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COMPARISON OF TIME AND TIME-FREQUENCY DOMAINS IMPULSIVE NOISE MITIGATION TECHNIQUES FOR POWER LINE COMMUNICATIONS

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Abstract: Impulsive noise is one of the foremost situations in power line communications that degrades the performance of orthogonal frequency division multiplexing used for the power line communications channel. In this paper, a channel version of the broadband power line communications is assumed when evaluating the bit error rate performance. Three impulsive noise environments are assumed, namely heavily, moderately, and weakly disturbed. The well-known time domain mitigation techniques are tested first. These are clipping, blanking, and mixing clipping with blanking. The results of Matlab simulations show that these time-domain mitigation techniques don't significantly improve the bit error rate performance. A hybrid domain of time and frequency mitigation technique is used to enhance the bit error rate performance. The Matlab simulation results show that this hybrid domains of time and frequency approach outperforms time domain nonlinearities and can largely improve the bit error rate performance. Signal to noise ratio gains of about 8 dB, 10 dB, and 10 dB are obtained for heavily, moderately, and weakly disturbed channels, respectively, using the domains of time and frequency mitigation technique at bit error rate of 10^{-3} when compared to the blanking time domain technique.

Keywords: *Blanking; clipping; impulsive noise; power line communications*

1. Introduction

Power lines are used as a transmission path in power line communication (PLC). This provides the advantages of natural interaction with the electrical grid, extensive line distribution, and inexpensive construction costs. The PLC channel environment, in contrast to traditional communication media, is extremely complicated and severe [1]. In PLC, there is no need to construct additional infrastructure. A coupling circuit injects a modulated carrier wave onto the transmission line to transmit data signals [2]. The use of power lines for broadband multimedia communications has increased dramatically in recent years. Communication through power lines, on the other hand, is difficult due to hostile channel characteristics. Attenuation, noise, and multipath propagation are the most important channel features that degrade the performance of high-speed communications [2]. Unlike some other communication routes, electrical cables' noise cannot be described exclusively in terms of Additive White Gaussian Noise (AWGN). It can be divided into five categories [3]. In addition, there is non-synchronized noise, which can take the form of asymmetrical impulses with narrow-band distortions or non-synchronous impulses that are synchronous to the same main supply frequency. The first three categories of noise are often stationary over long periods (seconds, minutes, or hours) and are referred to as

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background noise. The final two categories of noise are time-varying and may be summed up as impulsive noise. It's also possible to have unsynchronized noise, which may take the form of asymmetrical impulses or non-synchronous impulses that are synchronized to the same primary supply frequency but have narrow band distortions. Microseconds to milliseconds is the range of time it takes for this phenomenon to occur at random. According to tests on power lines, impulsive noise has a power spectral density (PSD) of at least 10-15 dB greater than background noise. Because of the severe channel features, communicating across power lines necessitates a transmission technique that can efficiently deal with hostile channel circumstances. Because of its resistance to multipath, selective fading, and other types of interference, Orthogonal Frequency Division Multiplexing (OFDM) is a popular alternative solution for Time Domain systems. OFDM is an established multicarrier transmission technology that has been used in several wideband digital communication systems, such as Digital Audio Broadcasting (DAB) and Wi-Max. In the face of impulsive noise, OFDM outperforms single-carrier systems [2,4]. This is because, OFDM, through the use of the Discrete Fourier Transform (DFT), distributes the influence of impulsive noise across several symbols. Signal interference can also be minimized by adding a Cyclic Prefix (CP) to OFDM signals. Despite OFDM's benefits in the situation of impulsive noise, mitigation measures should be applied to further restrict its influence on transmitting data. Using a nonlinearity before the OFDM receives a signal is a simple way to decrease the effects of impulsive noise. model presented in Chien et al. [3]. proposed an approach that has been addressed for typical wireless OFDM receivers, namely a time domain (TD) method. In this paper, the first three TD nonlinearities, namely clipping, blanking, and mixing both clipping and blanking, are explored for the impulsive noise reduction in OFDM systems over PLC channels using a worked PLC channel model presented in [3]. In addition to these TD techniques, a comparison is made with a hybrid Time and Frequency Domain TD/FD approach for impulsive noise reduction[5,6]. Three different impulsive noise situations are considered. These are heavily, moderately, and weakly disturbed. The remaining sections of this paper are organized as follows: Section II presents the system model. Section III explains the principles of the TD and TD/FD hybrid techniques. Section IV gives the computer simulation results and discussions. Finally, section V gives some conclusions obtained from the results.

2. System Model

2.1. OFDM Signal

OFDM has been used by a wide range of telecommunication networks, including WLANs, visible light communication systems [7,8], PLC systems , and digital video broadcasting (DVB) systems [9]. Several disturbances make it impossible to ensure communication performance in the PLC channel when using OFDM-based PLC systems [10,11]. A robust and efficient data recovery technique is imperative to establish reliable data transmissions over severe PLC channels [12]. The multi-carrier transmission method OFDM operates effectively on PLC channels. Data is divided into many orthogonal subcarriers using the Inverse Discrete Fourier Transform (IDFT) in OFDM systems. This transforms a fast serial data stream into several slower parallel data streams. OFDM's extended symbol period has the effect of reducing the influence of inter-symbol interference (ISI) generated by signal multipath. The discrete-time OFDM signal is written as:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s_k \, e^{j2\pi \frac{k\,n}{N}}, 0 \le \mathrm{n} \le \mathrm{N}-1 \qquad (1)$$

(s_k) is a series of symbols mapped from binary data. In this work, QPSK mapping is used with N carriers. Inter-channel interference (ICI) and inter-symbol interference are both eliminated by using an OFDM cyclic prefix (CP) at the beginning of the OFDM transmissions (ISI).

2.2 Channel Model

Traditional communication channels have considerably different topologies, structures, and physical qualities than power line networks [6]. Power lines, which were not built primarily for data transmission, present a hostile environment for higher frequency communication signals [13]. High-speed communications suffer from signal distortion caused by frequency-dependent cable losses, multi-path propagation, and noise as a result of using this hostile medium. These and other factors must be taken into account if power line communication is to be successful. This necessitates accurate and practical simulations of the transmission properties of the power line channel [14]. This is given by:

$$H(f) = \sum_{i=1}^{N_p} C_i e^{-(a_0+a_1 f^k)di} e^{-j2\pi f(di/vp)} \quad (2)$$

The number of multi-paths is Np, C_i and d_i are the ith path's weight and length. a_0, a_1, and k are used to model frequency-dependent attenuators. The first exponent indicates attenuation in the PLC channel, while the second exponent, with propagation speed vp, depicts the echo situation. Physical measurements were used to determine the attenuation parameters for the 4-path model [6]. In this research, this widely used model is used to simulate and investigate the effectiveness of strategies used in minimizing impulsive noise in real-world PLC systems.

2.3. Impulsive Noise

In Çürük [15], narrowband PLC time variations and nonwhite noise are represented mathematically for the first time. N. Andreadou [16] proposed a noise model for power line channels that is easy to apply. In F. Gianaroli [17] and M. A. Sonmez [18], empirical noise approaches are being studied . Noise in the channels of the power lines cannot be characterized as AWGN. Data transfer in a PLC environment may encounter many sorts of noise. Colored noise, narrow-band noise, and other types of noise fall within this category. Periodic impulsive noise that is asynchronous to the main supply frequency, impulsive noise that is synchronous to the same main frequency, and asynchronous impulsive noise are all types of impulsive noise. The five forms of noise may be classified as either continuous or non-continuous. The background noise (w_k) is modeled as an AWGN with a mean zero and variance (σ_w^2), while "In R. K. Ahiadormey [2], provides an impulsive noise (i_k),"

$$i_k = b_k g_k \quad (3)$$

Where (b_k)is the probability that impulsive noise would occur, resulting in the so-called impulsive index, an unstructured mean zero with variance zero are the properties of the white Gaussian process (σ_i^2) used to simulate the height of the impulse (g_k).

Impulsive noise is more likely to be encountered if the Poisson distribution has just a rate in units per second, then the chance of k events occurring in a second is equal to [19]:

$$p(k) = p(x = k) = e^{-\lambda} \frac{\lambda^k}{k!} \ , k = 0 ,1,2 \quad (4)$$

It follows a Gaussian distribution with a mean of zero and σ_i^2 as the variance. It is revealed in Figure 1 that the mean impulse rate was five per second.

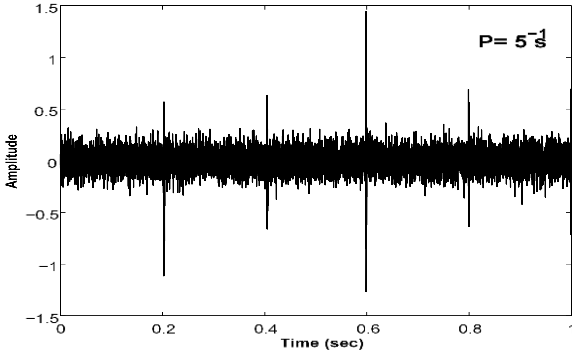

Figure 1. The Impulsive noise combined with (AWGN)

Three impulsive noise scenarios based on a PLC environment are studied to evaluate the efficacy of impulsive noise reduction strategies. These are heavily, moderately, and weakly disturbed. They are characterized by the average impulse rate as well as the impulsive index, which measures the number of impulses per second and the Disturbance Ratio (DR), which indicates the exact disturbed time and is computed as follows [3]:

$$\mathrm{DR}=\frac{\sum_{\mathrm{i=1}}^{\mathrm{Nimp}} t_{w.i}}{\mathrm{T_{tot}}} \tag{5}$$

"N_{imp}" is the total number of impulses in time T_{tot}, and $t_{w.\mathrm{i}}$ is the width of the ith impulse. The characteristics of these three situations are listed in table 1.

Table 1. The impulsive Features of the three Situations

Scenario	Impulsive index
Heavily disturbed	0.1
Medium disturbed	0.001
Weakly disturbed	0.0001

If s_k is the transmitted OFDM signal as given by Eq. (1), the received signal will be:

$$r_k = s_k * \mathrm{h} + w_k + i_k \quad k = 0,1,2,.,N-1 \tag{6}$$

Where h is the faded PLC channel impulse response with convolution represented by $(*)$ and are the Gaussian and impulsive noise signals w_k and i_k, respectively.

If p_n is the overall noise power (Gaussian noise plus impulsive noise), and p_x represents the average symbol power. The signal-to-noise ratio (SNR) is defined as:

$$SNR = \frac{p_x}{p_n} = \frac{p_x}{p_w + p_i} \tag{7}$$

Where p_w and p_i denote the background AWGN and impulsive noise power respectively. Because impulsive noise is modeled by a Poisson distribution that includes P impulses each second, the average impulsive noise power is given by:

$$p_i = P\sigma_i^2 \tag{8}$$

Where P is referred to the impulsive noise index, Hence [5]:

$$SNR = \frac{p_x}{p_n} = \frac{p_x}{\sigma_w^2 + P\sigma_i^2} \tag{9}$$

Where σ_i^2 is the average power of a single impulse during its $\mathrm{T_{noise}}$ period and is approximated by a Gaussian process as seen in eq. (3). To give a measure of the impulsive noise power as compared to AWGN noise power, a parameter B is suggested such that:

$$B = \frac{p_i}{p_w} = \frac{P\sigma_i^2}{\sigma_w^2} \tag{10}$$

3. Impulsive Noise Mitigation Techniques

3.1. Time Domain Impulsive Noise Mitigation Techniques

These techniques assume that the amplitude of the impulsive noise is greater than the OFDM signal amplitude. Therefore, the amplitudes of the sampled signals larger than a pre-set threshold value are presumed to be impacted by impulsive noise. When signal's amplitude reaches a certain threshold, amplitude clipping occurs, but the signal's phase remains unchanged. In contrast, amplitude blanking reduces signal's amplitude to zero. If T_c is the clipping threshold and T_b is blanking the threshold, then any sample having an amplitude lower than the threshold is considered to be correct OFDM and is passed unchanged, while those above the threshold are clipped to T_c . In blanking, every sampled signal having amplitudes below or equivalent to the threshold value, T_b , is passed and those above it are blanked off (replaced with zero). In the combined clipping/blanking method, T_c was chosen to be less than T_b , so samples having amplitudes lower than T_c , are passed while samples whose amplitudes are below the blanking threshold T_b are clipped to T_c , and samples having magnitudes above T_b are blanked off (set to zero).

Fig. 2 shows clipping, blanking, and the combined clipping/blanking of the OFDM signals.

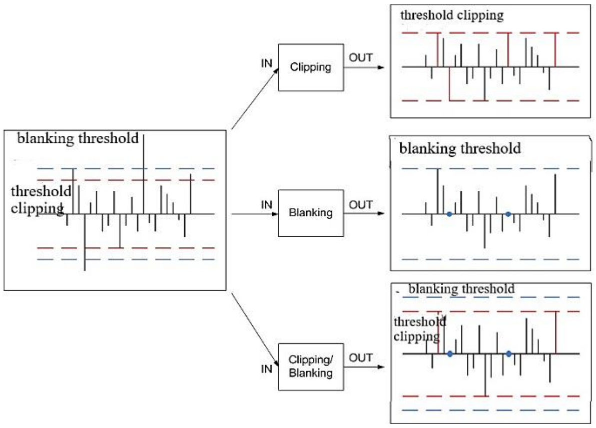

Figure 2. TD impulsive noise mitigation (clipping, blanking & clipping/blanking) schematics

Since the energy of the impulse noise is dispersed throughout the subcarriers in OFDM systems, the signal is more resilient to impulsive noise. Nonetheless, OFDM performance can be severely impacted by impulsive noise, especially on a medium-power line, if mitigation strategies are not used. Various approaches for reducing impulsive noise have been described in the literature [2,19,20]. Nonlinearity methods are often employed in real-world applications of impulsive noise suppression because of their simplicity [5] . Fast Fourier Transforms (FFTs)are utilized at the front end of an OFDM receiver before demodulation (FFT).

Fig. 3 shows an OFDM block diagram including a nonlinear block for impulsive noise reduction before (FFT) demodulation. These strategies just modify the signal's amplitude in response to a certain threshold, without changing its phase. The following equations describe the operation of TD mitigations:

1) Clipping

$$y_k = \begin{cases} r_k & |r_k| \leq T_c \\ T_c\, e^{j\omega(r_k)} & |r_k| > T_c \end{cases} \quad \mathrm{k} = 0,1,.,\mathrm{N}-1 \quad (11)$$

, T_c Is the threshold for clipping

2) Blanking

$$y_k = \begin{cases} r_k & |r_k| \leq T_b \\ 0 & |r_k| > T_b \end{cases} \quad \mathrm{k} = 0\,,1,\ldots., \mathrm{N}\text{-}1,\ T_b$$

is blanking threshold (12)

3)Mixing (clipping and blanking)

$$y_k = \begin{cases} r_k & |r_k| \leq T \\ \alpha T e^{j\omega(r_k)} & T < |r_k| \leq \alpha \mathrm{T} \quad \mathrm{k} = 0\,.1.\ldots.\mathrm{N}-1 \\ 0 & |r_k| > T \end{cases} \quad (13)$$

Where the clipping threshold (T_c) is smaller than the blanking threshold (T_b), r_k and y_k are nonlinear devices' input and output, respectively, and α is a scaling factor (α > 1) that determines the proportion between the blanking and clipping thresholds. Furthermore, it was discovered that the adaptive hybrid scheme could establish the nonlinear preprocessing methods that are based on lower limit performance because it optimizes both the scaling factor and the threshold [13].

To reduce BER, the clipping and blanking thresholds must be carefully chosen. If T_c or T_b is small, most OFDM signal samples are clipped or replaced with zeroes. This raises the BER. Nonlinear preprocessing, on the other hand, has no effect on the incoming signal at high values of T_c or T_b , therefore impulsive noise can have a significant impact on system performance.

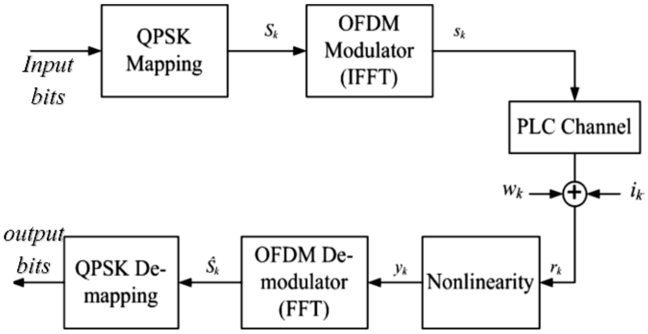

Figure 3. Impulsive noise mitigation in the TD of an OFDM-based PLC system.

It should be noted, however, that these time-domain techniques have a limited advantage in solving the problem of impulsive noise in the PLC channel. These techniques depend mainly on the assumption that the impulsive noise level is always higher than the level of the OFDM signal itself. This assumption is no longer valid when the impulse comes with positive polarity on the negative polarity of the OFDM signal or when the impulse comes with negative polarity on the positive polarity of the OFDM signal. In these two cases, which may represent 50% of the occurrence of the impulsive noise, all TD techniques fail to detect the impulse or even mistakenly detect it as shown in Fig.4.

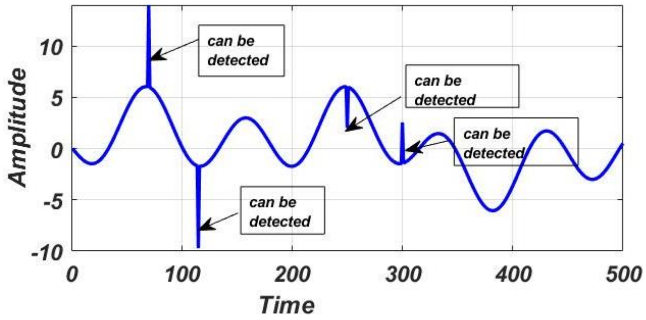

Figure 4. An OFDM signal with impulsive noise.

3.2. Hybrid Time and Frequency Domain (TD/FD) Mitigation Technique:

A FD approach can largely solve the problem of impulse detection in TD. A summary of this FD approach is given in this section.

After channel equalization and DFT demodulation, the signal at the receiver side of the OFDM system may be written as [5], [6]:

$$R_k^{(eq)} = S_k + W_k \hat{H}_k^{-1} + I_k \hat{H}_k^{-1} \text{ , } k = 0,1,\ldots\ldots,N-1 \quad (14)$$

For AWGN and impulsive noise, the DFTs are W and I, respectively. H is the channel transfer function. The algorithm's main goal is to provide an estimate using the phrase "impulsive noise"$I_k \hat{H}_k^{-1}$ and then subtract it from the results of equalization .i.e.

$$\widehat{D}_k = \hat{H}_k^{-1} \left(R_k^{(eq)} - S_k \right) \text{ ,} k = 0, 1,\ldots\ldots,N-1 \quad (15)$$

The phrase used to describe the entire amount of noise $\widehat{D}_k$ is then translated into the TD using IDFT, and the estimated impulsive noise signal $\hat{\imath}_k$ in the TD is obtained using a peak detector [6].

The channel transfer function is divided by the DFT of $\hat{\imath}_k$, which is then calculated. The following are the steps for obtaining the signal after impulsive noise reduction:

$$R_k^{(comp)} = R_k^{(eq)} - \hat{I}_k \hat{H}_k^{-1} \quad , k = 0,1,\ldots\ldots,N-1 \quad (16)$$

Following the OFDM systems shown in Figures (5) and (6), a TD preprocessor is used to minimize the impulsive noise of the received OFDM signals r_k. A blanking nonlinearity serves as the preprocessing. This method of combining nonlinearities is known to outperform blanking nonlinearities. After channel equalization and demodulation using DFT [21], a frequency-domain suppression approach is used to improve impulsive noise mitigation. For further reduction of impulsive noise in OFDM-based PLC systems, the combined TD/FD method is suggested. This is so-called a hybrid TD/FD.

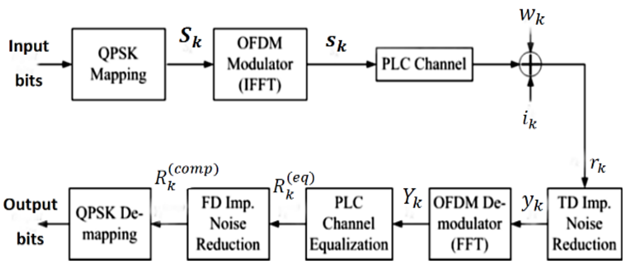

Figure 5. Hybrid Time/Frequency Domain (TD/FD) mitigation configuration.

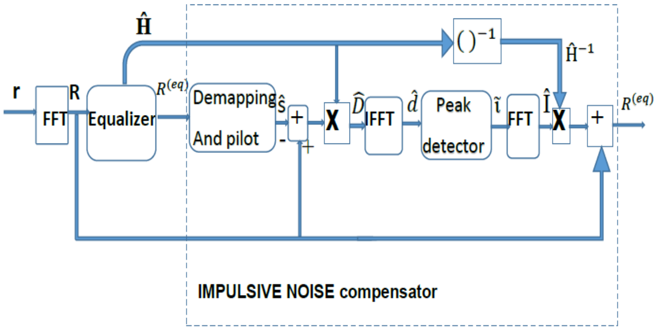

Figure 6. FD impulsive noise suppression

4. Experimental Results and Discussions

Matlab m.files are used to simulate the transmitter, receiver, and PLC channel. Table (2) shows different simulation parameters.

Table 2. Matlab simulation parameters

Type of modulation	QPSK
Number of OFDM carriers	256
Number of faded channel paths	4
Number of cyclic prefix	16
Number of transmitted bits	2*256*5000
Type of fading	Rayleigh Frequency selective
Number of pilots	2

4.1. Experimental Results without any Mitigation

4.1.1. The Effects of the Ratio between Impulsive Noise Power and Background Noise Power for the Same Impulsive Noise Index

This section demonstrates the effect of the ratio B given in eq. (10) for the same impulsive noise index P. Figure (7) shows the BER performance with the ratio B as a parameter. It is clear from these curves that the BER increases as the ratio B increases for the same P. This is quite expected since, as B increases, the impulsive noise power $P\sigma_i^2$ increases at the expense of increasing σ_i^2 for the same P.

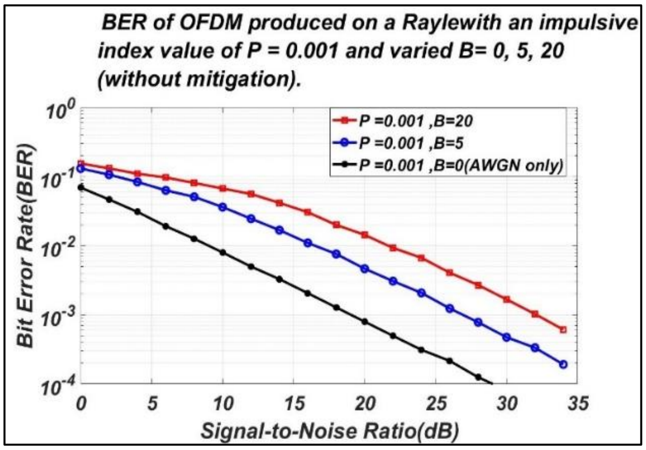

Figure 7. The BER of a Rayleigh channel plus impulsive noise with a fixed impulsive index of P=0.001

4.1.2. The Effects of the Impulsive Noise Index P for the same B Ratio

According to Figure (8), BER increases when the impulsive index P grows (P = 0.0001;0.01;0.1) for a fixed ratio B =5. As P is large, the BER increases and higher SNR is required when compared to AWGN alone. It's also worth noting that every subsequent rise in P raises the BER only at low SNR values.

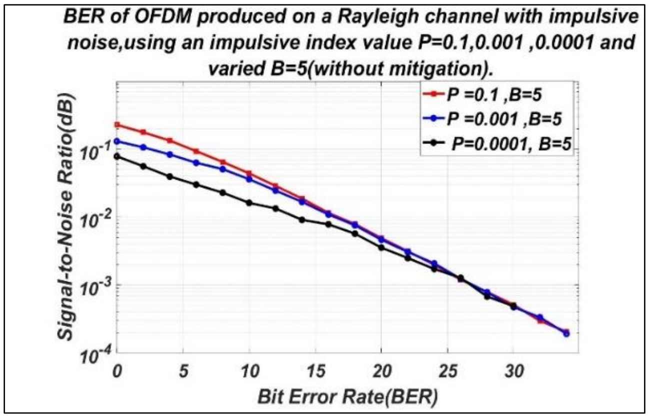

Figure 8. The effect of the impulsive index P on the BER for the same ratio B=5

4.2. Simulation Results with Time domain Mitigations

4.2.1 Heavily Disturbed PLC channel

Figure (9) shows that the three TD mitigations have almost the same performance for small SNR values. However, blanking approach beats the others slightly for high SNR values. Simulations also show that blanking is the best answer. This approach can occasionally outperform clipping and clipping/blanking. It is worth noting that in this setting, all three approaches yield small benefits at high SNR levels.

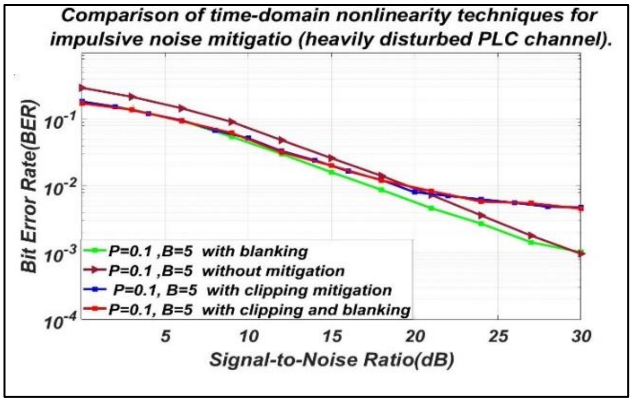

Figure 9. BER comparison of TD nonlinearity techniques for impulsive noise reduction (heavily disturbed PLC channel).

4.2.2 Moderately Disturbed PLC channel

As shown in Fig. 10, blanking nonlinearity outperforms the other two mitigation techniques for the "moderately disturbed channel". In this environment, all three mitigation techniques considerably combat the influence of impulsive noise, but for high SNR values, blanking nonlinearity can slightly reduce the BER of an OFDM-based PLC receiver.

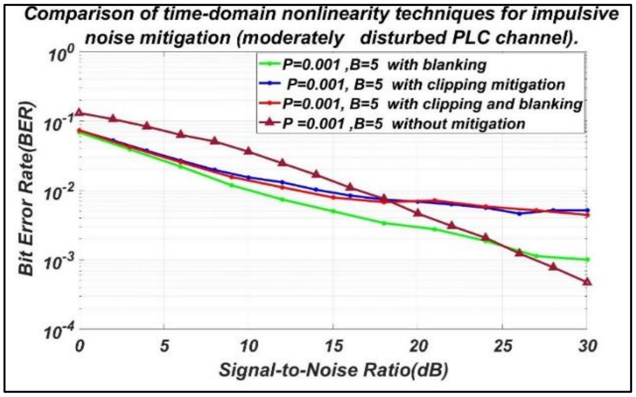

Figure 10. BER comparison of TD approaches to impulsive noise reduction (moderately disturbed PLC channel).

4.2.3 weakly Disturbed PLC channel

As shown in Fig.11, the combined (Blanking/Clipping) and clipping mitigation techniques have the same BER performance in the case of "weakly disrupted PLC". The BER advantage is clear only at higher SNR values.

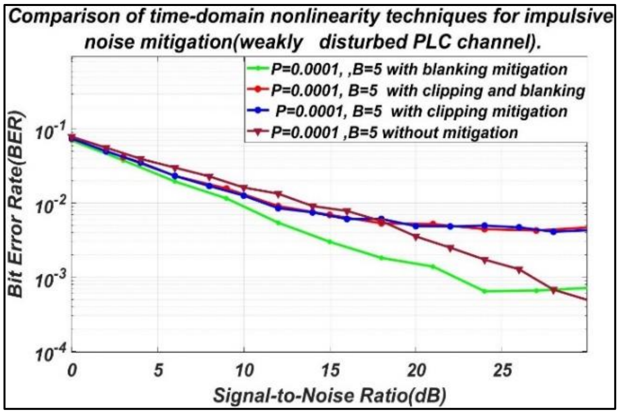

Figure 11. BER comparison of TD approaches to impulsive noise reduction (weakly disturbed PLC channel).

4.3. Simulation Results with Hybrid Time and Frequency Domain Mitigations

4.3.1 Heavily Disturbed PLC channel

In this noise scenario, and as shown in Fig.12, the hybrid TD/FD mitigation strategy outperforms TD blanking strategy for SNR greater than 10dB. For example, at BER of 10^{-3}, the TD/FD technique outperforms TD blanking by about 8 dB. The TD/FD approach gives this BER at an SNR of about 22dB, while a 30dB SNR is required to give this BER with blanking TD technique.

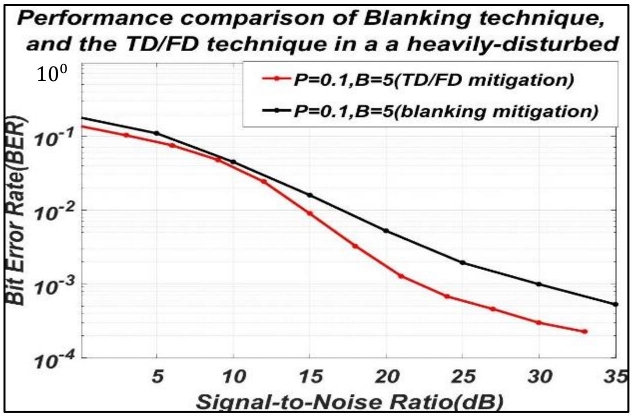

Figure 12. BER comparison of TD/FD and blanking TD for OFDM-based PLC in a noisy environment.

4.3.2 Moderately Disturbed PLC channel

As shown in Fig. 13, the hybrid TD/FD mitigation strategy outperforms TD blanking nonlinearities for all SNR values. For example, at BER of 10^{-3}, the TD/FD technique outperforms TD blanking by about 10dB. The TD/FD approach gives this BER at an SNR of about 20dB, while a 30dB SNR is required to give this BER with the blanking TD technique.

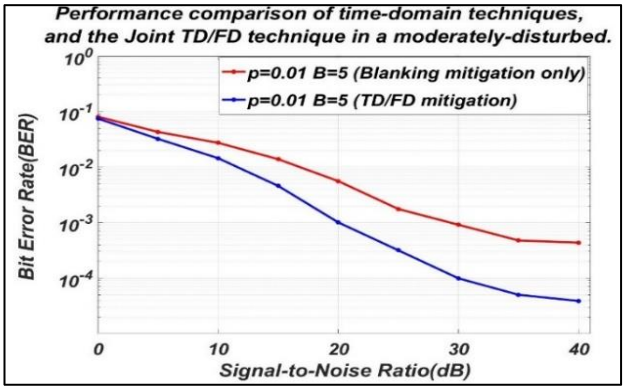

Figure 13. BER performance comparison of TD/FD and blanking TD techniques for OFDM-Based PLC in a moderately-disturbed environment

4.3.3 Weakly Disturbed PLC channel

Figure 14 shows the performance of the TD/FD approach in a PLC with impulsive noise that is weakly affected. Here, at BER of 10^{-3}, the TD/FD technique outperforms the TD blanking technique by about 10dB. The TD/FD approach gives this BER at an SNR of about 18dB, while a 28dB SNR is required to give this BER with the blanking TD technique.

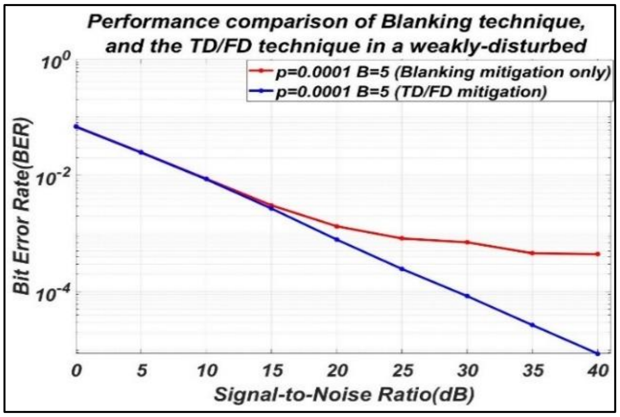

Figure 14.BER comparison of TD/FD and blanking TD for OFDM-based PLC in a weakly-disturbed environment.

5. Conclusions

The BER performance of time domain techniques (blanking, clipping and combined clipping/blanking) for the impulsive noise reduction in the OFDM system used in actual PLC channel conditions was examined in this research. Matlab computer simulations were used to compare these three techniques. The simulation results showed that these three-time domain techniques have limited ability to reduce the effects of impulsiveness. These results support the fact that all time-domain techniques assume that the impulsive noise level is always higher than the level of the OFDM itself. This assumption is no longer valid when the impulse comes with positive polarity on the negative polarity of the OFDM signal or the impulse comes with negative polarity on positive polarity of the OFDM signal. In these two cases which may represent 50% of the occurrence of impulsive noise, all-time domain techniques fail to detect the impulse or even mistakenly detect it which results in the worst BER performance.

A TD/FD technique showed a considerable enhancement in BER performance as compared with time domain techniques. For heavily, moderately, and weakly disturbed PLC channels and at BER of 10^{-3}, the SNR gains were about 8dB, 10dB, and 10dB, respectively, as compared with the SNR requirements using the blanking TD technique. Simulations validated a BER-based adaptive threshold selection technique. Combining time domain nonlinearities with a frequency domain technique reduces impulsive noise effects.

Additional work could look at the best way to design the synchronization frame structure to decrease both narrowband interference (NBI) and impulsive noise (IN) at the same time, which would improve spectrum efficiency and use fewer time and frequency resources. The influence of NBI and IN on novel coded modulation techniques can be studied in next-generation wireless communication.

Conflict of interest

The authors confirm that the publication of this article causes no conflict of interest.

Abbreviations

B	Ratio of impulsive noise power to AWGN noise power
BER	Bit Error Rate
FD	Frequency Domain
IN	impulsive noise index
P	impulsive noise index
PLC	Power Line Communications
TD	Time Domain
TD/FD	Hybrid Time and Frequency Domain

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