 0.5dB in an extremely heavily disturbed environment $\{p = 0.3\}$. Therefore, it can be summarized that the blind blanking technique has two advantageous properties. Firstly and unlike the existing techniques, this approach does not require any noise estimations to combat the IN, hence it avoids estimation errors and also reduces the receiver complexity. Secondly, a better performance is obtained relative to the unmodified method in terms of the output SNR. However, it is important to point out that these advantages are achieved at the expense of increased complexity in the transmitter.

VIII. Conclusion

In this paper we have introduced and elucidated a new method to improve the conventional blanking process in OFDM based power-line communication systems to mitigate IN by employing a PAPR reduction scheme. The results clearly demonstrate the robustness and superiority of the proposed technique in the form of minimized probability of blanking error and increase in the output SNR of up to 3.5dB. Furthermore, we have found that when $U \geq 64$, then it becomes feasible to optimally blank IN without the need for prior knowledge about its characteristics. This improvement, however, would be achieved at the expense of some computational complexity at the transmitter. The effect of multipath fading channel was also investigated and it was shown that the proposed technique can still provide considerable SNR gain over the unmodified method in such environments. Although only blanking was considered here, the proposed technique can be applied to OFDM receivers with other nonlinear preprocessors such as clipping, hybrid (blanking-clipping).

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