AN FEC-LMS HYBRID FILTER FOR MITIGATING IMPULSIVE NOISE IN POWER LINE COMMUNICATION

By

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ABSTRACT

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Power Line is a ubiquitous network and Power Line Communication (PLC) has the ability to provide broadband access to homes and workspaces. It does not need any new wiring or high cost for installation as this technology uses the existing infrastructure for data transmission. Although it has the potential to transmit the data over power line, the performance of PLC decreases due to the noise interferences produced by the electrical devices which are connected to the power line. In this research, investigations on the Bit Error Rate (BER) were done on a power line channel with Medium Access Control (MAC) protocol in the presence of impulsive noise with various noise reduction techniques. With the help of a software module for the simulation of PLC network, network simulator-3 model was developed to assess the behaviour of the PLC channel with the presence of impulsive noise. Reducing the BER caused by impulsive noise is one of the main challenges while transmitting data over power lines. Therefore, there is a need for impulsive noise reduction to reduce its noise effects and increase the performance of the network. It was found out that adaptive filters perform better in mitigating and reducing the effects of impulsive noise by decreasing the BER and increasing the throughput over a PLC system. An adaptive filter using Least Mean Squares algorithm is modelled for a PLC-MAC network with 26 nodes using network simulator-3. The performance of this network with the presence of impulsive noise (without noise reduction) and with adaptive noise reduction is compared and analysed. It was found out from the literature that forward error correction (FEC) performs better in impulsive noise reduction in PLC by reducing the BER. Therefore, FEC technique was combined together with adaptive Least Mean Squares (LMS) filter and a hybrid FEC-LMS noise reduction technique was proposed. The performance of FEC, adaptive LMS filter and hybrid FEC-LMS were compared against BER and throughput. The hybrid FEC-LMS noise reduction technique outperformed the FEC noise reduction technique and also the adaptive LMS noise reduction technique. The proposed hybrid FEC-LMS method reduced the BER significantly and showed significant improvement in PLC throughput.

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APPROVAL SHEET

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DECLARATION

I, JOLIZ ANTON V J hereby declare that this dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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LIST OF ABBREVIATIONS

AM	Amplitude Modulation
ASK	Amplitude Shift Keying
BCH	Bose, Chaudhuri and Hocquenghem
BER	Bit Error Rate
BFSK	Binary Frequency Shift Keying
BPL	Broadband over Power Line
BPSK	Binary Phase Shift Keying
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access/ Collision Detection
dBm	Decibel – milliwatt
DMT	Discrete Multi-Tone Transceiver
Eb/No	Energy Per Bit to Noise Density Ratio
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FM	Frequency Modulation

IoT	Internet of Things
KS – MAC	Korean Standard MAC protocol
LDPC	Low-Density Parity Check
LMS	Least Mean Squares
LT	Luby – Transform
MAC	Medium Access Control
NLMS	Normalized Least Mean Squares
Ns- 2	Network Simulator- 2
Ns- 3	Network Simulator- 3
OFDM	Orthogonal Frequency Division Multiplexing
OMNET++	Objective Modular Network Testbed in C++
PAM	Phase Amplitude Modulation
PENCA	Programmable Encoding architecture
PLC	Power Line Communication
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RLS	Recursive Least Square
RS	Reed – Solomon
TDMA	Time Division Multiple Access

TLT	Transmission Line Theory
WAN	Wide Area Network

CHAPTER 1

INTRODUCTION

1.1 Research Background

Communication is one of the major requirements in our day-to-day life. It is necessary for all technological developments. As of now, communication has entered into a modern field of study where the requirements for data communication are high speed, high data throughput, connection stability, privacy protection and ease of setup. So, there is a need for internet access with the aforementioned qualities. Among the existing communication techniques, power line communication plays a major role.

Power Line Communication (PLC) is a technology which uses the power lines for data transmission and it is a ubiquitous network. It does not need any extra wiring or any kind of installation process. Although initially, power line communication began as a slow analogue technology, it now plays a significant role in data communication due to its attractive features (Edward et al., 2010). Power Line Communication technologies are used for various applications like home automation to internet access that is often called as broadband over power line communication (BPL). Broadband over power lines is achieved without any impact over the electrical circuit even though the medium is being shared for both power and data transmissions. This is possible because power line works in the lower frequency of 50hz to 60hz while broadband works at a higher frequency between 40Khz to 250Mhz for data transmission (Mohsen et al., 2014). In 2011, Power Line Communication was the most adopted technology (Lin et al., 2013). Nowadays, there is a growing need for devices to be connected to the internet and communicate with each other. The current PLC infrastructure has the potential to support the growing need for the Internet of Things (IoT) (Benkhelifa, et al., 2014). As shown in Figure 1.1, the number of devices need to get connected to the internet have been increasing and by 2015, it was set to reach 25 billion and by 2020 it was set to reach 200 billion.

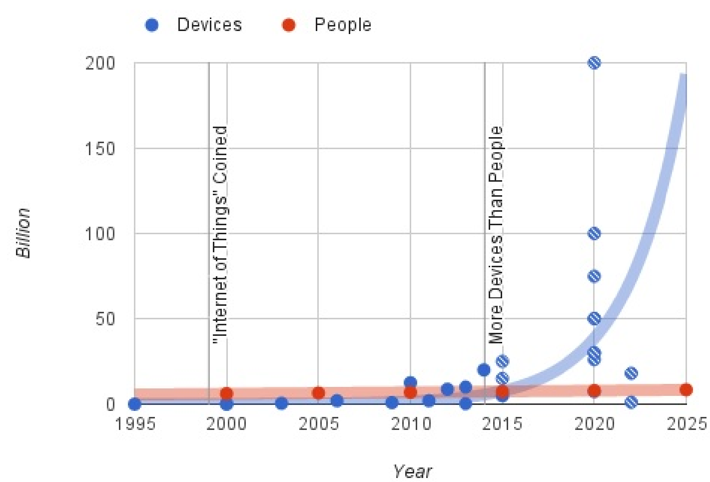

Figure 1.1: Rate of increase of devices connected together (source: Author's calculations based on data from ABI 2014)

Hence, in the last decade, Power Line Communication has gained a lot of attention. It can support data rates up to 1 Gbps (Mohsen et al., 2014). The infrastructure of broadband over power line is shown in (Rozaini, et al., 2014). Broadband over power line is achieved through the basic network elements of power line communication such as PLC modem, PLC base/master station, PLC-MAC (Medium Access Control) protocols. Hrasnica and Haidine (2001); Rahman, et al. (2011) have suggested MAC protocols for power line communication. The role of MAC protocol is to organize data into data frames and control access to shared network resources by multiple users (Do et al., 2007).

1.2 Problem statement

Despite its ubiquity and stability, power line communication must overcome some problems caused by the external devices connected to the power lines, That is, external noise and interference (Yoon et al., 2013).Some of the factors degrading the efficiency and speed of PLC are classified as follows:

i. Transmission channel characteristics
ii. Node characteristics

Issues such as noise, inter-channel interference, transmission line faults, problems in transmission channel modelling, harsh conditions of the power line channel, attenuation, signal distortion, data rate variations, limited bandwidth are grouped as “transmission channel characteristics”. Delay, packet loss, security issues, collision, data traffic, silent node problem, pulse collision, data loss, error in the data are grouped as "node characteristics".

PLC overcomes some of the major drawbacks of wireless communication such as network security-bridge, limited bandwidth and unstable channel characteristics. As it is a power line, the major source of error is impulsive noise which is the main cause of data loss. It restricts the performance of PLC and degrades its efficiency. Hence, a study on impulsive noise reduction is needed. In general, the noise level for the frequency ranging from 1 to 30 MHz is almost constant at -100 dBm. While for frequencies lower than this, the noise level reaches -60 dBm (Cabral, 2009). The noise level is directly proportional to the number of electrical devices that are connected to the power lines. The behaviour of noise is abrupt and finding out a solution to reduce the effects of this kind of noise to improve the network's performance would require more than just using the existing reduction methods. Therefore, a simulation and analysis of this impulsive noise can be used to better understand its behaviour for a PLC channel. Some of the existing problems in PLC are the collision, the problem in transmission channel modelling, data traffic, limited bandwidth, data loss, error in the data and noise. The existing noise reduction techniques are clipping, blanking, nulling, forward error correction (FEC) and filtering (Chaudhury and Sengupta, 2012; Takuya et al., 2012; Albrans et al., 2012; Aiyelabowo et al., 2014; Alina et al., 2016). The techniques such as clipping, blanking and nulling reduce the noise only to some extent and sometimes cause distortion (Deep et al., 2016). Therefore, the noise reduction techniques which perform better than the existing techniques are needed. FEC outperforms these existing noise reduction techniques (Jing and Brian, 2013). It is also shown in (Chaudhury and Sengupta, 2012) that the adaptive filter outperforms the existing noise reduction techniques. To further increase its performance by reducing the issues with the transmission channel, various protocols can be used. Hence a study on PLC-MAC protocol with the presence of impulsive noise and some methods to reduce its effects is required.

1.3 Research Objectives

The main objectives of the research are:

1. To identify the characteristics of impulsive noise and model the noise channel.
2. To analyse the PLC-MAC network performance with the presence of impulsive noise.
3. To introduce methods for improving the PLC network performance with the presence of impulsive noise.

1.4 Contribution

This research aims to present a high speed, efficient and a low-cost communication system by reducing the noise in the PLC-MAC network. The proposed research is successfully carried out using a popular network simulator, ns-3. Thus, an efficient PLC system can be implemented in the real world. The technique used in the research can be extended to develop new noise reduction techniques with high performance.

1.5 Organisation of the dissertation

The dissertation is organised as follows. Chapter 2 provides the background that is required to understand PLC better and to know the problems occur in PLC. Chapter 3 presents the simulation of the modelled PLC-MAC network, the modelled noise and the modelled noise reduction techniques. Analysis of the simulation results is provided in Chapter 4. In Chapter 5, results obtained are summarised and suggestions for future work are provided.

CHAPTER 2

LITERATURE REVIEW

This chapter focuses on power line communication (PLC). It provides the background that is required to understand the research done so far. The ongoing research under PLC is discussed followed by PLC MAC network, noise in PLC, noise reduction techniques in PLC and modelling techniques in PLC.

2.1 Power line communication

Different communication technologies such as wireless communication, wired communication, satellite communication, etc have been used for data transmission (Sumi and Prasanth, 2014). PLC is the process of sending data through power lines (electrical power supply networks). Both the electrical and data signals are transmitted in a single channel (Sumi and Prasanth, 2014). Like the other communication systems, PLC takes place in three basic blocks. They are the transmitter, the channel and the receiver. The role of the transmitter is to modulate the data and inject the data into the power line communication channel. The role of a power line channel is to transmit the data from the transmitter to the receiver. The role of the receiver is to demodulate the data (Sumi and Prasanth, 2014).

2.1.1 PLC for data transmission

PLC provides various services like home automation, internet access (broadband over power line), etc (Dietmar and Hamid, 2014). Broadband over PLC is a method of power line communication which allows high-speed data transmission over the electrical power distribution network (Yinjia et al., 2017). Broadband over power line communication has gained a lot of advantages in the last decade. It does not need any installation process and is capable of delivering data at a high speed (Mohsen et al., 2014). The infrastructure of broadband over power line is shown in (Rozaini, et al., 2014).

According to Sumi and Prasanth (2014), a basic PLC system for data transmission is shown in Figure 2.1. The model consists of three blocks as follows: the PLC transmitter, the PLC receiver and the PLC channel with noise.

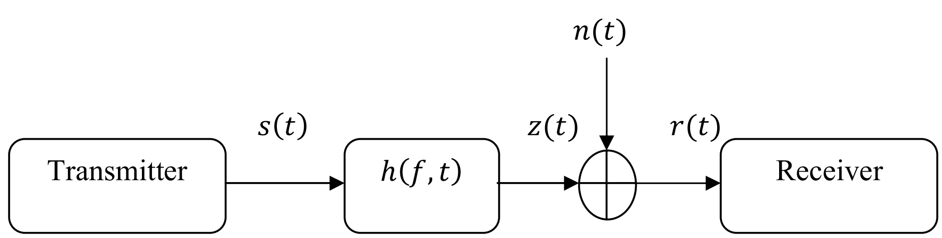

Figure 2.1: The basic PLC model (Sumi and Prasanth, 2015)

We notice that, $s(t)$ is the signal transmitted to the channel from the transmitter. $h(t)$ is the impulse response of the channel. $n(t)$ is the noise in the channel and $r(t)$ is the signal corrupted by the noise in the channel where, $r(t)$ is given as,

$$r(t) = s(t) * h(t) + n(t) \tag{2.1}$$

The development of PLC for internet, voice and data transmission requires the transfer characteristics of the network and it is required to analyse the performance using simulation. Therefore, an analytical model was developed by Zimmermann and Dostert (2002) to describe the complex transfer functions of typical power line networks. The proposed model was verified by a test network. The applicability of the proposed model to a real-world network was further shown. The proposed model can be used to investigate different network topologies and their impact on PLC system performance.

Andreadou and Pavlidou (2010) modelled a typical power line communication channel using Zimmermann's multipath channel model. The signal undergoes a multipath effect and was taken into account. The data sent from the transmitter follows a different route to reach the receiver (Zimmermann and Dostert, 2002). Hence, they have a different amount of delay. The frequency transfer function is needed to generate the PLC channel and is given in Equation 2.2. Figure 2.2 and Figure 2.3 illustrate the amplitude response and the phase response of the Zimmermann's multipath PLC channel.

The frequency transfer function was given by

$$H(f) = \sum_{i=1}^{N} g_i . e^{-(a_0 + a_1 f^k) d_i} . e^{-j2\pi f (d_i / v_p)} \tag{2.2}$$

where,

- i is the number of paths
- f is the frequency
- a_0 and a_1 are the attenuation parameters
- k is the exponent of the attenuation factor
- g_i is the weighting factor
- d_i is the length of the path i (measured in terms of metre)
- v_p is the phase velocity of electromagnetic waves

The parameters used in (Andreadou and Pavlidou, 2010) to simulate the Zimmermann's PLC channel were presented in Table 2.1 and Table 2.2.

Table 2.1: Attenuation parameters of a multipath PLC channel model

Attenuation parameters		
k=1	a_0=0	a_1=7.8 $*10^{-10}$s/m

Table 2.2: Path parameters of a multipath PLC channel model

Path-parameters		
i	g_i	d_i /m
1	0.64	200
2	0.38	222.4
3	-0.15	244.8
4	0.05	267.5

The existing MATLAB programs generate channel realization for individual links. Hence these can't be used to simulate a PLC network with multiple nodes (Fariba et al., 2013).

Fariba et al. (2013) developed a new software module for the simulation of PLC networks based on transmission line theory (TLT) principle. TLT principle explains the operating principles of transmission lines, types of transmission lines, length of the transmission line and how the energy is transferred along the transmission line. This PLC module simulates a PLC network with multiple nodes.

The major research going on under Power Line communication is Internet of Things (IoT). IoT is a network of devices, vehicles and items embedded with sensors, software and network connectivity which are connected together to collect and exchange data (Benkhelifa et al., 2014). Power Line Communication is used to build this ubiquitous network at home (Canete et al., 2011; Dietmar and Hamid, 2014).In this way, data can be successfully transmitted over the PLC channel even in rural areas that do not receive proper internet connection from other existing communication technologies such as coaxial cable systems or telephone lines due to various reasons (Darware et al., 2012). This has increased attention to PLC as it is more ubiquitous and more efficient. Past studies on PLC systems revealed the need for communication protocols for data transmission between the devices through the network.

2.2 PLC MAC network

The MAC layer provides a channel access control mechanism and is known as MAC protocol (Hrasnica and Haidine, 2001).According to the channel access control mechanism, the PLC MAC protocol can be divided into three. They are Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), Time Division Multiple Access (TDMA) and hybrid where most of the existing standards support hybrid mechanism (Chao et al., 2017). The types of protocols and its functions have to be studied to add a suitable MAC protocol to the MAC layer.

2.2.1 Types of MAC protocol

Hrasnica and Haidine (2001), Hrasnica et al. (2001), Hrasnica and Lehnert (2005), Joshi et al. (2008) and Lee et al. (2012) analysed different MAC protocols and suggested a suitable protocol for power line communication. The main task of a MAC protocol is to allocate and reallocate the channel for multiple users (Hrasnica and Haidine, 2001).

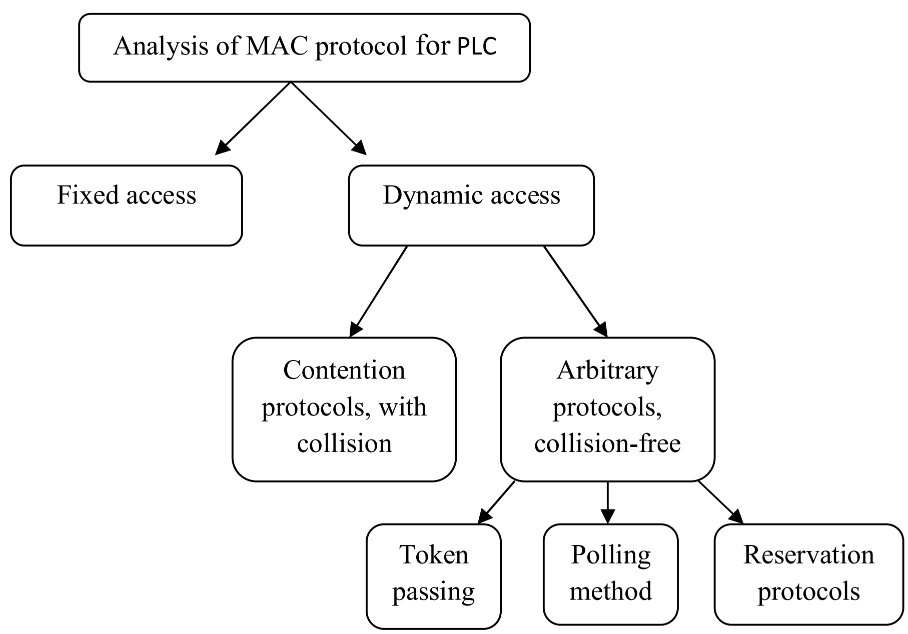

Figure 2.2: Analysis of PLC MAC protocols (Hrasnica et al., 2001)

Figure 2.2 shows dynamic access scheme is suitable for bursty traffic in data transfer in power line communication. Dynamic access scheme has two groups among which arbitrary protocols are suitable for PLC network (Hrasnica and Haidine, 2001). Hrasnica et al. (2001) and Hrasnica and Lehnert (2005) suggest reservation MAC protocol under arbitrary protocols is more suitable when dealing with hybrid traffic with variable data rates. An analysis of the reservation protocols showed that the reservation protocols outperformed the ALOHA random protocol (Hrasnica et al., 201). It was further suggested that it can be improved with the help of piggybacking method. A performance analysis was conducted among different protocols, where the ALOHA based protocols showed worst behaviour.

Hrasnica and Haidine (2001) proposed the reservation MAC protocols and defined a logical structure of the power line MAC layer. A PLC MAC layer was simulated and developed with different disturbance scenarios for the investigation. Also, various sizes of packets were transmitted to observe and analyse the network utilization, network throughput and access delays.

Do et al. (2007) investigated the MAC protocol with opera specification, which employs a time division multiple access (TDMA) technique. The protocol was analysed by means of analytical evaluations and the performance was evaluated with different parameters in terms of the protocol efficiency. The derivations were further validated by simulations.

2.2.2 MAC protocol for PLC network

In Andrew et al.(2015), it was said that some of the techniques like MAC protocols and FEC codes help to increase the data rate in PLC network. In the literature, a number of works have been done to design a MAC protocol for a power line communication system. Most of the PLC networks use MAC protocol based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) that is specified by the IEEE 1901 standard (Christina et al., 2014). For example, in Lee et al. (2012), a CSMA/CA protocol was presented for an indoor PLC home network.

According to Kim et al. (2008), existing protocols need to be enhanced for a better performance of PLC network. Lee et al. (2012) proposed a new multimedia MAC protocol for high-speed PLC, which is a combination of features from Home Plug and the IEEE 802.11e standard. The performance of the access mechanism of Home Plug and the proposed mechanism was further compared. Ns-2 was used to carry out the study. In addition to this, it was shown that the network throughput of the proposed system with MAC protocol showed higher performance than Home Plug 1.0when the number of nodes increases.

CSMA protocol family is classified as follows: Carrier Sense Multiple Access/ Collision Detection (CSMA/CD) and Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) which are the popular contention-based MAC protocols. To combine the advantages of contention based and contention free MAC protocols together, CSMA and TDMA schemes were combined together and hybrid protocols were suggested by Kim et al.(2008). Also, for a high-speed PLC in Korea, they developed a Korean standard PLC MAC protocol which is called as KS-MAC. The KS-MAC was modelled by using ns-2. The performance of KS-MAC has been measured under various scenarios. Further, the results of the simulator were compared with the actual field test results in order to verify the accuracy of the simulator. The access method of KS-MAC is based on the CSMA/CA. It has two mechanisms- one is carrier sense mechanism and the other is the backoff mechanism. Here the backoff mechanism is responsible for reducing the probability of collision. Figure 2.3 illustrates the implementation details of KS-MAC using ns-2.

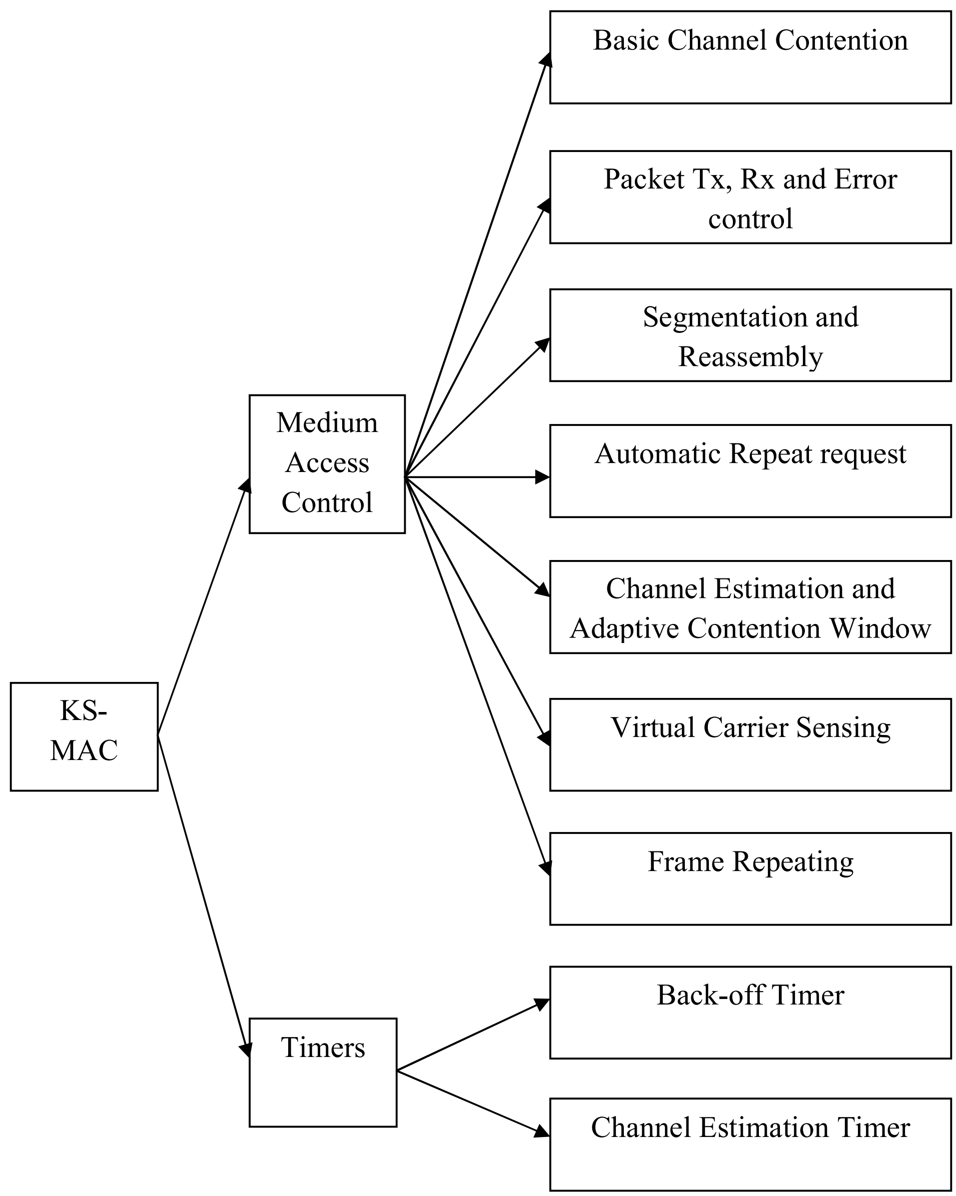

Figure 2.3: Modules in KS-MAC component (Kim et al., 2008)

Kim et al. (2008) proposed a PLC MAC protocol named Korea Standard power line MAC protocol (KS-MAC). This protocol standard uses the operation of CSMA/CA protocol in an indoor PLC home network.

2.2.3 Functions of MAC protocol

The MAC protocol manages the channel allocation and reallocation between users. This MAC protocol is introduced to the PLC network in order to avoid or reduce collision (Roberto et al., 2015). Carrier Sense Multiple Access (CSMA/CA) is a protocol used in PLC network which prevents collisions before they occur (Abhijit and Anurag, 2017). In this case, the node checks for the availability of the channel before it sends the packet. If the channel is busy, the node waits for a certain period and checks again to make sure the channel is not busy. This time period is called as the backoff factor which is counted down with the help of a back-off counter. When the backoff counter reaches zero, the packet gets transmitted from the node, if the channel is clear. If the channel is not clear when the backoff counter reaches zero, the process gets repeated by setting the back-off factor again.

The request-acknowledgement procedure discussed by Hrasnica, Haidine and Lehnert (2001) is given in Figure 2.4.

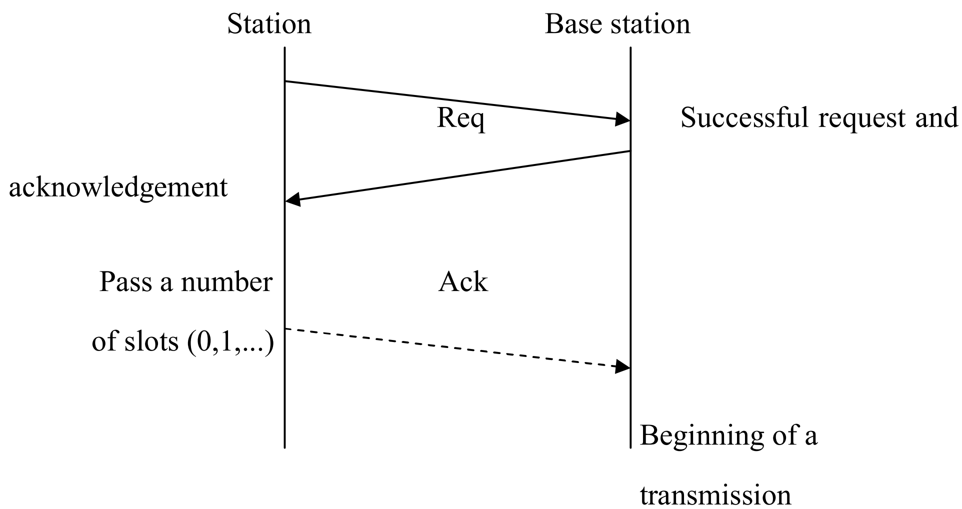

Figure 2.4: Request-acknowledgement procedure (Hrasnica et al., 2001)

According to Hrasnica et al. (2001), a transmission request arrives at the base station only if there is no disturbance or collision. If the request was successfully answered with an acknowledgement, the base station passes many data slots which have to be passed by the station. Hence the transmission begins.

It is known that the MAC protocol introduced in the PLC network allocates a single channel for multiple users. This MAC protocol is responsible for a collision-free transmission. In this research, the MAC layer was introduced in the PLC network by implementing CSMA/CA protocol.

When it comes to PLC, the MAC protocol has to overcome noise as well. Based on past studies, it is known that noise is one of the factors which disturbs and decreases the efficiency of PLC. Therefore, noise and its effects on PLC are reviewed in the following section.

2.3 Noise in PLC

As the power lines are initially not designed to transmit data, PLC is affected by different types of noise (Sumi and Prasanth, 2014). The study of noise and its effects on communication system began in 1918 (Mischa, 2009). To design a high-speed power line communication system, a detailed study on the characteristics of the noise channel is needed (Ma, et al., 2010). In PLC, one of the teething problems is the presence of noise (Mathew and Murukan, 2014; Nyete et al., 2015a). Noise disturbs the information or data sent by the transmitter to the receiver through the channel. The behaviour of noise in PLC is different from the behaviour of noise in any other communication systems. The type of noise present in PLC is non-Gaussian (alpha stable) type of noise while the type of noise in other communication systems is Gaussian-type noise. Do et al. (2007) discussed the impacts of noise on the PLC system and proposed a new method to model the temporary variations of noise. In Zimmermann and Dostert (2002) noise was modelled in the multipath power line channel.

Andreadou and Pavlidou (2010) proposed a practical noise model, Middleton noise model, which described the effects on an orthogonal frequency division multiplexing (OFDM) PLC system. The performance of the noise model was measured in terms of BER versus Eb/No (Energy Per Bit to Noise Density Ratio). To find out the influence of these parameters on the PLC network, various set of BER and Eb/No values have been tested.

Nyete et al. (2015b) modelled the characteristics of noise in the PLC network using alpha-stable noise model. Impulsive noise is one of the most severe sources of performance degradation in PLC. The aforementioned noise model effectively models impulsive noise. Because, impulsive noise has a heavy tail and is difficult to model using any other noise modelling techniques. There is no closed-form expression for their power spectral density functions (PDFs). This alpha-stable distribution has been modelled using the alpha-stable characteristic function (Laguna and Lopez, 2014).

They further modelled a time domain noise model for the PLC network based on channel measurements. This model is necessary for designing the receiver and the modulation schemes in PLC. Also, it was said that alternative noise modelling techniques should be explored to validate the outcomes of the research.

In Laguna and Lopez (2015), experimental evidence has been provided to conclude that the statistical properties of noise in the power line can be well captured with the help of alpha-stable distribution. An analysis was provided to show that the noise traces in PLC show a heavy tail which is hard to be described using a Gaussian distribution. Simulations were done to analyse the performance of the PLC network under different noise and noise modelling techniques. Finally, it was shown that the alpha-stable noise modelling technique in PLC helps to perform simulation studies in a more realistic way.

2.3.1 Types of noise

According to Laguna and Lopez (2014), noise can be categorized into two, background noise and impulsive noise. These can be further broken down into categories as shown in Figure 2.5.

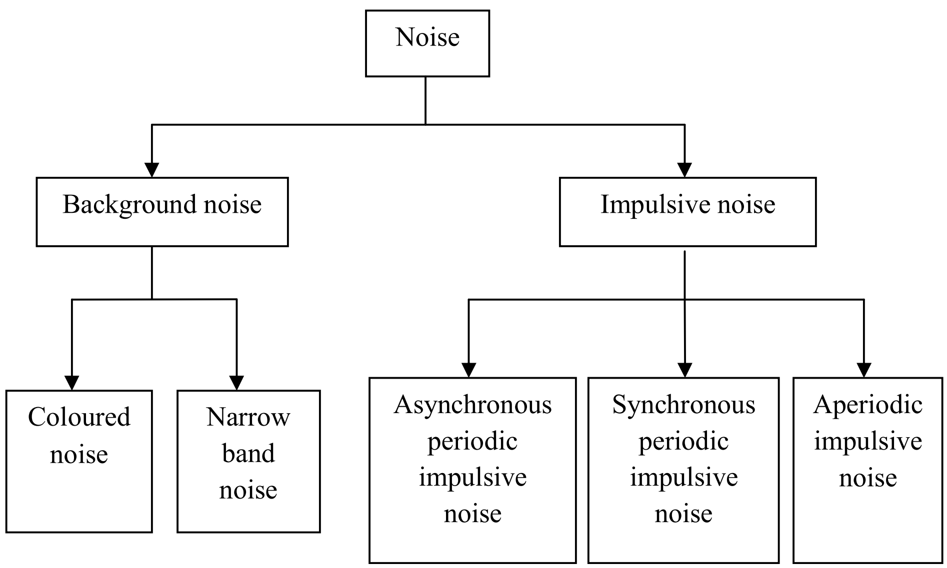

Figure 2.5: Types of noise (Laguna and Lopez, 2014)

Electronic equipment and external broadcast radio bands (Amplitude Modulation (AM), Frequency Modulation (FM) and amateur radio) cause background noise. It was shown that man-made noise (produced by electrical appliances) and atmospheric noise (lightning discharges in thunderstorms) are noises with impulsive behaviour and have a heavy tail (Tsihrintzis and Nikias, 1995; Ghannudi et al., 2010; Sun et al., 2012; Saleh et al., 2012; Laguna and Lopez, 2014; 2015).Luca (2011) reviewed the existing noise models for both background noise and impulsive noise for the PLC network.

It was shown that, to model coloured background noise, artificial neural network modelling is effective (Ma et al., 2010). Channels affected by additive noise were well explained by alpha stable statistics in Fahs and Abou (2012). Power lines undergo performance degradation due to electromagnetic interference and impulsive noise as they are not designed for the communication purpose (Andreadou and Pavlidou, 2010).

2.3.2 Impulsive noise

The type of noise occurs in other communication systems is Gaussian noise and the type of noise occurs in PLC is alpha-stable noise. Impulsive noise is a noise with alpha-stable behaviour. Noise in the power line network with impulsive behaviour causes high bit error rate (BER) (Milioudis et al., 2013; Sivaneasan et al., 2011). In PLC, the impulsive noise is mainly generated from electrical appliances connected to the power line (Yoon et al., 2013). Impulsive noise is hard to predict and in the transmitted data over PLC, it is the major source of error (Gui et al., 2009; Sun et al., 2012). In many practical cases, when manmade noise is involved, the measured noise shows impulsive behaviour (Sun et al., 2012; Shongwey, 2014). This impulsive noise is the cause of the low quality of PLC system which affects data transmission between the nodes. Therefore, Meng et al. (2005) made attempts to model noise from the signals produced by the household electrical devices. Pablo et al. (2011) modelled impulsive noise as a train of the pulse. It was explained using the formula given in Equation 2.3.

$$\sum_i c_i . p_i(t - t_i) \qquad (2.3)$$

Where,

- c_i is the complex amplitude
- phase p_i stands for the shape of the pulse
- t_i is the time in which the pulse arrives at the time domain

The efficiency of the network in the presence of impulsive noise in power line communication system was monitored using various computer simulation tools like MATLAB, ns-2, ns-3 and Objective Modular Network Test bed in C++ **(**OMNeT++) (Kellerbauer and Hirsch, 2011).

It is clear that impulsive noise is the main source of noise in PLC and this is complicated to model. Also, the noise modelling techniques for this kind of noise are reviewed. To increase the efficiency of PLC by decreasing the harmful effects of impulsive noise, there is a need for a noise reduction technique. Past studies on noise in PLC revealed that several noise reduction techniques have been used to increase the efficiency of the PLC network. In the following section, various noise reduction techniques in PLC are reviewed and the most suitable ones for the PLC network with MAC protocol are suggested.

2.4 Noise reduction in PLC

There is an urgent need for noise reduction techniques to abate the harmful effects of impulsive noise to enhance the performance of the network. The effects of impulse noise can be limited by using a level limiter (Ndo et al., 2010) and other existing noise reduction techniques such as clipping, nulling, FEC and filtering (Albrans et al., 2012; Chaudhury and Sengupta, 2012; Takuya et al., 2012; Aiyelabowo et al., 2014; Alina et al., 2016).

2.4.1 Noise reduction techniques

The existing noise reduction techniques are classified into four groups as time domain, time/frequency domain, error correction code and other techniques. Firstly, the time domain is a technique in which the amplitude of the signal changes according to a specified threshold with no change in the phase. Here, the impulsive noise mitigation takes place on the received signal before the Fast Fourier Transform (FFT) demodulation operation of the Orthogonal Frequency Division Multiplexing (OFDM). Secondly, time/ frequency technique takes place on the received signal at both before and after FFT demodulation of the OFDM system. Thirdly, the process of adding redundancy bits to the data bits which helps to detect and correct the error during the data transmission is called the error correction code technique.

Fourthly, Bayesian learning technique, recursive detection technique, adaptive filtering technique and PLC-DMT (Discrete Multi-Tone Transceiver) are the other mitigation techniques (Aiyelabowo et al., 2014).

Clipping, blanking and clipping/blanking come under time domain technique where the mitigation takes place before the OFDM demodulation. In time/frequency domain technique, the mitigation of impulsive noise takes place after the OFDM demodulation. In these techniques, it is assumed that the amplitude of the impulsive noise is greater than the amplitude of the OFDM signal. Therefore, it is assumed that the amplitude of the sampled signal is greater than the defined threshold value if the signal is affected by impulsive noise. In Ndo et al. (2010), mitigation of impulsive noise was done in PLC system with the help of clipping, blanking and the combination of both clipping and blanking.

Clipping is the process of changing/ clipping the amplitude of the signal according to a specific threshold without altering the phase of the signal. Blanking is the process of setting the amplitude of the signal to zero according to a specific threshold without altering the phase. The above-said techniques were used because of their simplicity. But the in-band distortion occurs during clipping affects the bit error rate (BER) performance (Aiyelabowo et al., 2014).

2.4.2 Forward Error Correction

PLC systems are looking forward to improve the quality of data transmission over a noisy channel. Various studies (Mehdi et al., 2011; Emad and Khaled, 2013; Jing et al., 2013; Nikoleta and Andrea, 2013; Khaled and Emad, 2014; Ramchander, 2014; Sri and Issa, 2014; Kumudini and Rahul, 2015; Masume and Mehran, 2015; Pramod and Nitin, 2015; Deep et al., 2016; Fang and Zhanxin, 2016; Li et al., 2016; Samir and Ahmed, 2016; Kelvin et al., 2017) have demonstrated impulsive noise mitigation techniques in PLC.

According to Yan (2011), FEC is the noise reduction technique which has been around for a while and used to enable efficient, high-quality data transmission over noisy power line channels. In Morgan et al. (1994), FEC coding was investigated to enhance the throughput and reliability of a PLC network over a noisy channel. BER and packet error rate analysis was conducted over noisy in-building power line network. It was noticed by using this FEC that the network has improvement with respect to BER and throughput. It was shown that Forward Error Correction (FEC) technique has a high capacity for mitigation impulsive noise in PLC (Yan, 2011; Aiyelabowo et al., 2014). Recently, there are significant advances in FEC technique. These advances are successfully used to increase the performance of data transmission over a noisy channel. In Dawn (2006), FEC was used along with packet loss concealment scheme under bursty loss conditions.

There are different FEC codes used in different cases. Two main categories of FEC codes are block codes and convolutional codes. There are different types of block codes such as Reed-Solomon (RS) codes, BCH (Bose, Chaudhuri, Hocquenghem) codes, Turbo codes, low density parity check (LDPC) codes and Hamming codes. Petr (2017) suggested that Hamming code is faster than the other FEC codes such as BCH codes, RS codes, Turbo codes and LDPC codes. A new approach based on BCH codes named programmable encoding architecture (PENCA) was proposed in Petr (2017) for multi error detection and correction. Xiaohan et al. (2013) compared the decoding performance of an overhead of four forward error correction coding schemes: repetition codes, intra-packet Reed-Solomon (RS) codes, inter-packet Luby-Transform (LT) codes and a concatenated RS and LT codes. Furthermost, some results were provided to show that the LT code is approximately ten times more error tolerant than the other codes. Figure 2.6 illustrates the function of a block coder where, k bits going into the block coder and the bits get encoded into n bits. n bits is the combination of k bits and redundancy bits.

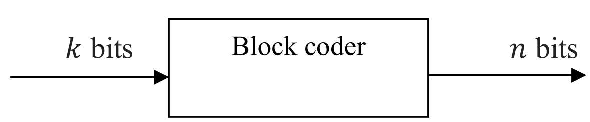

Figure 2.6: Block coder (Zheng, 2012)

FEC is a technique of adding redundancy bits to the data bits, where the redundancy bits carry no information. These redundancy bits are transmitted at the transmitter along with the data bits. Redundancy bits are then used at the receiver to detect and correct the errors occurred during data transmission (Aiyelabowo et al., 2014). This is done with the help of Hamming codes. Hamming code is the process of appending the redundancy bits to the data bits.

Figure 2.7 illustrates the addition of redundancy bits along with the data bits where, r is the redundancy bit and d is the data bit.

11	10	9	8	7	6	5	4	3	2	1
d	d	d	r	d	d	d	r	d	r	r

Figure 2.7: Redundancy bits positioning in Hamming codes (Aiyelabowo et al., 2014)

The larger the Hamming distance, the greater is the capability of the code to detect and correct errors in the presence of noise or errors introduced during transmission. As the capability of FEC increases, the number of errors that can be corrected also increases.

Figure 2.8 shows how FEC works.

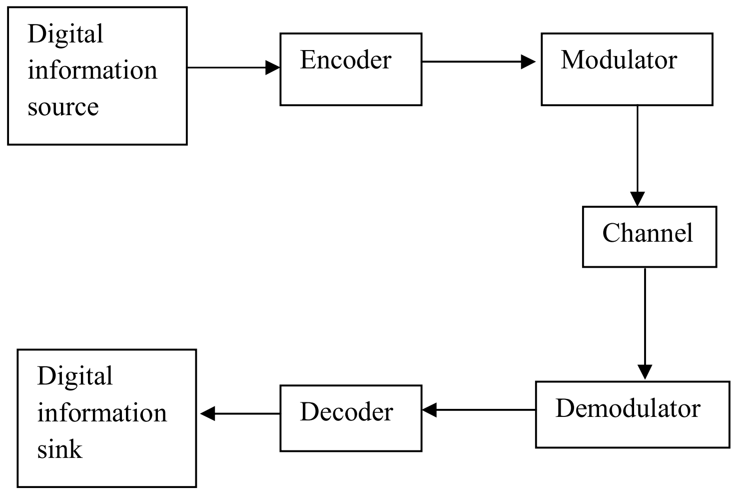

Figure 2.8: Working principle of FEC (Zheng, 2012)

In FEC, k bits of data will be transmitted to the encoder. The encoder adds redundancy bits along with k bits and n bits output will be given out to the channel. The presence of noise and some corruption in the channel, introduce some error. In the receiver end, the original data can be recovered from the decoder.

2.4.3 Adaptive filtering

Some studies (Ndo et al., 2010; Radek and Jan, 2010; Chaudhury and Sengupta, 2012; Ramchander, 2014; Sri and Issa, 2014; Kumudini and Rahul, 2015; Pramod and Nitin, 2015) have shown impulsive mitigation using adaptive filtering technique in PLC system. In Chaudhury and Sengupta (2012), it was shown that the adaptive filtering technique reduces the noise and increases the performance of the system in an effective manner while comparing with the other noise reduction techniques. In Kumudini and Rahul (2015) an adaptive filter design was proposed to mitigate noise. In Ndo et al (2010), an adaptive impulse mitigation system was proposed in order to mitigate impulsive noise and the proposed technique was validated over Home Plug AV physical later. Some adaptive filtering algorithms namely Lease Mean Squares algorithm (LMS), Normalised Least Mean Squares algorithm (NLMS) and Recursive Least Squares (RLS) are used to carry out the adaptive filtering technique. These adaptive filtering algorithms were introduced, and their performances were compared in Pramod and Nitin (2015). Sumi and Prasanth (2014) presented a technique to remove impulsive noise from the PLC network. An algorithm named periodic impulsive noise detection algorithm was used to detect the presence of noise and the noise was filtered with the help of adaptive notch filter. And also, to mitigate the effects of impulsive noise, adaptive filter using LMS algorithm was used. Then a performance analysis was done by comparing the BER of the PLC network with noise filtering and without noise filtering by using adaptive notch filter and by using adaptive LMS filtering (Sumi and Prasanth, 2014). Resulted BER showed that after adaptive filtering the BER had a significant decrease which resulted in significant decrease in the error data at the receiver end. Therefore, it is shown that PLC network with adaptive noise filtering gives better results in noise reduction. In (Songnong et al., 2017) adaptive filter was introduced to reduce the noise level. The BER was analysed and compared with and without filter for different noise levels.

In Radek and Jan (2010), noise reduction using adaptive filter for a communication system was discussed. The system was designed using MATLAB. This adaptive filter was used to mitigate the harmful effects of noise and the system was tested in the real-world. The LMS algorithm was used in this filtering technique and it was shown that this algorithm is simple, mathematically undemanding and it reached lower convergence rate. In real-world applications, for many filtering techniques, the values of the filter coefficients that achieve the best performance are not known, and adaptive filtering technique is used to solve such problems (Radek and Jan, 2010). It is shown that adaptive filtering with LMS algorithm is more prevalent.

According to Radek and Jan (2010), adaptive filter consists of two parts and the first part is made up of a filter, where finite impulse response (FIR) filters are used for adaptive filtration in the prevalent number of cases. Signal processing in FIR type filters strictly follows digital approach.

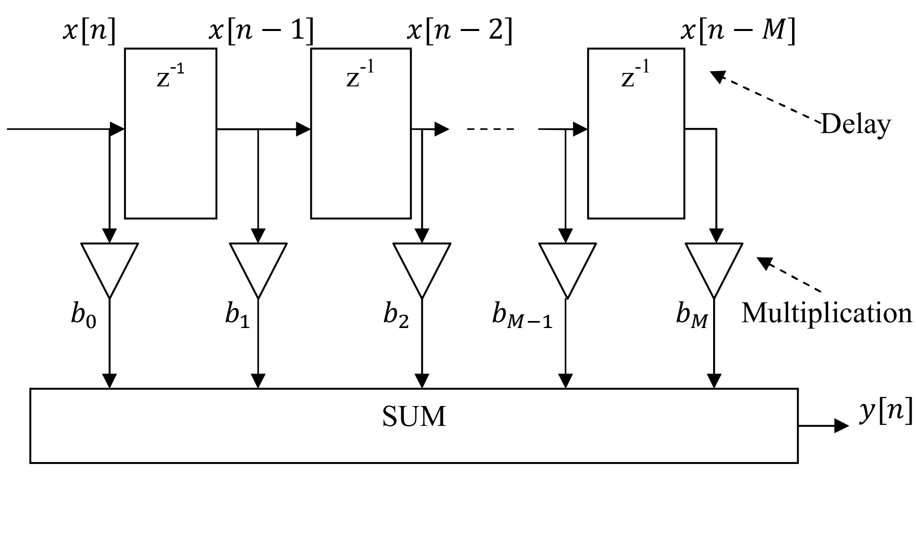

Figure 2.9: FIR digital filter structure (Radek and Jan, 2010)

Figure 2.9 illustrates the FIR digital filter structure. From the Figure 2.9, the differential equation for the filter with the input signal $x[n]$ and the output signal $y[n]$ was given as

$$y[n] = \sum_{k=0}^{M} b_k \, x[n-k] \qquad (2.4)$$

Where,

- $x[n]$ is the input signal
- $y[n]$ is the output signal
- b_k is the filter coefficient
- n is the filter order

In this way, impulsive noise can be successfully mitigated. Past studies on noise reduction techniques revealed that adaptive filtering and FEC are the best methods to mitigate impulsive noise.

In the following section, the parameters used to measure the performance of the network, modulation techniques used, the topology of the network and the modelling techniques used to carry out the research are reviewed.

2.5 Modelling techniques in PLC

2.5.1 Bit Error Rate

Bit errors are the number of error data received due to noise, interference, distortion or bit synchronization errors during data transmission. In PLC, Bit Error Rate (BER) is a parameter to monitor the performance of the system. In Munshi and Majumder (2015), an analytical approach was presented to analyse the performance of a PLC system affected by background noise, impulsive noise and crosstalk in terms of BER.

Yeduri et al. (2018) carried out a BER performance analysis of a narrowband PLC system with OFDM in the presence of background and impulsive noise on a multipath PLC channel and found that the impulsive noise produced high BER while comparing with the BER produced from the background noise. Further, it was found out that, the higher level of impulsive noise further increases the BER. A MATLAB model was developed to carry out the analysis and to investigate the behaviour of the PLC network. The performance of the PLC channel was also analysed while varying the Middleton class A model's parameters. It was also concluded that FEC/convolution codes and suitable filters can be used to mitigate and reduce the effects of impulsive noise on a PLC network by reducing the BER. In Chirawat (2017), BER performance was analysed for a broadband PLC system with OFDM transmission for different modulation techniques.

2.5.2 Modulation techniques

To modulate the phase of the carrier, modulation schemes are used. Among the various modulation techniques, OFDM and BPSK are widely used. OFDM (Orthogonal Frequency Division Multiplexing) PLC system can be used to model noise in a more realistic way. OFDM is a frequency division multiplexing scheme which is used as a digital multi-carrier modulation method (Lokesh et al., 2017).To carry data on several channels, a large number of closely spaced orthogonal sub-carrier signals are used. A modulation scheme is used to modulate each subcarrier. Binary Phase Shift Keying (BPSK) is the modulation scheme used by Vander (2012). For PLC, Andrea (2007) considered a bit – interleaved coded wide band impulsive modulated system. A form of orthogonal modulation was obtained by combining impulsive modulation with DS – CDMA (Direct Sequence – Code Division Multiple Access). This is used to multiplex the users. Yeduri et al. (2018) carried out a BER performance analysis of a narrowband PLC network in the presence of impulsive noise. A CSMA/CA based MAC protocol was introduced along with the impulsive noise. The BER was calculated for the network with different modulation schemes such as amplitude shift keying (ASK), BPSK and binary frequency shift keying (BFSK).

2.5.3 Topology

The power line network is different from each other by means of topology, structure and physical properties. Hence, a study on the topology and characteristics of a PLC network is necessary. It provides a deep understanding of the network and traffic information in the PLC based network (Galli et al., 2011). In Petr et al. (2012), an approach for modelling power lines with different network topologies was described and the basic apparatus for modelling unknown topology was prepared. Joshi et al. (2008) showed that the PLC networks are connected to the backbone communication network through a transformer station or through any other station in the network, building a tree structure. A base station which is placed in the transformer unit is responsible for the communication between the users in the PLC network and a wide area network (WAN). This is shown in Figure 2.10.

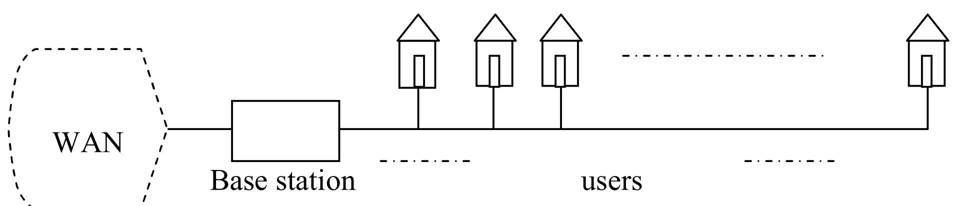

Figure 2.10: Logical bus topology of the PLC network (Joshi, Bhosale and Patil, 2008)

A signal transmitted from the base station to the users in the downlink direction is transmitted to all the network subsections; hence it is received by all users in the network. This shows that the PLC network can be considered as a logical bus structure. In order to avoid the collision, it uses MAC protocols such as CSMA/CD.

The electrical devices connected to the power line or disconnected from the power line describe the topology of the power line network. So, in most of the cases, the topology of the network can't be known. The constructed power line model in (Petr et al., 2012) investigates different network topologies and studied their effects on the system. As the devices in a home, commercial and industries can be connected in a ring topology, a network modelling technique to analyse ring topology was proposed to study the broadband PLC. In Rajpreet and Sanjeev (2015) the performance evaluation of a power line network was conducted for different network topologies namely star, tree and mesh using optimized Raman-EDFA hybrid optical amplifier. The performance was measured in terms of the number of users at different input signal powers. According to Rajpreet and Sanjeev (2015), among star, tree and mesh topologies mesh topology performs better in terms of quality factor and supports a large number of users. Xu et al. (2015) studied a novel smart grid application called the topology reconstruction and proposed a scheme for topology reconstruction of the power line networks.

To increase the number of users with less number of components, network topologies play a vital role in these days. Fariba et al. (2013) proposed a module which allows the power line network to be constructed using different topologies accepting the user-defined network topologies. Practically, the power line networks are connected in tree or radial topology with the help of existing channel modelling techniques for PLC (Meng et al., 2005). Tree topology is the connection of star topology over a bus topology.

Tree topology allows the existing network to expand. Therefore, a number of users can be connected to one node with secondary nodes.

2.5.4 Simulation tools

The efficiency of the network with the presence of impulsive noise in PLC system was monitored using various simulation tools like MATLAB, network simulator-2 (ns-2), network simulator-3 (ns-3) and OMNeT++ (Wehrle et al., 2010; Kellerbauer and Hirsch, 2011; Alonsa et al., 2015).

Among these simulators, ns-3 is the most efficient simulator to carry out various real-world simulations. Furthermore, the design of ns-3 allows the users to add, modify and replace modules based on the requirements (Chok and Abu, 2014). Fariba et al. (2013) proposed a new module to simulate PLC networks which showed a performance increase as compared to the other simulation tools due to the improved memory management.

In ns-3, the PLC network can be built with several numbers of nodes connected through the link which is considered as the power line channel.

Figure 2.11 illustrates the simple two-node PLC network (Jeneeth et al., 2014).

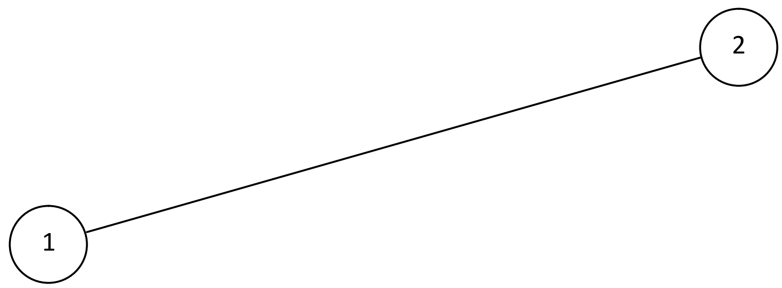

Figure 2.11: A simple two-node PLC network (Subashini et al., 2014)

Most of the studies discussed have shown that many existing communication techniques are complicated to design, expensive and at times have security problems. Hence a simple, ubiquitous and cost-effective communication system called "power line communication system" is considered as an alternative method for other communication systems. Here occurs some performance degradation due to the noise-causing electrical devices connected to the power line network. Therefore, a hybrid FEC-LMS noise reduction technique is proposed to overcome the effects of impulsive noise. This proposed system has the advantages as follows: it is simple to model, it reduces the BER to a great extent and it combines the advantages of both adaptive filtering technique and FEC technique together. As stated by Aiyelobowo et al. (2014), FEC is introduced because:

- It is shown that it outperforms the other noise reduction techniques
- Easy to implement
- It allows the receiver to detect the errors that occur in the data and corrects the errors without retransmission

As the noise level increases to a great extent, the errors are not correctable. To solve this problem, we introduce a hybrid technique where the errors could not be corrected by FEC are given to the adaptive filter. This corrects the error and makes the receiver to receive error-free data. This technique mitigates impulsive noise even though the noise level is higher. This is a new and original idea because it is the first time the hybrid FEC-LMS technique is being modelled for a PLC network with MAC protocol.

CHAPTER 3

METHODOLOGY

The flowchart in Figure 3.1 presents an outline of the methods used in this study in three phases: Phase 1, Phase 2 and Phase 3. Phase 1 covers the PLC MAC model and its performance analysis. Phase 2 covers the introduction of impulsive noise and performance analysis of the network with and without noise. Phase 3 covers the implementation of the proposed hybrid FEC-LMS noise reduction technique and enhancement of the network's performance with the presence of impulsive noise using this technique.

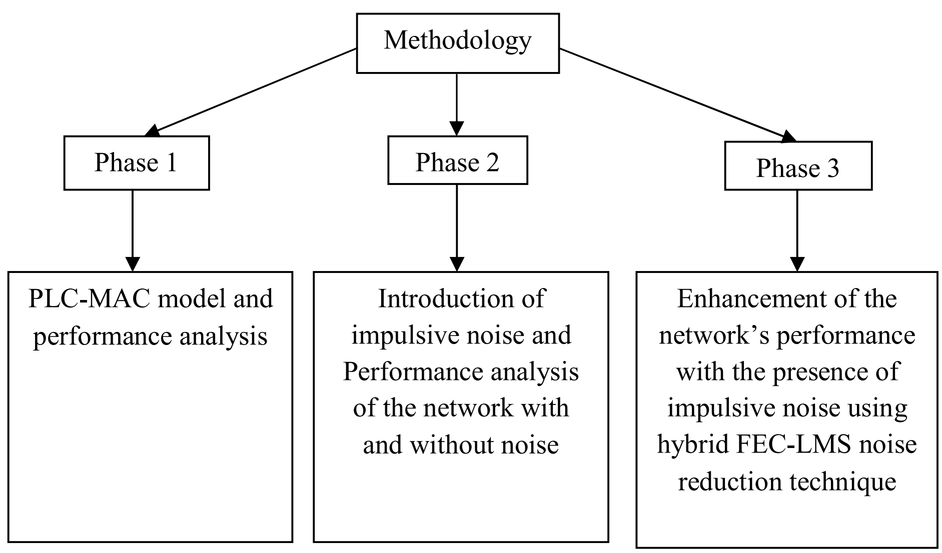

Figure 3.1: Flowchart of the research methodology

3.1 PLC MAC network model

Different from wireless communication, there is a lack of freely available software tools or modules to simulate data transmission in a PLC network with MAC layer (Fariba et al., 2013). The available tools have some limitations when it comes to wired communication, especially for power line communication. The existing MATLAB programs generate channel realisations for individual links. However, these can't be used for simulations in PLC network with multiple nodes (Fariba et al., 2013). Even in ns-3, there is no default module to simulate PLC network. Therefore, a new software module named "PLC channel simulator" was used to directly simulate the PLC network.

3.1.1 PLC channel generator module

PLC channel simulator that allows the generation of channel transfer function and noise in a PLC network based on Transmission Line Theory (TLT) principles is used to carry out this research. MAC functions and filter functions in the module were used to introduce MAC layer and noise mitigation in the PLC network. Network simulator-3 (ns-3) is widely used and contains readily available modules for various networking functionalities. Therefore, this module was built in ns-3 using waf command. After rebuilding ns-3 successfully, the PLC module was ready to use. Therefore, with the help of ns-3, PLC network was directly simulated using this software module and a new PLC network topology which is flexible enough to transfer data between nodes and capture the frequency selective and time behaviour of PLC channel was developed. This methodology relies on the knowledge of the topology, the cables/wires, nodes and the load.

PLC-MAC network was simulated by introducing CSMA/CA protocol with the help of MAC function in the PLC module. Hence, a PLC channel was simulated at the MAC layer for 26 nodes. Tree topology, which is a combination of a star topology and a bus topology, is used to build the network. Nodes of the bus topology are replaced with a complete star topology to form a tree topology. The reasons to choose tree topology are, tree topology can accommodate more nodes, the network does not get affected even if one of the nodes goes down and the maintenance is easy (Xu et al., 2015). The simulation was carried out using ns-3, which is a software to predict the behaviour of a computer network by calculating the interactions between some of the network entities such as hosts, packets, etc. The process was carried out using mathematical formulas and capturing the playing back observations from a production network. Then, the performance of the designed PLC network with MAC protocol was analysed without the presence of any noise. Figure 3.2 shows the setup of nodes in a tree topology. 1, 2, 3, 4, 5, 6, 7, 8 and 9 denote the Node 1, Node 2, Node 3, Node 4, Node 5, Node 6, Node 7, Node 8 and Node 9 respectively.

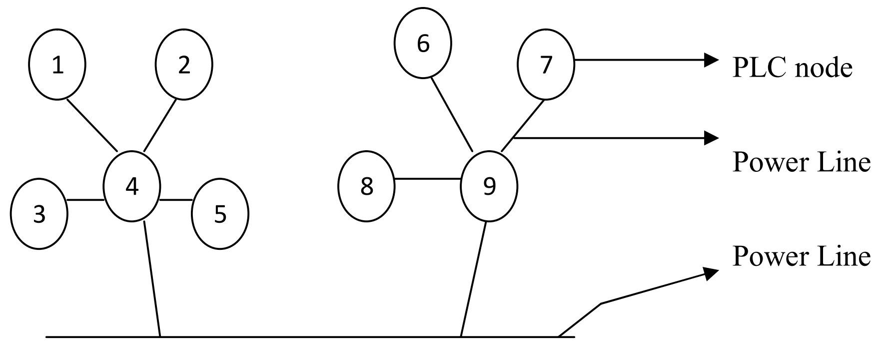

Figure 3.2: Tree topology

3.1.2 Introduction of impulsive noise to the PLC channel

The impulsive noise was simulated and introduced to the PLC-MAC network using the impulsive noise source function in the 'PLC channel simulator' module.

Impulsive noise model

Impulsive noise sources are modelled by two random processes which provide values for the durations the noise source being active and the noise source being inactive (the period between the pulses). The propagated noise power spectral densities will be switched ON and OFF at the receiver's interference model.

Constructor and destructor

ns3::PLC_ImpulsiveNoiseSource::PLC_ImpulsiveNoiseSource
(ptr<PLC_Node> src_node,

ptr<SpectrumValue noisePsd,

RandomVariable*pulselen_gen,

RandomVariable*pulsegap_gen)

Parameters

i. Src_node: The source node (PLC_Node) where the noise source is originated
ii. noisePsd: The power spectral density of the noise's waveform
iii. pulselen_gen: Random variable for the pulse duration generator
iv. pulsegap_gen: Random variable for the silence duration generator

Finally, the performance of the network was analysed with the presence of impulsive noise in terms of BER and throughput.

In Phase 3, after analyzing the results the methods to enhance the performance of the PLC-MAC network was studied. Aiyelobowo et al. (2014) considered forward error correction (FEC) as the best noise mitigation technique. Sumi and Prasanth (2014) showed that adaptive noise reduction technique outperforms all other existing noise reduction techniques. From the study, it is shown that the noise can be mitigated effectively using these techniques. Hence two noise reduction techniques namely FEC and LMS adaptive filter were introduced separately to the network in which impulsive noise was introduced. Finally, both the techniques were combined together, and a hybrid FEC-LMS noise reduction technique was proposed and introduced to the same network in which the impulsive noise was introduced. The performance of the network for each case was measured in terms of BER and throughput.

3.2 Forward Error Correction

The basic procedure for FEC is explained in Figure 3.3. FEC is an error correction technique used to detect and correct data errors during data transmission over noisy communication channels. The transmitter sends redundancy bits and the receiver recognizes only the portion of the data with no errors. Here, the redundancy bits allow the receiver to detect the errors that occur in the data and correct the errors without retransmission. Hence, the data gets enhanced at the receiver end.

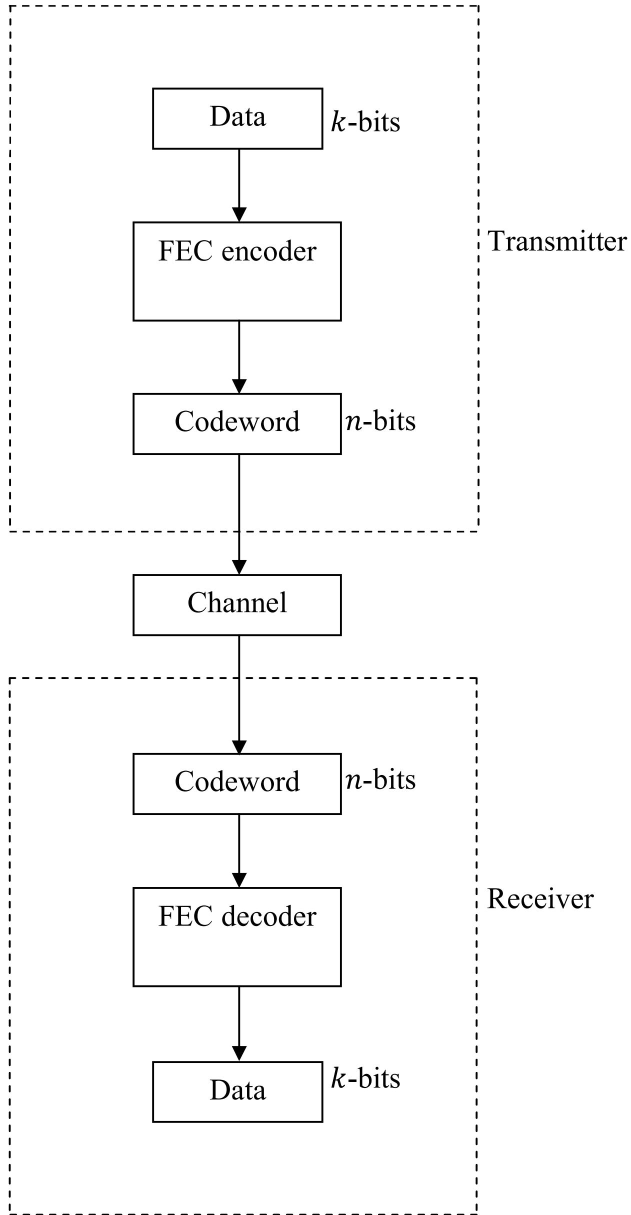

Figure 3.3: Basic block diagram for FEC

A codebook is used to map k-bits data sequences to n-bits code words where, $n > k$

Code rate, $r = \frac{k}{n} < 1$ (3.1)

The error correction of a data block was done with Hamming error correcting codes. It is a family of linear error correcting codes. Hamming distance was calculated between each of the code words. An example (5, 2) code is shown in Table 3.1.

Table 3.1: (5, 2) code for Hamming distance

Data Block	Codeword
00	00000 ($v1$)
01	00111 ($v2$)
10	11001 ($v3$)
11	11110 ($v4$)

The Hamming distances for the given code words are,

$d(v1, v2) = 3$

$d(v1, v3) = 3$

$d(v1, v4) = 4$

$d(v2, v3) = 4$

$d(v2, v4) = 3$

$d(v3, v4) = 3$

Hence the minimum distance between the codewords d_{min} is 3.

The Hamming distance between n-bits codewords $v1$ and $v2$ is defined as,

$$d(v1, v2) = \sum_{l=0}^{n-1} XOR\ (v1(l), v2(l)) \tag{3.2}$$

For some positive integer t_c, if a code satisfies Equation 3.3, the code can correct up to t_c bit errors in a received codeword.

$$d_{min} \geq 2t_c + 1 \tag{3.3}$$

Where, d_{min} is the minimum distance and is defined as,

$$d_{min} = \min_{i \neq j} d(vi, vj) \tag{3.4}$$

Equivalently, the number of guaranteed correctable errors per codeword is

$$t_c = [\frac{d_{min} - 1}{2}] \tag{3.5}$$

The number of guaranteed detectable errors per codeword is

$$t_d = d_{min} - 1 \tag{3.6}$$

According to Aiyelabowo (2014), FEC method offers the best noise mitigation.

3.3 Adaptive Least Mean Squares filtering

An adaptive filter is a filter which adapts itself to the input signal given to it and performs better in noise reduction. It is nonlinear and time variant which relies on a recursive algorithm. It has adaptation algorithms for adjusting the parameters automatically for improved performance.

Various algorithms used are,

i. Least Mean Squares (LMS) algorithm
ii. The Normalized Least Mean Squares(NLMS) algorithm
iii. The Recursive Least Squares (RLS) algorithm

The most popular and widely used adaptive algorithm is LMS algorithm which is based on the theory of Weiner filtering (Radek and Jan, 2010). LMS algorithm satisfies the properties of an ideal algorithm. It is practical to implement and adapt the coefficients quickly to minimize error. Hence the LMS algorithm is used in this research to mitigate impulsive noise. This algorithm was implemented with the help of PLC module built in ns-3.

The basic operation of the adaptive filter involves two processes.

i. Filtering process
ii. Adaptation process

The filtration process is responsible to produce the output signal with respect to the given input signal. The adaptation process is responsible to adjust the filter parameters to the environment. The basic block diagram of the adaptive filter is shown in Figure 3.4. The adaptive filter consists of two parts. The first part is made up of a filter and the finite impulse response (FIR) filter is used because of its advantages and stability. The second part of the filter is the adaptive algorithm where Least Mean Squares (LMS) algorithm was used.

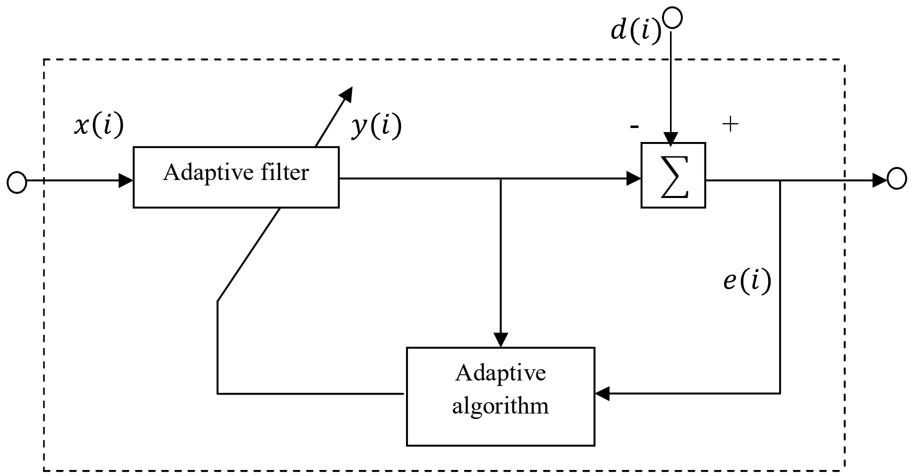

Figure 3.4: The basic block diagram of the adaptive filter

Adaptive noise reduction technique consists of two inputs. They are primary input/ desired signal $d(i)$ and the reference input signal $x(i)$. The primary input signal $d(i)$ is the PLC signal corrupted by impulsive noise and the reference signal $x(i)$ is the impulsive noise signal. This impulsive noise was filtered by the adaptive filter using LMS algorithm which produced the uncorrupted output signal $y(i)$. Then the output signal $y(i)$ is subtracted from the desired signal $d(i)$ to produce the error signal $e(i)$. That is the system output. The weight function $w$gets updated every iteration to get the new weight by doing the adjustments to the old weight. LMS algorithm adjusts its coefficients by itself. The LMS algorithm used in the adaptive filter to reduce the impulsive noise is as follows. Table 3.2 shows the parameters.

Table 3.2: parameters of adaptive filtering

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

3.4 Proposed hybrid technique

In (Hari and Sateesh, 2015; Lakshmi and Hemalatha, 2011; Masume and Mehran, 2015; Nima et al., 2015; Pu et al., 2017), it was shown that multilevel (hybrid) noise reduction performs better than single level noise reduction and it can offer better system performance. Alina et al. (2016) implemented adaptive filtering along with clipping to reduce impulsive noise in a PLC system. In this article, the received data at the receiver after demodulation was clipped over a defined threshold to mitigate the high peaks caused by the impulsive noise. The clipped data was then passed through the adaptive filter to remove the rest of the noise. These two techniques were used individually and in combination to each other. It was shown that the hybrid noise reduction technique produced better results than each individual method. It is clear from Alina et al. (2016) that hybrid technique outperforms the single level noise reduction, supporting the above said statement. In Ryan (2016), FEC was combined with Kalman filter to provide consistent packet delivery and to enhance the performance of the network. In this article, the forward error correction took place at the FEC module. Reed Solomon codes were used for forward error correction. After some testing, they found out that there was no significant variation in the performance of the system due to the presence of noise which is left uncorrected by FEC. Hence, they used Kalman filter to remove the rest of the error. It is clear that hybrid noise reduction is possible and efficient to improve the performance of a network. According to the literature, adaptive filter and FEC techniques performs better in noise reduction in PLC and are suitable to deal with impulsive noise. Impulsive noise has two groups: Periodic and aperiodic where, the periodic part produces high spikes comparing to aperiodic part. Periodic impulsive noise, due to the high spikes, causes high performance degradation of the network and hard to mitigate (Jing et al., 2013). According to Jing et al. (2013), 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 Sumi and Prasanth (2014), it was shown that an adaptive filter is 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 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 has two phases. The first phase of the system is FEC and the second phase of the system is adaptive LMS filter. The FEC was combined together with adaptive LMS filter and a hybrid FEC-LMS noise reduction technique was proposed in this research. The output of phase 1 (FEC) goes to phase 2 (Adaptive LMS filter). That is, 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 was given to the adaptive LMS filter for further enhancement (for the removal of periodic impulsive noise left un filtered by FEC). Hence, the impulsive noise left unfiltered by FEC was filtered by adaptive LMS filter. Hence, the accuracy is higher. One of the limitations of FEC is, when the number of data bits increases, some errors could not be corrected. Furthermore, the LMS filter can only handle processes with additive and unimodal noise. The proposed hybrid filter works better 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 was made compatible for FEC, where analog to digital conversion takes place. To implement the FEC technique, the k-bits data from the transmitter end was converted to the n-bits codeword with the help of codebook. The n-bits code word was allowed to pass through the power line channel affected by impulsive noise. The data got corrupted by the impulsive noise and an invalid codeword (error data) was received at the receiver end. Here the error correction was done with Hamming distance between each of the codeword. The receiver chose the valid codeword (error-free data) for the invalid code-word (error data) with the minimum Hamming distance.

For example, if the received invalid code-word (error data) is 00100.

The Hamming distance,

$d(00100, v1) = 1$

$d(00100, v2) = 2$

$d(00100, v3) = 4$

$d(00100, v4) = 3$

The receiver picks the code word with the minimum Hamming distance. In this case, the receiver picks the code word $v1$as it is the code word with minimum Hamming distance. And the codeword gets decoded as the data block 00. Hence the error-free data (enhanced data) is received at the receiver end. The enhanced data given out of FEC is in digital form. This is made compatible for adaptive LMS filter, where digital to analog conversion takes place.

This enhanced analog data was given to the adaptive LMS filter for further enhancement. The flowchart in Figure 3.5 demonstrates how the adaptive filter works. The desired signal $d(i)$ (enhanced data after FEC) is the signal with the presence of impulsive noise. The input signal $x(i)$ is where the impulsive noise signal was given. When the impulsive noise signal passed through the adaptive filter, the filtration process took place and the noise got filtered. The uncorrupted output $y(i)$ was given out. $y(i)$ is the product of the new weight and the reference input signal $x(i)$.

$$y(i) = w(i) * x(i) \tag{3.7}$$

The summation of old weights function and the product of step size factor, the error signal and the input signal gives a new weight.

$$w(i) = w(i-1) + \mu * e(i) * x(i) \tag{3.8}$$

The error signal was calculated by subtracting the filter output $y(i)$ from the desired signal $d(i)$.

$$e(i) = d(i) - y(i)) \tag{3.9}$$

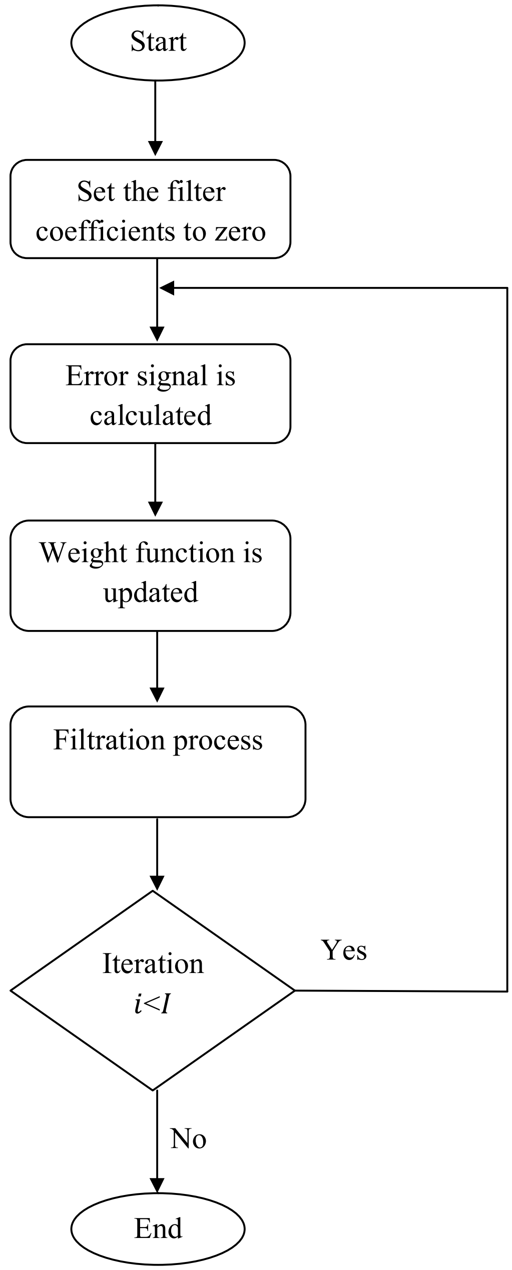

Figure 3.5: Flowchart of Adaptive LMS Algorithm

The process takes place in the proposed hybrid FEC-LMS noise reduction filter is shown in Figure 3.6.

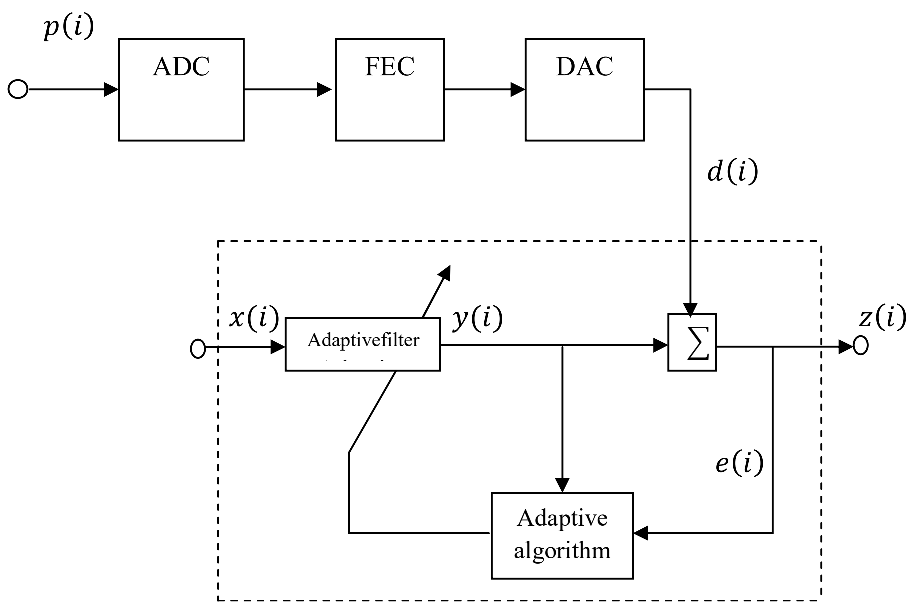

Figure 3.6: Block diagram of hybrid FEC-LMS filter

Where,

$p(i)$ is the PLC signal with impulsive noise

$x(i)$ is the impulsive noise signal

$d(i)$ is the enhanced data obtained after FEC

$e(i)$ is the error signal

$y(i)$ is the output of adaptive filter

$z(i)$ is the output of hybrid FEC-LMS filter

ADC–Analog to digital conversion; DAC–Digital to analog conversion

CHAPTER 4

RESULTS AND DISCUSSION

The simulation was carried out to measure the performance of the PLC network with impulsive noise and with noise reduction techniques (FEC, adaptive LMS filtering and the proposed hybrid noise reduction technique).

4.1 Simulation setup

Simulations were undertaken in ns-3 with the help of a software module named PLC channel simulator. The parameters used in the simulations are given in table 4.1.

Table 4.1: 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

Some of the parameters used in this simulation are modulation scheme, noise floor, step size, convergence rate and order of the filter. Quadrature Amplitude Modulation Phase Amplitude modulation (QAMPAM) and Binary Phase Shift Keying (BPSK) 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 $1e^{-9}$ to $60e^{-9}$ were introduced to the channel. Simulations were done and found out that the performance of the channel decreases as the noise floor increases. Therefore, a noise floor $15e^{-9}$ was used in this study. Step size/ convergence rate is the speed at which a convergence sequence approaches its limit. The convergence speed of the adaptive filter decreases by using a small step size. Hence, to improve the convergence speed of the adaptive filter, the step size must be increased. However, it should not be larger as it makes the adaptive filter become unstable. Hence, a suitable step size to achieve a better performance was used in this simulation. Order of a filter is the maximum number of delays used in the filter. Choosing the order of a 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 was chosen accordingly. Investigations were done for each parameter value and filter order 5 was used to carry out this experiment.

The comparison of FEC and LMS adaptive filter were carried out with the help of obtained BER and throughput. In this experiment, the simulations were carried out with 26 nodes. The distance between the nodes was varied ranging from 10 to 100 metres.

There was an exponential increase in BER and decrease in throughput when the distance between the nodes was set beyond 100 metres. The distance between the nodes was varied ranging from 100 to 1000 metres to analyse the behaviour of the network. This is shown in Figure 4.1. Beyond 100 metres, the performance of the PLC network decreases gradually. Even beyond 100 metres distance, the noise reduction techniques work similarly as they work for the distance below 100 metres. 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 (Fabio, 2012; Keyuan, 2014). Hence, the BER and throughput values were analysed for a network of 26 nodes, for a distance between the nodes varied between 10 to 100 metres.

According to Park et al. (2008), a typical power line might span across 5 to 50 km. In a PLC network, data signal can’t travel long distance due to attenuation, noise and distortion. As the distance increases, the signal attenuation increases and the effect of noise in the power line channel increases. In order to overcome these limitations, Lampe and Vinck (2011) discussed about the use of repeaters to build a PLC network over a long distance. However, it causes flooding problems thus lowering the performance of the network (Byung-Seok et al., 2008). This is one of the challenges to be overcome in the future research.

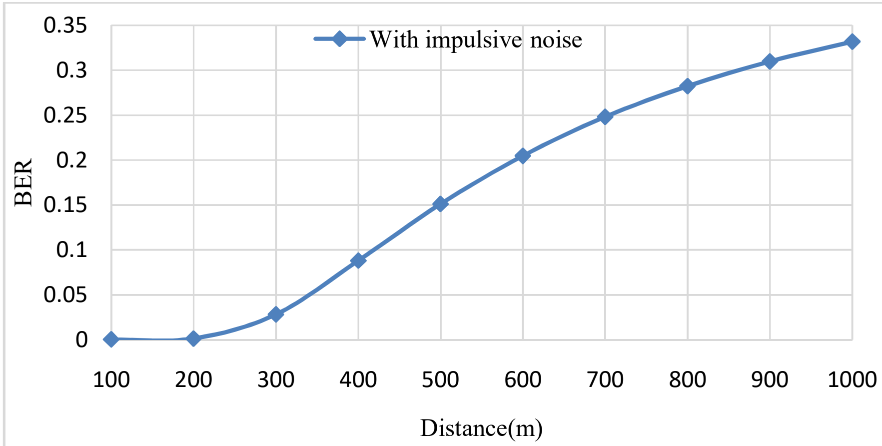

Figure 4.1: Distance ranging from 100 to 1000 metres

4.2 Comparison of BER

The performance of the PLC network was monitored by comparing the BER values. Figure 4.2 to figure 4.5 shows the BER versus distance for different noise reduction techniques. BER values were high when the impulsive noise was introduced to the network and decreases with the introduction of noise reduction techniques.

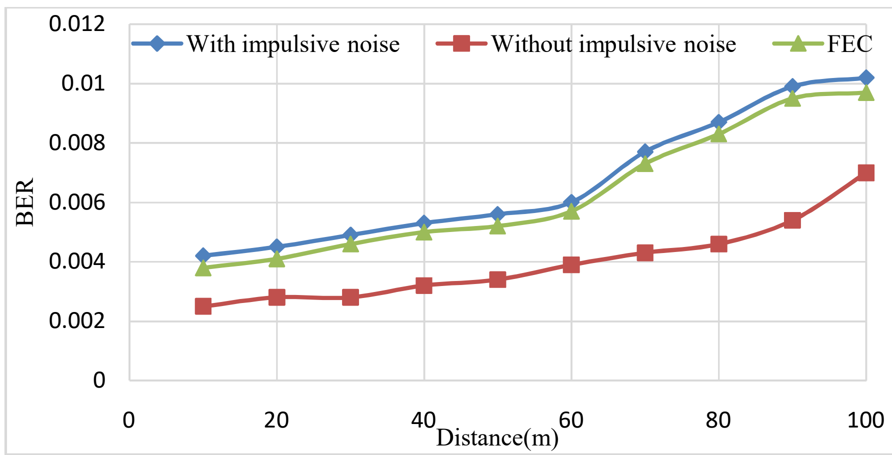

Figure 4.2: BER for FEC

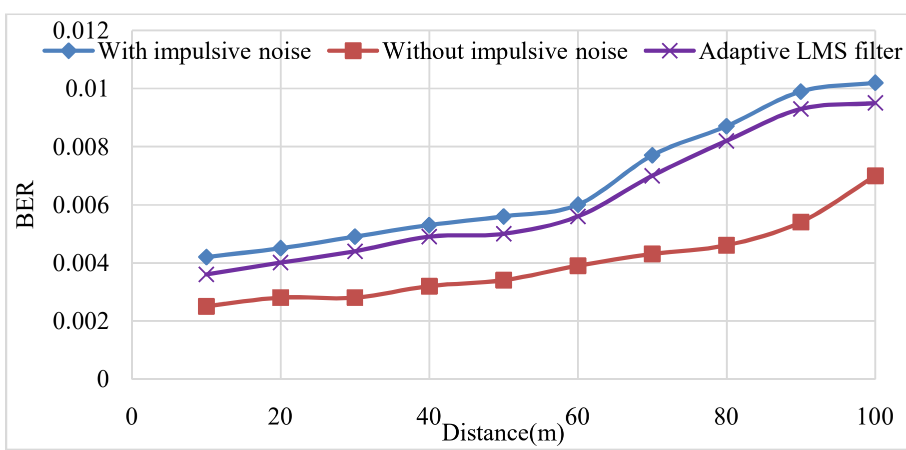

Figure 4.3: BER for LMS

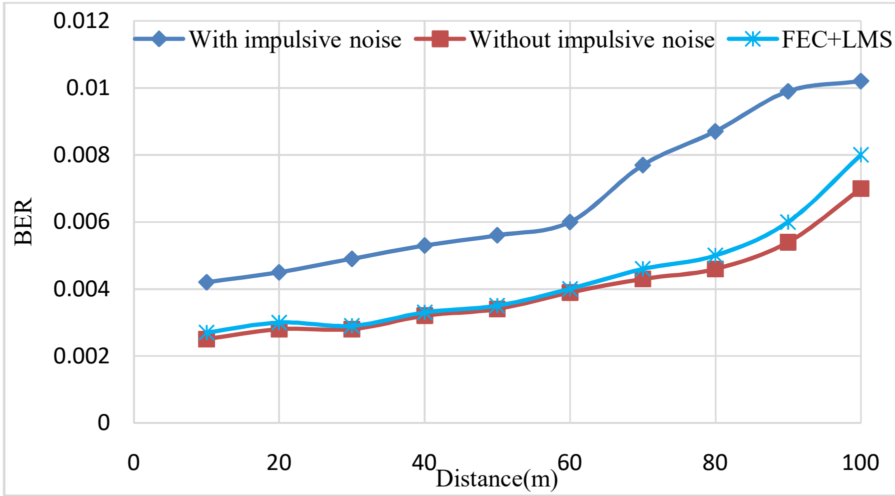

Figure 4.4: BER for FEC+LMS

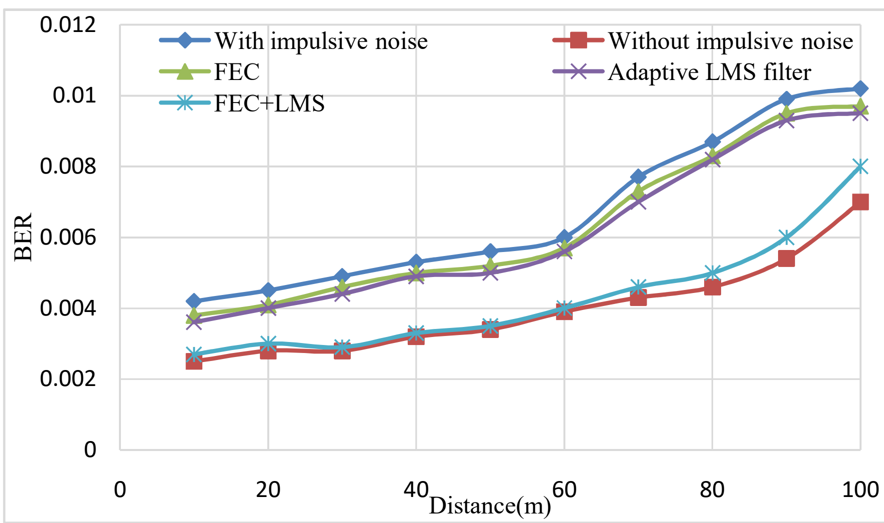

Figure 4.5: BER for comparison of FEC, LMS and FEC+LMS

The performance of the network with the presence of impulsive noise (without noise reduction) and with different noise reduction techniques was compared in terms of BER in Figure 4.2 to Figure 4.5. In these figures, without impulsive noise denotes the performance of the 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 hybrid FEC-LMS noise reduction technique.

In Figure 4.5, it was shown that the introduction of adaptive LMS filter performed better than FEC. The hybrid FEC+LMS noise reduction technique outperformed both the noise reduction techniques increasing the performance of the PLC-MAC network by decreasing the BER. The BER obtained even without the presence of impulsive noise is due to the presence of interference (another factor which affects the performance of PLC channel) in the PLC channel.

Table 4.2: Average BER with noise, without noise and with different noise reduction techniques

With noise	Without noise	FEC	LMS	Hybrid
0.00670	0.00391	0.00632	0.00615	0.00430

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 4.2. From Table 4.2, it is known that the hybrid FEC-LMS filter performs closer to without noise. The average BER decrease, while introducing FEC technique is 0.00038. The average BER decrease, while introducing LMS filtering technique is 0.00055. The average BER decrease, while introducing hybrid FEC-LMS noise reduction technique is 0.0024. Furthermore, the percentage decrease in BER from the baseline (with impulsive noise) was analysed using the formula shown in Equation 4.1, where x is the baseline (average BER with Impulsive noise) and y is the average BER with the noise reduction technique.

$$\text{Percentage decrease} = [(x - y)/x] * 100 \qquad (4.1)$$

The percentage of decrease in BER while introducing FEC technique is 5.97%. The percentage of decrease in BER while introducing LMS filtering technique is 8.95%. The percentage of decrease in BER while introducing hybrid FEC-LMS noise reduction technique is 35.82%.

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 mitigating the harmful effects of impulsive noise by 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.

4.3 Comparison of throughput

Figure 4.6 to Figure 4.9 shows the throughput versus distance for different noise reduction techniques. Throughput values are low when the impulsive noise is introduced to the network and increases with the introduction of noise reduction techniques.

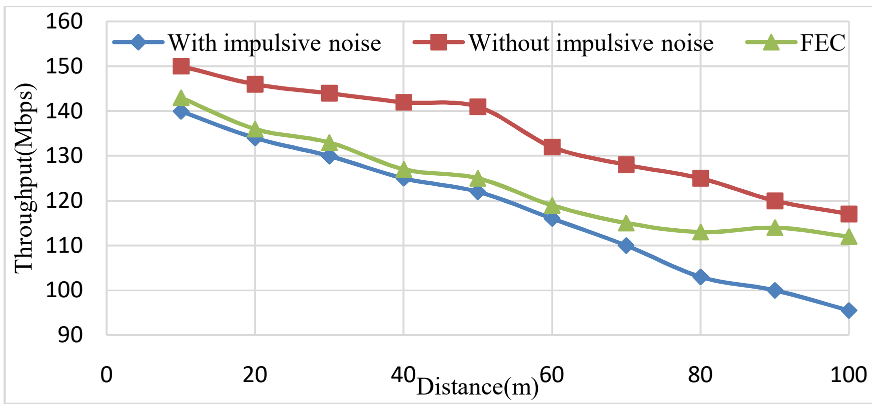

Figure 4.6: Throughput of PLC network with FEC

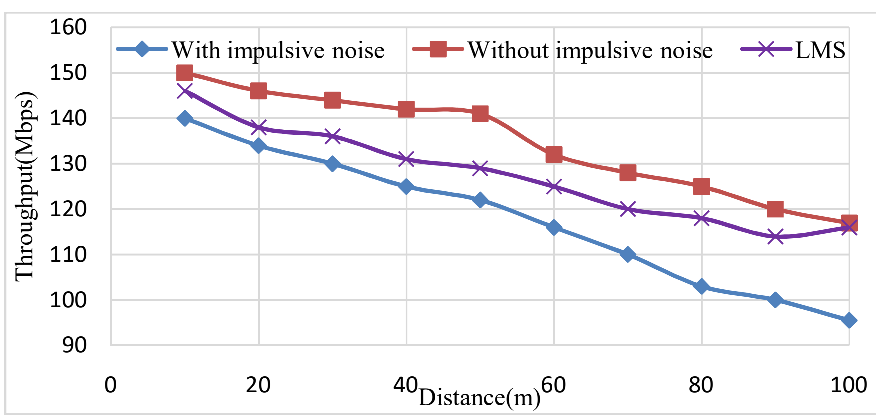

Figure 4.7: Throughput with LMS

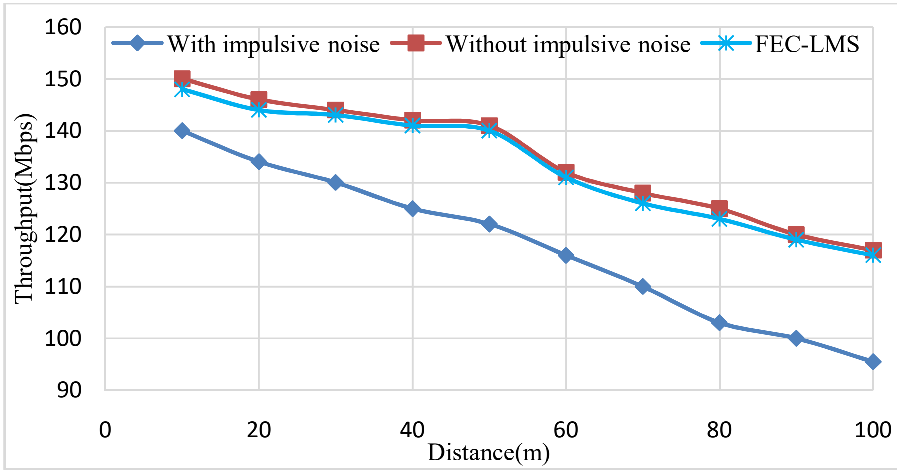

Figure 4.8: Throughput with FEC+LMS

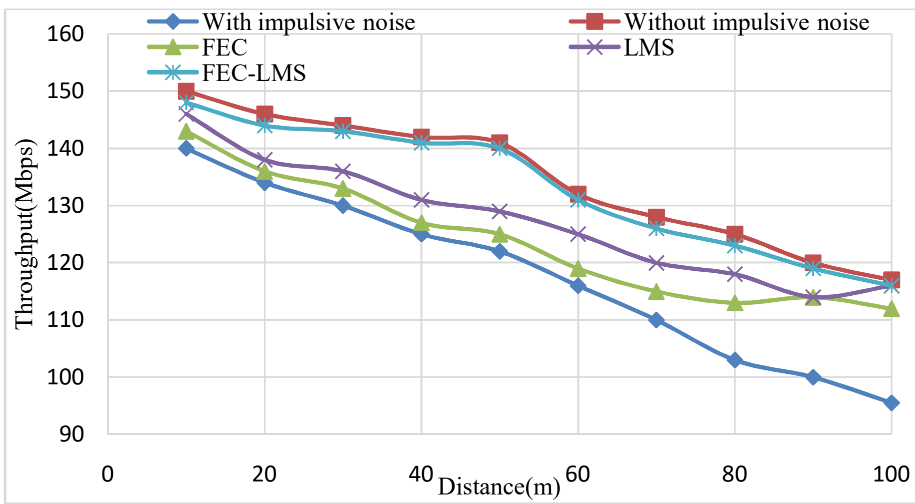

Figure 4.9: Throughput with a comparison of FEC, LMS and FEC+LMS

The performance of the network with the presence of impulsive noise (without noise reduction) and with different noise reduction techniques was compared in terms of throughput in Figure 4.6 to Figure 4.9.

It was shown in figure 4.9 that the introduction of adaptive LMS filter performed better than FEC. The hybrid FEC+LMS noise reduction technique outperformed both the noise reduction techniques increasing the performance of the PLC-MAC network by increasing the throughput. The decrease in throughput even without the presence of impulsive noise is due to the presence of interference (another factor which affects the performance of PLC channel) in the PLC channel.

Table 4.3: Average throughput with noise, without noise and with different noise reduction techniques

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

The average of obtained 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 4.3. It is clear from Table 4.3 that the performance of hybrid FEC-LMS filter is closer to without noise. The average throughput improvement while introducing FEC technique is 6 Mbps. The average throughput improvement while introducing LMS filtering technique is 9 Mbps. The average throughput improvement while introducing hybrid FEC-LMS noise reduction technique is 15 Mbps. Furthermore, the percentage of increase in throughput from the baseline (with impulsive noise) was analysed using the formula shown in Equation 4.2 for the three noise reduction techniques, where x is the baseline (average throughput with Impulsive noise) and y is the average throughput with the noise reduction technique.

$$\text{Percentage increase} = [(y - x)/x] * 100 \tag{4.2}$$

The percentage of improvement while introducing FEC technique is 5.08%. The percentage of improvement while introducing LMS filtering technique is 7.62%. The percentage of improvement while introducing hybrid FEC-LMS noise reduction technique is 12.71%.

It is clear from the throughput analysis that the proposed hybrid technique outperforms the other two noise reduction techniques. It 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 hybrid FEC-LMS noise reduction technique is close to a PLC network without noise.

Percentage of successful data transmission with impulsive noise, with FEC technique, with adaptive LMS filtering technique and with hybrid FEC-LMS technique was calculated using the formula 4.3.

Percentage of successful data transmission =

$$(x/\ Average\ throughput\ without\ noise)\ *\ 100 \quad (4.3)$$

x is the variable which is the average throughput value with impulsive noise, with FEC, with LMS and with hybrid FEC-LMS. The percentage of successful data transmission with impulsive noise is 87%, with FEC technique is 92%, with adaptive LMS filtering technique is 94% and with hybrid FEC-LMS technique is 98%.

4.4 BER and throughput for a different number of nodes

The experiment was also carried out for a different number of nodes ranging from 26 to 200 for an average of 10 to 1000 metres distance. It was noticed that there was a significant deterioration in BER performance due to the influence of impulsive noise. Hence the entire study was carried out using a network of 26 nodes. According to Munshi and Majumder (2015), BER occurs within the range of 10^{-10} to 10^{-1}because of 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.

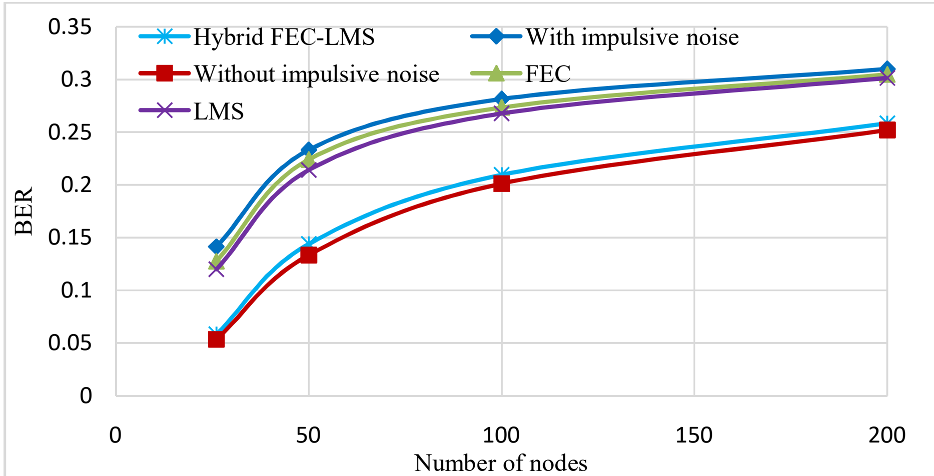

Figure 4.10: BER for different number of nodes

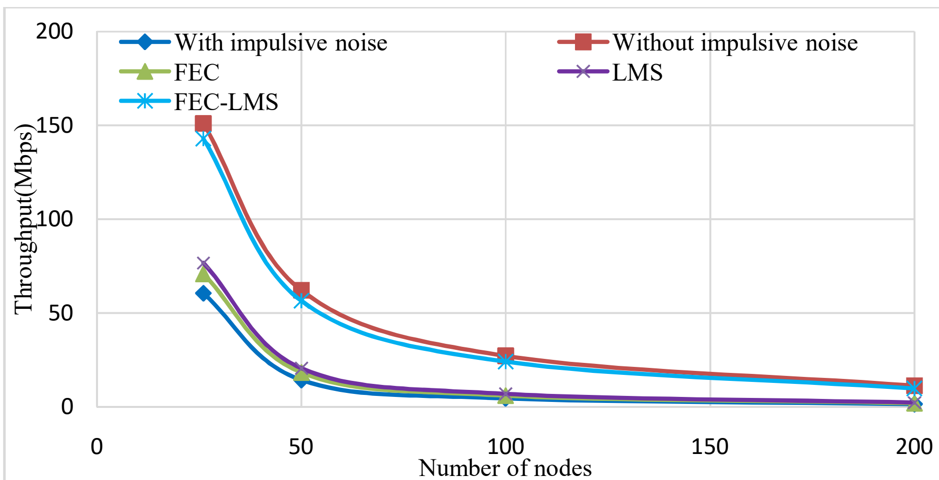

Figure 4.11: Throughput for different number of nodes

From Figure 4.10 and Figure 4.11, it is seen that there is a gradual increase in BER and a gradual decrease in throughput while increasing the number of nodes. It reaches a saturation point and there is no significant change in BER and throughput values. In figure 4.5, figure 4.9, figure 4.10 and figure 4.11, it is seen that the performance of the hybrid filter is more than double the times of FEC/LMS. So, the hybrid filter will perform better even though some changes are done to the parameters to enhance the performance of FEC/LMS. There is a minimal overhead on adding additional filtering mechanism.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The main objective of this study is to reduce the effects of impulsive noise in PLC-MAC network. Therefore, the impulsive noise characteristics were analysed initially. A PLC MAC network was simulated with 26 nodes. The impulsive noise was introduced to PLC-MAC to analyse its performance with impulsive noise and also the performance was analysed without impulsive noise.

Then FEC and adaptive LMS filter were introduced to mitigate the impulsive noise. FEC and adaptive LMS filter were introduced separately to analyse its performance and found out that the introduced adaptive filter with LMS algorithm is more prevalent. The adaptive LMS filter's performance is slightly better than the performance of FEC. Finally, to achieve the main objective of this study, both the techniques were combined together, and a hybrid FEC-LMS noise reduction technique was proposed to enhance the performance of PLC network in the presence of impulsive noise.BER analysis and throughput comparison have been done. It was further shown that the proposed (hybrid FEC-LMS) technique outperformed the other two noise reduction techniques.

The significance of this research includes

- The simulation model helps to study and analyse the impulsive noise
- The proposed noise reduction technique reduces the effects of impulsive noise
- The proposed noise reduction technique increases the performance of the network as close to a network without noise
- This helps the society to get a high speed, efficient, low-cost communication system

5.2 Future work

The current study focused on the investigation into the performance of the PLC MAC network in the presence of impulsive noise using FEC technique, adaptive LMS filtering technique and the proposed FEC-LMS hybrid filtering technique.

Adaptive filtering is a wide-open area for research. In the current research, the adaptive filtering technique was implemented with LMS filtering algorithm, but the other filtering algorithms were not analysed due to some limitations. Therefore, different filtering algorithms can be implemented and can be enhanced in the future to achieve a better performance. Different modulation schemes coupled with adaptive filtering technique can also be explored for future simulations.

During the impulsive noise reduction using FEC technique, forward error correction was done only with “Hamming distance”. Therefore, different types of error correction codes may be considered when carrying out such simulations in the future to find out which performs better.

To further enhance the performance of the PLC MAC network, the above-mentioned analysis may be conducted in the future.

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PUBLICATIONS

Based on findings from this research, two papers have been published-one in International Conference on IoT, Data Service and Security and another in IEEE 13th International Conference on Communications. A paper was accepted in IEEE International Conference on Smart Grid and Clean Energy Technologies. One journal paper had been submitted to Heliyon.

[1] Joliz, A., Madhavan, N., Goi, B. M. and Morris, E., 2017. Internet of Things over Power Lines in the presence of Alpha-Stable Noise. *International Conference on IoT, Data Science and Security*.

[2] Joliz, A., Madhavan, N., Goi, B. M. and Morris, E., 2017. Performance monitoring of power line communication MAC protocol in the presence of impulsive noise using ns-3. *IEEE 13th Malaysian International Conference on Communications.*

[3] Joliz, A., Madhavan, N., Goi, B. M. and Morris, E., 2018. Impulsive noise reduction in power line communication MAC protocol with adaptive filtering technique using network simulator-3. *IEEE International Conference on Smart Grid and Clean Energy Technologies*.

[4] Joliz, A., Madhavan, N., Goi, B. M. and Morris, E., 2018. Impulsive noise reduction in power line communication MAC network using Forward Error Correction and Least Mean Squares hybrid filter. Heliyon (Submitted).