POWER LINE COMMUNICATION FOR SMART GRID USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

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List of Acronyms

AWGN - Additive White Gaussian Noise

BAN - Building Area Network

BER - Bit Error Rate

BPSK - Binary-Phase Shift Keying

QPSK - Quadrature-Phase Shift Keying

BPLC - Broadband Power Line Communication

PLC - Power Line Communication

QAM - Quadrature Amplitude Modulation

RMS - Root Mean Square

Wi-Fi -Wireless-Fidelity

OFDM - Orthogonal Frequency Division Multiplexing

FFT - Fast Fourier Transformation

IFFT - Inverse Fast Fourier Transformation

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Abstract

Although views on the specific technology options for smart grids are still divided, there is agreement that heterogeneous communications networks are best suited. Power line communication (PLC) is promising as it is readily available and aligns with the power distribution network's natural topology. One of the new facts is that the smart grid communication system must be energy efficient. This research uses a cross-layer approach in multiple smart grid settings to discuss the energy efficiency of PLC networks.

This work utilizes three phases of data collection works to prove and analyze the probability of efficient network-wide packet delivery. Improving the distribution of packets effectively eliminates waste of energy.

This work proposes an energy-efficient multi-carrier modulation scheme OFDM at the physical layer.

This thesis work was done by 3 phases of data collection. From these stages, the feasibility of the PLC using OFDM for smart grid has been proved.

We have studied PLC networks for energy efficient purpose in the application of Smart Grid.

INTRODUCTION

The energy industry is at the forefront of a revolution that has never been seen before. Despite the enormous obstacles, the prospects are the same. Smart grid development represents a giant leap towards a smart, stable and sustainable future for electricity. It needs intellectual horsepower, new stakeholder programs, and cross-sector convergence between energy and ICT, however. A fundamental choice of design in smart grid is whether the enabling communication system will be based on wireless or wired technology, as evidenced by the proliferation of communication technologies in recent decades [1,2].

PLC has made tremendous strides in developing as a smart grid and other cyber physical systems candidate technology. While smart grid will be enabled by a heterogeneous array of communications systems, one of PLC's main advantages is that the electrical cables are readily available, minimizing connectivity costs and simplifying network management further. A common requirement among smart grid applications is that error-free transmission must be continuously supported by the enabling communication network. Because power cables have not been custom-made for communication, however, they pose serious challenges to data signals. Impedance, vibration, and attenuation in particular vary with time, place, and frequency, making them highly unpredictable. Certain problems include selectivity between frequencies and multi-pathing. Such factors impair system performance on the receiver in terms of achievable bandwidth, bit-error rate (BER), latency, signal-to-noise ratio (SNR) and can also impact the PLC system's power requirements [3].

MOTIVATION

The implementation of two-way communication systems has been described as a critical element to tackle the multitude of challenges facing the power grid. Although PLC has advanced over the past two decades in terms of standardization and use cases, but not in smart grid implementations. Unlike other PLC aspects such as channel characterization and noise modeling, PLC system’s feasibility and energy efficiency has so far received little attention [4]. With practical and theoretical approaches to data, this problem can be investigated. A variety of strategies have been proposed to handle the PLC systems.

In terms of experimental studies, it was stated that energy efficiency can be improved through optimal time allocation in the relaying scheme in a DF relay-assisted PLC network. A recent evaluation project across six European countries concluded that by installing DF multiple-input, multiple-output (MIMO) relays, static power consumption in PLC networks can be minimized [5].

Further tests with MIMO PLC devices showed that while energy consumption is primarily controlled by static power, dynamic power in some modems can be as high as 50%, with an average of 40%.

Within the dynamic capacity, data reception consumes 20-25 percent less energy than transmission [6,7]. From these studies, it can be concluded that PLC implementation in smart grid and energy efficiency in PLC can be approached in a variety of ways. Therefore, the main inspiration for this research is the prospect of exploring these areas and developing new energy-efficient PLC systems techniques and in this case such as: Orthogonal frequency division multiplexing (OFDM) [8,9].

RESEARCH OBJECTIVES

This work explores and proposes methods that can evaluate the implementation of Power Line Communication in smart grid that can increase energy efficiency. A combination of modeling, measurements, testing, and numerical analysis is needed when designing the system components. For order to fulfill this requirement, the proposed device components must be checked layer-by-layer [10].

- Part of this work discusses the topology of the LV distribution network on the network layer and proposes clustering smart meters in the neighborhood area network (NAN) into smaller sub-networks to increase data transmission capacity.

- One part of this study examines transmission processes at the adaptation level by considering a network where computers are required to transmit at a certain data rate to save energy [11,12]. This strategy is based on the premise that a feature of traffic load is the power consumption in PLC modems, so increasing the data rate constantly decreases power consumption.

- The later part of the work uses advanced processing techniques for modulation and simulation.

KEY CONTRIBUTIONS

The main contributions of this thesis are stated below.

- Through smartly adjusting the configuration of the communication network over the power lines, it is shown that interaction between smart meters and the utility network can be improved in terms of coverage and reliability which affect energy requirements through power line communication [13,14].

- Feasibility of PLC network for customer-friendly networks such as homes, offices and small industrial facilities. Part of this study provides strong evidence that the proposed low-power PLC network design could help in-building monitoring and control applications as they typically require low data rates. This result could potentially open up new opportunities for home and industrial users to develop management services [15,16].

- Proposal for a successful method for the transmission of data and cancellation of noises and mitigating the challenges faced by PLC. The proposed OFDM method can reduce the effects of unbalanced complexity in the design of the transmitter-receiver systems. It is assumed that many smart grid systems over power lines will be rapidly modified over the next few years. This will lead to a better packet routing and more efficient method for Smart grid at a lower price with data security and control.

CHAPTER - 1

1.1 Power Line Communications

Power Line Communications is a technology that exploits the existing electric power infrastructures to provide multimedia services for various applications, e.g., home or office networks, vehicles, by coupling radio frequency (RF) signals onto the power line. Depending on their operating frequencies, PLC can be categorized into: Ultra Narrowband (30 Hz-3 kHz), Narrow band (3-500 kHz), and Broadband (1.8-250 MHz) [Berger2014, p. 253–266] [17]. PLC systems have many advantages over other wired and wireless communication technologies. The first advantage is that PLC systems provide available access to the Internet anywhere there is an alternating current (AC) outlet, without any need for additional installations. In most cases, building a communication network using the existing AC electrical wiring is easy to install and very cost effective. Another potential benefit of PLC is the possibility of its use for smart grid applications since it could offer the opportunity to remotely control the appliances without supplementary installations [Galli2010]. This chapter provides an introduction to the PLC technology. Indeed, basic understanding of the main features of PLC systems is necessary for the investigation and development of new energy efficient PLC techniques [18,19]. This chapter will only focus 11 Chapter 1. Broadband Power Line Communications 12 on broadband PLC. The historical development and current advances in the PLC technology are first outlined. Then, after a brief description of the typical indoor PLC network structure, information related to PLC standardization is given. The main transmission techniques exploited by PLC systems and the related Electromagnetic Compatibility (EMC) issues are highlighted, and a brief overview of PLC channel and noise modeling is also provided. Finally, a conclusion is given in the last section.

1.2 Brief history of the PLC technology

Initially, the first applications using transmission over power lines were done for control, power line protection, maintenance and charging purposes [Yousuf2007]. Later, several factors such as the telecommunications market deregulation in USA, Europe and Asia and the birth and explosive growth of the Internet which was accompanied by greater demand for digital communications services, have made PLC an operative technology for many other applications. The first patents in this area date back to the early 1900s [Pavlidou2003] [20]. In 1913, automatic electromechanical meter repeaters were produced and in 1922 Narrowband PLC have started when the first carrier frequency systems began to operate over high-tension lines in the frequency range from 15 to 500 kHz for telemetry applications

[21].

Research in PLC has intensified and gained more popularity over the last two decades as new modulation and error control coding techniques were proposed, as well as new standards from industry alliances and standardization bodies. Today, the emerging PLC technologies become promising for both consumers and energy providers. Therefore, the interest in PLC spans several important applications such as broadband Internet access, Smart Grid applications (advanced metering and control, real-time energy pricing, peak shaving, mains monitoring, distributed energy generation, etc.), indoor wired Local Area Networks (LANs) for residential and business premises, in-vehicle data communications, aircraft, traffic light and street lighting control.

1.3 Indoor power line network structure

Residential and commercial indoor power line networks are usually composed of multiple circuits (or sub-circuits) that are interconnected through different Circuit Breakers (CBs). Several derivation boxes (DBs) are present in the circuit and each power line that starts from the DB terminates into one or several outlets. The connection between the distribution network and the residential network is done through the Main Panel (MP), where the electric meter is located. In addition, two different types of connections between the outlets and a DB are possible; a STAR connection, where each outlet is directly connected to a DB and a BUS connection, where the outlets are connected in parallel to a DB. An example of a two-sub-circuits PLC network is illustrated in Fig. 1.1. It shows a typical indoor PLC network including a group of power sockets where PLC modems can be plugged in. It contains two circuit breakers and two derivation boxes. This example can be representative of the majority of French and European indoor PLC network structures.

1.4 The status of broadband PLC standardization

There is a couple of international standards governing PLC. The dominant PLC standards in the market are IEEE1901 [IEEE2010] and (International Telecommunication Union Telecommunication Standardization Sector) ITU-T G.hn [ITU-T2010], [Oksman2009] [22,23]. On the one hand, the market ready products conforming to IEEE 1901 have been certified by either the HomePlug Powerline Alliance [HomePlug], in the USA and Europe, or the HD-PLC alliance [HD-PLC], mainly in Japan [24]. On the other hand, the marketready products conforming to ITU-T G.hn have been certified by the HomeGrid Forum alliance [HomeGrid][25]. The HomePlug family products are the most deployed in the market. The specifications available through the alliance for broadband PLC are: HomePlug 1.0 [HomePlug], HomePlug AV [HomePlugAV2007], HomePlug AV2 [HomePlugAV2-2012] and HomePlug Green PHY (GP) [HomePlug GreenPHY]. Hereafter we describe the main PLC standards and specifications in more details [26].

1.5 IEEE 1901

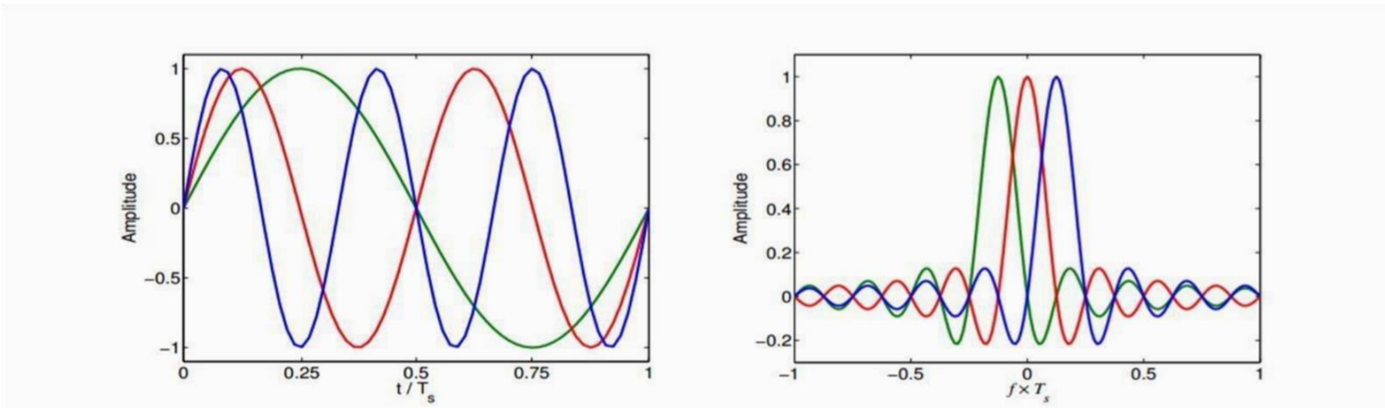
The IEEE 1901 standards are developed by the IEEE P1901 workgroup and define the technology for high-speed power line communications. The standard defines methods for both in-home networking and access networking (Internet access). The IEEE 1901.2010 standard uses transmission frequencies below 100 MHz and achieves high data rates up to 500 Mbps at the physical layer [27]. It includes two different physical layers, one based on Fast Fourier Transform (FFT) Orthogonal Frequency Division Multiplexing (OFDM) modulation (mainly in use in the USA and Europe) and another based on Wavelet OFDM modulation (restricted to Japan) [28]. The standard is also compliant with EMC limits set by national and international regulatory authorities, so as to ensure successful coexistence with wireless and other telecommunications systems.

1.6 Transmission techniques exploited by the PLC technology

Modulation The power line transmission environment is particularly hostile to digital communications, due to its strong frequency selective behavior, the presence of impulsive noise, etc. Therefore, the choice of a modulation technique that can stand up against the PLC channel peculiarities is very crucial.

Among a variety of techniques, including single-carrier, multi-carrier and spread spectrum [Agarwal2009], OFDM is considered as an excellent candidate for high data rate transmission over power line. OFDM is currently the most commonly used modulation scheme in PLC. Moreover, all PLC standards and specifications discussed previously, e.g., IEEE 1901, ITU-T G.hn, and HomePlug AV define physical layers based on OFDM [29]. The general idea of OFDM is to split high-speed data symbols into slow narrowband data streams. Specifically, a high rated serial data stream is divided into a number of sub-streams, and the data within each sub-stream are modulated, and transmitted simultaneously over parallel and separate subcarriers occupying a sub-band which is so narrow that the associated sub channel has a flat frequency response. Then, a frequency-selective channel becomes equivalent to a set of multiple flat-fading sub-channels, which allows the use of simple equalization [30].

In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other. This requires that the sub-carrier frequencies must fulfill the orthogonality condition, i.e., the sub-carrier spacing is $\Delta f = 1 / T_s$, where Ts is the useful OFDM symbol duration. Fig.(a) illustrates an OFDM signal in both frequency and time domains.



Time representation Frequency representation

Figure 1.1

In practice, the orthogonality allows for a simplified design of both the transmitter and receiver. That is, the modulator and the demodulator are implemented using the FFT algorithm on the receiver side, and inverse FFT on the transmitter side. Also, by dividing the data stream into N subcarriers, the symbol duration in a subcarrier will be N times longer than at the transmitter input, which means that each symbol occupies a narrower band but a longer time period. To avoid Inter Symbol Interference (ISI), a guard interval is introduced for each OFDM symbol. During this interval, which has to be filled with a cyclical extension of the same OFDM symbol, no useful data is transmitted. This extension is called the cyclic prefix (CP).

Finally, note that, a very important property of OFDM is its adaptability. Specifically, according to the PLC signal-to-noise ratio (SNR), it is possible to assign different data rates, constellation sizes and transmit power to distinct subcarriers in order to optimize the system performance in terms of bit rate or power consumption. This important property will be exploited as a resource allocation technique in this thesis in order to minimize the power consumption or to maximize the data rate of the system by appropriately allocating bits and transmit power to different sub-carriers.

1.7 PLC Standards and Regulations

Due to the diversity of the environment in which PLC may be applied, a lot of regulatory framework and standardization effort have been made at promoting co-existence and ensuring that PLC does not adversely affect other communication systems, especially wireless transmission in similar or close spectrum. Today, PLC systems are implemented in 9 kHz – 100 MHz band. In terms of spectrum regulation, Europe is a large market for PLC systems and European Committee for

Electro technical Standardization (CENELEC) is charged with regulating the strength of signal coupled to the power lines and the frequency band of operation. Given that the electric cables were made to carry

50Hz/60Hz, when PLC signals are coupled to power lines, EM emissions occur. Since the wavelength of BPLC signals are significantly short relative to the length of the transmission lines, the regulation of BPLC differ from that of NPLC. NPLC generally operate below 500 kHz, in Europe, the European Norm (EN) 50065 allows four frequency bands defined as CENELEC band A (3-95 kHz), CENELEC band B (95125 kHz), CENELEC band C (125- 140 kHz) and CENELEC band D (140-148.5 kHz) [31,32,33].

Region	Regulation	Remark
	Narrowband PLC	
Europe	EN 50065	CENELEC band A for utility, bands B-D for consumer use band C for CSMA/CA
	IEEE 1901.2 148.5-500 kHz	Not yet harmonised in Europe
USA	FCC part 15 9kHz - 490 kHz	Rules for carrier current devices
Japan	ARIB STD-T84	CSMA/CA required
	Broadband PLC	
Europe	EN 50561-1 1.6065-30 MHz	Dynamic power control static and dynamic notching
	EN 50561-3 30-87.5 MHz	Dynamic power control static and dynamic notching
USA	FCC part 15 1.705-80 MHz	Subpart G for access BPLC, interference mitigation,

Table 1.1: Global regulation of BPLC and NPLC frequency bands

1.8 PLC Channel Characterization and Measurements

One of the advantages of PLC is its use of existing power cables as communication channels. There are two acclaimed methods to determine the characteristics of a power line channel namely; top-down and bottom-up. They are described below.

1.8.1 Top-down Approach

In this approach, the power line channel is considered a black box in which measurements are carried out to determine the model parameters, a common example is the multipath model. In multipath model, channel behavior is determined by the number of signal paths present from which the physical propagation behavior is analyzed in terms of echoes arising from multiple reflections from points of impedance mismatch or discontinuity However, such measurements are subject to equipment calibration and errors caused by fine-grain details that might have been over looked.

$$H(f) = \sum_{i=1}^{n} g_i . A(f, d_i) . e^{-j2\pi f \tau_i}$$

Where, i is the number of paths (path with the shortest delay has index i = 1), gi is the weighting factor for path i, d_i is length of path i and τi the delay of path i. Furthermore, g_i is a product of transmission and reflection factors such that |gi | ≤ 1, paths with more transmissions and reflection have small value of gi. Also, longer paths contribute less to the signal arriving at the destination. The delay τi of a path is defined as

$$\tau_i = \frac{d_i\sqrt{\varepsilon_r}}{c} = \frac{d_i}{\nu_p}$$

Where εr is the dielectric constant of the insulating material and c, the speed of light. In the losses of the cable cause attenuation A (f, di) which increases with frequency and distance and can be expressed

as

$$A(f, d_i) = e^{-\alpha(f).d} = e^{-(a_0 + a_1 . f^k).d}$$

where a0 and a1 are attenuation parameters and k is the exponent of attenuation factor. We can see that although (2.3) captures the physical properties, they must be measured for each network to derive the channel model. By combining we obtain-

$$H(f) = \sum_{i=1}^{n} g_i(f) . e^{-(a_0 + a_1 . f^k).d_i} . e^{-j2\pi f(\tau_i)}$$

$$= \sum_{i=1}^{n} |g_i(f)| . e^{-(\gamma).d_i} . e^{-j2\pi f(\tau_i)}$$

Equations imply that the CTF can be modelled using the weighting factor g, cable attenuation A (f, d), and propagation delay e −j2πf(τi). When the system is matched, signal does not reflect back and there is no multi-path. The frequency response H(f) of a matched transmission line of length l simplifies to

$$H(f) = e^{-(\gamma l)}.$$

In the event of unmatched network, the signal undergoes three types of attenuation as it propagates toward the receiver.

- Attenuation caused by the heat loss and radiations along the power line. This line attenuation is always present and increases with length and frequency.

- Attenuation caused by reflections at unmatched joints. The interference of reflected signal with incident signal will increase or decrease attenuation depending on whether such reflection gives rise to destructive or constructive interference.

- The delayed version of the forward-propagating signal falling out of phase with the main incident forward signal results in destructive inference, hence adding to the overall signal attenuation.

1.8.2 Bottom-up Approach

The transmission line (TL) theory is regarded as a bottom-up approach. Unlike the multipath technique, it allows a-priori derivation of model parameters. At high frequencies, signal wavelength is much smaller than the length of the TL. This causes phase difference at different points in the circuits. Therefore, power cables ordinarily used for 50/60 Hz electrical signal may not be suitable for carrying signals whose oscillation rate is in the order of millions or billion times per second because energy tends to reflect from discontinuities along the cable such as connectors and joints and travel back toward the source [34]. These reflections prevent full signal power from reaching the destination. Given that wavelength is inversely related to frequency of electromagnetic wave carried on the line, TL analysis is required when the cable is longer than the transmitted signal's wavelength. Therefore, unlike circuit theory, the cable length is important in TL analysis. In PLC, the live (L) and neutral (N) cables are used to form a 2-conductor TL. The conductors are positioned within the insulator parallel to each other and are assumed to have uniform separation between them. On that basis, the 2-port transmission channel can be analyzed as an electric circuit in which each subsequent section acts as a small lumped circuit element to form an infinite series of two-port elementary components, each representing a short segment of the TL [35].

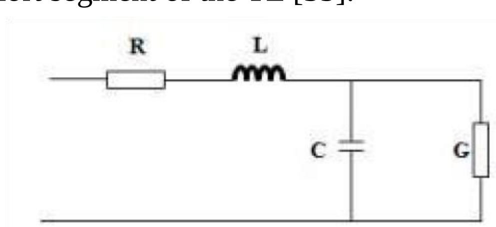


Figure 1.2 Equivalent circuit of 2-port transmission line

The equivalent circuit of one segment is illustrated in Figure where the resistor R, in series with the inductor L represents the distributed resistance and inductance of the line respectively. The capacitor created by the two lines is represented by capacitance C of the circuit and G represents conductance of the material that separates the cables. R, L, G and C are distributed values measured per unit length (m) and sometimes denoted as R', L', G' and C'. The parameters L, G and C are related to the physical properties of the material filling the space between the two cables such that

$$LC = \mu\varepsilon$$

$$\frac{G}{C} = \frac{\sigma}{\varepsilon}$$

where μ, ε, σ are the permeability, permittivity and conductivity of the medium around the conductors. R is the distributed resistance (in Ω/m), L the distributed inductance due to magnetic field around the conductors (in H/m), C is the capacitor created by the conductors represented by a shunt capacitor (in F/m) and G is the conductance of the dielectric material that separates the conductors measured in siemens per meter (S/m). R, L, G and C are called the primary line constants from which secondary line constants (attenuation constant, propagation constant and phase constant) can be derived. The two most important parameters in TL analysis are the propagation constant γ and the characteristic impedance Zc which are defined as

$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$ where angular frequency (in rad/s) $\omega = 2\pi f$. The propagation constant γ (which determines speed and attenuation of the electromagnetic wave) is a complex variable of the form α+jβ whose real part, α is the attenuation constant and imaginary part β is the phase constant. Similarly, characteristic impedance of the line is given as

$$Z_c = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}.$$

With the 2-port representation of the circuit, the transmission can be represented by its ABCD matrix; a 2x2 matrix showing relationship between input/output line voltage and current as illustrated in Figure

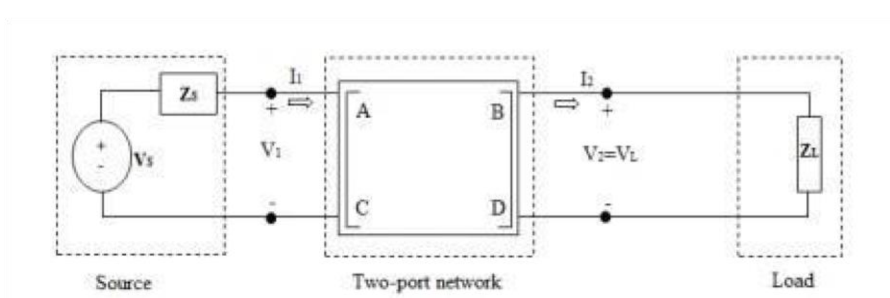


Figure 1.3: Two-port network showing the source and receiver

Elements of the matrix are complex numbers that depend on frequency. The ABCD matrix provides a mathematically convenient way to generate the CTF. For a two-port network, the ABCD matrix is defined as

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

The CTF (H) of the network in Figure 1.3 can be computed as

$$H(f) = \frac{V_L}{V_S} = \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S}$$

where ZS and ZL are source and load impedance respectively. The input impedance (Z1) of the two-port circuit can also be calculated as

$$Z_1 = \frac{V_1}{I_1} = \frac{AZ_L + B}{CZ_L + D}$$

The transmission matrix of a TL with characteristic impedance Zc, propagation constant γ and length l is given by

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} cosh(\gamma l) & Z_c sinh(\gamma l) \\ \frac{1}{Z_c} sinh(\gamma l) & cosh(\gamma l) \end{bmatrix}$$

Equation has been extensively used in literature, it is popularly known as the ABDC matrix and it shows that for a single segment 2-port transmission line of cable length l with primary line constants R, L, C, G, characteristic impedance Zc and propagation constant γ, the ABCD matrix can be mathematically derived, from which the CTF is computed without actual measurements. Hence, with the TL technique, transfer characteristics is topology-dependent, making it flexible and more predictable however, it is more computationally complex. Using the TL theory, complex networks can be approximated into series of cascaded two-port networks for easy analysis and modelling. Once the equivalent two-port subcircuits are obtained, it is possible to represent the entire power line channel with their transmission (ABCD) matrices. For example, consider a network with a branch in Figure

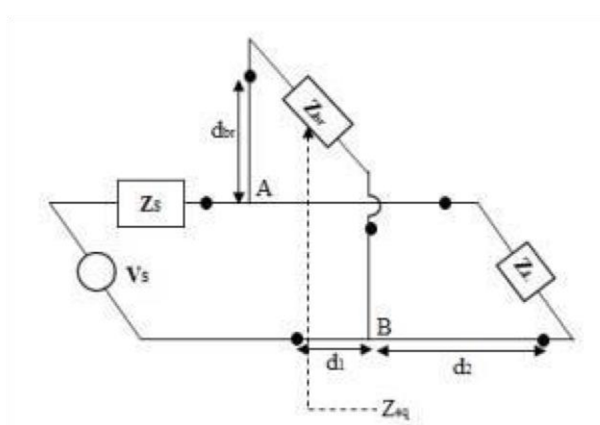


Figure 1.4: Transmission line with one branch

By replacing the branch with the equivalent impedance Zeq, which can be seen by terminals A and B, the network in Figure can be represented by the equivalent circuit in Figure

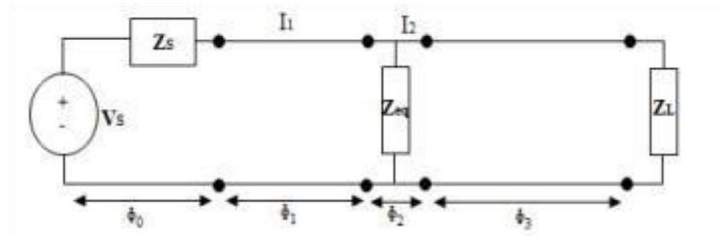


Figure 1.5: Equivalent circuit of Figure above

1.9 Modeling of PLC channel:

The electrical network topology, composed of several nodes and branches, leads to a complex communication channel with multiple propagation paths and frequency selective fading, in a similar way to classical wireless channels.

Therefore, indoor PLC channel modeling is one of the critical challenges in PLC systems. Two different approaches exist for PLC channel modeling, namely, the bottom-up and the top-down approaches.

1.9.1 Signal Propagation and Challenges in PLC

Communication signals are typically affected by various factors as they propagate through the power line channel. This section examines the challenges experienced during signal propagation in power lines and illustrates them with some examples.

1.10 Noise

Like all other communication systems, PLC is affected by noise. However, the noise in power lines is complicated as it consists of Gaussian and non-Gaussian components which can be worse if multiple sources are concurrently emitting non-Gaussian noise on the network [36]. For instance, the noise pattern in the substations is highly non-Gaussian; it is generally impulsive or bursty. Therefore, noise in power lines differs from the usual additive white Gaussian noise (AWGN) found in most other communication systems and overcoming the non-Gaussian components such as impulsive noise is one of the biggest challenges in PLC.

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Noise in power lines can be categorized into five groups**:**

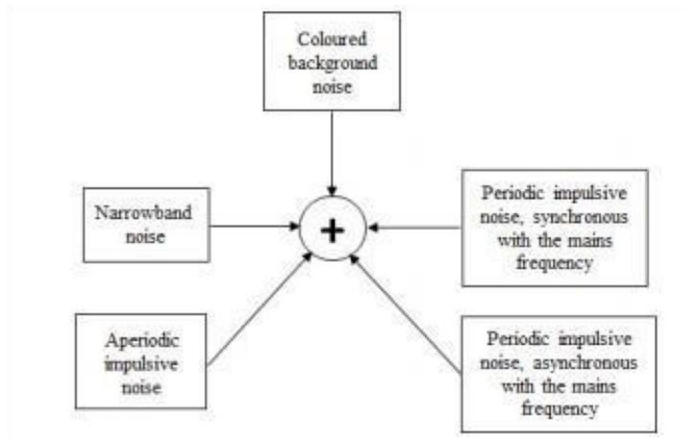


Figure 1.6: Types of noise in power line

1. Colored background noise: it occurs with relatively low power spectral density (PSD), varying with frequency. It is caused by summation of numerous low power noise samples generated by in-home electronic devices.
2. Narrowband noise: unlike colored background, narrowband noise originates from broadcast stations such as amplitude modulation (AM), frequency modulation (FM) stations, citizens' radios and other external sources transmitting within the 1-22MHz [37]. Periodic impulsive noise, asynchronous with the mains frequency: it is usually emitted by switched power supplies such that it occurs at a repetition rate between 50 and 200 kHz, with a discrete line spectrum spaced according to the impulse repetition rate [38].
3. Periodic impulsive noise, synchronous with the mains frequency: this occurs with a repetition rate of 50 or 100 Hz (in Europe) [39]. The impulses are of short duration (some microseconds) and have a PSD decreasing with frequency. This type of noise is caused mainly due to operations of silicon-controlled rectifiers (SCRs) which switch a certain number of times in every 50Hz (synchronously with the mains). For example, switching mode power supplies (in light dimmers) and direct current (DC)-DC converters are known sources of this type of impulse noise [40].
4. Aperiodic impulsive: this type of noise is sporadic in nature, with rapidly varying amplitude. This is caused by switching transients arising from connection and disconnection of electrical devices in the network. The impulses have duration of some microseconds up to a few milliseconds with random occurrence.

In the noise types 1 and 2, the root mean square (rms) of their amplitudes varies slowly and remain stationary for a long period ranging from minutes, hours to days, they are collectively classified as background noise while the last three are categorized as impulsive noise. Impulsive noise is characterized by short duration (microseconds to milliseconds) and high PSD which results in bit or burst errors in data communications. Other known sources of impulsive noise include drilling machine, vacuum cleaner, television set, liquid crystal display (LCD) monitor, CRT monitor, washing machines and other household appliances.

1.11 Conclusion

The basic concepts of PLC systems, and the most important elements for the understanding of the work in this thesis are presented in this chapter, including a brief history of the PLC technology, an overview about the indoor PLC network structure, the current status of standardization, the main transmission techniques used by the PLC technology and information about EMC issues in PLC. Finally, the chapter ends by giving a short overview of indoor PLC environment characterization, i.e., PLC channel and PLC noise.

Also, this chapter provided comprehensive analyses of noise modelling and channel characterization techniques. Lastly, energy efficiency in PLC was identified as an area that has not received sufficient research attention.

CHAPTER – 2

Comparison between wired and wireless Network Transmissions

2.1 Wired network:

1. The wired networks require that the cables are connected to each and every one of the computers in the network.

2. The cost of a wired network is lower compared to the wireless network since Ethernet, cables, and switches are not expensive.

3. Wired LAN offers better performance compared to wireless networks. The wired network can offer a bandwidth of 100 Mbps with Fast Ethernet technology [41].

4. Ethernet cables, the switches that are used in wired networks are reliable.

5. The security considerations for a wired network connected to the internet are firewalls. Firewall software can be installed on each computer.

2.2 Wireless network:

1. The wireless network can be configured in two ways. That is to say. Ad-hoc mode. Wireless devices require WLAN cards and access points for communication.

2. Wireless networks require equipment such as wireless adapters and access points that are quite expensive. The cost of wireless networks is high compared to wired networks.

3. The maximum bandwidth provided by the wireless network is approximately 11Mpbs [42].

4. The reliability of the wireless network is lower compared to the wired network.

5. WLANS uses equivalent encryption of privacy by cable (WEP) to protect the data. This makes wireless networks as secure as wired networks [43].

6. Laptops and other computing devices can move freely within the wireless network because the mobility of the wireless network is better compared to wired networks.

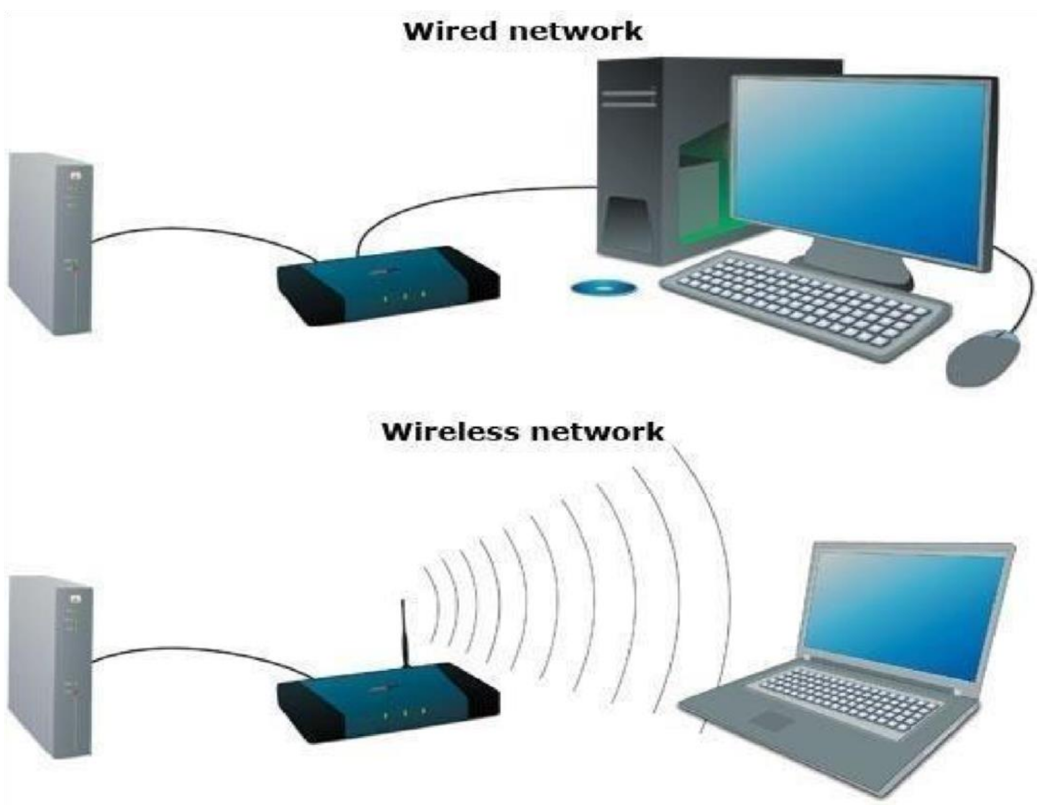


Figure 2.1: Wired and Wireless Technology

Bi-directional communication is an essential phase of clever grid however specific technologies will be chosen from present array and adapted to support the numerous desires of the grid.

This section gives a comparative analysis of wired and Wi-Fi applied sciences as properly as their suitability in the various network segments of the strength grid. It is located that the architecture in Figure 1 follows hierarchical design.

As every of the network segment carries out one-of-a-kind functions, the hierarchy suggests that their requirements will additionally differ.

For example, whilst the WAN covers a moderately giant geographical space (generating flora to transmission stations) and requires long range applied sciences such as worldwide interoperability for microwave access (WiMAX) or optical fiber, Ethernet, wireless constancy (Wi-Fi) and ZigBee are suitable in HANs. In reality, the end-to-end connectivity will be deployed on the groundwork of mix-and-match to cater for each network section from consumers end to the utility [44].

The list of conversation applied sciences and their features are summarized in Table 1.

Technology	Standard	Data rate (bps)	Range	Network
Fibre optic	PON	155 M-40 G	$\leq$ 100 km	WAN
DSL	ADSL, HDSL, VDSL	1- 100 M	$\leq$ 5 km	NAN,FAN
Coaxial	DOCSIS	172 M	$\leq$ 28 km	NAN,FAN
PLC	Broadband	14-1000 M	$\leq$ 200 m	CPN
	Narrowband	10-500 k	$\leq$ 150 km	NAN,FAN,WAN
Ethernet	IEEE 802.3	10 Mbps-10 G	$\leq$ 100 m	CPN
Wi-Fi	802.11	2-1000 M	$\leq$ 100 m	CPN, NAN,FAN
Z-Wave	Z-Wave	40 k	$\leq$ 30 m	CPN
Bluetooth	IEEE 802.15.1	721 k	$\leq$ 100 m	CPN
ZigBee	ZigBee	250 k	$\leq$ 100 m	CPN
WiMAX	IEEE 802.16	75 M	1 – 100 km	NAN,FAN,WAN
Cellular	2G,2.5G,3G,3.5G,4G	14.4k- 100 M	1 – 100 km	NAN,FAN
Satelite	LEO, MEO, GEO	1 M	100-6000 km	WAN

Table 2.1: Wired and wireless communication technology

Chapter - 3

Smart Grid

3.1 Smart grid

The Smart Grid is the modernization of the electrical energy delivery system. A smart grid differs from the normal grid in that it approves two-way conversation of electrical energy data, alternatively than a one-way flow. Smart grids allow actual time statistics series regarding electrical energy provide and demand during the transmission and distribution process, making monitoring, generation, consumption and renovation greater efficient.

Most electricity grids are primarily based on one-way interplay from the levels of generation to consumption. Smart grids, on the other hand, combine the action of all customers in the electricity network the usage of computer-based far off manipulate and automation. This two-way interplay is what makes the grid “smart"[45]. Like the internet, the Smart Grid consists of controls, computers, automation, telecommunication and equipment that work together, but in this case, these technologies work with the electrical grid to respond digitally to our shortly altering electric demand in order for the Smart Grid to work effectively, it relies on a complete gadget of smart technologies.

Generation - A huge variety of era sources that can respond rapidly to changing demand will be fundamental as intermittent renewables end up a necessary issue of the power system. As more electricity era sources are distributed, the Smart Grid will assist to successfully join all these electricity generating systems to the grid, provide facts about their operation to utilities and owners and provide information about how a lot surplus power is feeding back into the grid versus being ate up on site.

Distribution - Distribution intelligence allows an electric powered utility to remotely monitor and coordinate its distribution assets (transmission lines, substations etc.), operating them in an top of the line count number using either guide or computerized controls. The Smart Grid additionally presents outage detection and response capabilities, occasionally enabling the grid to “self-heal” [46].

Consumption - Computerized controls in any home and home equipment can be set up to speak with the clever grid and reply to alerts from your power company to limit their energy use at times when the strength grid is underneath stress from high demand, or to minimize strength consumption at excessive priced hours. Smart controls and appliances can predict consumption patterns and respond to a large set of pre-programmed variables to curb electricity use and costs.

Figure 3.1: Smart grid

To improve the performance and the stability of the overall energy transfer processes, Smart grid is an inevitable choice for the upcoming years for the world. We will use the concept of IoT among the transformers. A communication will be established among the connected transformers using power lines. The benefits associated with the Smart Grid include: More efficient transmission of electricity, quicker restoration of electricity after power disturbances, reduced operations and management costs for utilities, and ultimately lower power costs for consumers.

Procedures:

We will use PLC converters at each of the end of the transformers. It will be a two-way communication. For that purpose, we will have to use the below mentioned equipment to be specially built according to the necessity.

Wave Trap:

A wave trap is a device that allows only a particular frequency to pass through it that it filters the signals coming on to it. So, a wave trap is connected between buses and the transmission line which allow only 50 Hz signal to pass through it [47].

Resonant circuit:

It creates an electric circuit that has very low impedance at a certain frequency. Resonant circuits are often built using an inductor, such as a coil, connected in parallel to a capacitor.

Coupling capacitor:

A coupling capacitor is a capacitor which is used to couple or link together only the AC signal from one circuit element to another. The capacitor blocks the DC signal from entering the second element and, thus, only passes the AC signal [48].

-used to connect the transmitter and the receiver to the high voltage line. This provides low impedance path for carrier energy signal to HV line but blocks the power frequency circuit by being a high impedance path. The coupling capacitor may be a part of a capacitor voltage transformer used for voltage measurement.

3.2 Smart Grid of Transformers using Power Line Communication

To improve the performance and the stability of the overall energy transfer processes, Smart grid is an inevitable choice for the upcoming years for the world. We will use the concept of IoT among the transformers. A communication will be established among the connected transformers using power lines. The benefits associated with the Smart Grid include: More efficient transmission of electricity, Quick restoration of electricity after power disturbances. Reduced operations and management costs for utilities, and ultimately lower power costs for consumers is resulted from that.

What are we up to?

Our target is to check the feasibility of using PLC converters at each of the end of the transformers. It will be a two-way communication. For that purpose, we will have to use several equipment specially built according to our necessity.

We are going to use the concept of Broadband over power line (BPL), Narrow Band PLC, PLC over medium voltage lines and low voltage lines.

BPL is a system to transmit two-way data over existing AC MV (medium voltage) electrical distributions wiring between transformer and AC LV wiring between transformer and customer outlet [49].

-Avoids the expense of maintaining a dedicated network of antennas, radios and routers in wireless network.

-BPL uses some of the same ratio frequencies used for over our radio system. Modern BPL employs frequencies hopping spread spectrum to avoid using those frequencies actually in use, through early pre-2010 BPL standards did not.

Outcome

At present, our main target is to achieve a more efficient way for smart grid technology. We are working on a device that will make this process easier, safer and more efficient and stable. Cost reduction is one of the challenges that are met by the concept of PLC too. We will be able to build, control and maintain this process very easily.

Motivation

Electrification is viewed as the most giant success of the 19th century, as it is one provider that influences everyone. However, the electricity grid has been currently described as a product of speedy urbanization. That statement may also have originated from the reality that the contemporary power infrastructure is no longer notably unique from when it started over 100 years ago. Depleting herbal reserves, rising concerns on greenhouse emissions and global warming, call for sustainable era as nicely as the need to assurance energy security have all indicated that the normal grid can no longer meet the challenges faced by modern society.

While nearby occasions may additionally fluctuate throughout jurisdictions, the key troubles are summarized below:

1. Ageing infrastructure that has normally reached the cease of its beneficial life which results in sub-optimal performance.

2. Steady upward jostle in electricity demand which has resulted in grid imbalance, overloading or unplanned brownouts and blackouts.

3. Increased distance between era web sites and point of consumption, which worsen losses.

4. Environmental concerns on the important energy sources.

5. Variable power mix that includes distributed generations which are not readily supported with the aid of the common grid.

6. Adoption of greater renewable sources for sustainable generation, however, given their intermittent nature, sophisticated monitoring and control are needed to persistently keep a balanced grid.

7. Need to increase new consumption and pricing fashions to aid flexible consumption such as plug-in electric car (PEV) charging at off peak periods.

8. Increasing price of maintenance.

9. Consumer safety and regulatory strain for extra aggressive and lower energy prices.

10. Capacity margin to impervious provide in case of abrupt enlarge in demand.

While the above list is by using no skill exhaustive, it reasonably justifies the name for modernization of the grid. Advent of PEVs is modern and has further exposed the limitations of the legacy power grid. However, if correct harnessed, PEVs will assist to find new possibilities in terms of running them as strength islands to furnish energy to properties at some point of height demands, thereby averting the massive fees related with going for walks of high-capacity generators.

Stakeholders in the energy quarter (utilities, vendors, equipment manufacturers, regulators, consumers, lookup community) have realized the vast challenges plaguing the regular grid and in response, the thought of subsequent era strength grid, also acknowledged as clever grid was once developed as phase of the new energy management strategy. To avoid the identical pitfalls as the standard infrastructure, the clever grid integrates the cyber and physical factors of the grid to uncover new probabilities such as integrating renewable into the energy mix, using clever demand management strategies and lowering the electricity losses over the energy lines.

The smart grid will not solely fulfill its standard role of delivering electricity but will also guide evolution of end-use applications on sustainable basis. In describing the smart grid, there is no single universally accepted definition; it can be defined in simple terms and methods that are extra complex. However, the definitions include some common themes such as ICT, integration, automation and manipulate all of which ensure sustainable, monetary and secure end-to-end approaches inside the power value chain.

Therefore, a clever grid will be created that integrates superior monitoring and manipulate functionalities into the electrical energy grid the use of the energy of ICT. This improves efficiency, reliability and reduces environmental pollution. Although the legacy grid consists of constrained intelligence, it is mainly concentrated in central places such as era and massive transmission stations, while faraway components such as purchaser domains are absolutely passive. By including these themes, the energy grid transforms to a extra responsive and self-healing infrastructure that not only empowers consumers to come to be active stakeholders however also grant them with more statistics to make knowledgeable choices regarding their participation both as producers or consumers of energy.

The promises of clever grid include lower transmission/congestion cost, improved reliability, power quality, bendy height shaving, sustainability, strength security, greater efficiency and decreased cost of renovation (due to lower wear-and-tear in large generators).

At the end, the clever grid is recommended to each utilities and consumers. Following these realizations, it is widely agreed that improvement of a smarter grid is alternatively a necessity than choice. In view of this, system-wide monitoring and manage have been identified as principal layout aspects to be included in the clever grid. The position of the communication technologies is to facilitate timely change of statistics for sensing and manage operations that will make certain efficient generation, transmission, delivery and storage of electricity.

3.3 Smart Grid Application

Challenges

The standard power grid is seen in phrases of some central stations producing electricity and presenting it to give up customers with limited communication. In contrast, the underpinning science that interconnects smart grid machine factors is communication. Smart grid deployment can be approached in many ways.

Integration and Interoperability

The smart grid should allow utilities and shoppers to procure hardware or software and set up them into one-of-a-kind areas of the grid in a plug-and-play manner. As clever grid integrates technologies from exclusive vertical domains which are at different levels of maturity and investment, it is predicted that development of quite a number aspects of clever grid from thought to implementation will naturally appear at different speeds – utility layer services (fastest), ICT (fast), energy (relatively slower). It is therefore viable to encounter application-layer offerings without due regard for how they perform in one-of-a-kind systems working stipulations and their effects on other system components in phrases of co-existence and interoperability [50 51].

Considering the scope of smart grid, a large variable set wants to be tested. However, given the necessary nature of strength grid and the large funding it requires, it is practically challenging to conduct such tests on a giant scale [52 53]. To tackle this issue, the conversation structures have to be primarily based on fashionable diagram paradigms and protocols such as TCP/IP in order to substantially minimize interoperability and integration challenges in real implementations.

Scale and Complexity

The strength grid is evolving towards an automated infrastructure that uses smart applied sciences to screen and control power availability and quality, the on the spot and estimated load needs as well as the popularity of supporting systems. As conversation and records science (IT) industries converge to create large and extra complicated system-of-systems, the explosive amount of data bobbing up from end-use functions and their dependencies may upward shove to a scale unprecedented. To manage, save and use this data, power gadget and ICT want applicable handshake and coordination. It is therefore necessary to recognize the needs for communication sources in such allotted interactions.

Distributed Intelligence

One of the key drivers of smart grid thought is that as more buyers become self-reliant at specific times due to neighborhood power management systems or renewable generation, demand on the grid will range accordingly. While this is a sensible expectation, the variation might also happen nearly unpredictably. This requires that a vast amount of brain be devolved from the core of the strength of the network; toward the edges to allow give up units respond to network stimuli each time they occur.

Security and Privacy

Expanded skills for energy grid structures and networks such as distributed intelligence and broadband capabilities can notably enhance efficiency and reliability however, they can also introduce new protection concerns that are more complicated than imagined. The issues cover a wide spectrum ranging from physical safety of ICT and electrical equipment to cyber security including the vulnerabilities in hardware and software that will run in the electricity network. Similar to traditional records networks, supplying remote access to strength network property through verbal exchange hyperlinks increases accessibility, security risks and vulnerabilities as the complete network can be compromised via a single node. For example, smart meters are the most common factors on the demand-side performing as gateway in many cases. Unauthorized get entry to the clever meters can assist attackers steal valuable information or disrupt regular operation of the facility.

Metering in Smart Grid

Smart metering mechanically obtains consumption, reputation and diagnostic information from a power metering gadget and ships them to the utility through a communication network. Such statistics can be used for billing, forecast, planning and troubleshooting. It is the most fundamental smart grid application.

With smart metering, routine meter analyzing by means of personnel of utility companies is no longer required. Several requirements have been posted to regulate its implementation, most first-rate ones are ANSI C12.1-2008, IEEE 1377 and IEC 61968-9 [54]. Specific offerings associated with smart metering include:

Meter reading

The smart meter uploads its analyzing to a meter records management server (MDMS) by using reachable verbal exchange hyperlink according to a predefined schedule. Upload can also be on-demand to enable utility attend billing inquiries or verification of outage and service restoration.

Events and alarms

Primarily based on embedded intelligence, a clever meter may report system log or alarm to indicate modern-day or impending provider failures. Such messages encompass tamper alarm, disconnection, hardware failure, under voltage, over voltage, atypical electricity condition or any unusual match in the meter. These messages are sent to MDMS for further analysis and resolution.

Chapter - 4

Orthogonal Frequency Division Multiplexing

4.1 OFDM overview for PLC

Power lines have been at the beginning designed for AC energy distribution at 50 Hz and 60 Hz, and the characteristics of this channel present some technical challenges for statistics transmission at these frequencies [55]. This work gives structure for the physical layer of a PLC transceiver based totally on OFDM and the effect of a PLC transmission channel. An appropriate and broadly regularly occurring PLC channel model is used for simulation purpose. In reaching the intention and targets of this lookup work, simulation of PLC gadget was once applied the usage of OFDM as the choice of modulation scheme [56]. The outcomes bought in contrast with the theoretical QPSK end result exhibit that OFDM decreased the degrading impact of the PLC channel leading to a desirable performance. Furthermore, it is located that at a signal degree of 4dB, the simulated BER fits up with the required standard which is the theoretical QPSK value. At this signal level of 4dB, the theoretical and simulated BER graphs converge. This point gives the minimal BER tolerance of 10^{-2} that is ideal for statistics transmission over PLC. The results obtained compared with the theoretical QPSK result show that OFDM reduced the degrading effect of the PLC channel leading to a good performance. Furthermore, it is observed that at a signal level of 4dB, the simulated BER matches up with the required standard which is the theoretical QPSK value [57,58]. At this signal level of 4dB, the theoretical and simulated BER graphs converge. This point gives the minimum BER tolerance of 10-2 that is acceptable for data transmission over PLC.

Power Line Communication (PLC) definitely is a low-priced way to communicate, due to the fact no new wires are required, providing an existing last mile infrastructure. The use of power lines which had been firstly designed for AC power distribution at 50 Hz and 60 Hz, present some technical challenges for records transmission at these frequencies. OFDM is now extensively used as the most favorable modulation scheme for an extreme communication environment such as the PLC channel [59]. The characteristics of this channel introduce the impact of noise, attenuation and multipath propagation which are the essential challenges in imposing a PLC system. The application of OFDM in PLC enhances good performance through high spectral efficiency, resilience to Radio Frequency (RF) interference, and lower multi-path distortion. OFDM modulation scheme is now broadly adopted, owing to its robustness to selective fading multipath and extraordinary kinds of interference. Unlike single carrier modulation, OFDM is a multicarrier modulation technique, which employs a number of carriers, inside the allocated bandwidth, to deliver the information from source to destination. Each carrier may employ one of the countless reachable digital modulation techniques (BPSK, QPSK, QAM etc..,) or every so often a combination [60 61]. OFDM is very superb for communication over channels with frequency selective fading (different frequency aspects of the signal experience different fading). OFDM mitigates the hassle by converting the whole frequency selective fading channel into small flat fading channels (as viewed by means of the individual subcarriers) . The process of PLC entails the conversion of communication signal into a shape that will allow its transmission through electrical network. This thesis examines the sketch of the physical layer, data layer and the channel of transmission. The gadget is modeled, simulated and carried out using MATLAB and the impact of OFDM is measured in terms of Bit Error Rate (BER). The organization is as follows: Firstly, the channel mannequin and the employed OFDM system design are described. Then, analysis and simulation results are discussed. Finally, important conclusions have been drawn.

4.2 SYSTEM DESIGN

Orthogonal Frequency Division Multiplexing (OFDM) is viewed as the transmission scheme for Broadband over power lines (BPL) by most researchers. In OFDM, a high pace serial data stream is split into a variety of parallel slow data streams that are carried in multiple orthogonal subcarriers by means of Inverse Discrete Fourier Transform (IDFT). OFDM operation is carried out after the records is modulated using QPSK which is the enter facts stream. Subcarriers in the OFDM machine are overlapping and orthogonal, which enormously improves the spectral effectivity essential for a medium that has restrained spectral capacity like the electricity line. In this way, OFDM can fight frequency selective attenuation and multipath propagation effect. The discrete time OFDM signal can be expressed as:

$$\mathrm{s(n)} = \frac{1}{N}\sum_{k=0}^{N-1} S_k e^{\frac{j2\pi nk}{N}}$$

Where N is the number of sub-carriers, is a sequence of PSK or QAM symbols. In order to eliminate inter-channel interference (ICI) and inter-symbol interference (ISI), OFDM uses a cyclic prefix (CP) that is appended at the start of OFDM symbols [62]. The individual sub-streams are sent over N parallel sub-channels which are orthogonal to each other. Inverse fast Fourier transform (IFFT) on the OFDM transmitter side and Fast Fourier transform (FFT) FFT on the OFDM receiver side reduces system complexity, enabling OFDM to be easily implemented. Specifically, the OFDM Modulator System object modulates an input signal using orthogonal frequency division modulation.

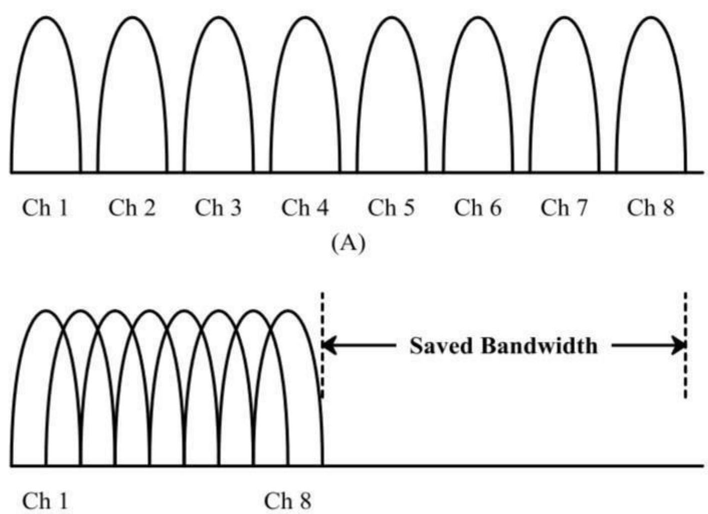
The output is a baseband representation of the modulated signal:

$$\mathrm{V(t)} = \sum_{i=0}^{N-1} \mathrm{Xi} * e_{J2\pi K\Delta ft}$$

where $\{X_i\}$ are data symbols, N is the number of subcarriers, and T is the OFDM symbol time. The data symbols, X_i, are usually complex and can be from any modulation alphabet, e.g., QPSK, 16QAM, or 64QAM [64,65]. Figure below shows an OFDM modulator. It consists of a bank of N complex modulators, where each corresponds to one OFDM subcarrier.

4.3 IFFT & FFT algorithm in OFDM

OFDM is a special multi-carrier transmission case where a single data stream is distributed across a number of lower-rate subcarriers. Increasing robustness against selective fading or narrowband interference is the main reason to use OFDM. In single carrier system if signal get fade or interfered then entire link gets failed whereas in multicarrier system only a small percentage of the subcarriers will be affected. The maximum signal bandwidth can be divided into N no overlapping frequency sub-channels in a traditional parallel data system. A separate symbol is modulated for each sub-channel, and then N sub-channels are multiplexed with frequency. The general practice of avoiding spectral overlap of sub-channels was applied to eliminate intercarrier interference (ICI). This is shown in fig below. This resulted in insufficient utilization of the existing spectrum.



(B)

Figure 4.1

Fig.(A) Spectrum of FDM showing Guard Bands; (B) Spectrum of OFDM showing Overlapped Subcarriers

An idea was proposed in the mid1960's to deal with this wastefulness through the development of frequency division multiplexing (FDM) with overlapping sub-channels [66]. The sub-channels were arranged so that the sidebands of the individual carriers overlap without causing ICI. This principle is shown in Fig (B). The carriers must be mathematically orthogonal in order to achieve this. The concept of OFDM was born out of this restriction. OFDM is a modulation and multiplexing combination. Multiplexing generally refers to different sources of independent signals. The signal itself is first divided into independent channels in OFDM, modulated by input, and then re-multiplexed to create the OFDM carrier. OFDM is a special case of FDM.

The fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) are derived from the main function, which is called discrete Fourier transform (DFT) [67]. In DFT, the computation for N-points of the DFT will be calculated one by one for each point. While for FFT/IFFT, the computation is done simultaneously and this method saves quite a lot of time. The equations for FFT/IFFT function can be derived from the general DFT equation:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{\frac{-j2\pi k}{N}}$$

X(k)represents the DFT frequency output at the k-the spectral point where k ranges from 0 to (N1) [68]. The quantity N represents the number of sample points in the DFT data frame. The quantity x(n) represents the nth time sample, where n also ranges from 0 to N-1. In general equation, x(n) can be real or complex. The input can be grouped into odd and even number.

4.4 OFDM transmitter

Here, the focus is on the FFT and IFFT part of the OFDM system.

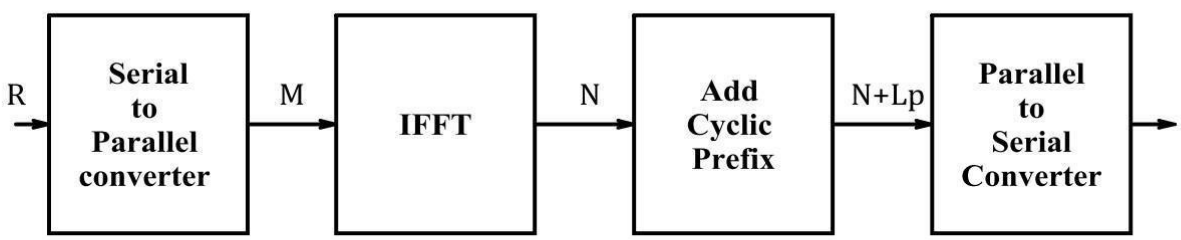


Figure 4.2

The input symbols are fed to the transmitter in series at R symbols/second. These symbols pass through a serial to parallel converter and output data on M lines in parallel [69]. The M symbols are sent to an IFFT block that performs N-point IFFT operation. The IFFT transform a spectrum (amplitude and phase of each component) into a time domain signal. An IFFT converts a number of complex data points, of length that is power of 2, into the same number of points in time domain. The output is N time-domain samples. In order to preserve the sub-carrier orthogonality a cyclic guard interval is introduced. In this case, assumed a cyclic prefix of length Lp samples is pre-pended to the

N samples. For example, assume N=4 and Lp=2; if the outputs of a 4-point inverse Fourier transform is [1 2 3 4], the cyclic prefix will be [3 4]. The cyclically extended symbol would be [3 4 1 2 3 4]. Therefore, the length of the transmitted OFDM symbol is N+Lp. Prepending the cyclic prefix aids in removing the effects of the channel at the receiver. ISI can occur when multi path channel cause delayed version of previous OFDM symbol to corrupt the current received symbol. If the value of Lp is greater than or equal to the size of the transmission channel, the ISI will only affect the cyclic prefix.

4.5 OFDM Receiver

The received symbol is in time domain and it is distorted due to the effect of the channel. The received signal goes through a serial to parallel converter and cyclic prefix removal. After the cyclic prefix removal, the signals are passed through an N-point fast Fourier transform to convert the signal to frequency domain. The output of the FFT is formed from the first M samples of the output. In 2011, K. Hari Krishna and T. Rama Rao proposed Pipeline architecture for WiMAX technology using Radix-4Decimation in frequency FFT algorithm [70,71]. They proposed a memory based recursive FFT design which has much less gate counts, lower power consumption and higher speed. The proposed architecture has three main advantages: fewer butterfly iteration to reduce power consumption, pipeline of radix–22butterfly to speed up clock frequency, and even distribution of memory access to make utilization efficiency in SRAM ports. They coded this design in Verilog hardware description language with increase in speed & performance of OFDM.

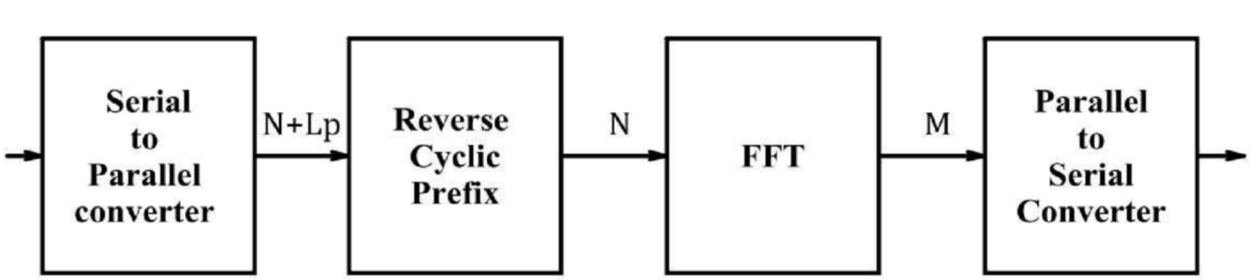


Figure 4.3: OFDM Receiver

In 2010, Mounir Ariouaet.al. [72] Proposed an optimized implementation of 8-point FFT processor with radix-2 algorithm in R2MDC architecture. The main issue in FFT operation is the complex multiplication so, they tried to reduce the complexity one of two proposed methods replaces the expensive complex multiplication. For this they have applied the methods to 8-point FFT and compared it to conventional FFT and R2MDC processor. They designed 8-point FFT with radix-2 in R2MDC architectures and was first coded in VHDL. Then they have proposed a novel 8point FFT processor based on pipeline architecture with no complex multiplication and compared to

Cooley-Tukey and R2MDC processor. The proposed architecture gives an advantage in terms of area, complex multiplication reduction approach for Large Points FFT. In 2005, Zheng Wang Et. Al. simplified the Complex Multiplication Operation in the Design of the FFT Structure for more general case in which the FFT point is only power of Two rather than Four. They Discussed

Theoretical Analysis of the Delay in R2MDC Structure. They Designed and Implemented one type Structure of FFT Processor for Multicarrier Communication System. For that the consideration of Design has several aspects as follows,

Adopt the DIF Algorithm because of the Finite Length Effect in the hardware, simplify the

Complex Multiplication Operation, replace the Shift Registers with Dual-Ports RAM, optimize The Reversed Order Structure. The Theoretical Delay Time of the proposed FFT Structure Is derived, and it has been implemented for more general usage of Multicarrier System. In 2013, Nilesh Chide, Et. Al. proposed the design of OFDM System using IFFT and FFT blocks and simulation was done on XILINX ISE. They implemented the OFDM block by block and finally incorrect all of them together to form complete OFDM circuit. Finally, their aim is to implement the core signal processing blocks of OFDM System using VHDL language. The different blocks of OFDM System such as QAM Modulator, 8-IFFT, 8-FFT and Demodulator are designed on Xilinx Project Navigator. These blocks are simulated on XILINX ISE Design Suite, tested for different patterns and results are compared. In 2012, Pradeep M. and Gowtham P. proposed an optimized implementation of the 8-point FFT processor with radix-2 algorithm in R2MDC architecture [73]. The butterfly- Processing Element (PE) used in the 8-FFT processor reduces the multiplicative complexity by using a real constant multiplication in one method and eliminates the multiplicative complexity by using add and shift operations in the proposed method [74]. So they proposed conventional FFT algorithm by using butterfly technique and then proposed algorithm has been implemented by using R2MDC architecture [75]. Then the analysis and design of FFT is done using VHDL. They proposed variable-length FFT processor that is suitable for various MIMO OFDM based communication systems. To reduce computational complexity and increase hardware utility, they adopt different radix FFT algorithms. The multiple path delay commutator FFT architectures require fewer delay elements and different radix FFT algorithms require fewer complex multiplications. In 2012, Manjunath Lakkannavar and Ashwini Desai [76] implemented the core processing blocks of an OFDM system, namely FFT and IFFT. The FFT and IFFT have been chosen to implement the design instead of the DFT and IDFT because they offer better speed with less computational time. In 2011, Pawan Verma and Harpreet Kaur developed FFT &IFFT algorithms to be used in OFDM systems. The speed enhancement is the key contribution of the main processing blocks in OFDM system so they have successfully implemented the 8-point IFFT & FFT algorithm using VHDL to be used in the architecture of OFDM transmitter & receiver. The performance of the main processing block of OFDM Trans receiver is upgraded by reducing the clock cycles. The real value inputs are given to FFT blocks while all the imaginary input values are zero [77]. Also, the accuracy in obtained results has been increased with the help of efficient coding in VHDL. The accuracy in results depends upon the equation obtained from the butterfly diagram.

4.6 OFDM system design

There are a number of choices of parameters for OFDM system design, for consideration. They are: number of subcarriers, guard time, symbol duration, sub carrier spacing, and modulation type per sub carrier. The number of carriers in an OFDM system is not only limited by the available spectral bandwidth, but also by the IFFT size. A FFT length of 128 and cyclic prefix length of 32 is used in this design [78]. Figure 4.4 shows the block diagram of the proposed OFDM based PLC system. The input signal bits undergo convolution encoding and interleaving before being mapped into QPSK symbols. The resulting data stream undergoes OFDM Modulation procedure realized by IFFT [79].

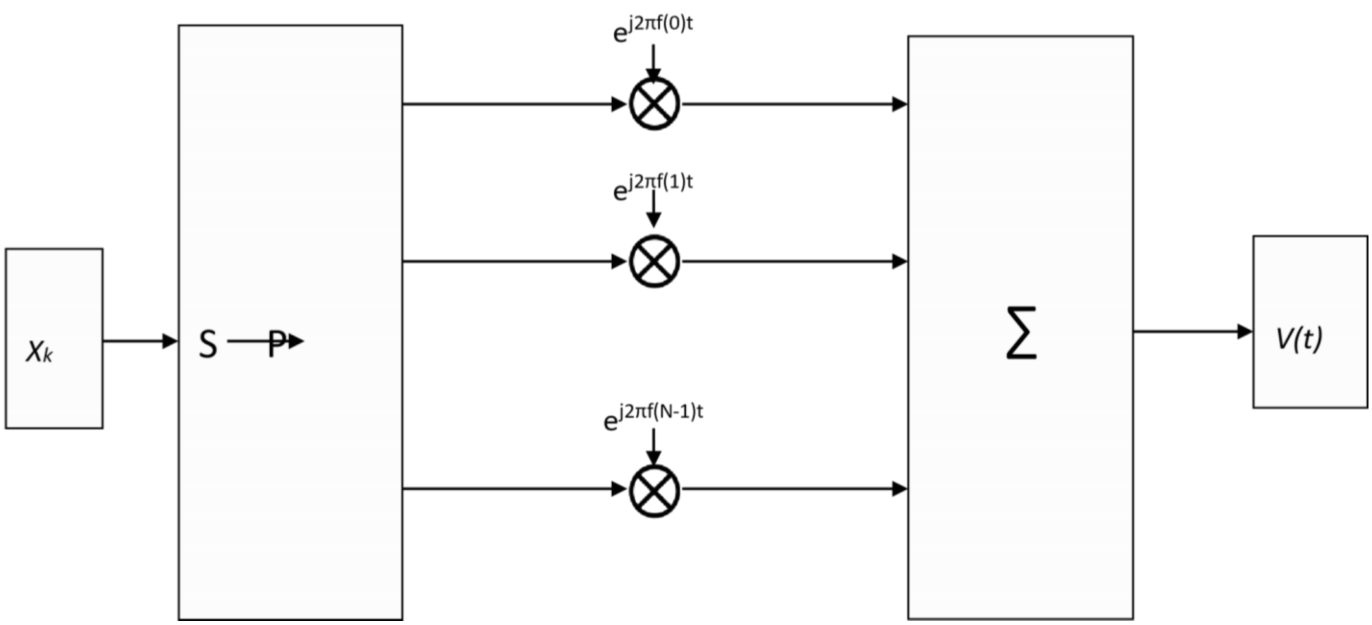


Figure 4.4: OFDM Modulator

Zimmermann and Dostert have proposed a practical channel model that is suitable for describing the transmission behavior of power line channels [80]. The model is based on practical measurements of actual power line networks and is given by the channel transfer function:

$$H(f) = \sum_{i=1}^{N_p} c_i e^{-(a_0 + a_1 f^k) d_i} . e^{-j2\pi f \frac{d_i}{v_p}}$$

Where Np is the multipath number, c_i and d_i are respectively the weighting factor and the length of the ith road. The parameters a_0, a_1 and k are based on frequency-dependent attenuation. The first exponential in the model reflects attenuation in the channel of the PLC, while the second exponential defines the echo scenario with the propagation v_p. C_i represents the weighting factor,

Exp $\{-(a_0+a_1 f^k)\, d_i\}$ the attenuation portion and $\exp(-j2\pi f \frac{di}{Vp})$ the delay portion[81,82].

The used parameters are given in table4.1.

Attenuation parameters		
K =1	$a_0 = 0$ $v = 3*10^8$	$a_1 = 7.8*10^{-10}$
Path parameters		
i	C	d/m
1	0.029	90
2	0.043	120
3	0.103	113
4	-0.058	143
5	-0.045	148
6	-0.04	200

7	-0.038	260
8	-0.038	322
9	-0.071	411
10	-0.035	490
11	-0.065	567
12	-0.055	740
13	-0.042	960
14	-0.059	1130
15	0.0491	1250

Table 4.1

The proposed channel model has two parts: background noise (I_{AWGN}) modeled as AWGN with mean zero and variance, and the impulsive noise I impulse is given by:

$$I_{impulse}=b_k g_k$$

Where b_k is the Poisson Process which is the arrival of impulsive noise, and g_k is white Gaussian process with mean zero and variance σ_i^2 [83].

The combined PLC channel function is modeled as given:

$$I_c = I_{impulse} + I_{Awgn}$$

$$I_c = H(f)$$

Therefore, the received signal after transmission is expressed as:

$$Y(n) = I_c \otimes S(n)$$

Chapter - 5

ANALYSIS AND SIMULATION RESULTS

5.1 Data Analysis from the phase 1

Experimental Works

Hardware Part

- Octopus Non-invasive AC currentsensor (**TA12-100**)
- Arduino UNO
- Laptop

Software Part

- Tera Term
- Microsoft Excel
- PLX_DAC

5.2 Data Collection and Result

- We took 3000 readings of current of a live wire for 1 hour.
- The size of the excel file was just 501 KB in size.
- Average bytes needed for transmission of each reading were very low.

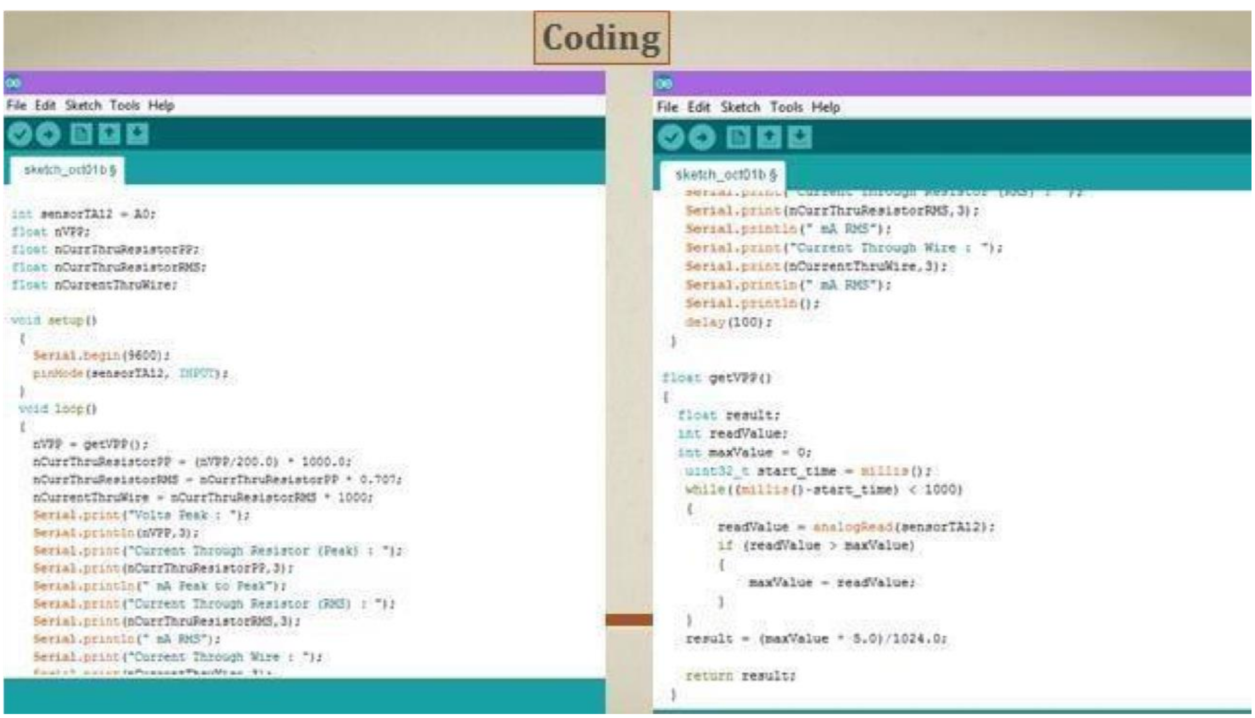


Fig 5.1: Coding in Arduino

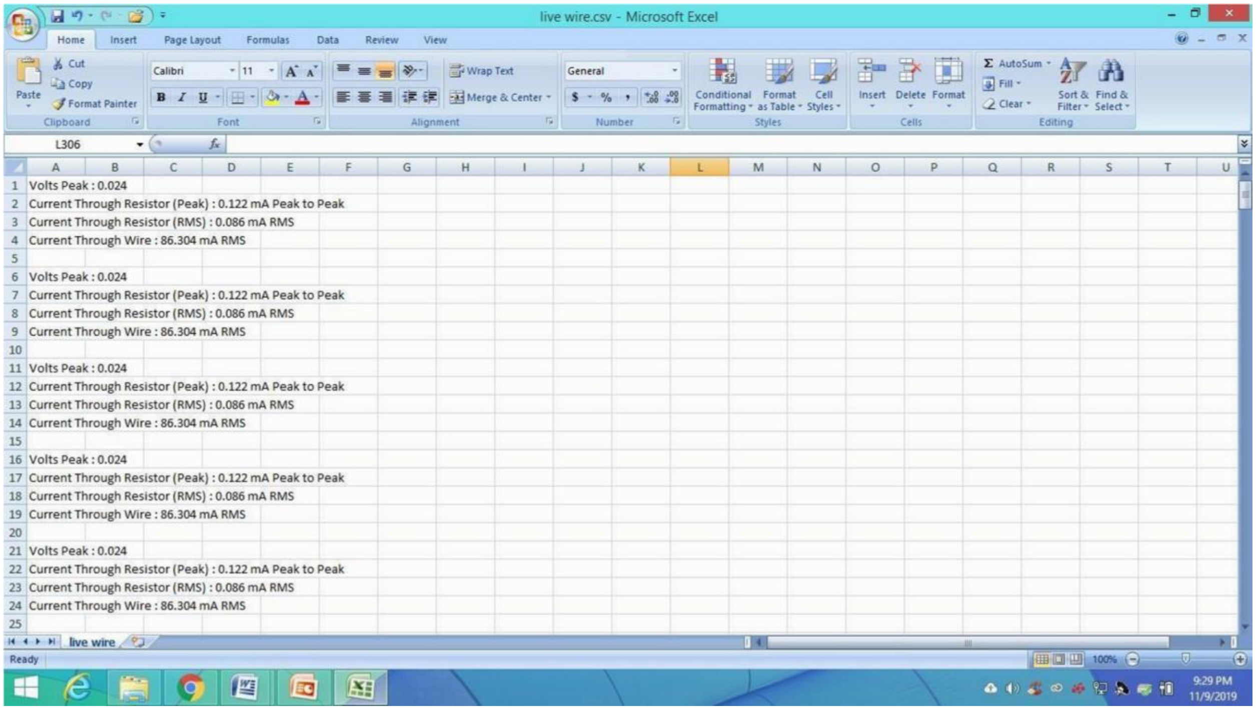


Figure 5.2: Data collection by Tera Term Software from current sensor

Phase2

Two PLC adaptors (one receiver and one sender) and one Wi-Fi router were used to perform this project. This was a comparison test between Wi-Fi and PLC.

Tools used: Iperf, windows PowerShell Iperf:

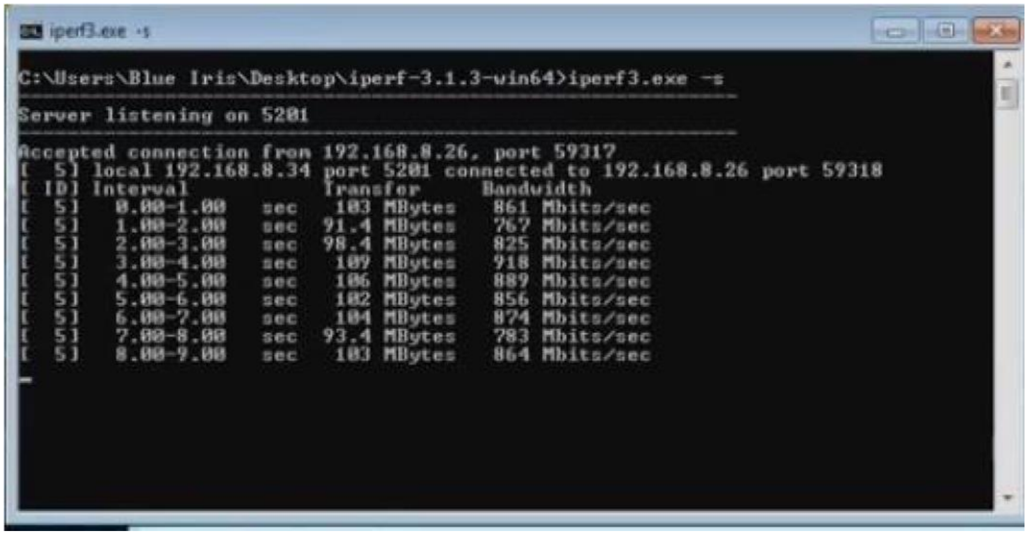
Iperf is a widely used tool for network performance measurement and tuning. It is significant as a cross-platform tool that can produce standardized performance measurements for any network.

Windows PowerShell

It is a task-based command-line shell and scripting language designed especially for system administration. Built on the .NET Framework, Windows PowerShell helps IT professionals and power users control and automate the administration of the Windows operating system and applications that run on Windows.

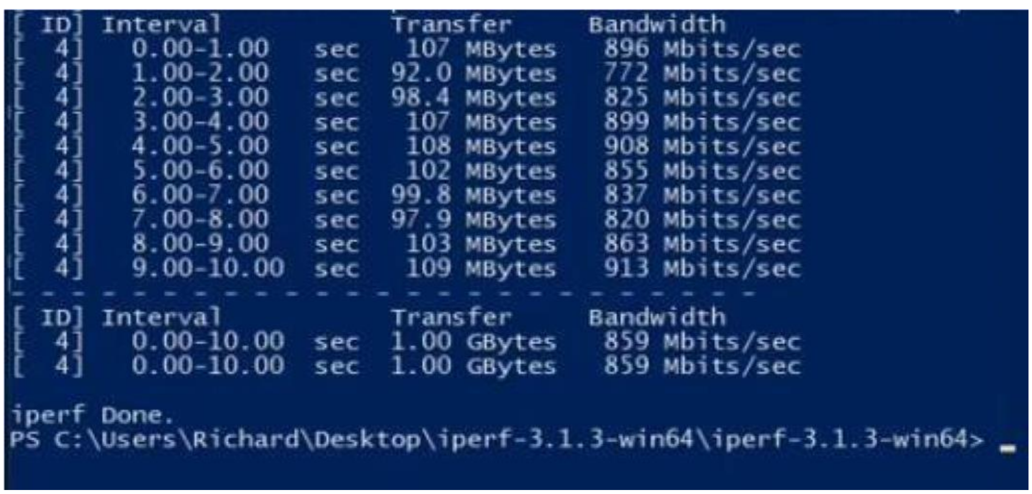
Result:

For Wi-Fi router: -



```
C:\Users\Blue Iris\Desktop\iperf-3.1.3-win64>iperf3.exe -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.8.26, port 59317
[  5] local 192.168.8.34 port 5201 connected to 192.168.8.26 port 59318
[ ID] Interval           Transfer     Bandwidth
[  5]   0.00-1.00   sec   103 MBytes   861 Mbits/sec
[  5]   1.00-2.00   sec  91.4 MBytes   767 Mbits/sec
[  5]   2.00-3.00   sec  98.4 MBytes   825 Mbits/sec
[  5]   3.00-4.00   sec   109 MBytes   918 Mbits/sec
[  5]   4.00-5.00   sec   106 MBytes   889 Mbits/sec
[  5]   5.00-6.00   sec   102 MBytes   856 Mbits/sec
[  5]   6.00-7.00   sec   104 MBytes   874 Mbits/sec
[  5]   7.00-8.00   sec  93.4 MBytes   783 Mbits/sec
[  5]   8.00-9.00   sec   103 MBytes   864 Mbits/sec
```

Figure 5.3(a): Readings from Iperf 3



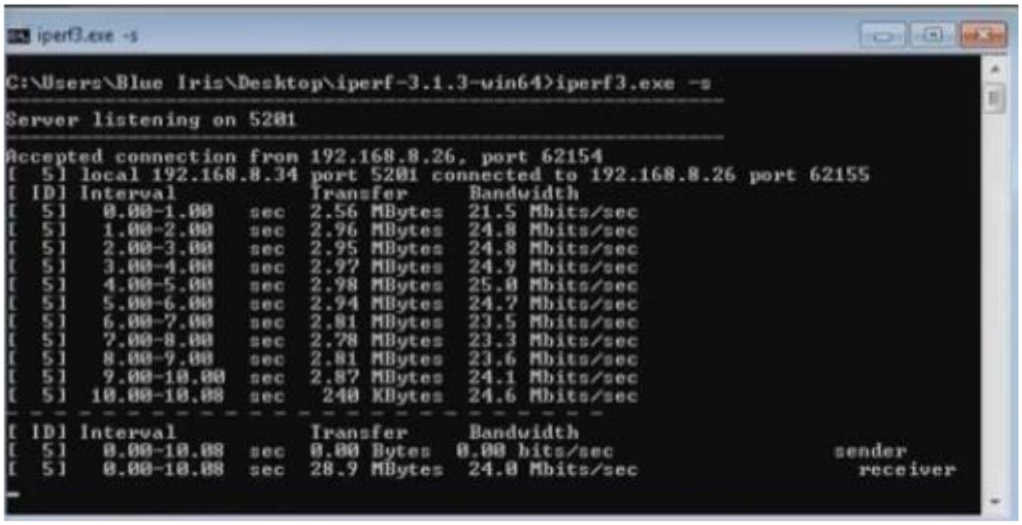
```
[ ID] Interval           Transfer     Bandwidth
[  4]   0.00-1.00   sec   107 MBytes   896 Mbits/sec
[  4]   1.00-2.00   sec  92.0 MBytes   772 Mbits/sec
[  4]   2.00-3.00   sec  98.4 MBytes   825 Mbits/sec
[  4]   3.00-4.00   sec   107 MBytes   899 Mbits/sec
[  4]   4.00-5.00   sec   108 MBytes   908 Mbits/sec
[  4]   5.00-6.00   sec   102 MBytes   855 Mbits/sec
[  4]   6.00-7.00   sec  99.8 MBytes   837 Mbits/sec
[  4]   7.00-8.00   sec  97.9 MBytes   820 Mbits/sec
[  4]   8.00-9.00   sec   103 MBytes   863 Mbits/sec
[  4]   9.00-10.00  sec   109 MBytes   913 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth
[  4]   0.00-10.00  sec  1.00 GBytes   859 Mbits/sec
[  4]   0.00-10.00  sec  1.00 GBytes   859 Mbits/sec

iperf Done.
PS C:\Users\Richard\Desktop\iperf-3.1.3-win64\iperf-3.1.3-win64>
```

Fig 5.3(b): Reading from the Windows PowerShell

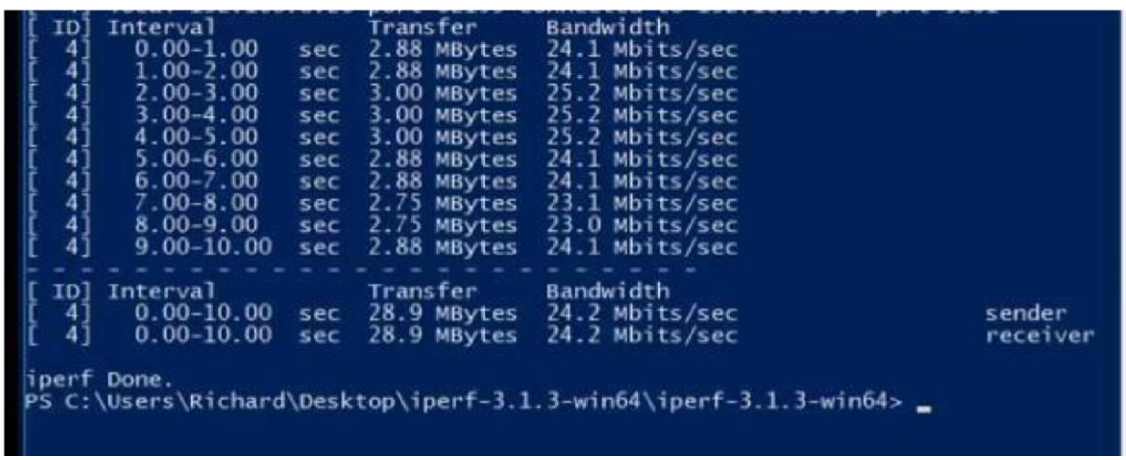
From the figures above, it can be observed that the maximum bandwidth was 859 Mbits/second.

For PLC adaptors:



```
iperf3.exe -s
C:\Users\Blue Iris\Desktop\iperf-3.1.3-win64>iperf3.exe -s
-----------------------------------------------------------
Server listening on 5201
-----------------------------------------------------------
Accepted connection from 192.168.8.26, port 62154
[  5] local 192.168.8.34 port 5201 connected to 192.168.8.26 port 62155
[ ID] Interval           Transfer     Bandwidth
[  5]   0.00-1.00   sec  2.56 MBytes  21.5 Mbits/sec
[  5]   1.00-2.00   sec  2.96 MBytes  24.8 Mbits/sec
[  5]   2.00-3.00   sec  2.95 MBytes  24.8 Mbits/sec
[  5]   3.00-4.00   sec  2.97 MBytes  24.9 Mbits/sec
[  5]   4.00-5.00   sec  2.98 MBytes  25.0 Mbits/sec
[  5]   5.00-6.00   sec  2.94 MBytes  24.7 Mbits/sec
[  5]   6.00-7.00   sec  2.81 MBytes  23.5 Mbits/sec
[  5]   7.00-8.00   sec  2.78 MBytes  23.3 Mbits/sec
[  5]   8.00-9.00   sec  2.81 MBytes  23.6 Mbits/sec
[  5]   9.00-10.00  sec  2.87 MBytes  24.1 Mbits/sec
[  5]  10.00-10.08  sec   240 KBytes  24.6 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth
[  5]   0.00-10.08  sec  0.00 Bytes  0.00 bits/sec                  sender
[  5]   0.00-10.08  sec  28.9 MBytes  24.0 Mbits/sec                  receiver
```

Figure 5.3 (c): Readings from Iperf3



```
[ ID] Interval           Transfer     Bandwidth
[  4]   0.00-1.00   sec  2.88 MBytes  24.1 Mbits/sec
[  4]   1.00-2.00   sec  2.88 MBytes  24.1 Mbits/sec
[  4]   2.00-3.00   sec  3.00 MBytes  25.2 Mbits/sec
[  4]   3.00-4.00   sec  3.00 MBytes  25.2 Mbits/sec
[  4]   4.00-5.00   sec  3.00 MBytes  25.2 Mbits/sec
[  4]   5.00-6.00   sec  2.88 MBytes  24.1 Mbits/sec
[  4]   6.00-7.00   sec  2.88 MBytes  24.1 Mbits/sec
[  4]   7.00-8.00   sec  2.75 MBytes  23.1 Mbits/sec
[  4]   8.00-9.00   sec  2.75 MBytes  23.0 Mbits/sec
[  4]   9.00-10.00  sec  2.88 MBytes  24.1 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth
[  4]   0.00-10.00  sec  28.9 MBytes  24.2 Mbits/sec                  sender
[  4]   0.00-10.00  sec  28.9 MBytes  24.2 Mbits/sec                  receiver

iperf Done.
PS C:\Users\Richard\Desktop\iperf-3.1.3-win64\iperf-3.1.3-win64>
```

Figure 5.3 (d): Readings from PowerShell

Here, the maximum bandwidth was only 24.2 Mbits/sec.

Result:

PLC has a lower bandwidth than that of the Wi-Fi.

Discussion:

Although PLC had a lower bandwidth according to our test results of project2, but from project1, we got that, it took only 48 bits of data for each reading. So, we do not need that much of high bandwidth for data transmission in smart grid application.

5.3 Simulation Results:

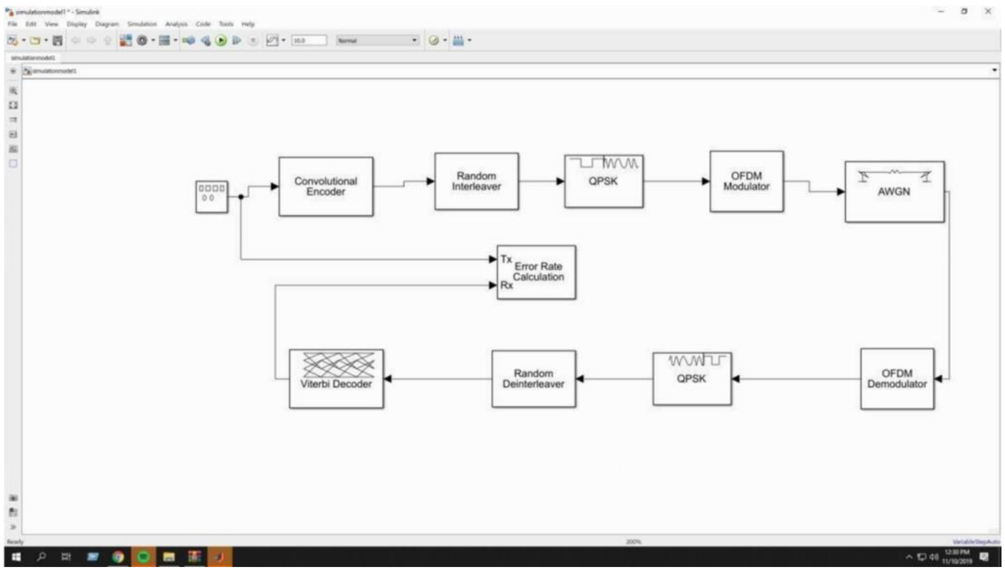


Figure 5.4 Simulink Model

In order to evaluate the performance of the designed system illustrated by the above Figure, the model is simulated using MATLAB R2018a. Emphasis is placed on the channel characteristic, OFDM performance and BER graph. The input signal is a stream of binary data, and Quaternary Phase Shift Keying (QPSK) is the preferred method of digital modulation.

5.4 Effect of the PLC and AWGN channel

The input data is shown below in figure below. It is a stream of data consisting of 96 binary digits. This represents the source into the system. It is encoded using convolutional encoder to aid against channel error, passed through an interleaver, QPSK and finally OFDM block.

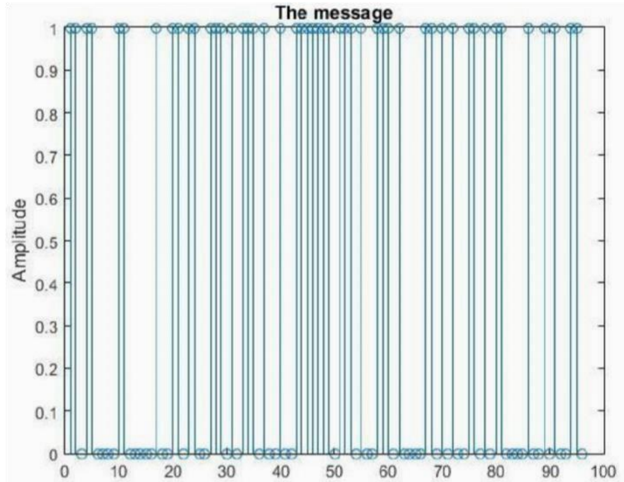


Figure 5.5: Input signal data

The channel function is a combined effect of PLC impulse noise and the AWGN Distortion added by the stream to the transmitted information encoded and modulated. The chart of the modulated signal that passes through the channel and is retrieved at the channel output indicates the distortion rate that the PLC channel adds. The channel output is a noise like signal. Therefore, it is not difficult to determine the effect the noise has on the transmitted signal.

The recovery responses of the system i.e., channel encoding and modulations, are measured against the ability to recover the original data from the distorted noisy signal introduced by the system. The diagram in figure below shows the scatter plot of the noisy signal generated by passing the modulated data through the channel.

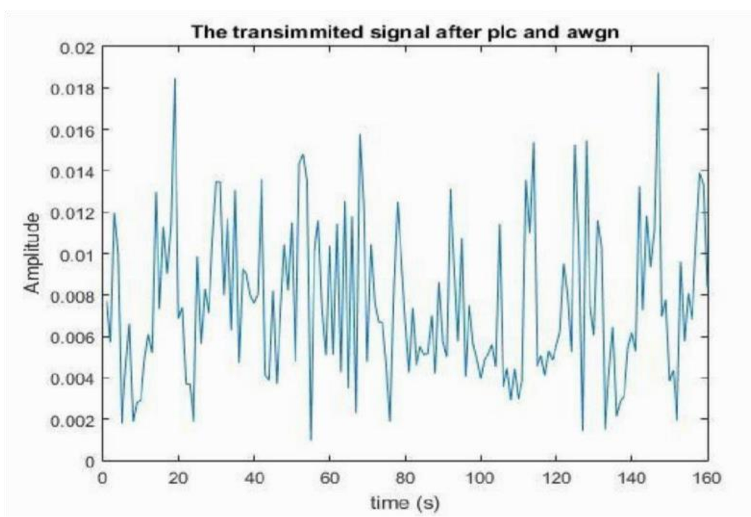


Figure 5.6: Transmitted data through PLC channel and AWGN

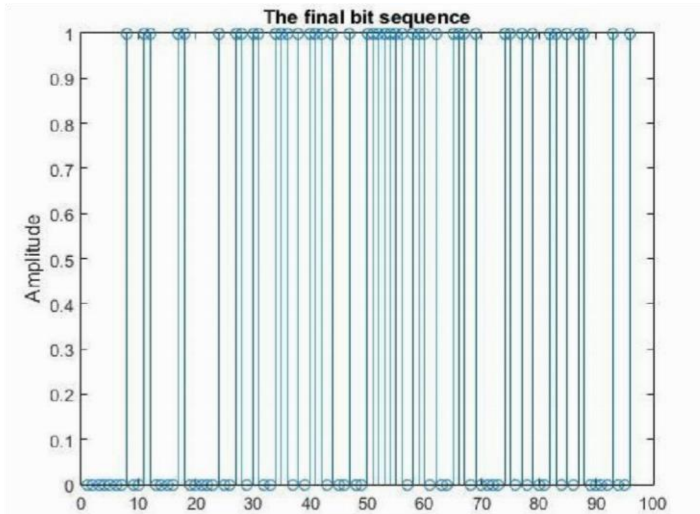


Figure 5.7: Recovered binary data

The recovered signal output is given in the Figure above. It is the result gotten after the distorted signal is recovered using FFT, QPSK demodulation, interleaver and Viterbi decoder respectively.

5.5 The BER (Bit Error Rate) plot

The BER plot gives the overall performance of the simulated system.

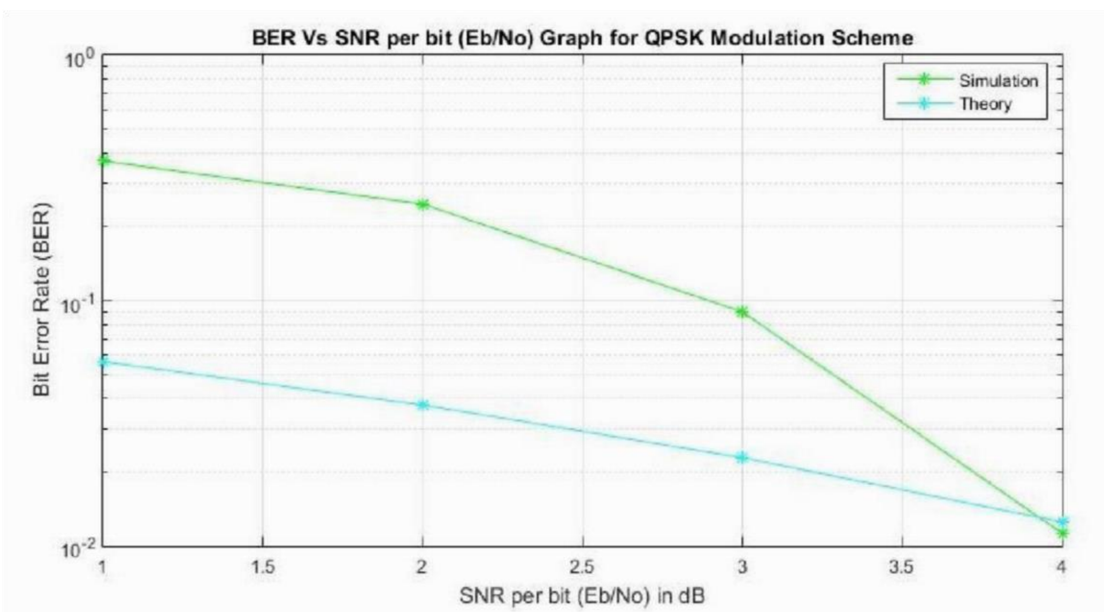


Figure 5.8: BER plot in MATLAB

5.6 PERFORMANCE RESULT USING BIT ERROR RATE (BER) GRAPH

A graphical comparison of the input and final output shown above can be made, but using the Bit Error Rate (BER) is a more appropriate approach. The system performance calculation is shown by the bit-error rate (BER). MATLAB's "biterr" function was used to compare two data sets, measuring the number of bit errors and the frequency of bit errors. The plot in BER plot, clearly shows the comparison between the simulated BER result for the channel and the theoretical QPSK BER curve. It can be observed that as the value of SNR increases, the BER of the simulated PLC system decrease and approaches that of the theoretical QPSK BER. At a SNR of 4dB, the theoretical and simulated BER graphs converge. This point gives the minimum BER tolerance of 10^{-2} that is acceptable for data transmission. The theoretical and simulated graphs of BER converge at a 4dB SNR. This point offers the minimum 10-2 BER sensitivity appropriate for PLC data transmission. The convergence frequency reaches zero at a 4dB signal point. The frequency of simulated data BER convergence is calculated in the table below. Ion over PLC. At a signal level of 4dB, the rate of convergence approaches zero. The rate of BER convergence of the simulated data is estimated below in table.

In the table below, the BER values of the simulated graph, represented by r1 in the code, as well as the BER values of the theoretical data represented by the from the graphs are given:

Bit error rate data for simulated and theoretical:

	Bit Error Rate (BER)		Rate of convergence
SNR (dB)	Simulated (r1)	Theoretical (thr)	(r1-thr)
1	0.3708	0.0563	0.3145
2	0.2472	0.0375	0.2097
3	0.0899	0.0229	0.067
4	0.0112	0.0125	-0.013

Table: 5.1

5.7 Conclusion of this Chapter

We have found that OFDM has proven to be effective in multi-path environments; a device combined with AWGN with an impulsive channel interface. The output signal was retrieved with a reasonable tolerable error rate relative to a hypothetical QPSK value for data transmission. It has been found that as the Eb / No increases, BER effectively decreases. The simulation results verified the correct operation and performance of OFDM system with the reduction of error rate as the signal power increases.

Chapter - 6

Conclusions and Future Work

With positive experiments and some commercial implementations of smart grid systems in some parts of the world, the move to a smart grid is already underway. The next step in this evolution is to create the most reliable, efficient and economical way of operating the smart grid. One area that needs changes is the enabling interaction system's energy consumption.

The conclusions of this thesis can be summarized as follows.

- Energy efficiency of PLC systems can be approached in a variety of ways, including network configuration, hardware design and signal processing.

- Smart grid can take advantage of existing LV distribution network to improve packet delivery over the PLC network for applications of smart metering and demand response.

- Low data rate transmission techniques such as can result in energy savings for monitoring and control applications such as energy management in homes.
- In PLC networks, impulsive noise is a major performance inhibitor of applications, hence smart techniques are needed to mitigate it.

- From design perspective, significant energy savings can be achieved by exploiting the OFDM system for symbol processing at the transmitter and impulsive noise cancellation (DPTE) at the receiver.

- The better performance of OFDM system comes at the expense of additional computational complexity however, system implementation can take advantage of the inexpensive, ultra-fast chips that are readily available.

Future work

In the future, our plan is to investigate how the various smart grid applications can benefit from the noise-immunity in terms of improved good put and network reliability. We will learn about the types of OFDM. We will perform comparative studies and hardware implementations.

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