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IMPULSIVE NOISE REDUCTION IN POWER LINE COMMUNICATION USING ADAPTIVE FORWARD ERROR CORRECTION FILTER

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ABSTRACT

In this article, noise reduction in power line communications (PLC) was studied with the aim to improve its bit error rate (BER) and throughput performance by mitigating the harmful effects of impulsive noise. To this end, a noise reduction technique based on hybrid forward error correction (FEC)-Least Mean Square (LMS) filtering is proposed. Simulation results show that the proposed hybrid FEC-LMS method shows significant improvement over the conventional FEC method and adaptive LMS filtering method in terms of BER and throughput.

Keywords: adaptive least mean squares filter, forward error correction, impulsive noise, medium access control, network simulator-3, power line communication.

1. INTRODUCTION

Broadband over power-lines has emerged as a promising technology with the advantage of using existing power-line networks for data transmission which potentially provides a huge cost reduction [1-5]. Such technology, also known as power-line communication (PLC), is capable of delivering data at a rate of up to 1 Gbps [6]. Moreover, PLC has been regarded as one of the key enabling technologies for the Internet of Things (IoT), where many devices can connect and communicate with each other over PLC networks. However, its high data rate is inhibited by factors such as attenuation and interference caused by various types of noises [7] [8]. The presence of these noises in PLC networks can result in significant performance degradation [9]. The noise can be categorized into two: background noise and impulsive noise. Each of these two noises can further be broken down into categories as shown in Figure-1.

It was found out that impulsive noise can cause stronger interference to PLC networks as it had been shown that man-made noise and atmospheric noise demonstrate impulsive behaviours with heavy tail characteristics [10]. Therefore, an in-depth analysis of impulsive noise is needed to understand its behaviour and to improve the performance of PLC networks [11]. In [12], forward error correction (FEC) had been found to be a better noise mitigation technique as compared to other existing noise reduction techniques such as time-domain techniques (e.g., clipping, blanking, nulling), time/frequency-domain techniques, Bayesian learning techniques, recursive detection techniques. In [13], it had been shown that adaptive noise reduction techniques using LMS algorithm outperform the existing notch filter to suppress periodic impulsive noise.

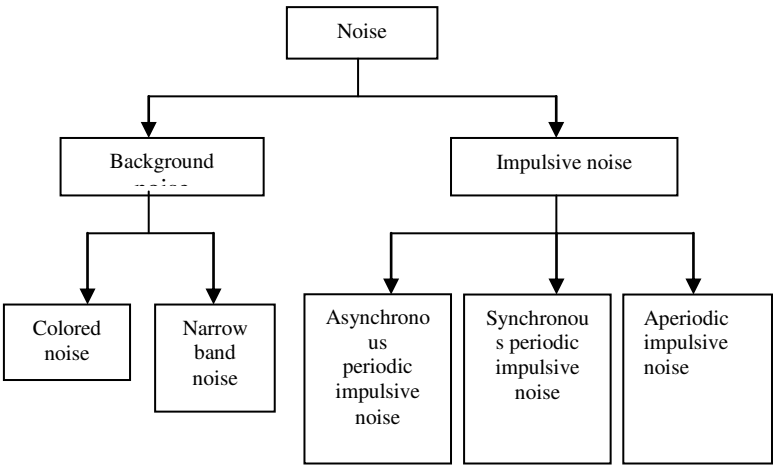

Figure-1. Types of noises.

The existing FEC technique can be used to filter the aperiodic impulsive noise partially. To perform the effective aperiodic impulsive noise cancellation there is a need for an adaptive algorithm. In this article, we propose a hybrid FEC-LMS technique to mitigate the impulsive noise problems in PLC networks. The combination of FEC

technique with an LMS adaptive algorithm greatly increases the performance of the aperiodic impulsive noise cancellation. The proposed technique is also compared with the FEC method and the adaptive LMS filtering method and simulation results show that the proposed technique outperforms the other two schemes in terms of bit error rate (BER) and throughput.

This article is organized as follows. In Section 2, PLC-medium access control (MAC) with and without impulsive noise is described. The FEC implementation is detailed in Section 3 and the adaptive LMS filtering method is explained in Section 4. The hybrid FEC-LMS noise reduction technique is proposed in Section 5. The simulation setup is given in Section 6. Results and discussions are presented in Section 7. Finally, conclusions are provided in Section 8.

2. PLC-MAC WITH IMPULSIVE NOSIE

There are several media access control (MAC) protocols that are candidates for this type of communication medium. The most common are dynamic protocols with contention, reservation protocols and arbitration protocols such as polling and token passing. However, power line networks typically form a bus or tree topology [27]. Due to the high noise levels of PLC, Carrier Sense Multiple Access (CSMA) may be the best candidate to be used in this environment due to the high possibility of packet collision in this network topology. The CSMA with collision avoidance (CSMA/CA) typically used in wireless networks is the most suitable variation of CSMA due to the difficulty in detecting the collision in a noisy environment [28].

PLC with a MAC protocol is one of the efficient methods to transmit broadband data over power lines. The MAC protocol allows the sharing of a power-line network by multiple users and avoids collisions. When the network topology becomes more complex, ambiguous and scalable, network simulation technologies become crucial [14]. In this article, a PLC network with a MAC protocol is modelled using the ns-3 simulator to investigate the performance of PLC in the presence of impulsive noise. In [15], an ns-3-based software module had been used to simulate data transmission between network nodes. As ns-3 is an open-source network simulator and it allows including new modules, ns-3 is more suitable to carry out this research. Several kinds of research studying networking protocol and communication networks have used ns-3 to carry out the simulation s where PLC networks can be modelled [16]. Therefore, in this article, PLC-MAC network is simulated with 26 nodes using the software module developed in [15].

3. NOISE REDUCTION USING FEC

In [16-20], noise reduction techniques such as clipping, nulling, FEC and filtering were introduced and developed. In clipping and nulling, the amplitude of the received signal gets limited once it exceeds a threshold. During this process, the in-band distortion affects the bit error rate (BER) performance. In [12], the FEC method offered the best impulsive noise mitigation compared to several other noise reduction techniques. The FEC method is actually an error correction technique used to detect and correct data errors during data transmission over noisy communication channels. Hence, it can be used to reduce the impulsive noise in power-line communication channels. In this technique, the transmitter sends redundancy bits and the receiver recognizes only the portion of the data without errors. Here, the redundancy bits allow the receiver to detect the errors that occur in the data and to correct the errors without retransmission. The basic procedure of FEC with Hamming distance is explained in Figure-2.

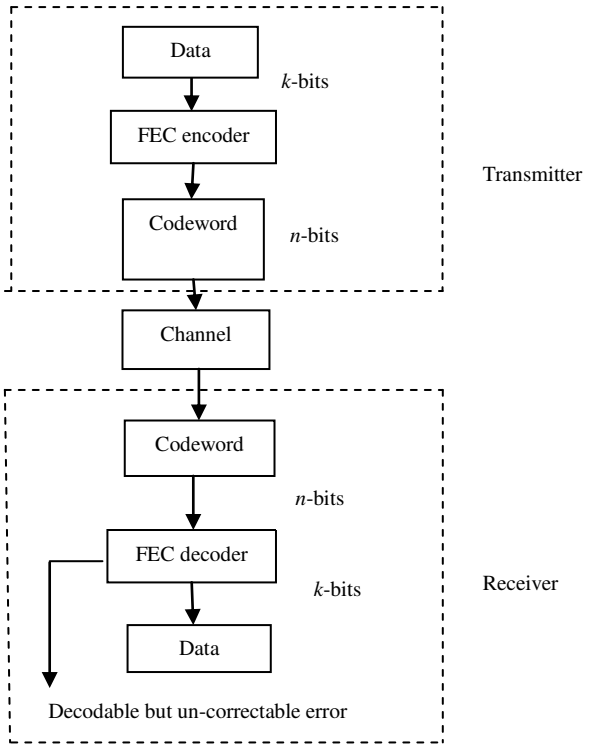

Figure-2. Basic block diagram for FEC.

A codebook is used to map k-bit data sequences to n-bit codewords, where

$$n > k, \tag{1}$$

$$\text{Code rate, } r = \frac{k}{n} < 1 \tag{2}$$

in which k is the length of the data block and n is the length of the code word. An example (5, 2) code is shown in Table-1.

Table-1. (5, 2) code.

Data Block	Code word
00	00000
01	00111
10	11001
11	11110

The error correction of a block code is done with "Hamming distance" between each of the code words. The Hamming distance between n-bit code words $v1$ and $v2$ is defined as

$$d(v1, v2) = \sum_{l=0}^{n-1} XOR\ (v1(l), v2(l). \quad (3)$$

For some positive integer t_c, if a code satisfies Equation 4, the code can correct up to t_c bit errors in the received code word:

$$d_{min} \geq 2t_c+1 \quad (4)$$

where d_{min} is the minimum distance defined as

$$d_{min} = \min_{i \neq j} d(vi, vj). \quad (5)$$

Equivalently, the number of guaranteed correctable errors per code word is

$$t_c = [\frac{d_{min}-1}{2}]. \quad (6)$$

The number of guaranteed detectable errors per code word is

$$t_d = d_{min} - 1. \quad (7)$$

In this article, FEC was introduced to reduce the effects of impulsive noise in the PLC-MAC network and its performance was analyzed.

4. ADAPTIVE LEAST MEAN SQUARE FILTER

In real-world applications, for many filtering techniques, filter coefficient values that would bring out the best performance is not known. Therefore, adaptive LMS filtering techniques are used to solve such problems [20]. The adaptive LMS filter is one that updates its filter coefficients dynamically. This adaptive filter consists of two parts. The first part is made up of a filter, which is usually a finite impulse response (FIR) filter because of its advantages and stability [21]. The second part of the filter is one where an adaptive algorithm is used. It is noteworthy that the LMS algorithm will be used as the adaptive algorithm in this study. The basic block diagram of the adaptive filter is shown in Figure-3.

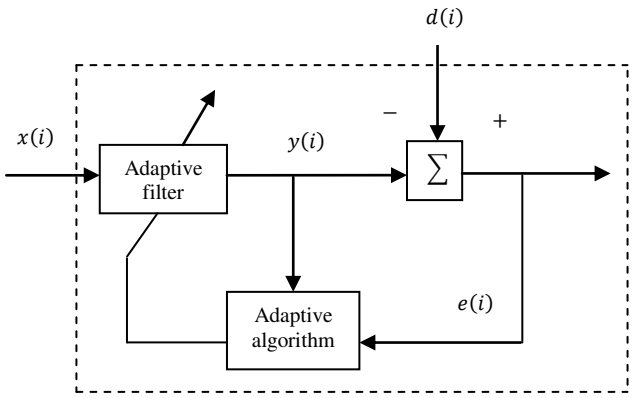

Figure-3. Basic block diagram of an adaptive filter.

The adaptive noise reduction technique consists of two inputs. They are the primary input signal (desired signal) $d(i)$ and the reference input signal $x(i)$. The desired signal $d(i)$ is the PLC signal corrupted by impulsive noise and the reference signal $x(i)$ is the undesired noise filtered out of the PLC system. The adaptive filter using the LMS algorithm filters the undesired noise and produces a clean output signal $y(i)$. Then, the output signal $y(i)$ is subtracted from the desired signal $d(i)$ to produce an error signal $e(i)$, that is the system output. The weight function w is updated every iteration to obtain a new weight value by adjusting the old weight value. This implies that the LMS algorithm can adjust its coefficients dynamically. The adaptive filtering algorithms undergo the filtering and adaptive procedure. During the filtering part, two values are estimated. First, the value of the filter output is generated.

$$y(n) = \sum_{i=0}^{m-1} w_i x(n-i) = w^T(n)x(n) \quad (8)$$

The LMS algorithm aims at curtailing the mean square error by amending the tap weight vectors. The tap weight adjustment at time n+1 is

$$\widehat{w}(n+1) = \widehat{w}(n) + \mu x(n)e^*(n) \quad (9)$$

Where μ is the step size parameter, the value of the error is found by subtracting the filter output from the wanted reaction. In the adaptive process, the filter regulates its factors in agreement to the wanted reaction.

$$e(n) = d(n) - y(n) = d(n) - w^T(n) \quad (10)$$

Table-2 shows the acronyms of the LMS algorithm used in the adaptive filter.

Table-2. LMS algorithm parameters.

Inputs		Outputs	
x	**input signal**	y	**output of the filter**
d	desired signal	e	error signal
M	filter length		
M	step size factor		
w	weight function		

5. PROPOSED HYBRID FEC-LMS TECHNIQUE

According to the literature, the adaptive filtering methods and FEC techniques perform better in noise reduction for PLC and are suitable to deal with impulsive noise. As visualized in Figure-1, impulsive noise has two variants: Periodic and aperiodic where the periodic part produces higher spikes compared to aperiodic part. As such, periodic impulsive noise causes significant performance degradation of the network, which is hard to mitigate [22]. According to [22], FEC can only mitigate aperiodic impulsive noise and it cannot mitigate periodic noise fully. However, it can be combined with other noise reduction technique to further mitigate periodic impulsive noise to a great extent. In [13], an adaptive filter was shown to be able to mitigate the periodic impulsive noise. When the periodic impulsive noise is detected, the adaptive filter filters the signal above a particular threshold frequency. Hence, there is a need for a hybrid FEC-LMS noise reduction technique to mitigate the aperiodic and periodic part fully.

The proposed hybrid FEC-LMS noise reduction technique consists of two phases. In the first phase of the system, FEC is implemented whereas, in the second phase of the system, an adaptive LMS filter is implemented. The main working principle of this proposed technique is that the enhanced data (after aperiodic impulsive noise removal and with the presence of some periodic impulsive noise which could not be removed using FEC) from FEC is fed to the adaptive LMS filter for further enhancement (for the removal of periodic impulsive noise left unfiltered by FEC). Hence, the impulsive noise left unfiltered by FEC was filtered by an adaptive LMS filter. Hence, the accuracy is higher. One of the limitations of FEC is that when the number of data bits increases, some errors could not be corrected. The proposed hybrid filter can work jointly to overcome these limitations. It combines the efficiency of FEC with the stable and computationally efficient adaptive LMS filter. The advantages of both the noise reduction techniques were combined together to produce an improved performance.

At first, the data signal from the power-line channel is made compatible for FEC, where analogue-to-digital conversion takes place. To implement the FEC technique, the k-bit data from the transmitter end is converted to the n-bit codeword with the use of a codebook. The n-bit codeword is then allowed to pass through the power-line channel corrupted by impulsive noise. The data corrupted by the impulsive noise and an invalid codeword (error data) will be received at the receiver end. Here, error correction is done based on the Hamming distance between each of the codeword. The receiver chooses the valid codeword (error-free data) for the invalid codeword (error data) with the minimum Hamming distance. Thus, the error-free data (enhanced data) is received at the receiver end. The output enhanced data of FEC is in digital form. This is made compatible for the adaptive LMS filter, where digital-to-analogue conversion takes place. This enhanced analogue data is then given to the adaptive LMS filter for further enhancement.

The process takes place in the proposed hybrid FEC-LMS noise reduction filter is shown in Figure-4.

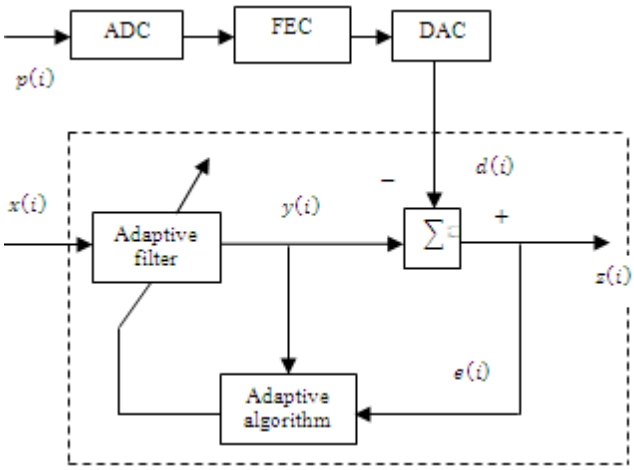

Figure-4. Block diagram of hybrid FEC-LMS filter.

In Figure-4, where $p(i)$ is the PLC signal with impulsive noise, $x(i)$ is the impulsive noise signal, $d(i)$ is the output enhanced data of FEC, $e(i)$ is the error signal, $y(i)$is the output of the adaptive filter, $z(i)$ is the output of the hybrid FEC-LMS filter, ADC-Analogue-to-digital conversion; DAC–Digital-to-analogue conversion.

6. SIMULATION SETUP

Simulations are performed using the ns-3 simulator with the use of a software module named the PLC channel simulator. Firstly, a PLC channel is simulated with the MAC layer for 26 nodes. As it had been shown in [23] that the performance of a PLC network becomes worse as the number of nodes increase, it is critical to evaluate our proposed filtering technique in such a scenario. In this setup, the research was carried out for a number of 26 nodes. Secondly, the impulsive noise is introduced to the PLC-MAC network. Thirdly, two noise reduction techniques namely the FEC and adaptive LMS filter are implemented to the network in which impulsive noise is introduced. Finally, the proposed hybrid FEC-LMS noise reduction technique is implemented in the same network in which the impulsive noise is introduced. The performance of the network for each case is measured in terms of BER and throughput. The flowchart of the research methodology is shown in Figure-5.

The settings of parameters used in this simulation, which are the modulation scheme, noise floor, step size, convergence rate and order of the filter, are shown in Table-3. QAMPAM (Quadrature Amplitude Modulation Phase Amplitude modulation) and BPSK (Binary Phase Shift Keying) are modulation schemes more suitable for PLC and are used at the transmitter end to modulate the data before transmission. The noise floor is the measure of the total level of impulsive noise introduced in the power line channel. Initially, different noise floors ranging from $10^{-9}$to 60×10^{-9}were introduced to the channel. Simulations are done and found that the performance of the channel decreases as the noise floor increases. Therefore, a noise floor $15 \times 10^{-9}$is used in this study. The step size/ convergence rate in equation 9 is the speed at which a convergence sequence approaches its limit. Using a small step size decreases the convergence speed of the adaptive filter. Hence, the step size must be increased to improve the convergence speed of the adaptive filter. However, it should not be larger as it makes the adaptive filter become unstable. Hence, a suitable step size to achieve better performance is used in this simulation. The order of a filter is the maximum number of delays used in the filter. Choosing the order of the filter is a trial and error process as it affects the convergence speed and steady-state error of the adaptive filter. Choosing a small filter order increases the convergence speed. Therefore, the filter order is chosen accordingly. Investigations are done for each parameter value and filter order 5 is used to carry out this experiment.

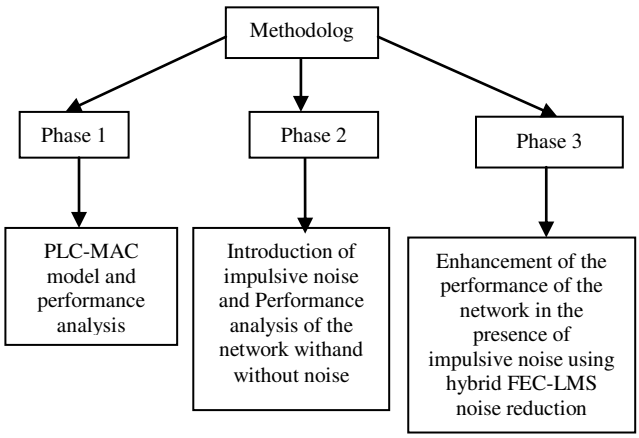

Figure-5. Flowchart of the research methodology.

Table-3. Simulation parameters.

Number of nodes used	26
Distance between the nodes	10 to 100 metres
Modulation scheme	QAMPAM, BPSK
Noise floor	$15e^{-9}$
Step size/ Convergence rate	0.2
Order of filter	5

7. RESULTS AND DISCUSSIONS

The comparison of FEC and adaptive LMS filter are carried out in terms of BER and throughput. In this experiment, the simulations are carried out with the node distance between 10 to 100 meters. It is noteworthy that there is an exponential increase in BER and a decrease in throughput when the distance between the nodes was set beyond 100 meters. The distance between the nodes was varied ranging from 100 to 1000 meters to analyses the behaviour of the network, as shown in Figure-6. Beyond 100 meters, the BER performance of the PLC network degrades gradually. Even beyond a distance of 100 meters, the noise reduction techniques work similarly as they work for the distance below 100 meters. This is shown in Figure-9 and Figure-10. Typically, while considering a PLC network in a house, the electrical appliances are not so far away and there are routers to connect the network. Therefore, there is no need for a PLC network to span across long distances [24] [25]. Hence, the BER and throughput values are analyzed for a network of 26 nodes, for a distance between the nodes varied between 10 to 100 meters in the subsequent results.

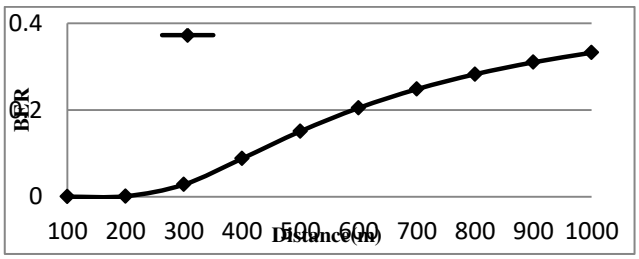

Figure-6. Distance ranging from 100 to 1000 metres.

In Figure-7 to Figure-10, the performance of the PLC network with the presence of impulsive noise and with different noise reduction techniques are evaluated in terms of BER and throughput. Note that in the figures, “without impulsive noise” denotes the performance of the PLC-MAC network without the presence of impulsive noise, “with impulsive noise” denotes the performance of the network with the presence of impulsive noise, “FEC” denotes the performance of the network with forward error correction, “adaptive LMS filter” denotes the performance of the network with adaptive noise reduction technique using LMS algorithm and “FEC+LMS” denotes the performance of the network with our proposed hybrid FEC-LMS noise reduction technique. Figure-7 shows the BER versus distance between the nodes for different noise reduction techniques. The BER values are high when the impulsive noise is introduced to the network and decreases with the introduction of noise reduction techniques.

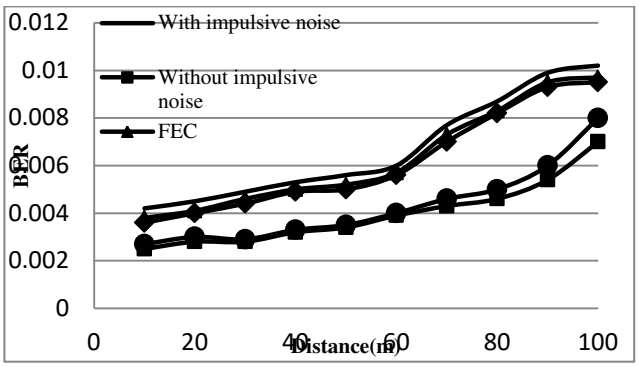

Figure-7. BER graph for comparison of FEC, LMS and FEC+LMS.

From Figure-7, it is clear that the adaptive LMS filter performs better than FEC. However, the proposed hybrid FEC-LMS noise reduction technique outperforms both the FEC and the adaptive LMS filter.

Table-4. Average BER.

With noise	Without noise	FEC	LMS	Hybrid
0.0067	0.00391	0.00632	0.00615	0.0043

The average of obtained BER for different cases (with impulsive noise, without impulsive noise, with FEC technique, with LMS filtering technique and with hybrid FEC-LMS noise filtering technique) is shown in Table-4. From this table, it is known that the hybrid FEC-LMS filter achieves conditions that closely approximate those without noise. We found that the amount of average BER reduction achieved by the FEC technique is 0.00038 and that by the LMS filtering technique is 0.00055. However, the amount of the average BER reduction achieved by the proposed hybrid FEC-LMS noise reduction technique is 0.0024, which is significantly higher than the other two techniques. The percentage of reduction in BER from the baseline (with impulsive noise) can be analyzed using the formula shown in Equation 11.

$$\text{Percentage decrease} = [(X)-(Y)/(X)] * 100 \quad (11)$$

Where X is the baseline (average BER with impulsive noise) and Y is the average BER with the noise reduction technique. The percentages of reduction in BER with the FEC technique, the LMS filtering technique, and the hybrid FEC-LMS noise reduction technique are 5.97%, 8.95%, and 35.82%, respectively.

It is clear from the BER analysis that the proposed hybrid technique outperforms the other two noise reduction techniques. It increases the performance of the PLC network by mitigating the harmful effects of impulsive noise and decreasing the bit error rate. Hence, the BER of a PLC network with hybrid FEC-LMS noise reduction technique is close to a PLC network without noise.

Figure-8 shows the throughput versus distance for different noise reduction techniques. The throughput values are low when the impulsive noise is introduced to the network but improves with the introduction of noise reduction techniques.

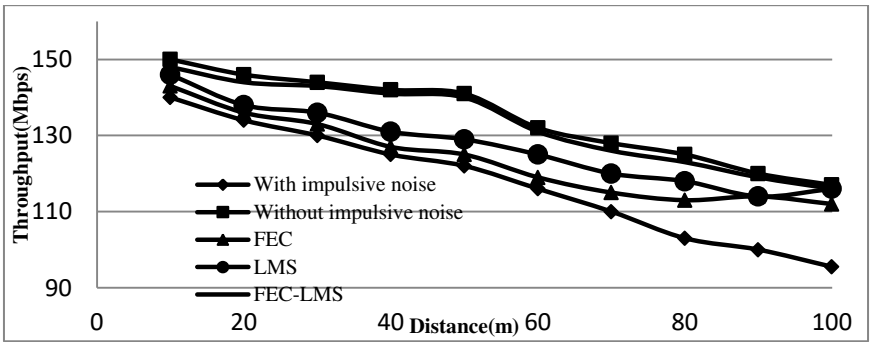

Figure-8. Throughput graph for comparison of FEC, LMS and FEC+LMS.

From Figure-8, the network throughput improves with different noise reduction techniques. It is shown that the adaptive LMS filter performs better than the FEC while the proposed hybrid FEC+LMS noise reduction technique outperforms the other noise reduction techniques.

Table-5. Average Throughput.

With noise	Without noise	FEC	LMS	Hybrid
118	135	124	127	133

The average throughput for different cases (with impulsive noise, without impulsive noise, with FEC technique, with LMS filtering technique and with hybrid FEC-LMS noise filtering technique) is shown in Table-5. It can be observed from Table-5 that the performance of the proposed hybrid FEC-LMS filter approximates that without noise. The average throughput improvement with the FEC technique is 6 Mbps while that with the LMS filtering technique is 9 Mbps. Nonetheless, the average throughput improvement with the proposed hybrid FEC-LMS noise reduction technique is 15 Mbps. Again, the percentage of increase in throughput from the baseline (with impulsive noise) is analyzed using the formula

shown in Equation 12 for the three noise reduction techniques.

Percentage increase = [(Y)-(X)/(X)] * 100 (12)

where X is the baseline (average throughput with Impulsive noise) and Y is the average throughput with the noise reduction technique.

The percentages of improvement with the FEC technique, the LMS filtering technique, and the hybrid FEC-LMS noise reduction technique are 5.08%, 7.62% and 12.71%, respectively.

Clearly, the proposed hybrid technique outperforms the other two noise reduction techniques in terms of throughput because the former increases the performance of the PLC network mitigating the harmful effects of impulsive noise by increasing the throughput. Hence, the throughput of a PLC network with the proposed hybrid FEC-LMS noise reduction technique approximates to a PLC network without noise.

To further understand the network with a larger number of nodes, the simulation is also carried out for a different number of nodes ranging from 26 to 200 for an average of 10 to 1000 meters distance between the nodes. It is noticed that there is a significant deterioration in BER performance due to the influence of impulsive noise. According to [26], BER occurs within the range of 10^{-10} to 10^{-1} due to the presence of impulsive noise. In this study, the BER values range between 10^{-4} and slightly less than 10^{-1} and the proposed noise reduction technique corrects this range of values.

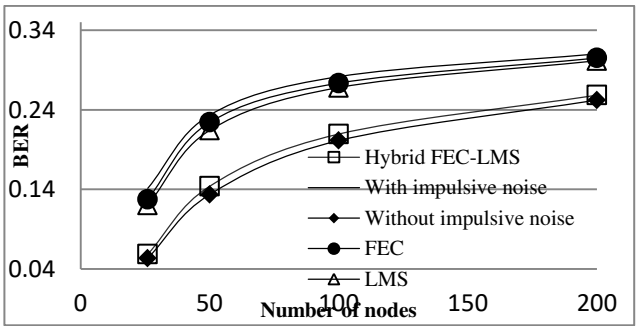

Figure-9. BER for different number of nodes.

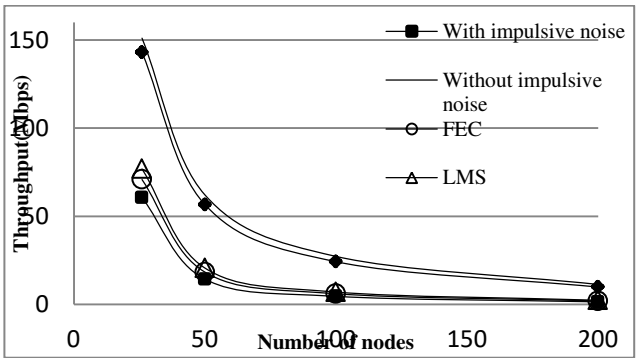

Figure-10. Throughput for different number of nodes.

Figure-9 and Figure-10 show a gradual increase in BER and a gradual decrease in throughput when the number of nodes increases. It reaches the saturation point beyond 200 nodes and there is no significant change in BER and throughput values.

In Figures 7-10, it can be implied that the proposed hybrid filter performs significantly better than the other two noise reduction techniques. Furthermore, the performance of a PLC network with the proposed hybrid filter closely matches the performance of a PLC network without noise. Hence, the hybrid filter outperforms the other noise reduction techniques even though some parameters have been optimized to enhance the performance of FEC/LMS.

8. CONCLUSIONS

In this article, we have proposed a hybrid FEC-LMS noise reduction technique to mitigate the effects of impulsive noise in PLC-MAC networks. The LMS adaptive algorithm is combined with FEC to filter out the aperiodic impulsive noise. It has been found that the proposed hybrid FEC-LMS noise reduction technique outperforms the conventional FEC technique and adaptive LMS filtering technique in terms of BER and throughput.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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