Reduction of the Effect of Impulsive Noise on Image Transmission in OFDM-Based Power Line Communications

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***Abstract*—Sending multimedia data (e.g. data, image and video) using Power Line Communications (PLC) has been growing significantly. In fact, impulsive noise (IN) causes significant degradation which restricts communication performance in PLC. In this paper, we propose to study the impact of IN on image communication in Orthogonal Frequency Division Multiplexing (OFDM) based PLC. A strightforward conventional iterative IN reduction algorithm, presented in [9] can be applied to improve bit-error rate (BER) in OFDM system. But, this iterative algorithm is insufissant to improve the visual quality Peak Signal-to-Noise Ratio (PSNR) performance in image communication. First, we study its performance in terms of BER and PSNR using a convolutional encoder (CE). Then, we modify its concept by introducing CE and Viterbi decoder into the iterative algorithm. Finally, we aim to show the impact of BER degradation on visual quality PSNR performance of the reconstructed image. Our results lay out that the proposed method provides good PSNR and visual quality improvement than the conventional algorithm with and without CE.**

***Index Terms*—Iterative impulsive noise reduction, OFDM, Power line communications (PLC), Multimedia applications.**

I. Introduction

Lately, transmission of multimedia data (e.g. data, image and video) using Power Line Communications (PLC) is receiving a huge amount of research interest. The PLC technology uses already-existing electrical networks to deliver high-speed broadband communications [1]. It is a known fact that Orthogonal Frequency Division Multiplexing (OFDM) is the most convenient transmission technique for such communication channels and is used mostly in several communication systems including, DSL (Digital Subscriber Line), Terrestrial digital TV (DVB-T), Wireless and PLC.

However, one of the serious challenges for PLC technology is to overcome additive noises [2], such as colored background noise, narrowband noise, periodic impulsive noise asynchronous to the main frequency (50 or 60 Hz), periodic impulsive noise synchronous and asynchronous impulsive noise. Such noises are mainly generated by the electrical appliances connected to the indoor power lines and by switched power supplies. Particularly, in case the power of impulsive noise is very high, this will affect a large number of OFDM sub-carriers leading to performance degradation [3], [4]. Therefore, reduction techniques should be used in order to improve performance of PLC systems. To study this typical noise, we use the widely accepted model in PLC, namely the Middeleton's class A (MCA) noise model [5].

Impulsive noise (IN) mitigation in OFDM-based communication systems in domains such as, DSL, Wireless and PLC is a field of active research [6]–[16]. A simple and widely used technique to reduce the effect of IN is to apply nonlinearity techniques to the received time-domain (TD) signal [6]–[8]. This operation consists in clipping or blanking (replacing with zeros) the high signal amplitudes above the selected threshold value. The drawback of this techniques is that imperfect identification of IN components can cause clipping/blanking the unimpaired amplitudes of the original signal resulting in bit error rate (BER) degradations. In [9]–[13], authors propose iterative methods to estimate IN in TD and substruct it from the received signal in TD or in the frequency-domain (FD) after Fast Fourier Transform (FFT) operation at the receiver, using a threshold detector that either can be adaptive or non-adaptive. Whereas others alike [12] and [14], use techniques similar to channel decoding called Syndrome Decoding (SD) technique, for IN mitigation by exploiting the information carried on null and pilot tones that are used for synchronization or channel estimation. Recently, IN reduction using compressed sensing (CS) and sparse bayesian approache (SBL) techniques have been proposed in [15] and [16]. These techniques use null tones of the received signal to estimate IN and substruct it by considering the sparsity of IN in TD. The drawback of SD, CS and SBL techniques is that the IN mitigation depends on the number of null and pilot tones in a way that their increase leads to a loss of bandwidth and a reduced throughput.

In this paper, we focus on the conventional iterative suppression algorithm (CISA) for mitigating the IN effects proposed in [9]. First of all, in a standard OFDM based PLC system a Forward Error Correction (FEC) is used. The role of FEC technique is to improve BER degradation. So, we study the performance of the CISA by applying a simple convolutional encoder (CE) in two scenarios of IN using MCA model, namely heavily perturbed and weakly perturbed environements. We have noticed that, although the CE improves better the BER performances, the CISA is insufissant to improve the visual quality PSNR performance in image communication. After that, we modify the CISA's concept by introducing CE and Viterbi decoder (VD) into the CISA. The CE improves the noise estimation at the current iteration and after IN mitigation the latter is greatly attenuated at the VD output. Finally, we aim to study and analyse the performance of the proposed method in terms of BER and Peak Signal-to-Noise Ratio (PSNR) and to show the impact of BER degradation on visual quality PSNR performance of the reconstructed image. The simulation results show that, for a determined optimal threshold; the PISA reduces the effect of IN significantly than the CISA, resulting in improvement of PSNR degradations approximatively by 14 decibels (dB) in weakly perturbed IN environment.

The paper is organized as follows. In section II, we present the background of the paper: OFDM system, impulsive noise model and the iterative impulsive noise suppression algorithms. In Section III, the proposed algorithm is discussed. The simulation results are discussed in Section IV. Finally a conclusion and future works are given in Section V.

II. Background

A. OFDM System

We consider the OFDM system model whose complex baseband equivalent is illustrated in Fig. 1. The input data a_k is first encoded by CE to produce a coded sequence x_k. The coded sequence x_k is then passed through the OFDM Modulator, whose output is the transmitted OFDM signal s_k. In order to generate s_k, the binary code sequence x_k is mapped using Quadrature Phase Shift Keying (QPSK) into modulation complex symbols x'_k and an inverse fast fourier transform (IFFT) is performed on the N symbols. Where, the N-point discrete time OFDM signal can be expressed as

$$s_k = \frac{1}{\sqrt{N}} \sum_{K=0}^{N-1} x'_k e^{j2\pi \frac{kn}{N}}, \qquad n = 0, 1, ..., N-1 \tag{1}$$

Where $\frac{1}{\sqrt{N}}$ is the scale factor and k is the index of OFDM block sub-carriers.

It should be noted that, the insertion of guard interval is rule out, since the frequency-selectivity of the PCL channel is not considered. The received TD signal after down-conversion, analog-to-digital conversion assuming perfect synchronization, additive white Gaussian noise (AWGN) and IN can be expressed as follows:

$$r_k = s_k + w_k + u_k, \qquad k = 0, 1, ..., N-1 \tag{2}$$

Where, r_k represents the received TD signal, s_k is the OFDM transmitted signal, w_k is the AWGN noise and u_k is the IN.

At the receiver, the process is reversed to obtain the estimated data $\hat{a_k}$, by doing impulsive noise reduction, OFDM Demodulator (FFT) and hard decision for Viterbi decoder.

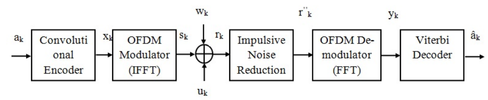

Figure 1. Block diagram of the OFDM-based PLC system.

B. Impulsive Noise model

To study the effect of IN in OFDM-based PLC system, a suitable noise model namely the Middleton class A (MCA) noise model is used [5]. The MCA is a statistical-physical IN model. The model is derived from electromagnetic interference events and can be represented as an superposition of statistically independent impulsive sources that are Poisson-distributed in their arrivals in time. From [5], the probability density function (PDF) is given by

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

Where $\sigma_m^2 = (\sigma_u^2 + \sigma_w^2) . \frac{\frac{m}{A} + \Omega_{GIR}}{1 + \Omega_{GIR}}$, m is the number of mixture components, $A \in [10^{-2}, 1]$ is the impulsive index, σ_u^2 is the impulsive noise variance, and σ_w^2 is the Gaussian noise variance and $\Omega_{GIR} \in [10^{-6}, 1]$ is the Gaussian-to-Impulsive variance ratio.

C. Conventional iterative suppression algorithm

The effect of IN may be got around by applying an iterative algorithm, which reduces efficently the energy of the IN in TD at the frontend of OFDM receiver. A strightforward iterative IN suppression algorithm was proposed in [9]. The basic idea behind the iterative suppression algorithm is to find a good estimate for IN in the time or frequency domains and cancel it from the received signal. Indeed, the IN estimation is based on a threshold detector, which determines whether the noise is part of IN or AWGN. The block diagram of the conventional iterative suppression algorithm (CISA) is shown in Fig. 2.

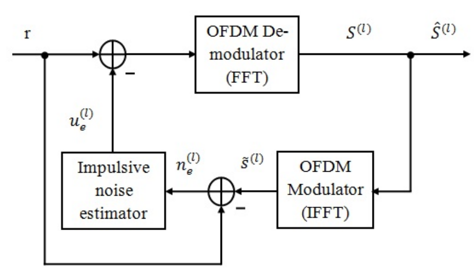

Figure 2. Block diagram of the CISA.

In the following, we briefly review the iterative algorithm as given in [9]. For the purposes of notation, $\hat{S}^{(l)}$ designates the output data $\hat{a}_k$ in Fig. 1. Generally, the noise estimation is based on a threshold detector, which decides whether the noise is part of the impulsive noise or the Gaussian noise. In Fig. 2, r is the received signal, l is the number of iterations, and $\hat{S}^{(l)}$ is the final output. At each iteration, the algorithm try to find a good estimate of the impulsive noise $n_e^{(l)}$ in TD and cancel it from the received signal r using a threshold detector in the impulsive noise estimator. After seven iterations the effect of IN is greatly reduced resulting in good BER performances on OFDM transmission. Following up on the CISA presented in Fig. 2, we first study its performance under IN channel by using a CE at the transmitter and a hard decision for Viterbi Decoder (VD) at the receiver. The block diagram of the CISA using VD is shown in Fig. 3.

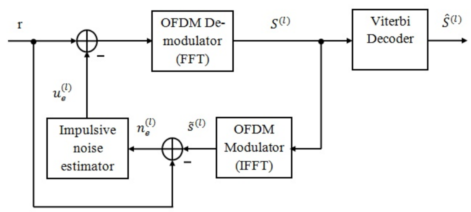

Figure 3. Block diagram of the CISA using CE and VD.

III. Proposed Impulsive Noise Iterative Algorithm

Despite the BER improvements made by the CISA in presence of CE. The visual quality PSNR performance in image communication still degraded. Given that, we modify the iterative receiver in Fig. 3 by introducing CE and VD into the iterative process to improve the noise estimation in the current iteration, in order to avoid errors on the output of the receiver. The block diagram of proposed iterative suppression algorithm (PISA) is depicted in Fig. 4.

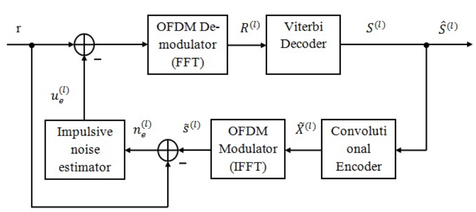

Figure 4. Block diagram of the PISA.

In the proposed scheme, r is the received signal, l is the number of iterations, and $\hat{S}^{(l)}$ is the final output. The steps in OFDM Demodulator and Viterbi Decoder are exactly the reversed process done by the transmitter. The received signal is transformed by FFT into frequency domain. Then, an QPSK de-mapper is applied to the signal followed by Viterbi decoding to obtain output data $\hat{S}^{(l)}, l \geq 0$, represents the result of the lth iteration. As for the process in Convolutional Encoder and OFDM Modulator, they are used to reconstruct the transmitted signal to obtain a more relevant IN estimation. The result, $n_e^{(l)} = r - \tilde{s}_e^{(l)}$ represents the total noise resulting from AWGN and impulsive noise at the lth iteration. In fact, for each iteration the estimate noise $n_e^{(l)}$ becomes more relevant using the estimated transmitted signal $\tilde{s}_e^{(l)}$ from the previous iteration. Next, the Impulsive noise estimator is applied to $n_e^{(l)}$ to estimate the amplitudes at the positions of the IN. The function of the impulsive noise estimator is

$$u_e^{(l)} = \begin{cases} 0, & |n_e^{(l)}| \leq T \\ n_e^{(l)}, & |n_e^{(l)}| > T \end{cases} \tag{4}$$

Where T is a threshold detector. However, the threshold T is used to decide whether the amplitudes $|n_e^{(l)}|$ belong to the impulsive amplitudes or to the AWGN noise. Finally, expecting that $u_e \approx u$ we substruct the IN estimate from the received signal in (2) and pursue as if only AWGN noise is present. Starting the next iteration, Viterbi decoder output is more relevant. Consequently, the effect of IN is reduced, resulting in higher performance of the OFDM receiver. The PISA can be described as follows.

Algorithm 1 PISA

$l = 0$
$r^{(0)} = r$
repeat until stop criterion is valid
$R^{(l)}$ = OFDM_Demodulator($r^{(l)}$)
$S^{(l)}$ = Viterbi_Decoder($R^{(l)}$)
$\tilde{X}^{(l)}$ = Convolutional_Encoder($S^{(l)}$)
$\tilde{S}^{(l)}$ = OFDM_Modulator($\tilde{X}^{(l)}$)
$n_e^{(l)} = r^{(l)} - \tilde{S}^{(l)}$
$u_e^{(l)}$ = Impulsive_noise_estimator($n_e^{(l)}$)
$r^{(l+1)} = r^{(l)} - u_e^{(l)}$
$l = l + 1$
end repeat
$\hat{S}^{(l)} = S^{(l)}$

In this algorithm, if $\hat{S}^{(l+1)} = \hat{S}^{(l)}$ for the first time, the iteration stops. The iteration loop is also terminated, if a maximum number of iterations is exceeded.

IV. Simulation Results

To evaluate the performance of the iterative IN reduction algorithms, computer simulation was carried out in two scenarios using MCA model, namely heavily perturbed and weakly perturbed environments. In this simulations, the two different scenarios of IN, namely heavily perturbed scenario for A=0.1, Ω_{GIR} =0.01 and A=0.01, Ω_{GIR} =0.01 corresponds to weakly perturbed scenario, are considered. A convolutional encoder with code rate $\frac{1}{2}$ is applied at the transmitter and hard decision for Viterbi decoder at the receiver. The OFDM transmitted signal have a number of data sub-carriers equal to 1024. The performance obtained in terms of BER have about 10^4 OFDM symbols and a number of transmission bits is about 2×10^7. As for the performance measured in terms of PSNR, the number of OFDM symbols are about 500 and a number of transmission bits is about 5×10^5. The Signal-to-Noise Ratio (SNR) in all figures is defined as

$$SNR = 10 \times log_{10}(\frac{1}{\sigma_w^2}) \tag{5}$$

A. Performance of iterative algorithms in terms of BER

To study the performance of the iterative algorithms in terms of BER, the selected threshold T in (4) has to be thoughtfully chosen. We could search for an optimal threshold value that minimizes the BER performance. To this end, computer simulations in heavily and weakly cases were carried out. Fig. 5 illustrates the optimal thresholds for an SNR value equal to 8 dB under the two cases. However, the threshold values T from 0.1 to 3.2 can be used as an optimal thresholds in both cases and the iterative algorithms (Fig. 2, Fig. 3 and Fig. 4) would accomplish good BER performances. In the following, we use two optimal threshold values $T = 2.2$ for the weakly case and $T = 0.8$ for the other scenario.

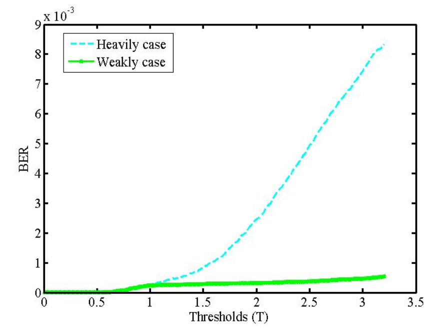

Figure 5. BER vs. different thresholds (T) in heavily and weakly cases.

Fig. 6, illustrates a comparison between the iterative algorithms in weakly perturbed environment (A=0.01). In this simulations, the number of iteration is fixed at two iterations and any further iteration does not improve the BER performances. Simulation results are compared and obtained using the threshold value $T = 2.2$.

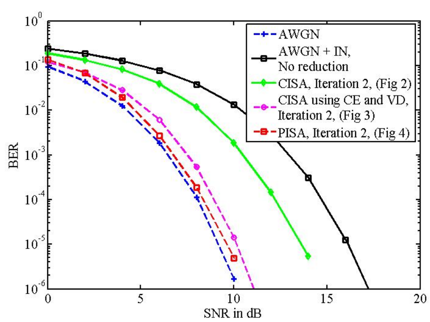

Figure 6. BER vs. SNR, coded-1024-OFDMQPSK under AWGN + IN), $T = 2.2$, weakly case.

In Fig. 6, the result shows that the CISA (Fig. 2), improves the BER performances than the case without mitigation (AWGN+IN, No reduction curve) at the second (2nd) iteration. It can be noticed from Fig. 6, although the CISA using CE and VD improves better than the CISA approximatively by 3 dB, the latter technique (PISA, Fig. 4) outperforms the former by about 4 dB for SNR values from 0 dB to 10 dB. Also, even if the selected threshold (e.g. thresholds from 0.1 to 3.2 of Fig. 5) is not optimal, the BER performances will not get worst than the AWGN + IN, No reduction curve.

Fig. 7, provides a comparison between the iterative algorithms in heavily perturbed environment (A=0.1). Results are obtained using the optimal threshold value $T = 0.8$.

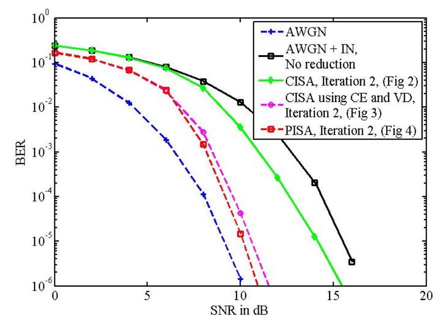

Figure 7. BER vs. SNR, coded-1024-OFDMQPSK under AWGN + IN, $T = 0.8$, heavily case.

In Fig. 7, results of the simulation show again that; the CISA achieves good BER improvement by about 2 dB at high SNR values ($SNR >= 10dB$); compared to the case AWGN+IN, No reduction curve. Besides, the simulation results show that the PISA provides the best BER improvement at SNR values ($SNR >= 8dB$) in heavily perturbed environment. On the other hand, all three techniques achieve slightly improvement at low SNR values ($SNR <= 8dB$); compared to the AWGN reference curve. Finally, we remark that the PISA significantly improves the BER performance in both IN scenarios and it works efficiently in weakly perturbed environment.

B. Performance of iterative algorithms in terms of PSNR

After studying and comparing the BER performances of the iterative algorithms, in this subsection, we study and analyse their ability to reduce the effect of IN on image communication in terms of PSNR and the visual quality of the reconstructed image at the receiver. In our simulations, a sequence of binary data obtained from a grayscal image is transmitted after doing 8×8 Discrete Cosine Transform (DCT) and quantization. Fig. 8 illustrates the transmitted image in grayscal mode.

Figure 8. Transmitted image (grayscal) 250×250 pixels.

The PSNR in all figures is defined as $PSNR = 10 \times log_{10}(\frac{255^2}{MSE})$, where MSE is the mean square error between the transmitted image and the reconstructed image at the receiver. The number of iteration is fixed at three iterations since any further iteration does not improve the PSNR performances.

Fig. 9, illustrates a comparison between the iterative algorithms in weakly perturbed environment (A=0.01). Simulation results are compared using the optimal threshold value $T = 2.2$. In comparison to the case without cancellation (AWGN + IN, No reduction curve), the result shows that the PISA (for high SNR values ($SNR >= 6dB$)) significantly improves the PSNR performances at the 3rd iteration.

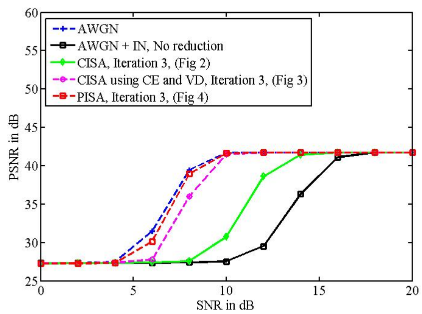

Figure 9. PNSR vs. SNR, coded-1024-OFDMQPSK under AWGN + IN, $T = 2.2$, weakly case.

Similarly, as we have demonstrated in Fig. 6 (BER peformances in weakly IN case); although the threshold is not optimal any further iteration does not increase the PSNR performances and the performance of the iterative algorithms will not get worst than the case with no reduction (Fig. 9, AWGN + IN, No reduction curve). Results of the simulation demonstrate, once again; significant improvement of the PSNR performances in weakly perturbed scenario using threshold value $T = 2.2$. As can be seen from Fig. 9, despite CISA using CE and VD (Fig. 3) improves the PSNR performances better than the CISA (Fig. 2) by about 10 dB. The PISA (Fig. 4) outperforms the CISA using CE and VD (Fig. 3) by about 2 dB for SNR values from 8 dB to 12 dB. In addition, the PISA (Fig. 4) and the CISA (Fig. 3) achieve comparable results in terms of PSNR performances for high SNR values ($SNR >= 10dB$).

Fig. 10 shows the reconstructed image of the CISA for $SNR = 8dB$ at the 3rd iteration. As shown in Fig. 10, the IN has a tendency to degrade the visual quality of the transmitted image with block zones seemingly black and white and appearing quite randomly.

Fig. 11, illustrates the reconstructed image of the CISA using CE and VD for $SNR = 8dB$ at the 3rd iteration. Fig. 11 shows that, although the PSNR quality of the reconstructed image is improved by 10 dB than the CISA (Fig. 10), the block zones can still be noticed. In other words, the obtained PSNR quality of 36.23 dB has no correlation with the perceived picture quality. This means that the PSNR only reflects in image visual quality if highly improved; result which was not given by the optimal threshold we used for the CISA using CE and VD. (Fig. 3).

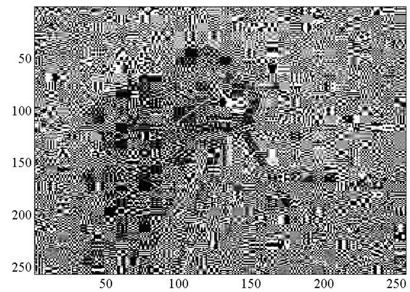

Figure 10. Reconstructed image, CISA (Fig. 2), Iteration 3, weakly case. $T = 2.2$, SNR=8dB, PSNR=27.61dB.

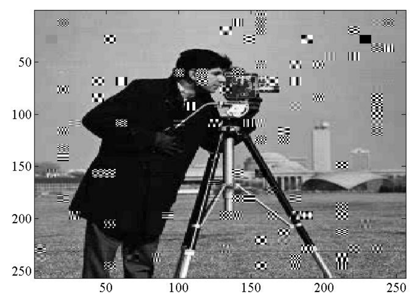

Figure 11. Reconstructed image, CISA using CE and VD (Fig. 3), Iteration 3, weakly case. $T = 2.2$, SNR=8dB, PSNR=36.23dB.

Fig. 12, shows the effect of reconstructed image enhancement using the PISA for $SNR = 8dB$ at the 3rd iteration. Fig. 12 shows that, although the PSNR quality of the reconstructed image is improved by approximatively 2 dB than the CISA using CE and VD (Fig. 11), the block zones can still be perceived. In other words, the PISA shows its limits in improving the visual quality of the reconstructed image for low SNR values ($SNR <= 8dB$), that remains unsatisfactory even if the PSNR is slightly improved.

Figure 12. Reconstructed image, PISA (Fig. 4), Iteration 3, weakly case. $T = 2.2$, SNR=8dB, PSNR=38.71dB.

On the other hand, as it can be seen from Fig. 13 and Fig. 14, our results lay out that the CISA using CE and VD (Fig. 3) and the PISA (Fig. 4) provide the same PSNR performances for $SNR = 10dB$ at the 3rd iteration. The reconstructed images have a good visual quality (the same quality visual of the transmitted image in Fig. 8) and the PSNRs are improved by 10 dB than the CISA (Fig 2) and approximatively by 14 dB than the case without cancellation (Fig. 9, AWGN + IN, No reduction curve).

Figure 13. Reconstructed image, CISA using CE and VD (Fig. 3), Iteration 3, weakly case. $T = 2.2$, SNR=10dB, PSNR=41.72dB.

Figure 14. Reconstructed image, PISA (Fig. 4), Iteration 3, weakly case. $T = 2.2$, SNR=10dB, PSNR=41.72dB.

In fact, introducing redundancy and by exploiting the noise's structure in TD, the PISA greatly reduces the energy of the IN, leading to good quality visual of the reconstructed image at the receiver. As a matter of fact, our results showed that although the PSNR improvement at low SNR values ($SNR <= 8dB$); the actual visual quality of the reconstructed image remained degraded.

V. Conclusion

Summing up, we have applied iterative algorithms to delibitate the effects of impulsive noise (IN) on multimedia data transmission. This paper displayed a proposed iterative suppression algorithm (PISA) using Viterbi decoder that improve the performance of OFDM-based PLC system in terms of Bit Error Rate (BER) and Peak Signal-to-Noise Ratio (PSNR), in presence of two different scenarios of IN, namely heavily perturbed and weakly perturbed environments. In fact, simulation results have shown that, for a determined optimal threshold value as a parameter; the PISA reduces the effect of IN significantly in weakly case. The simulation outcomes demonstrated that, the PISA has provided great BER improvement (in weakly scenario) in terms of BER. Furthermore, our study focussed on the study and analyse of the impact of BER improvement on the PSNR performances. Our results layed out that, the PISA improved the PSNR quality of the reconstructed image by approximatively 14 dB at $SNR = 10dB$, leading to great perceived visual quality of the reconstructed image. Finally, our future work would be seeking improvement of the visual quality of image communication in PLC system, by either finding solutions to improve the thresholds of our PISA in order to get better PSNR results at low $SNR <= 8dB$ values; or prospecting further techniques. Also, we plan to reduce complexity implementations of the proposed method.

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