Noise Mitigation over Powerline Communication Using LDPC-Convolutional Code and Fusion of Mean and Median Filters

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Abstract: In this paper, we propose a new impulse noise mitigation approach in Orthogonal Frequency Division Multiplexing (OFDM) signals over Powerline communication (PLC) channel. Recently LDPC-Convolutional Code (LDPC-CC) has received much interest as an alternative to LDPC codes for its advantages and low complexity. The proposed approach exploits the redundancy introduced by LDPC-CC and cyclic prefix (CP) added to the OFDM transmitter to recover noisy coefficients. It is based on the fusion of median and mean of their neighboring coefficients using a window and a dynamic threshold calculated on the basis of noise variance and the peak value of the noise in the received signal. Detection of noisy coefficients takes into consideration the neighboring coefficients. The proposed technique presents a good robustness to impulse noise performance without adding a big complexity to the transmission system. Promising results have been achieved by the proposed approach when compared to filtering and coding techniques alone.

1 INTRODUCTION

Interest in PLC technology as a broadband multimedia connectivity solution to and within the home continues to grow in a rapid pace. The driving advantage of this technology is that it exploits the already existing and ubiquitous power line distribution infrastructure to provide broadband multimedia services to customers. Because power lines were originally designed for AC power distribution at 50 Hz and 60 Hz, the characteristics of this channel present some technical challenges for data transmission at higher frequencies. A big degradation can be caused by impulse noise generated over powerline channel.

OFDM modulation, deployed in the vast majority of today's networks is used in the PLC channel (Anatory et al., 2009). It is a promising technique for increasing the bandwidth of narrowband power line communications (Lakshmi et al., 2008). Although OFDM reduces the effect of impulsive noise in data transmission, it is necessary to employ mitigation techniques in order to cope with PLC channel conditions and achieve higher data rates.

Recent investigations have studied different approaches for noise mitigation over PLC. The simplest of such methods is to precede the conventional OFDM demodulator with a blanker or a clipper (Haffenden et al., 2000). This method is widely used in practice because of its simplicity and ease of implementation. Theoretical performance analysis and optimization of blanking was first investigated by Zhidkov in (Zhidkov, 2004) and (Zhidkov, 2006), where a closed-form expression for the signal-to-noise ratio (SNR) at the output of the blanker was derived and the problem of blanking threshold selection in the presence of impulse noise was addressed. On the other side, a multitude of works have studied the performance of LDPC codes on PLC channel (Tanner, 1981 and MacKay, 1999). The authors of (Andreadou, 2007), e.g., have shown that LDPC codes can perform better than Reed–Solomon or convolutional codes on PLC channel. In (Wada, 2004), it was found that the performance of LDPC codes is superior to that of the Turbo codes (Berrou et al., 1993) under a cyclo-stationary Gaussian noise environment.

In this paper we present an OFDM-PLC noise mitigation in two steps: first, we use LDPC-CC to protect the source data, since they present more advantages over the LDPC codes. Then, in the second step, we use a fusion of mean and median

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filter (FMMF) to compensate the impulse noise generated over PLC channel by exploiting the redundancy introduced by LDPC-CC and CP.

The rest of the paper is organized as follows. In section 2 the models for OFDM system, PLC channel and impulsive noise are reviewed. In section 3, the proposed noise mitigation approach based LDPC-CC/FMMF is explained. Section 4 presents the simulation results of the proposed technique in practically proven PLC channel conditions. Then in section 5 conclusions and perspectives are drawn.

2 SYSTEM MODEL

A general system model of indoor PLC OFDM systems is depicted in Fig. 1. With a LDPC-CC coded OFDM transmitter, the signal sequence to be transmitted, given as Y_n, is first LDPC-CC coded and then serial-to-parallel (S/P) converted to form the N data streams Y_n, where $0 \leq n \leq N-1$. The S/P output is subcarrier modulated using BPSK, QPSK or QAM, etc., prior to the application of the N-point inverse discrete Fourier transform (IDFT) process (Canete et al., 2006), that is,

$$x_k = \sum_{n=0}^{N-1} S_n \exp(j\frac{2\pi nk}{N}), \quad 0 \leq k \leq N-1 \qquad (1)$$

where IDFT indicates IDFT process, and S_n is the subcarrier modulated signal. In order to combat inter-channel interference (ICI) and inter-symbol interference (ISI), OFDM uses a CP that is appended at the start of OFDM symbols.

The k output streams of x_k are then parallel-to-serial (P/S) converted and used to modulate a radio frequency (RF) carrier for transmission over the desired communications channel.

Generally, noise in the channel can be considered as impulsive noise (Zimmermann and Dostert, 2002) The OFDM receiver simply reverses the transmission process and after the RF demodulation, the received OFDM signal r_k is modeled as follows:

$$r_k = x_k * h_k + n_k = x_k * h_k + i_k + w_k \qquad (2)$$

where h_k, w_k, and i_k are the channel impulse response, AWGN, and impulsive noise representations, respectively. * indicates a convolution operation and n_k is the aggregation of w_k and i_k. The resulting sequence r_k is then S/P transformed into a parallel format and CP was being removed. A N-point DFT process is applied:

$$R_n = \sum_{k=0}^{N-1} r_k \exp(-j\frac{2\pi nk}{N}), \quad 0 \leq k \leq N-1 \qquad (3)$$

where DFT indicates DFT process. The N-point DFT is then P/S converted with a subcarrier demodulation process corresponding to the subcarrier modulation used during transmission. In our research, the FFT and IFFT are utilized for the implementation of DFT and IDFT, respectively. When a channel equalizer is not considered, we can represent R_n as

$$R_n = S_n H_n + I_n \qquad (4)$$

where H_n is the channel frequency response and I_n is impulsive noise in frequency domain.

2.1 Powerline Channel Model

The power line network differs than other communication channels in topology, structure, and physical properties.

In this paper, we adopt a widely accepted and practically proven PLC multipath channel model (Canete et al., 2011).

Numerous reflections are caused at the joints of the network topology due to impedance variations. Factors such as multipath propagation and attenuation are considered when designing PLC model.

The PLC model used is a bottom-up model which is usually based on transmission line theory. This approach requires perfect knowledge of the targeting power network, including its topology, the used power line cable and load impedances of terminals. These network elements are modeled mathematically so that they can be incorporated to generate the channel. The channel model was proposed in (Canete et al., 2011), it is shown in Fig. 2 and is based on a particularly simple topology of a PLC network with few transmission lines and loads to derive a parametric model that still preserves the essential behavior of these channels in the HF band (up to 30 MHz). The line lengths or the loads impedance are generated from independent statistical distributions, the topology gives a natural correlation to the behavioral parameters of the channel response, like the attenuation and the RMS-DS (root mean squared delay spread).

After measuring many electrical appliances (Canete et al., 2006), the observed behavior can be classified into three groups: approximately constant impedances (a not very common case); time-

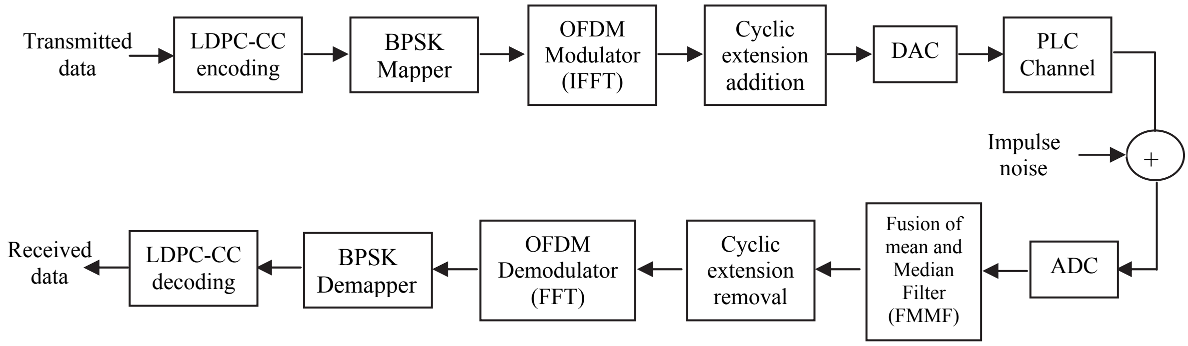

Figure 1: OFDM-PLC system model used in the simulation process.

invariant but frequency-selective impedances; and time-varying and frequency selective impedances.

For the *constant impedances*, reasonable values are {5, 50, 150, 1000, ∞}Ω. They represent, respectively, low, RF standard, similar to transmission line *Z*0, high, and open circuit impedances. For the *frequency-selective impedances* an adequate model is a parallel RLC resonant circuit, whose impedance can be described as,

$$Z(w) = \frac{R}{1 + jQ(\frac{\omega}{\omega_0} + \frac{\omega_0}{\omega})} \qquad (5)$$

where R is the resistance at resonance; ω_0, resonance angular frequency; and Q, quality factor (which determines selectivity).The second group corresponds to a more "harmonic" impedance variation along the mains period that can be modeled as,

$$Z(\omega, t) = Z_A(\omega) + Z_B(\omega)\left|\sin\left(\frac{2\pi}{T_0}t + \emptyset\right)\right|;\ 0 \le t \le T_0 \qquad (6)$$

This function contains a rectified sinusoid synchronized with the mains voltage. It has three parameters: the offset impedance, Z_A; the amplitude of the variation, Z_B; and a phase term ∅, which serves to reference the variation with respect to the mains voltage zero-crossing. The simplified network layout used in PLC modeling can be observed in Fig.2.

The model presented so far permits the generation of PLC channels at random to create representative channels in a statistical sense. The generation is addressed by proposing parameter values or ranges, based on many channel and load measurements, and on some intuitive decisions from the physics of the problem. The following parameters are suggested for LTI channel generation in the frequency band up to 30 MHz: Discrete-frequency resolution: N = 2048 points in the positive axis, the resolution is 14 kHz (Canete et al., 2011).

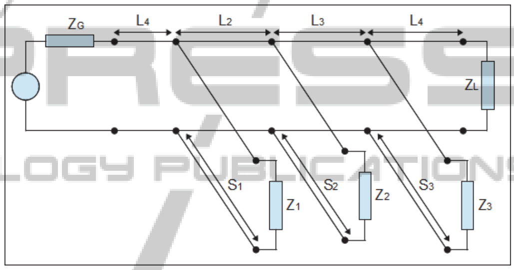

Figure 2: Network topology for the PLC model used in the simulation.

2.2 Impulse Noise Model

Serious efforts have been made in order to find the time and frequency characteristics of the impulse noise ((Zimmermann and Dostert, 2002, Degardin et al., 2002) and prevent severe signal degradations. Interference generated by this noise at a receiver within a PLC network can be modeled by a Poisson model (Korki et al., 2011). The impulse noise used in evaluation step is given by

$$i_k = b_k g_k \qquad (7)$$

where b_k is the Poisson process which is the arrival of impulsive noise, and g_k is white Gaussian process with mean zero and variance $\sigma_i{}^2$. The arrival of impulses is modeled according to the Poisson process, and the impulsive noise amplitudes are modeled based on the Gaussian process with a mean of zero and variance $\sigma_n{}^2$. This means that impulsive noise will occur according to a Poisson distribution with a rate λ units per second, so that the probability of an event of m arrivals in unit time is:

$$P_p(t) = P_p(T = t) = e^{-\lambda}\frac{\lambda^t}{t!}, \quad t = 0,1,2,\ldots \qquad (8)$$

3 IMPULSE NOISE MITIGATION SYSTEM

3.1 LDPC-Convolutional Codes

In this paper, we use a class of convolutional codes defined by a low density parity-check matrix and an iterative algorithm of the decoding of these codes (Felstrom and Zigangirov, 1999) in order to reduce the impulse noise generated over the powerline channel.

The choice of using LDPC-CC is motivated by the fact that it is simple to encode, since the original code construction method yields to a shift register based systematic encoding. It is suitable for transmission of continuous data as well as block transmissions in frames of arbitrary size where LDPC can transmit only block of fixed length. For a given complexity LDPC-CC has better performance than LDPC block codes and has excellent BER performance under AWGN.

An (m_s, J, K) regular LDPC convolutional code is a set of sequences v satisfying equation $vH^T = 0$, where

$$H^T = \begin{bmatrix} H_0^T & \dots & H_{m_s}{}^T(m_s) & & \\ & \ddots & & \ddots & \\ & & H_0{}^T(t) & \dots & H_{m_s}{}^T(t+m_s) \\ & & \ddots & & \ddots \end{bmatrix} \quad (9)$$

where m_s is the memory and T is the period of the LDPC-CC, and t ∈ Z is the time index (Felstrom and Zigangirov, 1999). The submatrices $H_i{}^T(t+i),\ i = 0,\dots,M$ are $c \times (c-b)$ binary matrices, where b is the number of information bits that enter the encoder, and c is the number of coded bits that exit the encoder at a given time index. The rate of the code is $R = b/c$. Submatrices H^T are defined as

$$H^T = \begin{bmatrix} h_i{}^{(1,1)}(t) & \dots & h_i{}^{(1,c-b)}(t) \\ \vdots & & \vdots \\ \vdots & & \vdots \\ h_i{}^{(c-1,1)}(t) & \dots & h_i{}^{(c,c-b)}(t) \end{bmatrix} \quad (10)$$

The memory is equal to the largest i such that $H_i{}^T\ (t+i)$ is a nonzero matrix, and $T = M(c-b)$. An example parity-check matrix for $M = 6$ rate-1/2 LDPC-CC is shown in Figure 3.

The associated constraint length is defined as $v_s = (m_s+1).c$. The Tanner graph of an LDPC convolutional code has an infinite number of nodes. However, the distance between two variables nodes that are connected by the same check node is limited by the syndrome former memory m_s of the code.

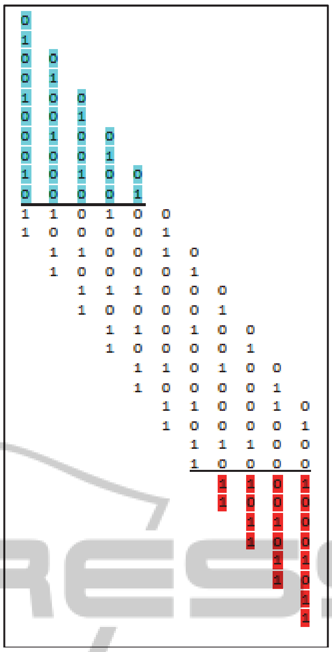

Figure 3: An example parity-check matrix,H^T, for a rate-1/2 LDPC-CC.

As a consequence, the decoding of two variable nodes that are at least (m_s+1) time units apart from each other can be performed independently, since they do not participate in the same parity-check equation. This allows continuous decoding that operates on a finite window sliding along the received sequence. Encoder structure is shown in Fig. 4. Message passing LDPC codes decoding bases on min-sum algorithms. The corresponding H^T generated from with parity check matrix is used for decoding. The decoder will only update statistics corresponding to the non-highlighted section of H^T. It manages data flow between sub-decoder (min-sum decoder) period and between iterations.

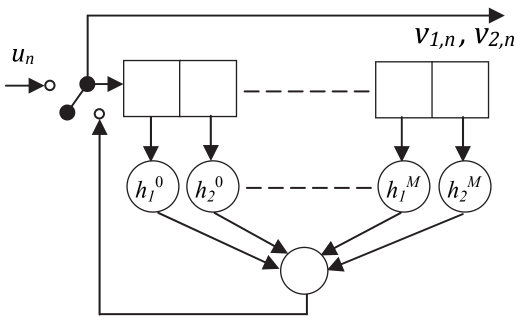

Figure 4: Convolutional codes encoder structure.

$$y_k = \begin{cases} |\alpha.M+\gamma.\text{Med}|\ , & \text{if } |r_k| \geq T_c \ and\ |r_k| < r_{k-1} \text{ and } |r_k| < r_{k+1} \\ r_k, & \text{if } |r_k| < T_c \end{cases} \tag{11}$$

3.2 Fusion of Mean and Median Filter

All practical Coded OFDM (COFDM) systems contain redundancy not only in the form of an error control code (e. g. Turbo-code or LDPC), but also in the form of a cyclic prefix (CP), added by the OFDM transmitter to reduce the inter-block interference (IBI) caused by multipath propagation. By exploiting the redundancy introduced by LDPC-CC and CP we propose an impulse noise mitigation based on the fusion of mean and median values of their neighboring coefficients using a window, as shown in Fig. 5. The window size is selected based on the performances obtained for each size in term of SNR and BER of reconstructed data approach that recovers denoised OFDM coefficients of the transmitted signal based on the fusion of median and mean.

3.2.1 Fusion Strategy

Mean filter is arithmetic simpleness and rapid calculation speed. But there are some disadvantages given as follows. Signal coefficients will be blurred by mean filter processing with equal weighting coefficient. It is very sensitive to impulse noise, the bad effect of the extremeness coefficients can be diffused to other coefficients around. Also, it doesn't consider the relativity between signal samples. From the analysis above, the typical mean filter algorithm can be improved greatly by optimizing the weighting coefficient.

Adaptive median filter can reduce the distortion of signal through removing the extremeness value of window w and reserving the pic value with middle level. However, with the increase of noise density, the denoising effect of adaptive median filter gets worse, especially when Gaussian noise exists too. In order to achieve the better denoising effect and preserve the signal coefficients well, mean filter technique is necessary to be combined.

3.2.2 Noise Detection and Reduction

The detection of noisy coefficients in the received OFDM signal is performed by calculating a noise threshold and by comparing the central pixel in the window to its neighbors. If the central coefficient is bigger than the noise threshold and their neighbors, it will be considered as a noisy coefficient and it will replaced by the fusion of mean and median values of neighbors as indicated in equation (11). Else if it is bigger than the noise threshold and smaller or equal to one of their neighbors, it will be considered as noiseless coefficient and its value will be preserved.
where T_c is the noise threshold value, r_k and y_k are the input and output of the thresholding system, respectively. α and γ denote the relative weights of importance of mean and median filters of the neighboring coefficients. M and Med reprente the mean and median values repectively.

By analyzing the effect of impulse noise on OFDM signal, we can see that it generates a series of peak values which have large amplitudes in comparison with other coefficients values.

Based on the work realized by Donoho et al (Donoho and Johnstone, 1995) and on an experimental study, we have found that the noise threshold T_c has a relation with the noise variance and the peak value of the noisy signal. For these reasons, we have proposed a new threshold function that estimates noise threshold in OFDM signal, as it is mentioned in the equation (12)

$$T_c = \frac{\sigma.\sqrt{2.\log(N)}}{(1+\sqrt{1+\frac{\beta}{2}})} \tag{12}$$

where N is the signal length, σ is the noise variance which is well known in wavelet literature as the Universal threshold. It is the optimal threshold in the asymptotic sense and minimizes the cost function (Donoho and Johnstone , 1995).
An estimate of the noise level σ was defined based on the median absolute deviation given by

$$\hat{\sigma} = \frac{Median(\{|\ r_k(\text{i})|\}}{0.6745}, i = 1, 2, \ldots, N \tag{13}$$

and

$$\beta = \sqrt{\frac{\max\{|\ r_k(\text{i})|\}}{Median(\{|\ r_k(\text{i})|\}}} \tag{14}$$

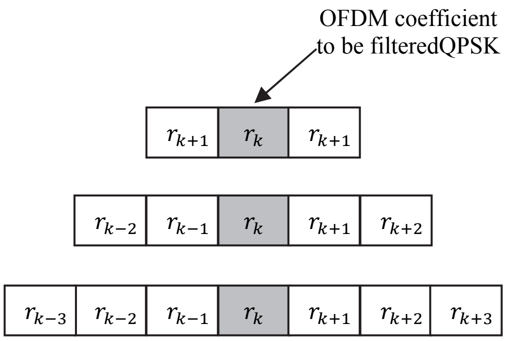

Figure 5: The different windows used in the simulation.

Estimate the noise threshold T_c is a delicate task; it must be carefully selected to minimize the BER in the receiver. If T_c is too small, most of the received samples of the OFDM signal will be clipped resulting in poor BER performance. On the other hand, for very large T_c, clipping will have a negligible effect on the received signal, allowing most of the impulse noise to be part of the detected signal, hence degrading performance. Therefore, a simulation based on the proposed method is used to analyze the effects of different window sizes. It seems that larger window includes more information. However, the statistical results in Table 1 indicate that it is not so. As the window size becoming larger, SNR declines proportionally. Therefore, the OFDM signal coefficients are correlated in a small neighborhood. So we choose the window (L = 3). The proposed algorithm can be summarized in the following steps

Step 1. Calculate the peak value of the received noisy OFDM signal β and estimate the Noise variance $\hat{\sigma}$ using equation (14) and (13) respectively.

Step 2. Estimate the noise threshold value T_c using equation (12).

Step 3. Filter the received signal using equation (11) and a 1x3 window.

Step 4. Repeat steps 1,2 et 3 for all coefficients of the noisy OFDM signal.

4 SIMULATION RESULTS

Matlab software was utilized to study the performance of the proposed combined LDPC-CC/FMMF impulsive noise mitigation technique.

A random signal is mapped into a BPSK symbols and modulated using OFDM with 128 subcarriers and passed through a PLC multipath channel. The noise generated is considered as an impulse noise. The arrival of this noise is assumed to follow a Poisson distribution and is added to the transmitted signal. Clipping, blanking and proposed noise mitigation approaches are then employed in the OFDM receiver and their performances are compared.

Table 1: Improvement reached by the proposed adaptive noise clipping system for different window sizes at 0 [dB].

Windows size	SNR(dB)
L=3	9.842
L=5	9.315
L=7	8.679
L=9	8.213

In the clipping approach, we precede the OFDM receiver with clipping nonlinearity as indicated in the equation (15), where T_c is the clipping threshold. While in the blanking scheme we use a blanking nonlinearity as show in the following equation (16), where A_0 is the blanking threshold. Note that both nonlinearities are of amplitude type (i.e. phase of the signal is not modified).

Different scenarios of impulsive noise, with different impulse burst probabilities of occurrence are considered to evaluate the performance of proposed noise mitigation system. For the presented work, simulation results are obtained using the following fusion parameters, $\alpha = 0.7$, $\gamma = 1.2$.

4.1 Impact of LDPC-CC

Since the performance of LDPC decoder depends on the convolutional code period, it is reasonable to discuss the impact of this period on the LDPCCC performance against impulse noise. Fig. 6 shows how this period can affect the BER.

Secondly, the effect of the impulse busts probability is studied. Figure 7 shows how different values of the impulse probabilities occurrence impinge the system performance.

It is observed that when the impulse burst probability increases, the system performance drops.

$$r_k^{comp} = \begin{cases} r_k, & if\ |r_k| < T_c \\ A_0 e^{j arg(r_k)}, & \text{otherwise} \end{cases} , \quad k = 0,1,\dots,N-1 \tag{15}$$

$$r_k^{comp} = \begin{cases} r_k, & if\ |r_k| < T_b \\ 0, & \text{otherwise} \end{cases} , \quad k = 0,1,\dots,N-1 \tag{16}$$

In fact, Fig. 7 shows a serious degradation of LDPC-CC performance under PLC circumstances with the increasing of impulse bursts probability. It is clear, that LDPC-CC shows less obvious improvement under impulse probability occurrences $p = 0.05$ and $p = 0.1$ as compared with the performance obtained under $p = 0.005$ and $p = 0.01$.

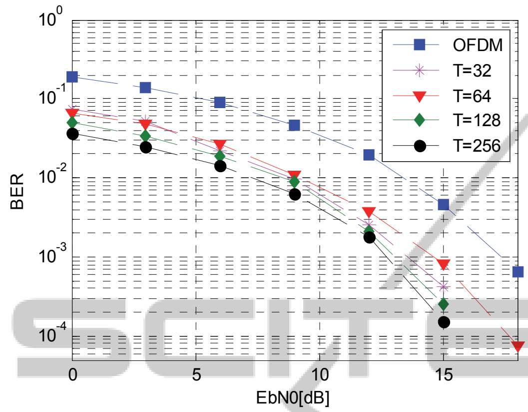

Figure 6: Impact of convolution period on LDPC-CC performance against impulse noise.

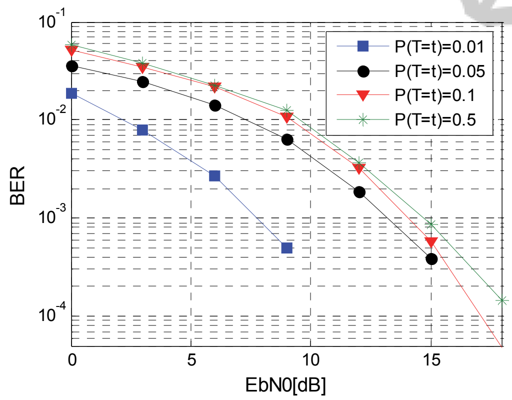

Figure 7: Impact of impulse noise probability on LDPC-CC performance.

This behavior is anticipated, because when the impulse noise lasts longer, it damages more data blocks leading to greater errors at the receiver. Moreover, LDPC-CC codes are designed for AWGN reduction, the error correction capability drops to a large extent since noise in practice differentiates seriously from the assumed AWGN in the decoding process

4.2 Impact of FMM Filter

A FMMF has been introduced earlier in Section 2.3 for the detection and removal of impulse noise. Various impulse noise probabilities are considered 0.01, 0.05 and 0.1 and which implies that 1%, 5% and 10% of the received OFDM samples will be affected by impulse noise, respectively.

Here, we give the results obtained by comparison of proposed FMMF against clipping and blanking approaches. As can be observed from Fig. 8, the proposed FMMF algorithm greatly improves the performance in terms of BER. It has a good aptitude for noise reduction especially with low SNR. For example at a SNR=0 dB, more than 5% gain in BER can be obtained.

The results of this comparative study show that proposed HMMF performs better than the clipping and blanking nonlinearities in the three impulse noise scenarios. On the other hand, in a weakly impulsive environment, clipping nonlinearity may slightly outperform the blanking scheme.

4.3 Impact of LDPC-CC/FMMF

Data transmission is carried out on a PLC channel. The combination of FMMF and LDPCCC helps to improve the robustness of transmitted data against multipath effect and impulse noise generated over the PLC channel. In this simulation, the BER performances of LDPC-CC/FMMF with LDPC rate-1/2 and a convolutional code period T=256, and at various impulse noise probabilities are illustrated in Figure 9. As one can see, the BER results of joint FMMF-LDPCCC system has been improved with comparison of using only LDPCCC or FMMF alone. For example, we have more than 12% improvement in BER in case of applying the proposed LDPC-CC/FMMF system at a SNR=0 in comparison with using OFDM-PLC without a noise reduction approach.

Also, it can be concluded from Figure 9 that proposed LDPC-CC/HMMF scheme has more noise reduction capability for lower impulse bursts probabilities, as illustrated in Figure 9.a (e.g., for $p = 0.01$). While this capability is decrease with the increasing of impulse probabilities occurrence, as indicated in Figure 9.b and 9.c (e.g, for $p = 0.1$).

The result verifies the principle that combined LDPC-CC/FMMF has superiority in performance but with slower convergence speed with the increasing of impulse probability occurrence. The proposed scheme succeeds in improving the performance; however the result is still not good enough for real world application especially for high impulse bursts probability.

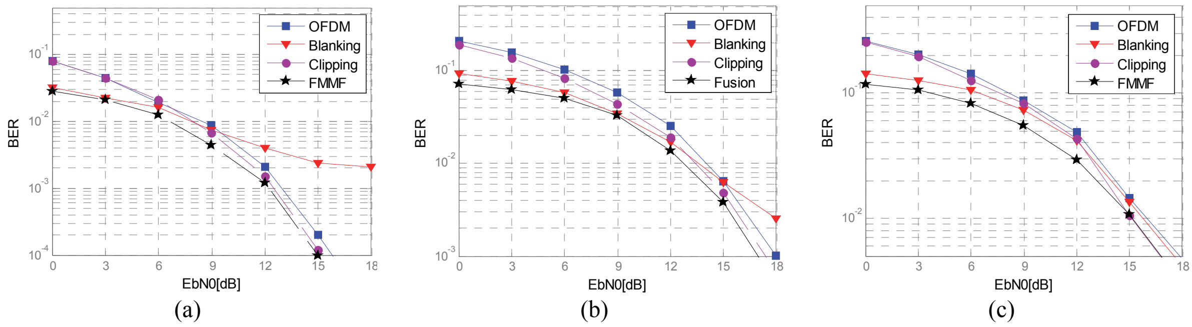

Figure 8: Performance comparison of FMMF, clipping, blanking nonlinearity for OFDM-Based PLC for: a) $p = 0.01$) , b) $p = 0.05$ and c) $p = 0.1$.

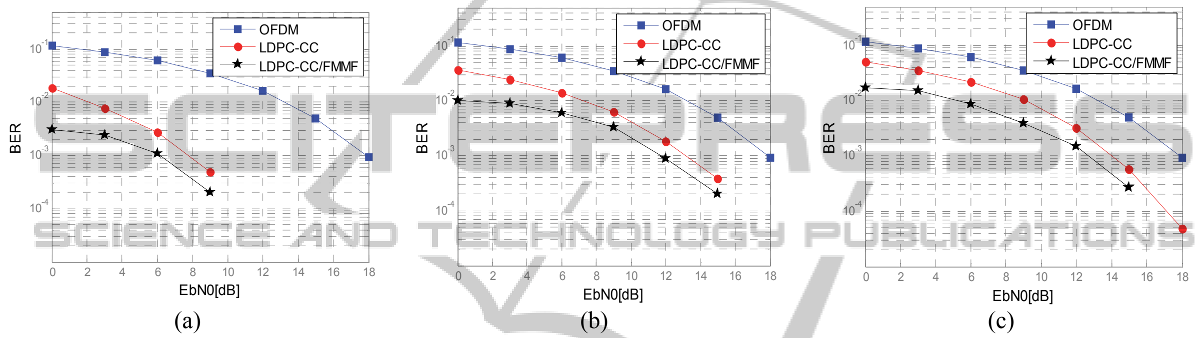

Figure 9: Performance of LDPC-CC and combination of LDPCCC and FMM filter for: a) = 0.01) , b) $p = 0.05$ and c) $p = 0.1$.

5 CONCLUSIONS

From the simulation results, the Combination of LDPC-CC and FMMF gives more enhancement in respect of BER than using LDPC-CC or FMMF alone. When SNR is about 12dB, the BER drops down below 10^{-5} for $p = 0.01$ and below 10^{-4} for $p = 0.05$ and $p = 0.1$. However, the increase of impulse probability occurrence affects LDPC-CC capacity of noise detection and correction which can reduce the efficacy of this decoding scheme.

As a perspective to this work, we propose to adapt the LDPC-CC decoding process to increase error correction capability for impulse noise.

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