Iterative algorithms for impulsive noise reduction in OFDM-based power line communications

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Abstract: Power line communications (PLC) is a technology that permits data transmission using electrical networks. In the last few years, multimedia transmission (e.g., audio, image and video) over electrical signals has received a huge amount of research interest thanks to the already-existing indoor networks. However, impulsive noise presents the most impairments in PLC systems caused by switching transients in the in-home networking. In this paper, we propose some iterative suppression algorithms based on accurate impulsive noise estimation, using an adaptive threshold under a target false alarm probability. The proposed algorithms detect the amplitudes of impulsive noise, and then cancel them iteratively from the received contaminated signal. The results show that the proposed algorithms provide noticeable improvement in terms of bit error rate, peak signal-to-noise ratio, and visual reconstructed image quality, when compared to that of the conventional methods.

Keywords: power line communications; orthogonal frequency division multiplexing; multimedia transmission; impulsive noise; iterative suppression algorithms; false alarm probability; impulsive noise estimation; bit error rate; peak signal-to-noise ratio; visual image quality.

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1 Introduction

Nowadays, multimedia data (e.g. audio, image and video) transmission using power line communications (PLC) is receiving a huge amount of research interest. Broadband communications over in-home networking are specified by the IEEE 1901 standard (Galli and Logvinov, 2008). In fact, PLC exploits the power line as a transmission medium for multimedia transmission (Haidine et al., 2004). Accordingly, the existing electrical network and the ubiquitous outlets are the main advantages for PLC technology, which can provide an alternative solution for high speed broadband communications. For instance, the PLC systems could be highly integrated into the internet of things (Bhuiyan et al., 2015) and wireless sensor networks (Li et al., 2015; Ning et al., 2016; Samarah, 2016) in order to build ubiquitous in-home networks.

Multimedia communication over PLC is not an easy task because of the harsh characteristics of the transmission medium which typically exhibits high bits/symbols error rates and visual quality degradation. In fact, multimedia content delivery on PLC infrastructures undergoes severe impairments due to multipath propagation and impulsive noise (Zimmermann and Dostert, 2002a), caused by the high number of branches, varying impedance, and switching transients in the PLC network. Orthogonal frequency division multiplexing (OFDM) is such a suitable transmission technique for PLC. It can deal with multipath propagation and impulsive noise due to long symbol OFDM duration, cyclic prefix (CP) insertion, equalisation technique, and the spreads over multiple sub-carriers of the fast Fourier transform (FFT) operation at the receiver (Ma et al., 2005). Nevertheless, it is worth noting that, when impulsive noise exceeds a certain threshold, it may affect OFDM sub-carriers leading to a dramatic performance degradation. Therefore, reduction techniques should be used in order to improve the performance of PLC systems.

1.1 Related work

Impulsive noise reduction in OFDM systems is a field of active research (Zhidkov, 2008; Al Mawali et al., 2009; Mengi and Vinck, 2010; Lin et al., 2013; Hu et al., 2014; Kumar and Sahoo, 2014; Al-Naffouri et al., 2014; Laksir and Tamtaoui, 2016; Himeur and Boukabou, 2016). A simple technique is to apply conventional non-linear preprocessor techniques, such as clipping and blanking (replacing with zeros) the amplitudes of the received time-domain signal above a predefined threshold value. However, imperfect identification of impaired samples may cause additional distortion in the desired signal, resulting in bit error rate degradation. Zhidkov (2003), Mengi and Vinck (2010), Hu et al. (2014) and Laksir and Tamtaoui (2016) have proposed some iterative threshold-based algorithms to estimate impulsive noise, then cancel it from the received signal either in time or frequency domains. Huimin et al. (2016) proposed a novel method for removing non- Gaussian image noise in natural images, based on a statistical model of the decomposed contour-let coefficients. Recently, Al-Naffouri et al. (2014) and Lin et al. (2013) introduced promising impulsive noise reduction approaches based on compressed sensing and sparse Bayesian frameworks. These techniques exploit the sparse structure of impulsive noise and pilot tones in order to estimate and cancel impulsive noise. The drawbacks of these techniques are that they require a large number of null and pilot tones which leads to a loss in the bandwidth and a reduction of the throughput.

1.2 Our contribution

This paper has been significantly extended from a previous work (Laksir and Tamtaoui, 2016), which discussed preliminary work on the technical aspect of image transmission enhancement over impulsive noise in OFDM-based PLC. In this paper, we provide an adaptive threshold (under a target false alarm probability), in order to enhance performance of the conventional iterative algorithms (Mengi and Vinck, 2010; Laksir and Tamtaoui, 2016); by considering both multipath PLC channel and impulsive noise. The proposed technique is fully applicable for impulsive noise estimation and cancellation in OFDM-based communications systems (including wireless standards, digital subscriber lines, and PLC). The contribution of this paper is as follows:

- Firstly, combining the iterative impulsive noise suppression algorithm with the Viterbi decoder, the proposed technique shows better impulsive noise estimation and cancellation in presence of multipath PLC channel moderately and heavily corrupted by impulsive noise, while maintaining great perceptible quality of the reconstructed images.
- Secondly, impulsive noise estimation is more relevant using the adaptive threshold than the optimal threshold in Laksir and Tamtaoui (2016). The proposed adaptive threshold is inspired from consecutive mean excision algorithms for outlier (signal) detection (Vartiainen et al., 2010). To the best of our knowledge, this approach has not been tested for impulsive noise estimation and suppression in OFDM-based PLC systems.

The remainder of the paper is organised as follows. Section 2, is dedicated to background presentation, including OFDM system, PLC channel model, impulsive noise model, and conventional iterative suppression algorithm presentations. In Section 3, the proposed iterative algorithms are discussed. The simulation results are presented in Section 4. Finally, a conclusion and further perspectives are given in Section 5.

2 Background

2.1 OFDM system

It is worth noting that OFDM is a major candidate for PLC systems (Ma et al., 2005), primarily due to its high spectral efficiency, its robustness against inter-symbol interference and frequency-selective channel that arise out of the multipath propagation. Besides, the long symbol duration and the cyclic prefix (CP) are the key advantages of OFDM that can reduce the effect of multipath propagation. Its complex baseband transmitted signal can be expressed as:

$$s_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n e^{j2\pi \frac{kn}{N}}, \; k = 0,1, \ldots, N \tag{1}$$

where $\frac{1}{\sqrt{N}}$ is the scale factor, N is the number of subcarriers, k is the index of OFDM block sub-carriers, and x_k represents a sequence of a coded quadrature phase shift keying (QPSK) symbols.

2.2 PLC channel model

To study the impact of multipath PLC channel on image transmission, we adopt a typical channel model proposed by Zimmermann and Dostert (2002b). The channel model was obtained from practical measurements, and summarises the characteristics of indoor power line networks by a channel transfer function formula in the frequency range from 500 KHz to 20 MHz described by:

$$H(f) = \sum_{i=1}^{N_{taps}} \rho_i . e^{-(a_0 + a_1 f^k) d_i} . e^{-j2\pi f \frac{d_i}{v_p}} \tag{2}$$

where N_{taps} is the number of channel taps, ρ_i is the weighting factor, d_i is the length of the i^{th} path, a_0, a_1, and k are the attenuation parameters and v_p is the propagation speed. In this paper, we use the weighting factor, attenuation and path parameters for a four-path (N_{taps} = 4) PLC channel model. The attenuation parameters are: $k = 1$, $a_0 = 0$, $a_1 = 7.8 * 10^{-10}$ s/m. The other parameters set are listed in Zimmermann and Dostert (2002b).

2.3 Impulsive noise model

An appropriate and widely used noise model to represent impulsive noise on the electrical network is the middleton's class A (MCA) noise model (Middleton, 1977). Basically, the MCA model is a statistical-physical model of man-made electromagnetic interference, and it consists of white Gaussian background and non-Gaussian impulsive noise. According to the model, the instantaneous impulsive noise amplitude is given by the probability density function (PDF) formula as follows:

$$p(u) = e^{-A} \sum_{m=0}^{\infty} \frac{A^m}{m!} . \frac{1}{\sqrt{2\pi\sigma_m^2}} \exp\left(-\frac{u^2}{2\sigma_m^2} \right) \tag{3}$$

where $\sigma_m^2 = (\sigma_g^2 + \sigma_u^2) . \dfrac{\frac{m}{A} + \Omega_{GIR}}{1 + \Omega_{GIR}}$ is the total noise power, m is the number of mixture components representing a summation parameter of weighted sum of Gaussian pdfs, $A \in [10^{-2}, 1]$ is the impulsive index and represents the average number of impulses per unit time, σ_g^2 is the Gaussian noise variance, σ_u^2 is the impulsive noise variance, and $\Omega_{GIR} = \frac{\sigma_g^2}{\sigma_u^2} \in [10^{-6}, 1]$ is the mean power Gaussian-to-impulsive noise ratio. For small A (e.g. for $A = 0.1$, 9.5% of the samples are contaminated by impulsive noise). The impulsive noise has a predominantly impulsive type noise, whereas the higher is A the closer is the MCA to a Gaussian noise.

2.4 Conventional iterative suppression algorithm

The basic idea behind the conventional iterative impulsive noise suppression algorithm is to estimate the amplitudes of impulsive noise based on a threshold detector, and cancel them from the contaminated received signal in the time-domain (Mengi and Vinck, 2010; Laksir and Tamtaoui, 2016) at the front-end of OFDM receiver or in the frequency-domain after FFT (Zhidkov, 2008), iteratively. In the following, we briefly review the conventional suppression algorithm as given in Mengi and Vinck (2010). In Figure 2, r is the contaminated received signal, l is the number of iterations, and $S^{(l)}$ is the de-mapper output data. The conventional algorithm performs the following operations:

- First, CP removal, FFT and de-mapper process are similar to the receiver (OFDM receiver Figure 1). The de-mapper block maps each element of $R^{(l)}$ on a signal point in the QPSK constellation to obtain output data $S^{(l)}$, $l \geq 0$, which represents the result of the l^{th} iteration without taking a hard decision rule at its output.
- Next, the IFFT and CP insertion are used to obtain a relevant estimation of the transmitted OFDM signal $\dot{s}^{(l)}$ in (1), and subtracted from the received signal r described by

$$n^{(l)} = r - \dot{s}^{(l)} \triangleq w^{(l)} + u^{(l)} \tag{4}$$

  where $n_k = w_k + u_k$ represents the estimation of the total noise in time-domain.
- Then, the impulsive noise term u_k is estimated by the following rule

$$u_{est}^{(l)} = \begin{cases} 0, |n^{(l)}| \leq T \\ n^{(l)}, |n^{(l)}| > T \end{cases} \tag{5}$$

where l is the number of iterations, $u_{est}^{(l)}$ represents the estimate impulsive noise, $n^{(l)}$ is the total noise resulting from AWGN and impulsive noise, and T is a threshold detector defined in Mengi and Vinck (2010) which determines whether the total noise $n^{(l)}$ is part of the impulsive noise or the AWGN.

- Finally, the estimated impulsive noise $u_{est}^{(l)}$ is cancelled iteratively from the received signal until only AWGN remains.

3 Proposed iterative suppression algorithms

This section presents the proposed iterative suppression algorithms combined with Viterbi decoder, based on two different approaches for estimating impulsive noise in time-domain:

1. selected optimal threshold via simulation (Laksir and Tamtaoui, 2016)
2. adaptive threshold defined under a desired false alarm probability.

In the following subsections, we first introduce the proposed algorithms only under impulsive noise, and then under multipath PLC channel corrupted by impulsive noise.

3.1 Impulsive noise and non-multipath PLC channel

Figure 1 illustrates the block diagram of a conventional coded OFDM-based PLC systems, where its received time-domain signal can be expressed as:

$$r_k = s_k + w_k + u_k, \; k = 0, 1, \ldots, N-1 \tag{6}$$

where r_k represents the received signal, s_k is the OFDM transmitted signal in (1), w_k is the additive white Gaussian noise (AWGN), and u_k is the impulsive noise. At the receiver, the process is reversed to obtain the output bits stream S_{out}, by doing CP removal, FFT, de-mapper, and hard decision for Viterbi decoder, respectively.

As a matter of fact, although the conventional algorithm (Figure 2) improves better the BER performances, it has shown limits in improving the visual quality of the reconstructed image in OFDM-based PLC. Hence, it is advantageous to employ Viterbi decoder at the output of the conventional algorithm to improve the perceptual image quality at the receiver. The block diagram of the conventional iterative suppression algorithm using Viterbi decoder is shown in Figure 3, based on the optimal threshold derived from the simulation in the impulsive noise estimation (5).

Figure 1 Conventional block diagram of OFDM-based PLC system: non-multipath PLC channel

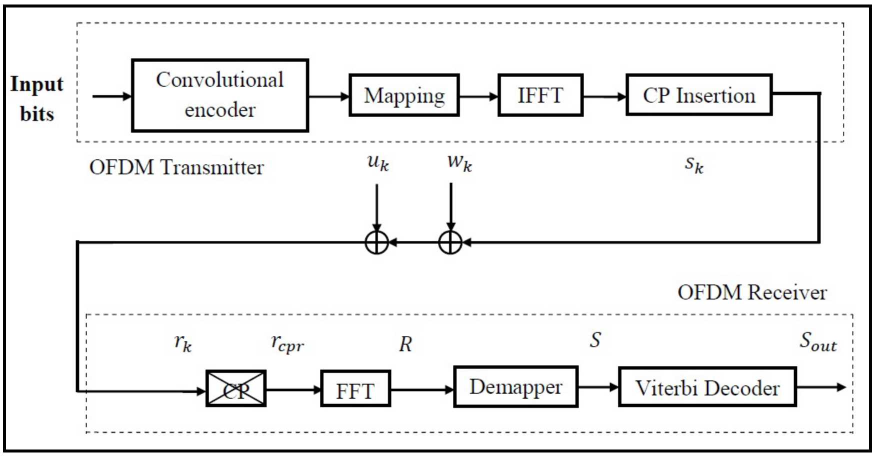


Figure 2 Block diagram of the conventional iterative approach: non-multipath PLC channel

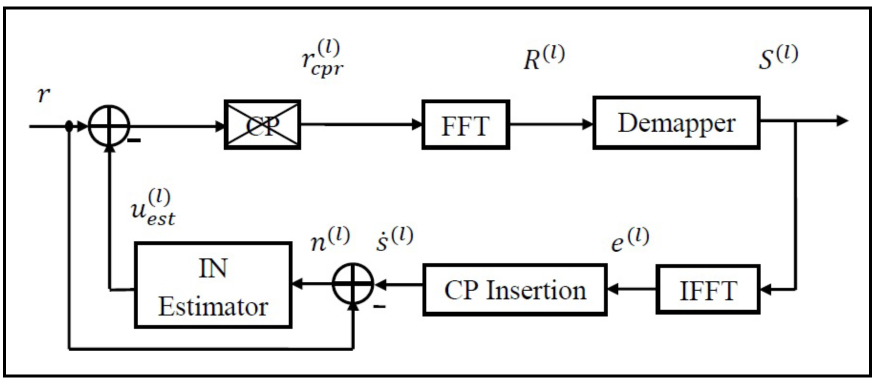


Figure 3 Block diagram of the conventional iterative approach with Viterbi decoder: non-multipath PLC channel

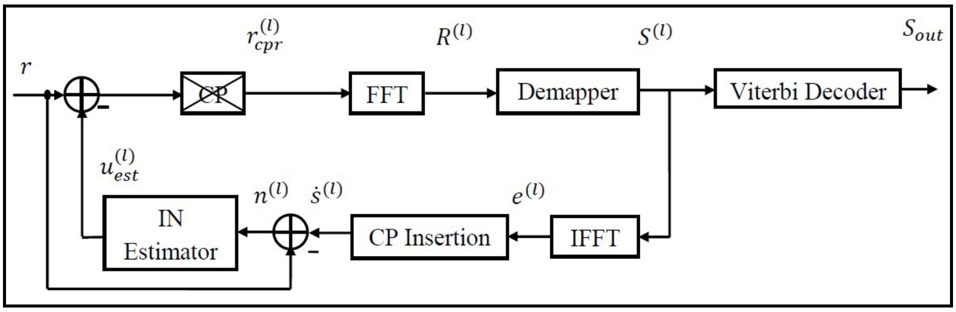


Table 1 Summary of proposed iterative algorithm (Figure 4): non-multipath PLC channel

Step 1. Compute the noise variance $\sigma^2_{n^{(l)}} = \frac{1}{N}\sum_{i=1}^{m} \lvert n^{(l)} \rvert^2$
Step 2. Compute the impulsive threshold $T_{cfar} = \nabla \sigma^2_{n^{(l)}}$, where $\nabla = 4.6$
Step 3. Comparison: reject samples if $\lvert n^{(l)} \rvert^2 > T_{cfar}$
Step 4. Iterate former steps until the maximum number of iterations is achieved

It is worth noting that when the amplitude of impulsive noise increases, the performance of the proposed algorithm (Figure 3) decreases. To deal with this issue and hence improve the overall performance of the algorithm, we propose an adaptive threshold motivated by consecutive mean excision algorithms for outlier (signal) detection (Vartiainen et al., 2010). Accordingly, the Viterbi decoder is introduced into the algorithm's iterative process in order to compensate transmission errors in the l_{th} iteration. The block diagram of the proposed iterative algorithm is presented in Figure 4, summarised in Table 1, and is emphasised below:

- Firstly, the impulsive noise estimation under a desired false alarm probability $P_{df\,a}$ is performed by the following function:

$$u_{est}^{(l)} = \begin{cases} n^{(l)}, & \text{if } \lvert n^{(l)} \rvert^2 > T_{cfar} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

  where T_{cfar} represents a threshold detector defined as $T_{cfar} = \nabla \sigma^2_{n(l)}$, where ∇ is a desired false alarm probability given by $\nabla = -ln(P_{df\,a})$. The adaptive threshold changes according to the variance of the estimate total noise $\sigma^2_{n(l)}$ at each iteration. For example, $P_{df\,a} = 1\%$ (0.01) results in $\nabla = 4.6$.

- Secondly, after impulsive noise removal in the l_{th} iteration, Viterbi decoder's output is more relevant at the next iteration, and hence the performance of the OFDM-based PLC system is improved which results in better perceptual image quality at the receiver.

3.2 Impulsive noise and multipath PLC channel

It is also shown that multipath PLC channel may affect the perceptual image quality as seriously as the impulsive noise does. In this subsection, we investigate the ability of the proposed iterative algorithms to reduce the impulsive noise on image transmission under the multipath PLC channel. Figure 5 depicts a block diagram of a conventional coded OFDM-based PLC. Let us denote r_k the received time-domain signal over multipath PLC channel, AWGN, and impulsive noise as

$$r_k = s_k \otimes h(t) + w_k + u_k, \; k = 0, 1, \ldots, N-1 \tag{8}$$

where $s_k = s(\frac{kT_s}{N})$ represents the sampled signal of $s(t)$ in (1), the symbol $\otimes$ is the convolution operator, and $h(t)$ is the impulse response of the multipath PLC channel in (2).

It is worth mentioning that the issue of multipath channel is out of scope here. In this paper, CP and equalisation are used to minimise the effect of inter-channel interference and inter-symbol interference caused by the multipath PLC channel. Figure 6 illustrates the extended iterative algorithm using Viterbi decoder and the optimal threshold, based on zero-forcing equaliser (under the assumption of perfect channel estimation at the receiver). The steps of the proposed algorithm are as follows:

- First, CP removal, FFT, equaliser and demapper are exactly same with the OFDM receiver in Figure 5.
- Then, the output of IFFT, CP Insertion, and the convolution block can be expressed as:

$$v^{(l)} = e^{(l)} \otimes h(t) \triangleq s_k \otimes h(t) \tag{9}$$

where $v^{(l)}$ represents the convolution between the estimated OFDM signal and the impulse response $h(t)$ of (2).

- After that, the estimate total noise $n^{(l)}$ is obtained by cancelling $v^{(l)}$ from the received signal in (8).
- Next, the rule in (5) is applied to $n^{(l)}$ in order to reconstruct the impulsive noise, using the selected optimal threshold via simulation.
- Finally, expecting that $u_{est} \approx u$, the estimated impulsive noise is cancelled from the received signal in (8). The iteration loop takes end if the maximum number of iterations is exceeded.

Figure 4 Block diagram of the proposed iterative approach: non-multipath PLC channel

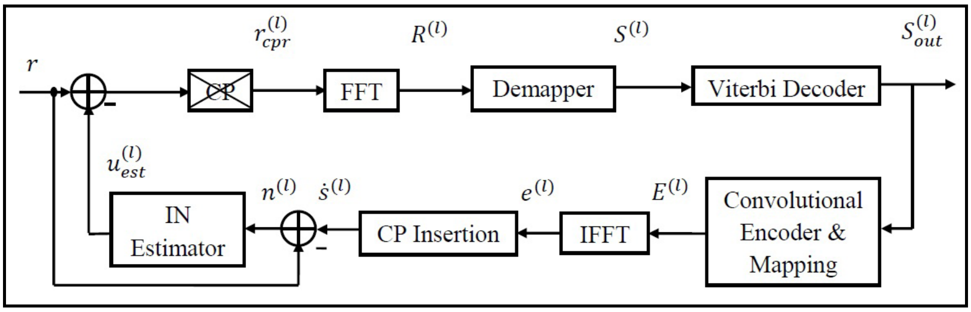


Figure 5 Conventional block diagram of OFDM-based PLC system: with multipath PLC channel

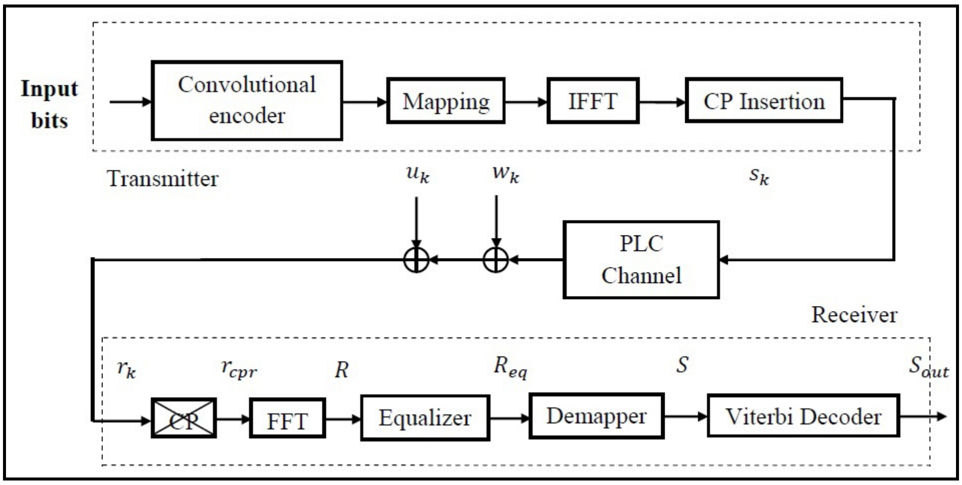
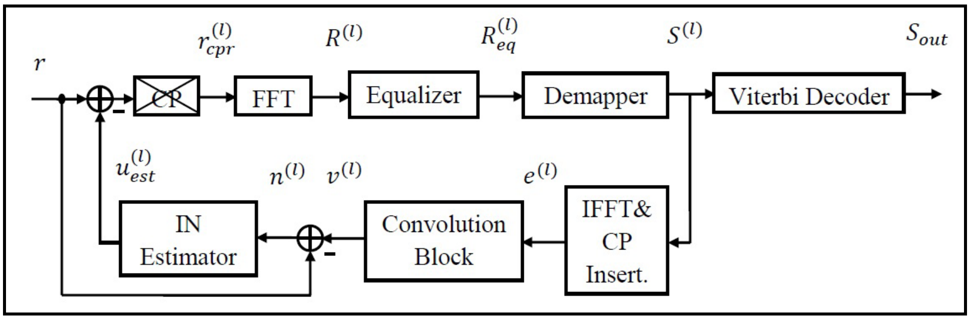


Figure 6 Block diagram of the conventional iterative approach with Viterbi decoder: with multipath PLC channel



Similarly, as mentioned in Subsection 3.1, the proposed algorithm (Figure 6) using the optimal threshold does not significantly improve the PSNR quality of the reconstructed images under multipath PLC channel altered by impulsive noise. To this end, we modify the iterative receiver in Figure 6, by introducing Viterbi decoder into the iterative process, to improve impulsive noise estimation and removal in each iteration, and to avoid errors on the output of the receiver. Accordingly, the impulsive noise amplitudes are estimated by applying the proposed adaptive threshold. The second proposed algorithm is summarised in Table 2, and its block diagram is depicted in Figure 7.

The shortcoming of the proposed iterative approaches is that the computational complexity of the proposed algorithms is likely to incur additional time processing and hardware costs, due to Viterbi decoder and N-point IFFT blocks.

4 Simulation results

This section provides simulation results to evaluate the performance of the proposed algorithms. The system specifications considered for the experimental study are given in Table 3. The performance metrics and the key proprieties validated by simulations are provided, respectively.

Figure 7 Block diagram of the proposed iterative approach: with multipath PLC channel

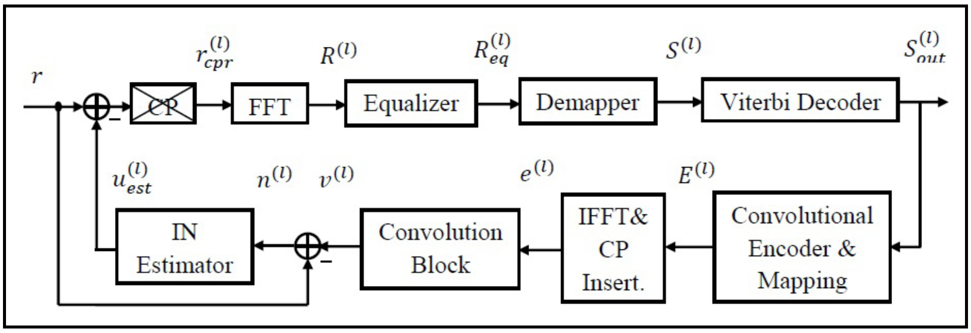


Table 2 Summary of proposed iterative algorithm (Figure 7): with multipath PLC channel

Step 1. Given the Viterbi decoder output $S_{l\ out}$, reconstruct the transmitted signal $v^{(l)}$ in (9)
Step 2. Substrate $v^{(l)}$ from the received signal r in (8)
Step 3. Compute the noise variance $\sigma^2_{n^{(l)}} = \frac{1}{N}\sum_{i=1}^{m}\left\|n^{(l)}\right\|^2$
Step 4. Apply the proposed adaptive impulsive noise estimator in (7)
Step 5. Substrate the estimate impulsive noise u_{est} from the received signal r
Step 6. Iterate former steps until the maximum number of iterations is achieved

Table 3 System specifications considered for simulations

The number of sub-carriers: $N = 1024$
The IFFT size is: 1024
The length of CP: 3
The convolutional encoder rate 1 2
The mapping type: QPSK
Impulsive noise model: Middelton Class A with two scenarios: 'moderately disturbed' ($A = 0.1$, $\Omega_{GIR} = 10^{-4}$) and 'strongly disturbed' ($A = 0.35$, $\Omega_{GIR} = 10^{-4}$)
PLC channel model: Zimmerman and Dostert 4-path model

4.1 Performance metrics

The performances of the proposed algorithms are evaluated in terms of BER, peak signal-to-noise ratio (PSNR), and the perceptible reconstructed image quality. The signal-to-noise ratio (SNR) is defined as:

$$SNR = 10log_{10}\left(\frac{1}{\sigma_w^2}\right) \quad (10)$$

where σ_w^2 is the variance of AWGN noise. Regarding the perceptible image quality of the proposed algorithms, the input gray-scale image Lena of size 512 × 512 is employed as a standard greyscale test image, which is compressed using discrete cosine transform (DCT) and quantisation based joint photographic experts group (JPEG) standard (Al-Ani and Awad, 2013).

4.2 Key proprieties validated by simulations

The simulation results show that, the proposed iterative approach achieved a better resilience to impulsive noise, and some noticeable improvement in terms of BER, PSNR, and visual reconstructed image quality. This is due to the perfect identification of impulsive noise amplitudes using the adaptive threshold detector, which allows better noise estimation and cancellation, in addition to Viterbi decoder which minimises the errors on the output of the OFDM-Based PLC receiver, iteratively. Besides, for the 'moderately disturbed' impulsive scenario with non-multipath PLC channel, the proposed algorithm (Figure 4) achieved a PSNR gain of about 8 dB at $SNR = 8$ dB, leading to great perceptible quality of the reconstructed image compared to the conventional iterative approach (Figure 3). Regarding the PLC channel affected by strongly impulsive noise scenario, the PSNR of the reconstructed image without cancellation [Figure 21(a)] has been improved by approximately 4 dB. Moreover, the number of iterations is fixed at two iterations, since any further iteration does not improve the BER as well as the PSNR performances.

For Subsection 4.3 the proposed iterative approach (denoted as 'Proposed iterative approach (Figure 4), $\nabla = 4.6$, Iteration 2') is compared with those from previous impulsive noise reduction approaches proposed in Mengi and Vinck (2010) and Laksir and Tamtaoui (2016), in terms of BER, PSNR, and the perceptual quality of the reconstructed images. The performance of the coded

OFDM-based PLC receivers denoted in all figures as 'AWGN + Impulsive Noise, (1/2 Coded)'. For Mengi's method (denoted as 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)'), we set $T = 3\sigma_n$ as a threshold parameter. As for Laksir's method, denoted as 'Conventional iterative approach (1/2 Coded) (Figure 3), $T = 0.8$, Iteration 2', we set $T = 0.8$ as optimal threshold.

Regarding Subsection 4.4, performance comparison of the proposed iterative approach for reducing impulsive noise under multipath PLC channel is provided, in terms of BER, PSNR, and the perceptual quality of the reconstructed images. Moreover, for the conventional iterative approach (Figure 6), we could search for optimal thresholds (from 0.0001 to 0.5, searching step is 0.0001) that minimise the BER in presence of both multipath channel and impulsive noise, and we set two optimal thresholds $T = 0.05$, and $T = 0.03$ for 'moderately disturbed' ($A = 0.1$) and 'strongly disturbed' ($A = 0.35$), respectively. The performances of the proposed approach Figure 7, using $\nabla = 4.6$ are compared with the coded OFDM-based PLC systems (Figure 5 and Figure 17), and the conventional iterative approaches (Figure 6, using $T = 0.05$, and $T = 0.03$).

4.3 Performance under impulsive noise and non-multipath PLC channel

In this subsection, the performances of the proposed algorithm (Subsection 3.1, Figure 4) under impulsive noise and non-multipath PLC channel are provided in terms of BER, PSNR, and the visual reconstructed image quality.

4.3.1 Performance comparison in terms of BER

Figure 8 and Figure 9 show the plot of BER versus SNR values from 0 dB to 20 dB, under two impulsive noise scenarios : 'moderately disturbed' ($A = 0.1$) and 'strongly disturbed' ($A = 0.35$), respectively. In Figure 8, 'moderately disturbed' impulsive noise scenario, the simulation result shows that the 'AWGN + Impulsive Noise, (1/2 Coded)' outperforms the 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)' by about 2 dB for all SNR values range. It can be noticed from Figure 8 that the 'Conventional iterative approach (1/2 Coded) (Figure 3), $T = 0.8$, Iteration 2' performs better than the conventional iterative approach (Uncoded), with noticeable gain in terms of *SNR* by about 4 dB at $BER = 10{-}_4$. On the other hand, the 'Proposed iterative approach (Figure 4), $\nabla = 4.6$, Iteration 2' performs better, and outperforms the conventional iterative approach (1/2 Coded) using the optimal threshold $T = 0.8$ by about 2 dB for low SNR values (≤ 8 dB). This seemed to indicate that the proposed approach using the adaptive threshold ($\nabla = 4.6$) as a parameter allows better identification of impulsive noise amplitudes and cancellation; in addition to Viterbi decoder which minimises the errors on the output of the OFDM-Based PLC receiver.

For 'strongly disturbed' impulsive noise scenario, Figure 9 illustrates that the 'AWGN + Impulsive Noise, (1/2 Coded)' achieves an SNR gain by about 4 dB compared to 'AWGN + no Impulsive Noise cancellation', and the 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)' achieves the worst BER performance. Accordingly, the achievable SNR gain obtained by 'Conventional iterative approach (1/2 Coded) (Figure 3), $T = 0.8$, Iteration 2' is approximatively equal to 5 dB, compared to the uncoded conventional iterative approach. However, the performance gap in terms of SNR decreased between the conventional iterative approach (1/2 Coded) and the proposed iterative approach, compared to achievable SNR gains in 'moderately disturbed' impulsive noise scenario (Figure 8) especially at low SNR values ($SNR \leq 8$ dB). Furthermore, the proposed iterative approach outperforms the coded conventional iterative approach by about 1 dB in terms of SNR gain, thanks to its ability to provide accurate impulsive noise estimation based on the adaptive threshold.

Figure 8 BER performance, under AWGN + Impulsive Noise 'moderately disturbed' scenario: non-multipath PLC channel (see online version for colours)

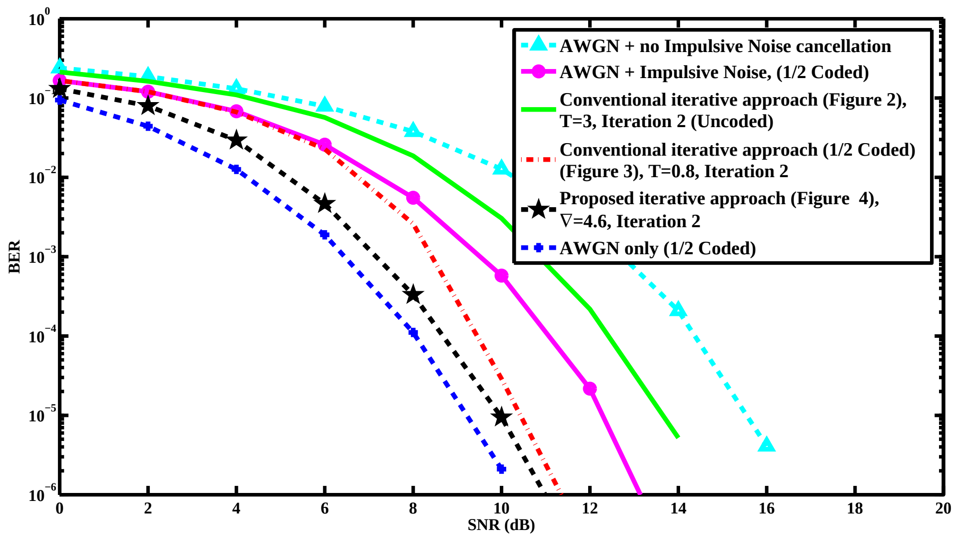


Figure 9 BER performance, under AWGN + Impulsive Noise 'strongly disturbed' scenario: non-multipath PLC channel (see online version for colours)

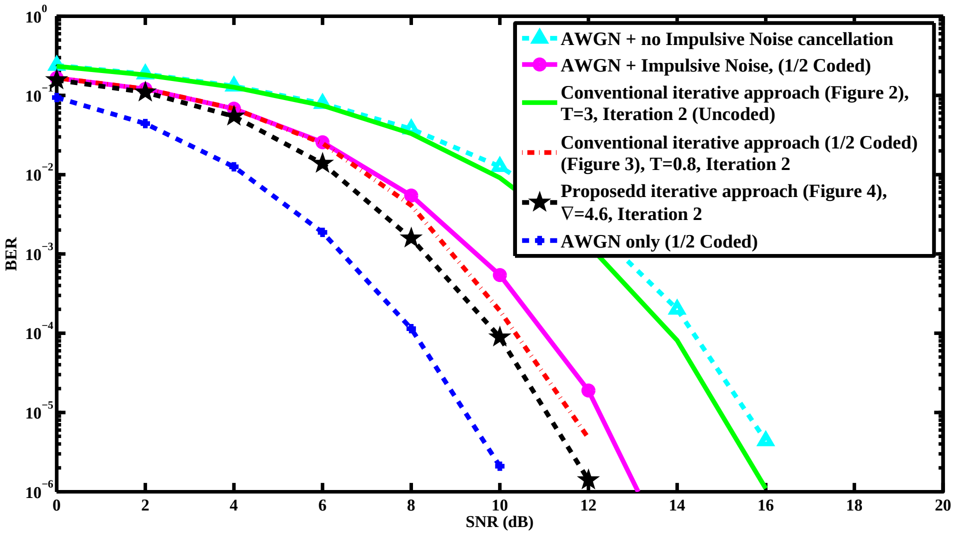
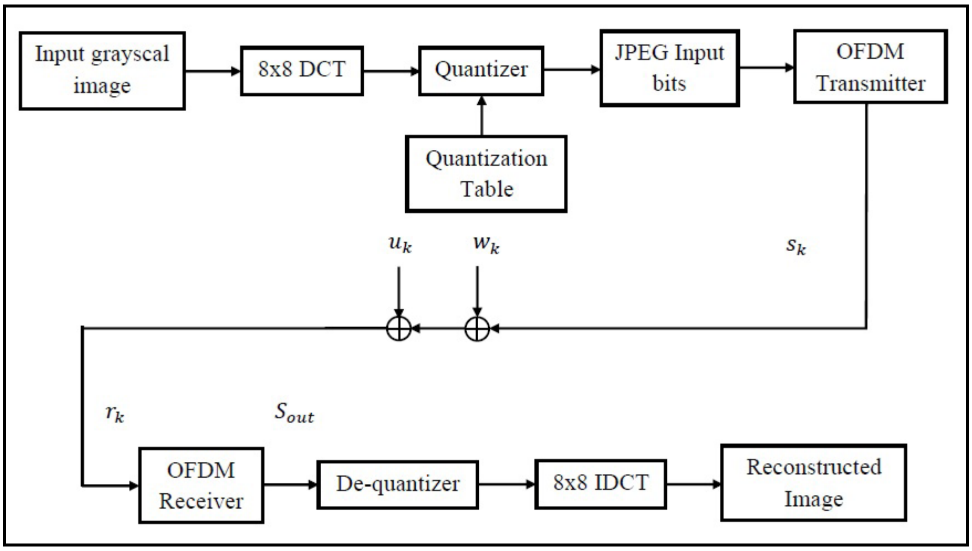


Figure 10 Simplified block diagram of the JPEG encoder/decoder OFDM-based PLC: non-multipath PLC channel



4.3.2 Performance comparison in terms of PSNR

In this sub-subsection, the performance of the proposed approach on the quality PSNR between the original and the reconstructed image is provided. First of all, Figure 10 depicts a simplified block diagram of the JPEG encoder/decoder OFDM-based PLC, where the JPEG bits stream is passed through the OFDM transmitter (Figure 1), AWGN, and impulsive noise. Then, the image is received and passed through the OFDM receiver (Figure 1), De-quantiser, and 8x8 IDCT before being reconstructed.

Figure 11 and Figure 12 illustrate the plot of PSNR vs SNR values from 0 dB to 18 dB, under 'moderately disturbed' (A = 0.1) and 'strongly disturbed' (A = 0.35) impulsive noise scenarios, respectively.

Figure 11 shows that the 'AWGN + Impulsive Noise, (1/2 Coded)' outperforms the 'Conventional iterative approach (Figure 2), T = 3, Iteration 2 (Uncoded)', by achieving a PSNR gain of approximately 6 dB at SNR value equal to 10 dB. Besides, the 'Conventional iterative approach (1/2 Coded) (Figure 3), T = 0.8, Iteration 2' outperforms the uncoded conventional iterative algorithm by about 5 dB at SNR = 10 dB. On the other hand, the 'Proposed iterative approach (Figure 4), ∇ = 4.6, Iteration 2' performs best with ∇ = 4.6, and outperforms the conventional iterative approach (1/2 Coded) by about 8 dB for low SNR value (SNR = 8 dB). The results show the effectiveness of the proposed iterative approach using the adaptive threshold, which enhances the quality of the transmitted image in terms of PSNR, especially at SNR range values from 6 dB to 12 dB.

Figure 11 PSNR performance, under AWGN + Impulsive Noise 'moderately disturbed' scenario: non-multipath PLC channel (see online version for colours)

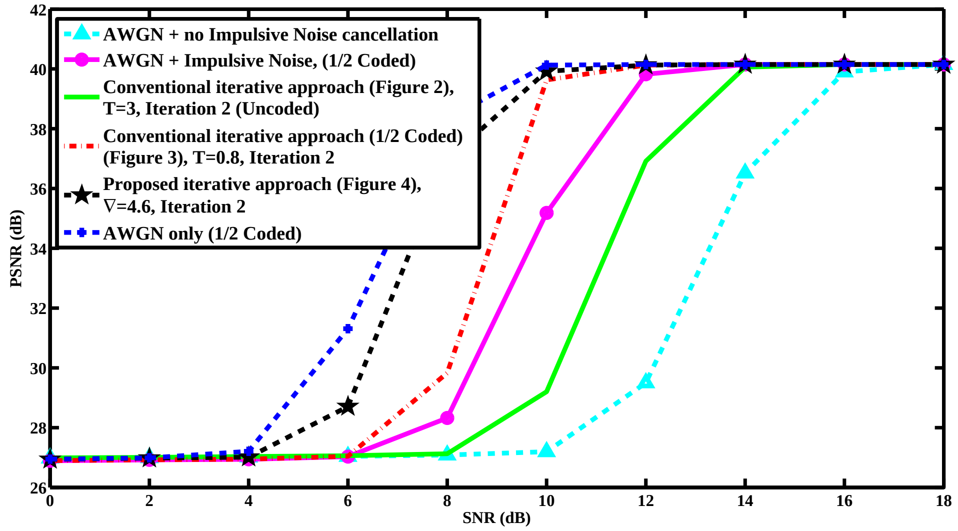
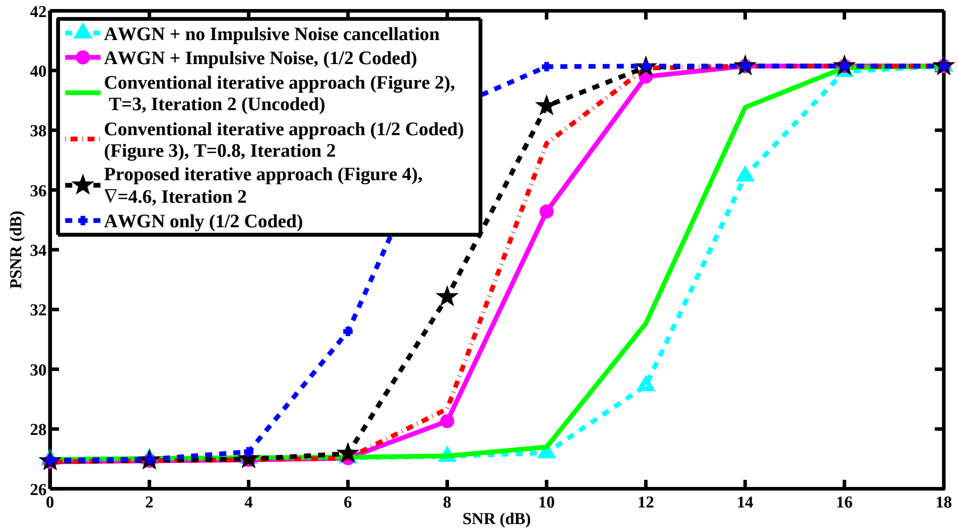


Figure 12 PSNR performance, under AWGN + Impulsive Noise 'strongly disturbed' scenario: non-multipath PLC channel (see online version for colours)



For 'strongly disturbed' impulsive noise scenario, Figure 12 shows that the achievable PSNR gain of the proposed iterative approach (Figure 4, $\nabla = 4.6$) decreased slightly, compared to the other impulsive noise scenario. Although the noise has a higher impulsiveness in this scenario, the proposed iterative approach proved to reduce the energy of high impulses, specifically at SNR values from 6 dB to 10 dB. In addition, the proposed iterative approach is significantly more efficient than conventional iterative approach (1/2 Coded) using the optimal threshold T = 0.8. On the other hand, the conventional iterative approach (Uncoded, T = 3) achieved the worst PSNR improvements in this scenario. This simulation demonstrates once again that the adaptive threshold can certainly provide a better impulsive noise estimation, and thus enhances the PSNR performances compared to the other techniques.

4.3.3 Visual reconstructed image quality

In this sub-subsection, the PSNR improvements through the proposed algorithms on the perceived visual quality of the reconstructed images are provided. Figure 13 and Figure 14 display comparisons of the various reconstructed images in moderately and strongly impulsive noise scenarios at $SNR = 10$ dB, respectively.

It can be seen from Figure 13(a) that the impulsive noise degraded the visual quality of the transmitted image with block zones, seemingly black and white and appearing quite randomly. Figure 13(b) shows that although the 'AWGN + Impulsive Noise, (1/2 Coded)' outperforms the uncoded conventional iterative approach, by approximately 6 dB in terms of PSNR, the effective quality of the reconstructed image is still degraded. This may indicate that the PSNR improvement only reflects on image visual quality, if highly improved (i.e., 6 dB PSNR improvement is not sufficient enough). Alternatively, the proposed iterative algorithm achieves a PSNR gain of approximately 13 dB, as displayed in Figure 13(e). As a result, the visual quality of the image has been highly improved [the same perceptible quality of the transmitted image obtained in Figure 13(f)], along with the PSNR improvement.

For 'strongly disturbed' impulsive noise scenario, results of the simulation demonstrate once again, that the perceived quality of the reconstructed images would be enhanced only if the PSNRs were highly improved. Figure 14(c) shows that the 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)' achieved the worst image enhancement. On the one hand, the coded conventional iterative algorithm [Figure 14(d)] improved the visual quality of the reconstructed image, and achieved comparable visual quality obtained by 'AWGN + Impulsive Noise, (1/2 Coded)' [Figure 14(b)]. On the other hand, the proposed iterative approach [Figure 14(e)] performed better in terms of perceptual reconstructed image quality in this scenario.

Figure 13 The reconstructed images, 'moderately disturbed', at $SNR = 10$ dB, (a) 'AWGN + no Impulsive Noise cancellation' (b) 'AWGN + Impulsive Noise, (1/2 Coded)' (c) 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)' (d) 'Conventional iterative approach (1/2 Coded) (Figure 3), $T = 0.8$, Iteration 2' (e) 'Proposed iterative approach (Figure 4), $\nabla = 4.6$, Iteration 22' (f) 'AWGN only (1/2 Coded)'

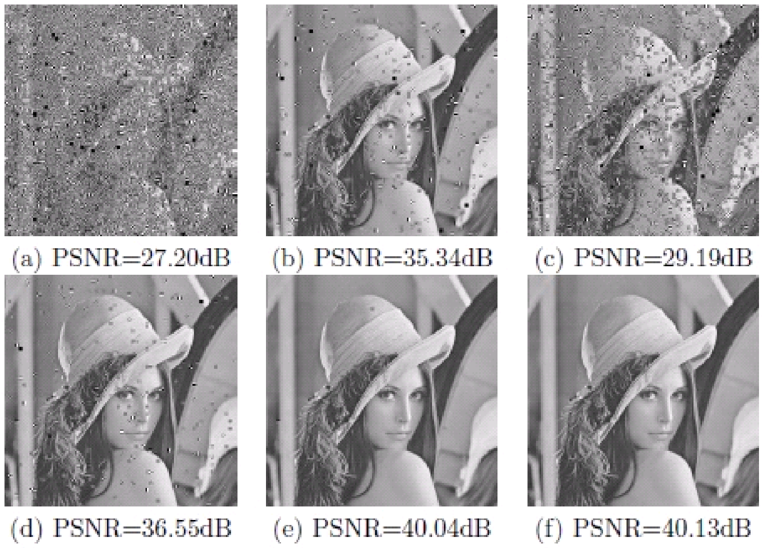
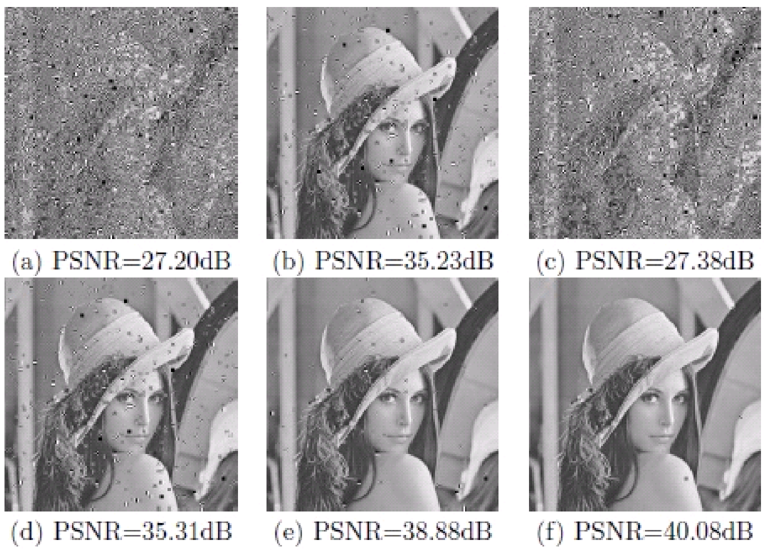


Figure 14 The reconstructed images, 'strongly disturbed', at $SNR = 10$ dB, (a) 'AWGN + no Impulsive Noise cancellation' (b) 'AWGN + Impulsive Noise, (1/2 Coded)' (c) 'Conventional iterative approach (Figure 2), $T = 3$, Iteration 2 (Uncoded)' (d) 'Conventional iterative approach (1/2 Coded) (Figure 3), $T = 0.8$, Iteration 2' (e) 'Proposed iterative approach (Figure 4), $\nabla = 4.6$, Iteration 22' (f) 'AWGN only (1/2 Coded)'



4.4 *Performance under impulsive noise and multipath PLC channel*

In this subsection, we investigate (using computer simulations) the ability of the proposed algorithm (Subsection 3.2, Figure 7) to reduce the effect of impulsive noise in the presence of multipath PLC channel, affected by moderately and strongly disturbed impulsive noise scenarios.

4.4.1 *Performance comparison in terms of BER*

Figure 15 and Figure 16 illustrate comparisons between the proposed approaches under multipath PLC channel affected by 'moderately disturbed' and 'strongly disturbed' impulsive noise scenarios, respectively.

Figure 15 shows that 'Proposed iterative approach (Figure 7), $\nabla = 4.6$, Iteration 2' performs better compared to 'Conventional iterative approach (1/2 Coded) (Figure 6), $T = 0.05$, Iteration 2' and 'PLC channel with AWGN + Impulsive Noise, (1/2 Coded)'. Therefore, the BER performances are significantly improved by introducing Viterbi decoder into the iterative algorithm with adaptive threshold, compared to the previous techniques as well as when no cancellation is applied. Accordingly, the proposed iterative approach greatly reduces the energy of impulsive noise through multipath PLC channel, leading to good achievable gain by approximately 7 dB compared to when cancellation is not applied, especially at high SNR values (from 32 dB to 40 dB). Regarding the multipath PLC channel affected by 'strongly disturbed' impulsive noise scenario, Figure 16 shows that, as the impulsiveness of the noise increases, all the proposed approaches have achieved comparable BER performances, with the best BER improvement attributed to the proposed algorithm using the adaptive threshold (1 dB over the other approaches), especially at high SNR values ($SNR \geq 34$ dB).

Figure 15 BER performance, under AWGN + Impulsive Noise 'moderately disturbed' scenario: with multipath PLC channel (see online version for colours)

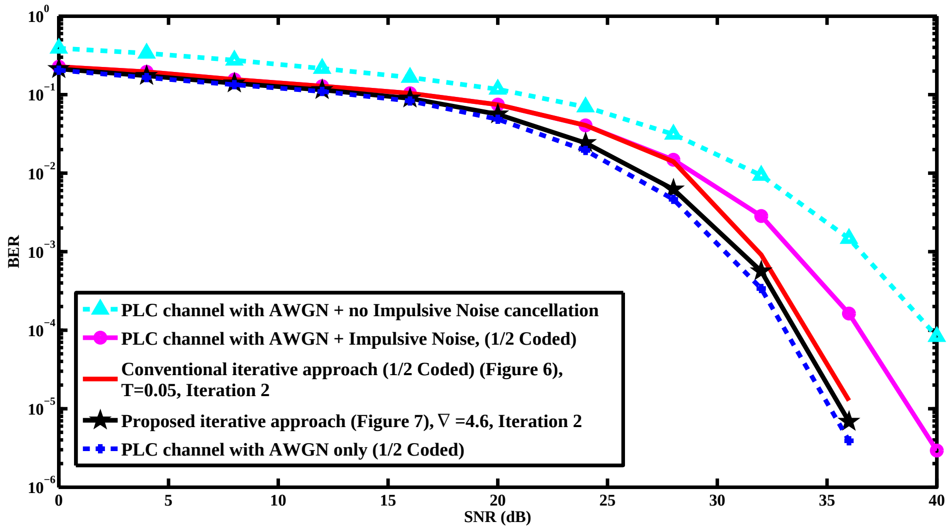
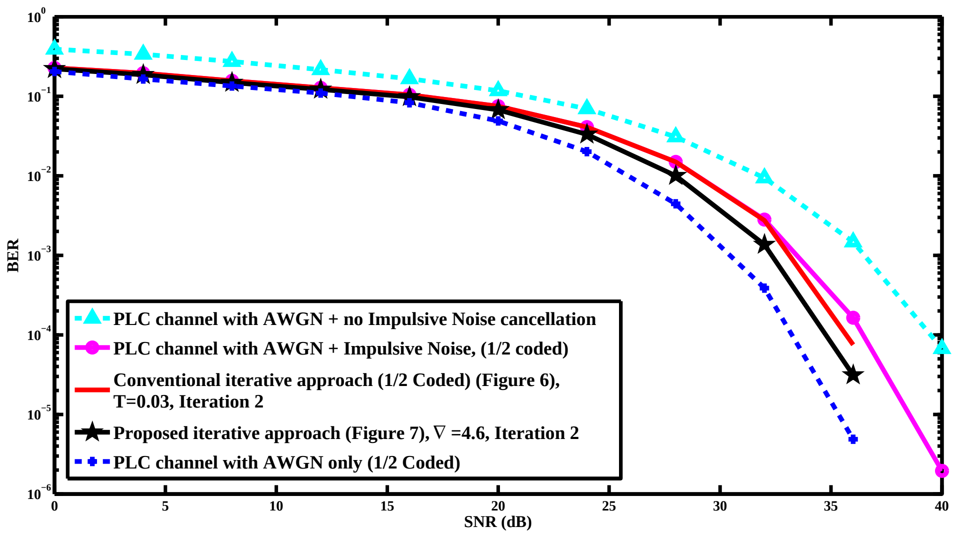


Figure 16 BER performance, under AWGN + Impulsive Noise 'strongly disturbed' scenario: with multipath PLC channel (see online version for colours)



4.4.2 Performance comparison in terms of PSNR

In this sub-subsection, the performances of the proposed iterative algorithm in terms of PSNR are provided. To carry out these simulations, Figure 17 depicts a simplified block diagram of the JPEG encoder/decoder OFDM-based PLC with multipath PLC channel. The JPEG bits stream is passed through the OFDM transmitter (Figure 5), multipath PLC channel, AWGN, and impulsive noise. Finally, the received signal is passed through the OFDM receiver, De-quantiser, and 8x8 IDCT before being reconstructed.

Figures 18 and 19 illustrate the PSNR performances of the proposed iterative algorithm, under multipath PLC channel in presence of 'moderately disturbed' and 'strongly disturbed' impulsive noise scenarios. It can be drawn from Figure 18 that the proposed iterative approach performs best compared to the conventional iterative approach (1/2 Coded), and deeply enhanced the PSNR performance compared to when no impulsive noise cancellation is applied, by about 4 dB at *SNR* = 32 dB.

For 'strongly disturbed' impulsive noise scenario, Figure 19 shows that the achievable SNR gap of the proposed iterative approach decreased by approximately 2 dB, as compared to the other impulsive noise scenario, especially for SNR range from 0 dB up to 28 dB. As a matter of fact, results of the simulation demonstrate once again that, increasing the impulsiveness of the impulsive noise decreases both BER and PSNR performances of the proposed technique. This is true as the average number of impulses per unit time *A* decreases, which corresponds to a harsh medium for image transmission.

Figure 17 Simplified block diagram of the JPEG encoder/decoder OFDM-based PLC: with multipath PLC channel

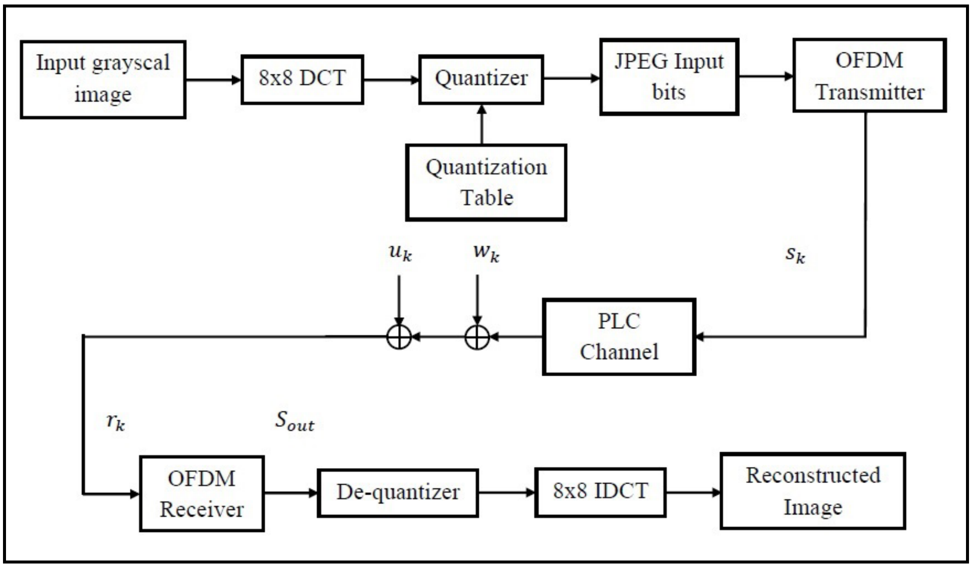


Figure 18 PSNR performance, under AWGN + Impulsive Noise 'moderately disturbed' scenario: with multipath PLC channel (see online version for colours)

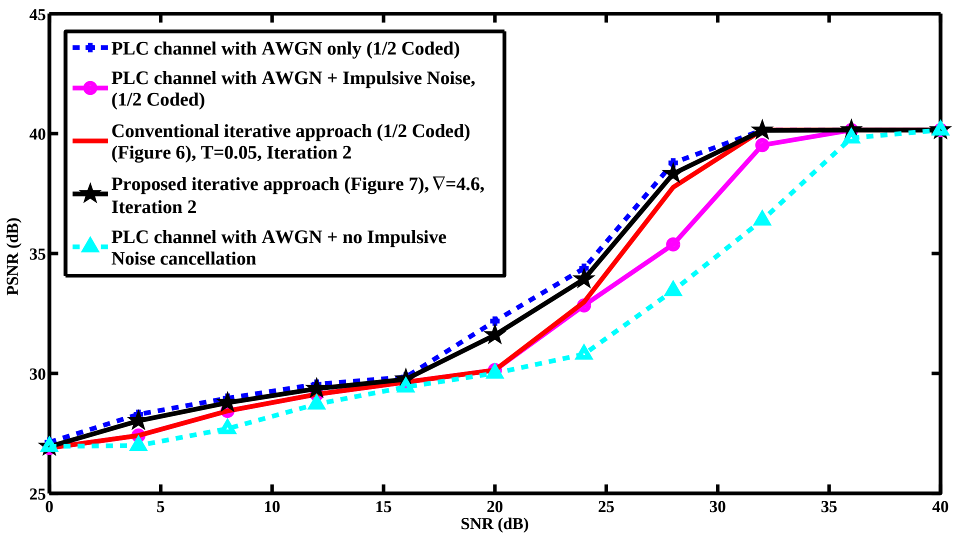


Figure 19 PSNR performance, under AWGN + Impulsive Noise 'strongly disturbed' scenario: with multipath PLC channel (see online version for colours)

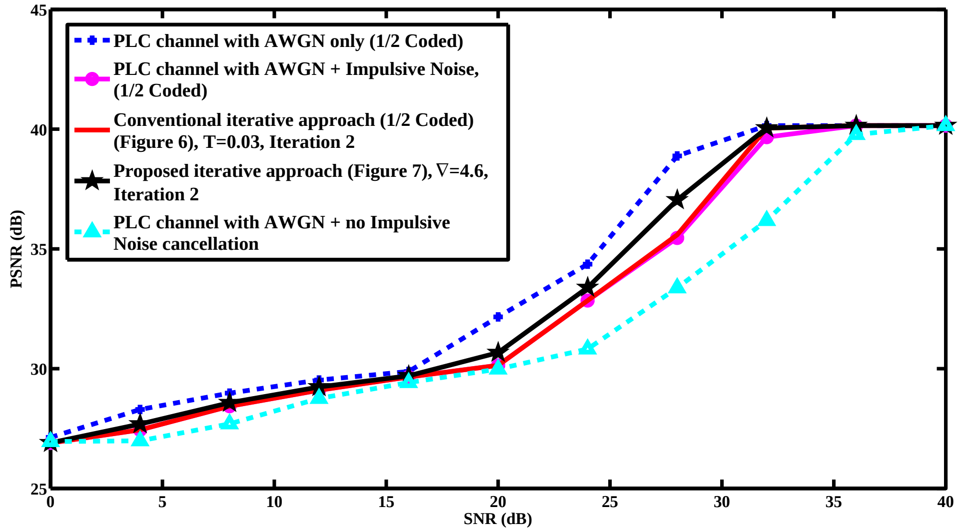
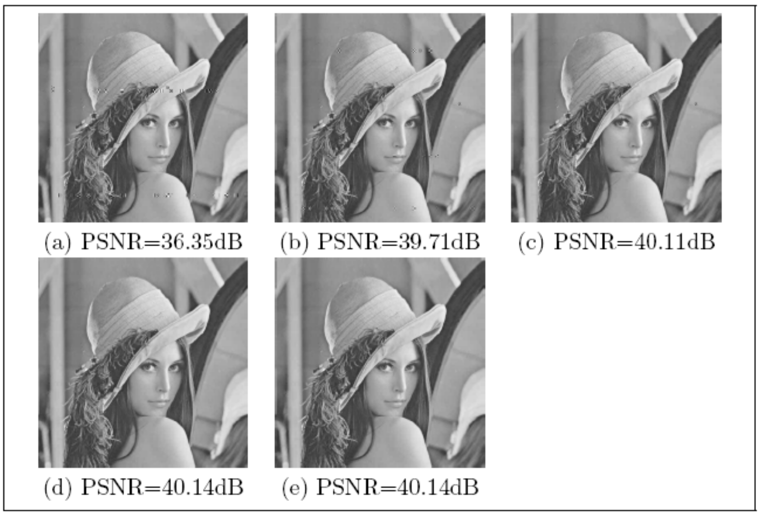


Figure 20 The reconstructed images, Figure 18 'moderately disturbed', at *SNR* = 32 dB, (a) 'PLC channel with AWGN + no Impulsive Noise cancellation' (b) 'PLC channel with AWGN + Impulsive Noise, (1/2 Coded)' (c) 'Conventional iterative approach (1/2 Coded) (Figure 6), *T* = 0.05, Iteration 2' (d) 'Proposed iterative approach (Figure 7), ∇ = 4.6, Iteration 2' (e) 'PLC channel with AWGN only, (1/2 Coded)'



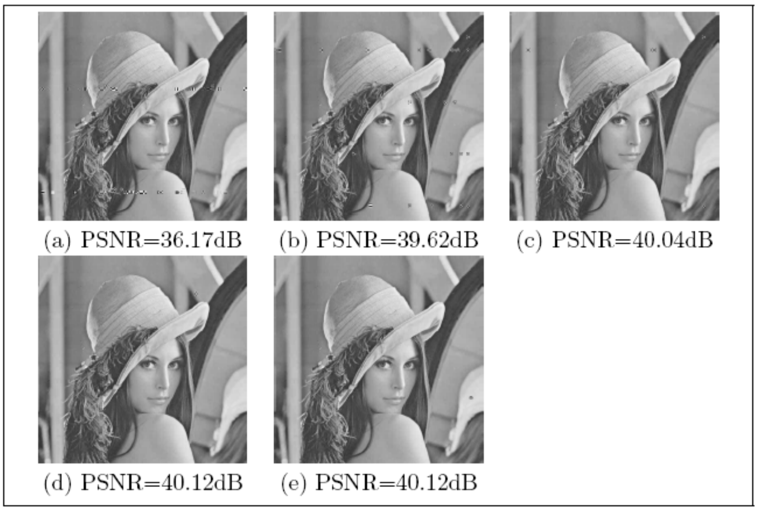
4.4.3 Visual reconstructed image quality

Figure 20 and Figure 21 display the various perceived quality of the reconstructed images at the receiver, under multipath PLC channel altered by moderately and strongly disturbed impulsive noise scenarios at *SNR* = 32 dB, respectively.

Figure 20(a) shows that, the multipath PLC channel and the impulsive noise degraded the visual quality of the transmitted image in burst, which contains a series of adjacent row block zones seemingly black and white. Figure 20(d) shows that the perceptual quality of the reconstructed image using the proposed iterative approach is comparable to that of the conventional iterative approach [Figure 20(c)]. In addition to the high quality of the image, Figure 20(d) has the same PSNR quality as Figure 20(e) which is the reference reconstructed image. Besides, the proposed iterative algorithm has performed a slight PSNR gain of 0.03 compared to the conventional iterative approach (1/2 Coded) [Figure 20(c)].

Regarding the multipath PLC channel affected by 'strongly disturbed' impulsive noise scenario, the results show that the conventional iterative approach (1/2 Coded) [Figure 21(c)] and the proposed iterative approach [Figure 21(d)] achieve the same PSNR performances with good visual quality of the image [the same quality visual of the reference image in Figure 21(e)]. It can be noticed from Figure 21(c) and Figure 21(d) that, for such multipath PLC channel and impulsive noise conditions; the PSNR has been improved by approximately 4 dB compared to the reconstructed image without cancellation [Figure 21(a)], with a 0.08 dB advantage for Figure 21(d) compared to Figure 21(c).

Figure 21 The reconstructed images, Figure 19 'strongly disturbed', at SNR = 32 dB, (a) 'PLC channel with AWGN + no Impulsive Noise cancellation' (b) 'PLC channel with AWGN + Impulsive Noise, (1/2 Coded)' (c) 'Conventional iterative approach (1/2 Coded) (Figure 6),T = 0.03, Iteration 2' (d) 'Proposed iterative approach (Figure 7), ∇ = 4.6, Iteration 2' (e) 'PLC channel with AWGN only, (1/2 Coded)'



5 Conclusions

In this paper, we have applied iterative impulsive noise suppression algorithms to reduce the effects of impulsive noise on image transmission in OFDM-based power line communications (PLC). This paper displayed some iterative algorithms using the adaptive threshold under a target false alarm probability that proved the ability to enhance the performance of bit error rate, peak signal-to-noise ratio (PSNR), and visual reconstructed image quality in the presence of multipath PLC channel moderately and strongly corrupted by impulsive noise. Our results demonstrated that, in the presence of multipath PLC channel moderately corrupted by impulsive noise, the proposed technique achieved a PSNR gain of approximatively 4 dB at SNR = 32 dB, leading to great perceptible quality of the reconstructed image. Finally, our future work would be seeking improvement of the proposed algorithms, with application to video transmission over the same configurations, or prospecting further techniques.

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