Improved DPTE Technique for Impulsive Noise Mitigation over Power-Line Communication Channels

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Abstract

Signal blanking is a simple and efficient method commonly used to reduce the impact of impulsive noise (IN) over power-lines. There are two main ways to implement this method, namely, a) the unmodified scheme and b) the dynamic peak-based threshold estimation (DPTE) technique. Concerning the first, in order to optimally blank IN the noise characteristics must be made available at the receiver otherwise the system performance will degrade dramatically. Whereas in the DPTE case, only estimates of the signal peaks are required to achieve best performance. In this paper, however, we propose to enhance the capability of the conventional DPTE technique by preprocessing the signal at the transmitter side. To evaluate system performance, we consider the probability of blanking error (P_b), probability of missed blanking (P_m) and probability of successful detection (P_s). In light of this, closed-form analytical expressions for the three probabilities are derived which are then validated with simulations. The results reveal that the proposed DPTE technique can significantly minimize both P_b and P_m and maximize P_s. It is also shown that the proposed system is able to attain up to 3.5 dB and 1 dB SNR enhancement relative to the unmodified and the conventional DPTE techniques, respectively, as well as improving the symbol error rate performance.

Keywords: Blanking, impulsive noise, OFDM, peak-to-average power ratio (PAPR), power-line communications (PLC), smart grid, signal-to-noise ratio (SNR).

1. Introduction

Since no single technology can be a perfect solution for all smart grid scenarios, a heterogeneous set of networks should be adopted for better realization of this technology such as Wi-Fi, coaxial-cables, fiber optics, power-line networks etc [1]. The fact that power-lines are already in existence makes it more attractive for smart

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grid developers to retrofit such networks for communications. This technology is commonly known as power-line communications (PLC). For reliable communications over PLC channels, however, it is of utmost importance to overcome few obstacles including impulsive noise (IN), frequency-dependent attenuation, multipath fading and electromagnetic compatibility issues [2, 3, 4, 5, 6]. In particular, IN is the main concern characterized by a short duration with random occurrence rate and a high power spectral density [7]. In order to evaluate the system performance in IN environments an accurate noise model is required. Middleton class-A noise model, [8, 9], has been the most widely accepted analytical model used in analyzing PLC systems and therefore will be adopted in this work.

Several methods with different degrees of complexity have been reported to enhance the performance of orthogonal frequency-division multiplexing (OFDM) based receivers in IN channels [10, 11, 12, 13]. 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 [14, 15]. This method is widely used in practice because of its simplicity and ease of implementation [16, 17, 18]. In general, imperfect recognition of IN signals may lead to nulling the uncorrupted samples or overlooking the corrupted ones in which cases the probability of blanking error and probability of missed detection will worsen and consequently performance will deteriorate. On the contrary, better recognition of IN will improve the probability of successful detection resulting in more reliable communication. Determining the optimal blanking threshold (OBT) remains the key for improving these probabilities. Two different techniques have been introduced in the literature to determine the OBT, namely, the unmodified [19, 20] and the dynamic peak-based threshold estimation (DPTE) [21]. The former technique relies on the assumption that in order to find the OBT, the noise characteristics must be accurately known apriori in the form of signal-to-impulsive noise ratio (SINR) and the IN probability of occurrence. This, however, constraints the applicability of this technique as such an assumption can be very difficult to fulfill in practice because of the dynamic nature of the PLC channel. Furthermore, the authors in [21] showed that even for small error estimations of the IN parameters, the performance of the unmodified technique will degrade rapidly.

On the other hand, the DPTE technique allows estimating the OBT independently of the IN parameters by using estimates of the transmitted signals' peak-to-average power ratio (PAPR) which can be accomplished by exploiting a look-up table based algorithm with uniform quantization [22]. Not only that, this technique can also achieve a gain of up to 2.5 dB over the unmodified one if the signal peaks can be estimated precisely at the receiver. Motivated by these advantages, in this paper we propose to enhance the capability of the DPTE technique by preprocessing the OFDM signal at the transmitter in such a way to make the IN more distinguishable at the receiver and this could be done by applying a PAPR reduction scheme such as the partial transmit sequence (PTS) scheme at the transmitter [23]. Processing the OFDM signal in such a way in combination with applying the DPTE technique is able to minimize the probability of blanking error and probability of missed detection while improving the probability of successful detection. The proposed system will be referred to in this paper as DPTE-PTS technique. Therefore, the contribution of this paper is twofold. First, closed-form expressions for the three aforementioned probabilities are derived and validated with simulations for the unmodified system, and for conventional DPTE and DPTE-PTS techniques, performance is evaluated by means of computer simulations. For more quantitative characterization of the system performance, the output SNR and symbol error rate (SER) of the unmodified, conventional DPTE and DPTE-PTS systems are also investigated. The results reveal that the proposed system is able to reduce the probability of blanking error and the probability of missed blanking considerably as well as improving the probability of successful detection. Furthermore, it is shown that DPTE-PTS system can attain a gain of up to 3.5 dB and 1 dB in the output SNR with respect to the unmodified and the conventional DPTE techniques, respectively, in addition to providing better SER performance.

The rest of the paper is organized as follows. In Section 2, the system model is presented. Theoretical expressions for the probability of blanking error, probability of missed blanking and probability of successful detection are derived and some simulation results are presented for the unmodified, conventional DPTE and DPTE-PTS systems in Sections 3, 4 and 5, respectively. Section 6 outlines the simulation results for the output SNR and SER for the three systems. Finally, conclusions are drawn in Section 7.

2. System Model

Fig. 1 illustrates the system diagram of this study. The information bits are first mapped into 16QAM symbols which are then grouped into vectors each of length N as $\{\mathbf{S}_k,\, k = 1, 2, \ldots, N\}$. $\mathbf{S}_k$ is then partitioned into M disjoint sub-blocks $\mathbf{S}_k^{(m)} = \left[S_0^{(m)}, S_1^{(m)}, \ldots, S_{N-1}^{(m)}\right]$, $m = 1, 2, \ldots, M$, and all sub-carriers which are already represented in another sub-block are set to zero so that $\mathbf{S}_k = \sum_{m=1}^{M} \mathbf{S}_k^{(m)}$. Then the IFFT is employed for each sub-block to produce $s_k^{(m)} = \text{IFFT}\left\{\mathbf{S}_k^{(m)}\right\}$. After that each sub-block is multiplied by a different phase weighting factor $b^{(m)}$. The peak value optimization block iteratively searches for the optimal combination of the phase weighting factors that offer the minimum PAPR. Once the optimal weighting factor is determined, all the sub-blocks are summed $\bar{s}_k = \sum_{m=1}^{M} b^{(m)} s_k^{(m)}$ and then transmitted. In general, the PAPR of the OFDM signal is defined as

$$\text{PAPR} = 10\text{log}_{10}\left(\frac{\max|\bar{s}(t)|^2}{\mathbb{E}\left[|\bar{s}(t)|^2\right]}\right), \quad 0 < t < T_s \tag{1}$$

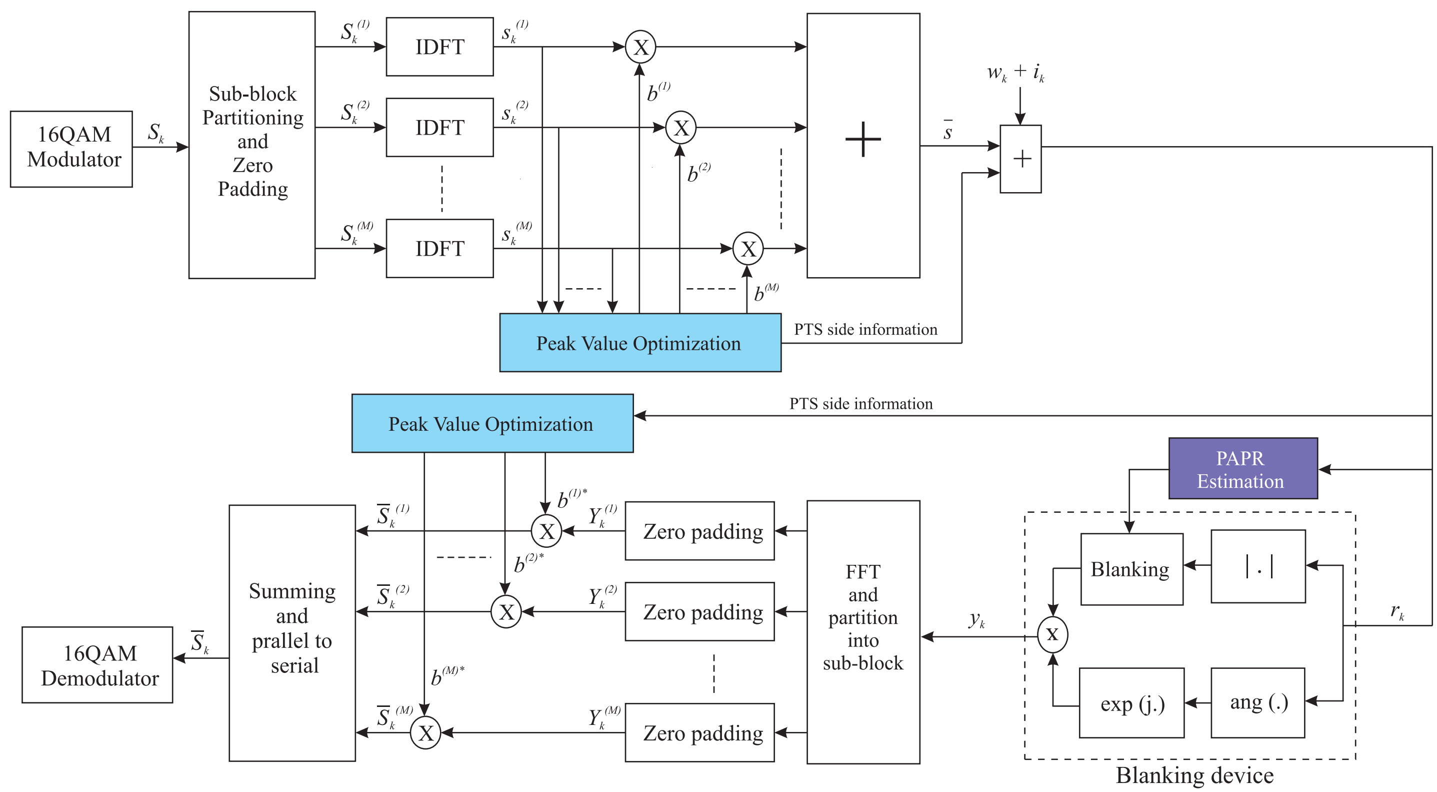


Figure 1: Block diagram of OFDM system with a PAPR reduction scheme at the transmitter and DPTE-based blanking at the receiver.

where T_s denotes the active symbol interval and $\mathbb{E}[.]$ 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] [1]. In this paper, we adopt the well-know Bernoulli-Gaussian model to characterize the noise over PLC channels, [26] which is written as

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

where

$$i_k = b_k g_k, \quad k = 0, 1, 2, \ldots, N-1 \tag{3}$$

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

$$P(b_k) = \begin{cases} p, & b_k = 1 \\ 0, & b_k = 0 \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{4}$$

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

$$P\left(n_k\right) = (1-p)\, \mathcal{G}\left(n_k, 0, \sigma_w^2\right) + p\, \mathcal{G}\left(n_k, 0, \sigma_w^2 + \sigma_i^2\right) \tag{5}$$

where $\mathcal{G}\left(.\right)$ is the Gaussian PDF given by (6), σ_w^2 and σ_i^2 are the AWGN and IN variances which are related to the input SNR and SINR as input $\mathrm{SNR} = 10\log_{10}\left(\frac{\sigma_s^2}{\sigma_w^2}\right)$ and $\mathrm{SINR} = 10\log_{10}\left(\frac{\sigma_s^2}{\sigma_i^2}\right)$, respectively.

$$\mathcal{G}\left(x, \mu, \sigma_x^2\right) = \frac{1}{\sqrt{2\pi\sigma_x^2}} \exp\left(-\frac{\left(x-\mu\right)^2}{2\sigma_x^2}\right) \tag{6}$$

It should be menitoned that in order to demonstrate the lower bound performance of the proposed DPTE-PTS method, the impact of the channel, which could slightly reduce the achivable gains, on the signal peaks is

[1] Note that oversampling can significantly increase the system computational complexity since more processing is now performed [25].

not considered in this work. Under perfect synchronization condition the received signal has the following form

$$r_k = \begin{cases} \bar{s}_k + w_k, & \mathcal{H}_0 \\ \bar{s}_k + w_k + i_k, & \mathcal{H}_1 \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{7}$$

where $\bar{s}_k$, w_k and i_k are assumed to be mutually independent. The null hypothesis $\mathcal{H}_0$ implies the absence of IN, $P(\mathcal{H}_0) = (1-p)$, whereas the alternative hypothesis $\mathcal{H}_1$ implies the presence of IN, $P(\mathcal{H}_1) = p$. At the front-end of the receiver, blanking is applied and depending on the scenario considered we have three distinct techniques.

- Unmodified Technique: in this system PTS is not applied and only one typical OFDM modulator is used. At the receiver conventional blanking is applied as

$$y_k = \begin{cases} r_k, & |r_k| \leq T \\ 0, & |r_k| > T \end{cases} \quad k = 0, 1, \ldots, N-1 \tag{8}$$

where T is the blanking threshold, r_k and y_k are the input and output of the blanker, respectively. The blanking threshold must be carefully chosen for achieving best performance. It is important to stress the fact that determining the OBT in this technique requires accurate knowledge about the characteristics of IN which may not be easily obtainable in practice. In [19], a theoretical expression for the OBT[2] (T_{opt}) was derived as a function of IN parameters (11) as well as the output SNR given as

$$\text{SNR}_{unmod.} = \frac{2}{\mathbb{E}\left[A_n^2\right]} \tag{9}$$

while $\mathbb{E}\left[A_n^2\right]$ is given by (10), $A_n = |\bar{n}_k|$ where $\bar{n}_k$ is the samples of the total noise at the output of the blanking device, i.e. $\bar{n}_k = y_k - \bar{s}_k$. These expressions will be used to provide a comparative analysis to show the superiority of the proposed system and also to verify the accuracy of our simulation model.

- Conventional DPTE Technique:

In this system, blanking is performed based on the OFDM symbol peak estimates irrespective of IN characteristics [21] and works as follows

[2]OBT refers to the blanking threshold that maximizes the output SNR for given noise parameters.

$$\mathbb{E}\left[A_n^2\right] = 2\left(1-p\right)\left[\sigma_w^2\left(1-\sigma_w^2\right)\left(\frac{T^2}{2\left(1+\sigma_w^2\right)}+1\right)\right.$$

$$\left. .e^{-\frac{T^2}{2\left(1+\sigma_w^2\right)}}\right] + 2p\left[\left(\sigma_w^2+\sigma_i^2\right)+\left(1-\sigma_w^2-\sigma_i^2\right)\right.$$

$$\left. \cdot\left(\frac{T^2}{2\left(1+\sigma_w^2+\sigma_i^2\right)}+1\right)e^{-\frac{T^2}{2\left(1+\sigma_w^2+\sigma_i^2\right)}}\right] \quad (10)$$

$$T_{opt} = \sqrt{\frac{2\left(1+\sigma_w^2\right)\left(1+\sigma_w^2+\sigma_i^2\right)}{\sigma_i^2}\ln\left(\left[\frac{1+\sigma_w^2+\sigma_i^2}{1+\sigma_w^2}\right]^2\frac{\left(1-\sigma_w^2\right)}{\left(1-\sigma_w^2-\sigma_i^2\right)}\frac{\left(p-1\right)}{p}\right)} \quad (11)$$

$$y_k = \begin{cases} r_k, & |r_k| \leq \mathrm{P} \\ 0, & |r_k| > \mathrm{P} \end{cases} \quad k = 0,1,\ldots,N-1 \quad (12)$$

where P is the estimated peak of the associated OFDM.

- DPTE-PTS Technique:

This system is similar to the conventional DPTE one but with applying a PTS modulator at the transmitter, see Fig. 1 and its principle is

$$y_k = \begin{cases} r_k, & |r_k| \leq \tilde{\mathrm{P}} \\ 0, & |r_k| > \tilde{\mathrm{P}} \end{cases} \quad k = 0,1,\ldots,N-1 \quad (13)$$

where $\tilde{\mathrm{P}}$ is the estimated OFDM symbol peak value when PTS scheme is applied, $\tilde{\mathrm{P}} < \mathrm{P}$. After the blanking device, y_k is passed through the FFT to produce $\mathbf{Y}_k = FFT\left\{y_k\right\}$ which is then partitioned into M disjoint sets $\left\{\mathbf{Y}_k^{(m)} : m = 0,1,\ldots N-1\right\}$ and zero padding is performed such that $\mathbf{Y}_k = \sum_{m=1}^{M}\mathbf{Y}_k^{(m)}$. Using the inverse phase weighting factors $\left\{b^{(m)*}, m = 1,2,\ldots,M\right\}$, $\bar{\mathbf{S}}_k^{(m)} = b^{(m)*}\mathbf{Y}_k^{(m)}$ and the signal after summing and parallel-to-serial device is given as $\bar{\mathbf{S}}_k = \sum_{m=1}^{M}\bar{\mathbf{S}}_k^{(m)}$.

For better realization of the proposed technique, it is important to review the PAPR reduction of the PTS scheme. In the unmodified system only one IFFT operation is required whereas in the PTS scheme M IFFT operations are performed. In the latter scheme a set of phase weighting factors is usually selected for generating the phase weighting sequences. Assuming that there are W phase weighting factors in this set, the optimal

PAPR is found after checking W^{M-1} different combinations and the number of bits required to represent the side information is $\log_2\left(W^{M-1}\right)$. The amount of PAPR reduction for this scheme depends on the number partitions (M) and the number of phase weighting factors (W) [3]. The reduction in the PAPR implies that more of the transmitted signal energy is contained close to the average value and hence IN will becomes more distinguishable at the receiver resulting in a more efficient implementation of the DPTE technique as presented below.

3. 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 $P\left(B\,,\,\mathcal{H}_0\right)$, where B is the event of blanking the received signal exceeding T, and can also be expressed as

$$P_b = \Pr\left(A_r > T\,|\,\mathcal{H}_0\right)\; P\left(\mathcal{H}_0\right) \tag{14}$$

In the absence of IN, the amplitude of the unmodified received signal has Rayleigh distribution with parameter $\sigma^2 = \sigma_s^2 + \sigma_w^2$, and therfore the corresponding pdf, $f_{A_r}\left(.\right)$, can be written as

$$f_{A_r}^{\{unmod\}}\left(r\,|\,\mathcal{H}_0\right) = \frac{r}{\left(\sigma_s^2+\sigma_w^2\right)}\; e^{-\left(\frac{r^2}{2\left(\sigma_s^2+\sigma_w^2\right)}\right)} \tag{15}$$

From the definition in (14), P_b is found as

$$\begin{aligned} P_b^{\{unmod\}} &= \int_T^{\infty} f_{A_r}^{\{unmod\}}\left(r\,|\,\mathcal{H}_0\right)\mathrm{dr} \\ &= e^{-\left(\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2\right)}\right)}\left(1-p\right) \end{aligned} \tag{16}$$

For the PTS-based system, P_b is found by means of simulation. The reason why no analytical expressions are derived for this system is because this require the signal distribution at the output of the PTS modulator

[3] In all our investigations in this paper, the phase weighting factors are chosen from $W = \{\pm 1, \pm j\}$ since the authors in [23] showed that a restriction to four phase weighting factors can provide a significant peak reduction.

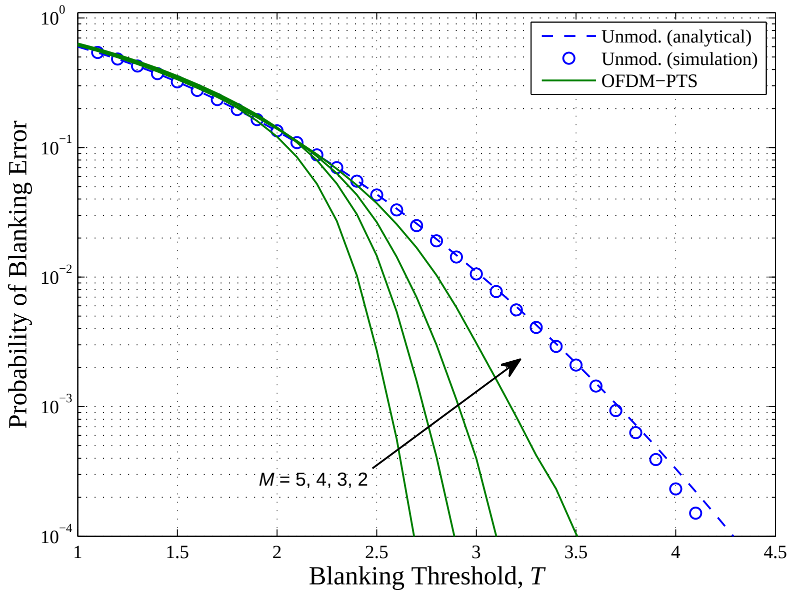


Figure 2: Probability of blanking error versus blanking threshold for different values of M when $W = 4$.

which is not available in the literature. Our simulations from this point onward are based on an OFDM system consisting of $N = 256$ sub-carriers with 16QAM modulation and the OFDM signal power is normalized as $\sigma_s^2 = (1/2)\, E\left[|s_k|^2\right] = 1$. Fig. 2 illustrates the probability of blanking error for the unmodified and PTS-based systems with input SNR = 40dB for various values of M. For the unmodified system it is obvious that the analytical and simulated results are in good agreement. It is also clear that the behavior of the probability can be divided into two regions. The first region is when $\{T \lesssim 2\}$ during which PTS-based system does not provide any probability reduction in comparison with that of the unmodified system. At $\{T = 2\}$, it can be seen that about $\{\simeq 10\%\}$ of the signal samples will exceed this threshold irrespective to M. In the second region $\{T > 2\}$, however, it is noticeable that the PTS-based system minimizes the probability of blanking error compared to the unmodified system and that the probability is inversely proportional to M and T. For instance when $\{M = 5\}$ and at blanking threshold of 2.5, the probability is reduced by about 1.5 order of magnitude whereas for blanking threshold of 2.75, the probability is minimized by about 2.5 orders of magnitude. This implies that the system performance will improve for higher values of M as will be further discussed later.

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 through the IN channel two other important measures of the system performance, which highly depend on the IN characteristics, should be used instead. These measures are the probability of missed blanking (P_m) and the probability of successful detection (P_s) both of which are investigated below.

4. Probability of Missed Blanking

P_m is the probability that the affected signals are not blanked and is given by the joint probability $P\left(\bar{B}\,,\,\mathcal{H}_1\right)$ where $\bar{B}$ denotes the absence of blanking. In this section we investigate P_m for the unmodified, conventional DPTE, and DPTE-PTS techniques.

4.1. Unmodified Technique

For this system, the probability of missed blanking is expressed as

$$P_m = P\left(A_r < T \,|\, \mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right) \tag{17}$$

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

$$f_{A_r}^{\{unmod\}}\left(r \,|\, \mathcal{H}_1\right) = \frac{r}{\left(\sigma_s^2 + \sigma_w^2 + \sigma_i^2\right)}\, e^{-\left(\frac{r^2}{2\left(\sigma_s^2+\sigma_w^2+\sigma_i^2\right)}\right)} \tag{18}$$

From the definition in (17), P_m is found as

$$\begin{aligned} P_m^{\{unmod\}} &= \int_{-\infty}^{T} f_{A_r}^{\{unmod\}}\left(r \,|\, \mathcal{H}_1\right) \mathrm{dr} \\ &= p\left(1 - e^{-\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2+\sigma_i^2\right)}}\right) \end{aligned} \tag{19}$$

In this subsection, we assume perfect detection of IN parameters and therefore T can be replaced with T_{opt} found from (11).

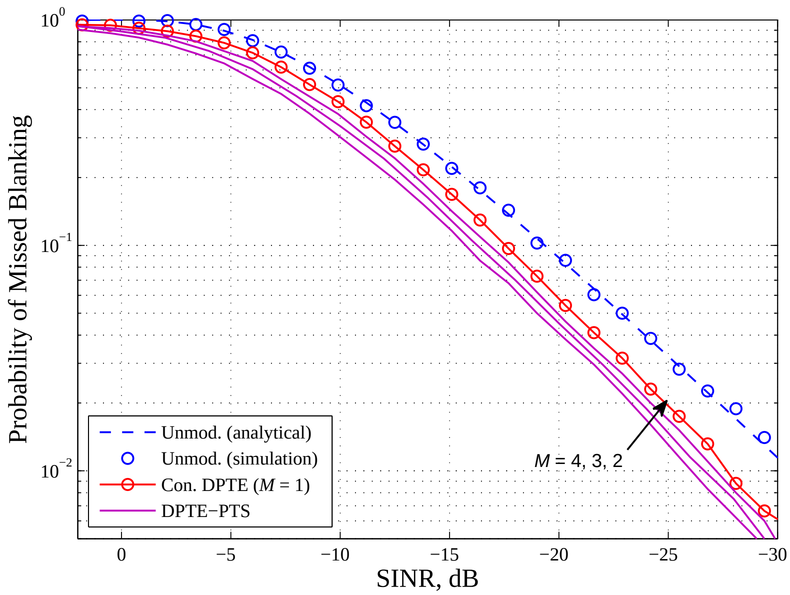


Figure 3: Probability of missed blanking versus SINR for the unmodified, conventional DPTE and DPTE-PTS techniques with various values of M when $W = 4$.

4.2. Conventional DPTE Technique

In this system, P_m is determined as

$$P_m^{Con.\,DPTE} = P\left(A_r < \mathrm{P}\,|\,\mathcal{H}_1\right)\; P\left(\mathcal{H}_1\right) \tag{20}$$

where P is the peak value of the associated OFDM symbol when PTS is not applied.

4.3. DPTE-PTS Technique

In this scenario, P_m is found as

$$P_m^{\{DPTE-PTS\}} = P\left(A_r < \tilde{\mathrm{P}}\,|\,\mathcal{H}_1\right)\; P\left(\mathcal{H}_1\right) \tag{21}$$

where $\tilde{\mathrm{P}}$ is the peak value of the associated OFDM symbol when PTS scheme is deployed.

Fig. 3 depicts some numerical results of (19) as a function of SINR along with simulation results for the unmodified, conventional DPTE and DPTE-PTS systems when input SNR = 40dB for various values of M. It can be seen that the analytical and the simulated results for the unmodified system are matching. It is important to highlight the fact that the results of the unmodified system are obtained under the assumption of perfect IN detection, i.e. substituting $T = T_{opt}$. Nonetheless, it is clear that the unmodified system has the worst performance and that the conventional DPTE system outperforms the unmodified one. It is also interesting to note that the DPTE-PTS system offers the best performance and as M increases the performance improves. Furthermore, it can be observed that, for the three systems, as IN becomes smaller the probability of missed blanking worsens and it improves for very low SINR values. 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.

5. Probability of Successful Detection

P_s is another important performance measure after the OFDM signal is passed through the PLC channel and is defined as the probability of correctly blanking the contaminated samples. P_s is given by the joint probability $P\left(B\,,\,\mathcal{H}_1\right)$ and is discussed below for the unmodified, conventional DPTE and DPTE-PTS techniques.

5.1. Unmodified Technique

In this system, P_s is given as

$$P_s = P\left(A_r > T \,|\, \mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right) \tag{22}$$

In the presence of IN and by using (18), P_s is determined as

$$\begin{aligned} P_s^{\{unmod\}} &= \int_T^{\infty} f_{A_r}^{\{unmod\}}\left(r \,|\, \mathcal{H}_1\right) \mathrm{dr} \\ &= p\, e^{-\frac{T^2}{2\left(\sigma_s^2+\sigma_w^2+\sigma_i^2\right)}} \end{aligned} \tag{23}$$

Again and since perfect detection of IN parameters is assumed, T can be replaced with T_{opt} (11).

5.2. Conventional DPTE Technique

For the conventional DPTE technique, P_s is calculated as

$$P_s^{\{Con.\,DPTE\}} = P\left(A_r > \mathrm{P} \,|\, \mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right) \tag{24}$$

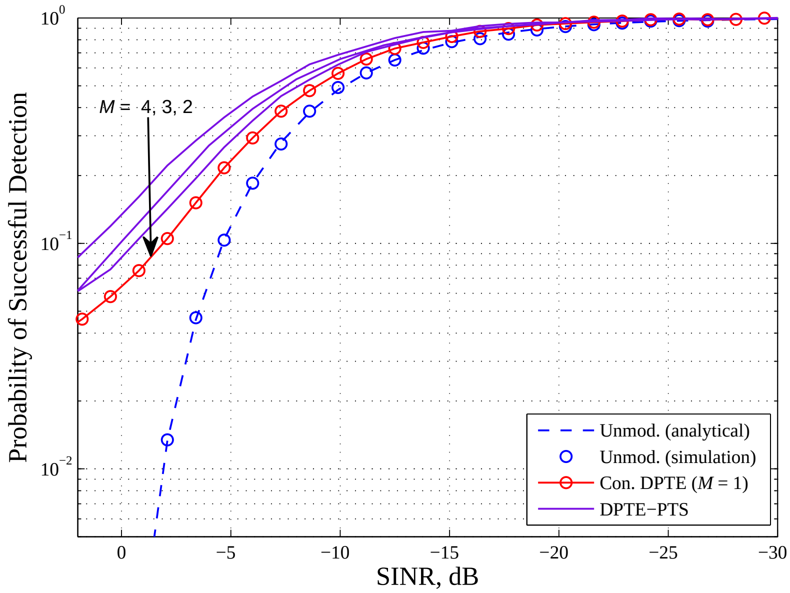


Figure 4: Probability of successful detection versus SINR for the unmodified, conventional DPTE and DPTE-PTS techniques with various values of M when $W = 4$.

5.3. Conventional DPTE Technique

In this scenario, P_s is found as

$$P_s^{\{DPTE-PTS\}} = P\left(A_r > \tilde{\mathrm{P}}\,|\,\mathcal{H}_1\right)\, P\left(\mathcal{H}_1\right) \tag{25}$$

Fig. 4 shows the numerical results of (23) along with simulation results for the unmodified, conventional DPTE and DPTE-PTS systems for various values of M. For the three systems it can be seen that the probability of successful detection improves as SINR becomes smaller and this probability approaches 1 for very low SINR values. This is due to the fact that in this region IN amplitudes are so high, compared to the useful OFDM signal, that all the three techniques can perfectly detect the noise pulses. At the other extreme, however, when IN is low P_s is minimized and this is justified as follows. When SINR becomes closer to zero, the amplitude of the OFDM and IN signals become more comparable and this will lead to inaccurate blanking. Similarly as in the previous section it is noticeable that as M increases, performance becomes better. As a final remark on these results, it can be observed that P_m and P_s are inversely proportional.

6. Output SNR and SER Performance

For more quantitative characterization of the proposed technique, we have conducted extensive computer simulations to analyze the output SNR and SER performance. The output SNR is determined as

$$\mathrm{SNR}_{DPTE} = \frac{\mathbb{E}\left[|\bar{s}_k|^2\right]}{\mathbb{E}\left[|y_k - \bar{s}_k|^2\right]} \tag{26}$$

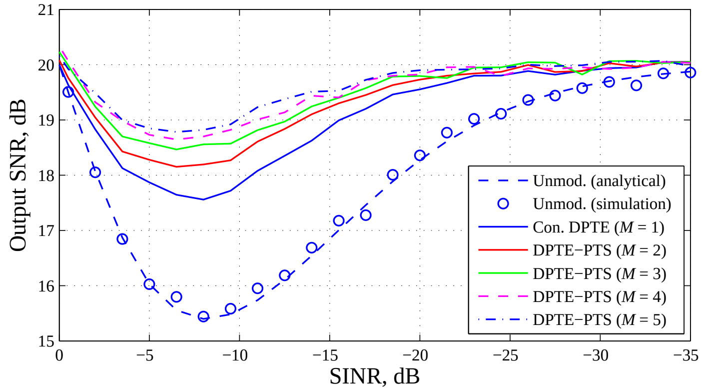
Fig. 5 illustrates the output SNR versus SINR for the unmodified, conventional DPTE and DPTE-PTS techniques with different values of M for $\{p = 0.01,\, 0.03,\, 0.1\}$. The analytical results of the unmodified technique are obtained from (9) with the assumption that IN characteristics are accurately determined at the receiver and, hence, the OBT in (11) is used. The good agreement between the analytical and simulation results indicates the accuracy of our simulation model. It is clear that the proposed technique always outperforms both the unmodified and the conventional DPTE techniques for all IN probabilities and, as anticipated, this enhancement increases as M becomes larger and p becomes smaller. It is also evident that as SINR becomes extremely small, the performance enhances. This is due to the fact that increasing the pulse amplitudes makes it more distinguishable at the receiver and hence more efficient blanking is performed. Furthermore, it is worthwhile pointing out that the worst performance is observed in the intermediate SINR region, i.e. $-15\text{dB} \lesssim \text{SINR} \lesssim -5\text{dB}$, and this can be justified as follows. In this SINR region, the noise amplitudes are slightly higher than the OFDM signal samples which makes this region most sensitive to blanking errors and therefore poorest performance is noticed here.

However, the SNR metric alone is not enough to infer the communication performance and therefore we have also considered the SER performance. Fig. 6 presents the SER versus SINR corresponding to the output SNR curves in Fig. 5, for the unmodified, conventional DPTE and DPTE-PTS systems with various values of p and M. The analytical results of the unmodified technique are found by substituting the output SNR calculated from (9) into [27]

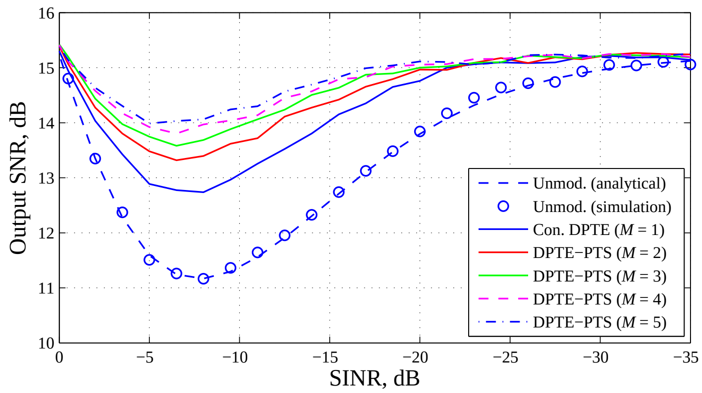
$$S_e = 1 - \left[1 - 2\left(1 - \frac{1}{\sqrt{L}}\right) Q\left(\sqrt{\frac{3\,\mathrm{SNR}_{unmod.}}{L-1}}\right)\right]^2 \tag{27}$$

where L is the constellation order which is 16 in this case (16QAM) and $Q(.)$ is the Gaussian $Q-$function defined as

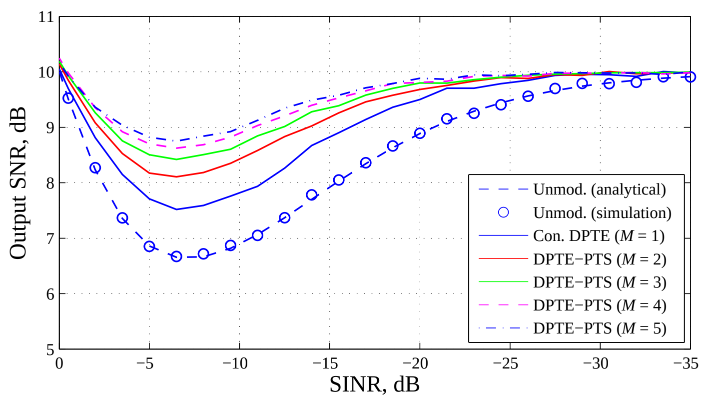
$$Q\left(x\right) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} exp\left(-\frac{x^2}{2}\right) \mathrm{dx} \tag{28}$$



(a) $p = 0.01$



(b) $p = 0.03$



(c) $p = 0.1$

Figure 5: Output SNR versus SINR for the unmodified, conventional DPTE and DPTE-PTS techniques for different values of p and M.

From Fig. 6 it is shown that the analytical results, obtained from (27), correlate well with the simulated ones and same trends as in the output SNR curves can be observed. It is worthwhile mentioning, however, that recovering the side information of the PTS scheme is crucial and in order to achieve best performance in practice, such information must be protected by using proper channel coding and interleaving schemes. It should also be noted that the proposed DPTE-PTS system is more complex than both the unmodified and conventional DPTE systems since more processing is performed at the transmitter and receiver sides which increases with increasing M. In addition, the conventional DPTE scheme has higher computational complexity relative to the unmodified system.

7. Conclusion

In this paper we investigated the performance of the DPTE technique combined with the PTS scheme in OFDM-based PLC systems as a means to mitigate IN. The analysis provided clearly demonstrates the superiority of the proposed system in terms of minimizing the probability of missed blanking and probability of blanking error as well as enhancing the probability of successful detection. Furthermore, the output SNR and SER performance of the proposed system have also been examined. The results reveal that DPTE-PTS system can provide up to 3.5 dB and 1 dB output SNR improvement with respect to the unmodified and conventional DPTE techniques, respectively. It was also presented that increasing the number of partitions of the PTS scheme will result in a better performance. However, this would be achieved at the expense of some computational complexity at the transmitter.

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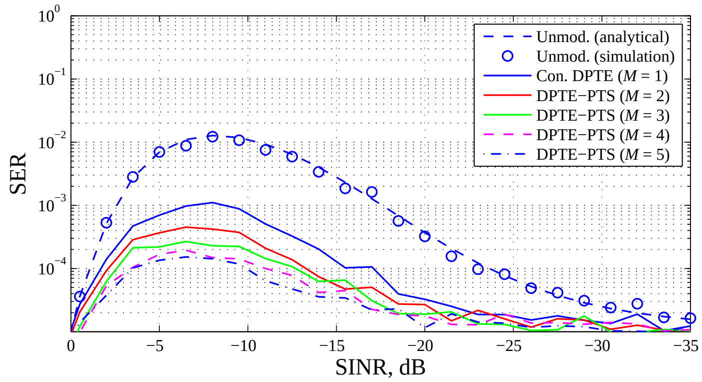
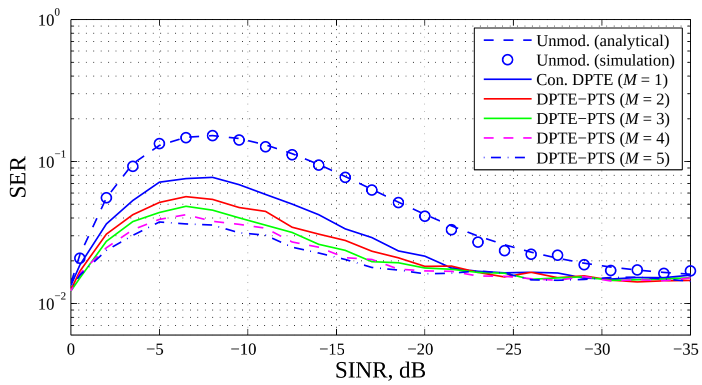
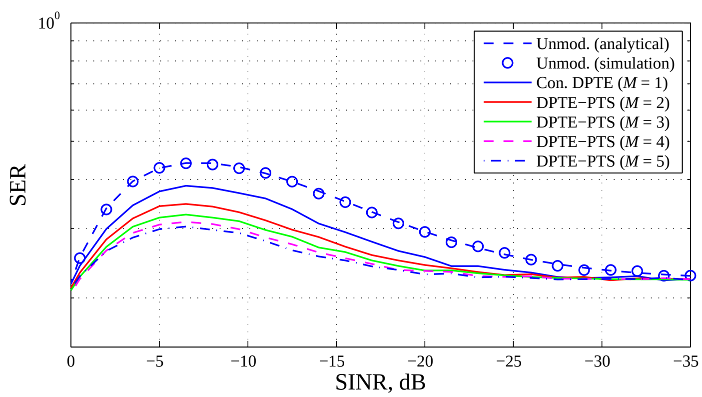


(a) $p = 0.01$



(b) $p = 0.03$



(c) $p = 0.1$

Figure 6: SER performance versus SINR for the unmodified, conventional DPTE and DPTE-PTS techniques for different values of p and M.

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