ANALYSIS OF CONVENTIONAL LOW VOLTAGE POWER LINE COMMUNICATION METHODS FOR AUTOMATIC METER READING AND THE CLASSIFICATION AND EXPERIMENTAL VERIFICATION OF NOISE TYPES FOR LOW VOLTAGE POWER LINE COMMUNICATION NETWORK

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ABSTRACT

ANALYSIS OF CONVENTIONAL LOW VOLTAGE POWER LINE COMMUNICATION METHODS FOR AUTOMATIC METER READING AND THE CLASSIFICATION AND EXPERIMENTAL VERIFICATION OF NOISE TYPES FOR LOW VOLTAGE POWER LINE COMMUNICATION NETWORK

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In this thesis, the conventional low voltage power line communication methods is investigated in the axis of automated meter reading applications and the classification and experimental verification of common noise types for low voltage power line communication network. The investigated system provides the real time transmission of electricity consumption data recorded by electricity meters, initially to a local computer via a low voltage line through a low speed PLC (Power Line Carrier) environment and subsequently to a corporate network through a high speed data transmission medium. The automated meter system provides a more effective tracking and data acquisition, a more detailed and vigorous knowledge about consumer behavior for subscriber assessment in electricity distribution in association with a brand new management and system supervision concept in electricity distribution control and management technology. The theoretical studies are experimentally verified for the Turkish low voltage power infrastructure through laboratory experiments performed in METU Electrical and Electronics Engineering Department, Electrical Machines and Drives Laboratory and R&D Laboratories of

MAKEL facilities in Hadımköy. The single phase voltage of the mains line between the phase and neutral is monitored to exhibit the disturbing effects of various noise sources. The resulting voltage spectrum is logged by using digital data acquisition devices in time and frequency domain. The waveforms are converted to frequency domain using the Fast Fourier Transform (FFT) functions of the MATLAB. The experimental results are compared to the theoretical findings obtained through literature survey.

Keywords: Power Line Communication, Automatic Meter Reading, Digital Data Acquisition, Low Voltage Distribution Network, Time Domain Analysis, Frequency Domain Analysis, Fast Fourier Transform.

ÖZ

KONVANSİYONEL ALÇAK GERİLİM GÜÇ HATLARI KULLANILARAK OTOMATİK SAYAÇ OKUMA METODLARININ ANALİZİ VE ALÇAK GERİLİM GÜÇ HATLARINDAKİ GÜRÜLTÜ TİPLERİNİN SINIFLANDIRILMASI VE ANALİZ EDİLMESİ

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Şubat 2009, 249 sayfa

Bu tezde düşük voltajlı güç hatları üzerinden bilgi aktarımı metodlari otomatik sayaç okuma uygulamaları ekseninde incelenmiştir. Ayrıca düşük voltajlı güç hatlarında görülen gürültü tipleri sınıflandırılarak ve deneysel olarak doğrulanmasına çalışılmıştır. Uzaktan sayaç okuma metodu, elektrik sayaçları tarafından okunan elektrik tüketim verilerinin gerçek zamanda PLC (Power Line Carrier) ortamı ile AG (Alçak Gerilim) hatları üzerinden düşük bir veri iletişim hızı ile önce mahalli bir bilgisayara aktarılmasını ve buradan da daha yüksek bir veri iltişim hızı ile şirketin ana bilgisayarına aktarılmasını öngörmektedir. Bu metod ile, elektrik dağıtımında abone tahakkukunda daha etkin bir izleme, veri toplama, abone davranışları hakkında daha detaylı ve etkin bir şekilde bilgi sahibi olunması mümkündür. Uzaktan sayaç okuma metodu ile, elektrik dağıtım sistemi kontrol ve işletme teknolojisinde yeni bir işletme ve sistem denetim anlayışı öngörülmektedir. Teorik çalışmalar, ODTÜ Elektrik Makineleri ve Sürücüleri ve de Hadımköy MAKEL fabrikalarında yapılan laboratuvar deneyleriyle Türkiye düşük voltajlı güç şebekesi üzerinde doğrulanmıştır. Şebekenin tek faz voltajı, faz nötr arasında ölçülerek değişik gürültü kaynaklarının etkileri gözlemlenmiştir. Oluşan voltaj ve güç spektrumları zaman ve frekans ekseninde kaydedilmiştir. Zaman ekseninde kaydedilen voltaj ve güç spektrumları frekans eksenine MATLAB programının Fast Fourier Transform özelliği kullanılarak çevrilmiştir. Deneysel sonuçlar teorik bulgularla karşılaştırılmıştır.

Anahtar sözcükler: Güç Hattı İletimi, Uzaktan Sayaç Okuma, Dijital Data Elde Etme, Düşük Voltajlı Dağıtım Şebekesi, Zaman Ekseninde Analiz, Frekans Ekseninde Analiz, Fast Fourier Transform

To my family,

Nuri Danışman

Sümer Yılmaz

Orhan Danışman

Handan Danışman

Ece Yılmaz

Bige Yılmaz

Zeynep Aran

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CHAPTER 1

PLC: USING POWER LINES FOR DIGITAL COMMUNICATIONS

1.1 INTRODUCTION

Power line communication can be simply described as the distribution of data and other signals via electric power distribution wires. Briefly, electric power is transmitted over high voltage transmission lines following generation, distributed over the medium voltage and converted to low voltage in the distribution transformers to be used in consumer premises. PLC can be applied at each stage. However, power line communication over the low voltage power line is the main concentration of this thesis work. A low voltage line (LVL) is defined as the power line that includes all the devices connected to the secondary side of a distribution transformer which is a medium voltage to low voltage transformer. All PLC systems operate by adding a modulated carrier signal on the mains wiring system [1].

1.1.1 Scope of the Thesis

Research and development on the all aspects of the PLC technology has been continuing in the metering industry and in the academic world. Academic research is mainly focused on the modeling of low voltage power line distribution networks, design of the coupling circuits and network topologies. Motivation of these studies is to design and produce more efficient and cost effective low power networks. As described in the early chapters of the thesis, development of intelligent protocols, algorithms and circuit models for low voltage power line communication which results in efficient, robust and cost-effective power line communication methods is challenging.

In this thesis, the conventional noise types for low voltage power line network is identified and the classified noise types are verified by laboratory experiments on the Turkish low voltage power line network. The literature of the low voltage power line networks characteristics and the automatic meter reading methods are reviewed first. Then, the conventional noise types are classified for the low voltage power line networks depending on the literature studies and finally the measurements and observations for the theoretically defined noise types are verified via experiments in METU EE Machinery and Drives Laboratories and R&D laboratories of MAKEL in Hadımköy.

The first 5 chapters of the thesis include the comprehensive theoretical studies about the methodology of low voltage power line communication based automatic meter reading, power line channel communication applications in European and Turkish markets, the advantages of power line communication technology compared to the competitive technologies and the characterization of power line communication methods.

Similar to other communication media such as RF and wireless, PLC operates in a noisy environment with various noise sources occurring concomitantly. The noise types and their typical sources are studied in details in Chapter 6. The identified noise types are background noise, impulsive noise, harmonic noise and narrowband noise. These noise types are statistically analyzed and some of them are explicitly defined as a function of frequency and distance.

In Chapter 7, the graphical results and interpretations of these classified noise types are presented through the experiments performed in METU EE Machinery and Drives Laboratories and R&D laboratories of MAKEL in Hadımköy. Prior to these experiments, different line coupler design were developed and simulated over the Simplorer to obtain proper line coupler circuits. The lie coupler also functions as a high pass filter, blocking the nominal 50 Hz power signal component and spectral components with low frequencies. The power and voltage spectrum of the resulting test data were logged in time and frequency domain using the digital data acquisition devices and spectrum analyzer. The time data is converted to the frequency domain by using Fast Fourier Transform functions of MATLAB and implementing a simple code in MATLAB (See Appendix B)

Measurements are performed between the phase and neutral line using the nearest socket to the incoming mains cable at the laboratory premise. All external noise sources are switched off. As a result, the interferences observed are either generated in the laboratory building and adjacent buildings and transmitted over the low voltage network or picked up by the power lines influenced by the broadcast signals. Moreover, the measured noise sources are positioned at equal distance from the source and observation point.

For the digital data acquisition, the sampling frequency is set to 1 MHz. As a result, the resulting power spectrums are logged for 5 seconds at a sampling rate of 1M sample per second, leading to a resolution of 0.2 Hz in the frequency response.

Initially no noise sources are connected to the line to measure the background power spectrum in the frequency domain. During the theoretical in Chapter 6, studies spectrum fitting and statistical analysis methods are employed in several literatures. In Chapter 7, the power spectrums obtained are investigated in the frequency domain. Note that, during the experiments the target is not to model the background noise but to investigate the applicability of noise models to the Turkish low voltage network. The experiments are confined to the frequency range between 9 to 150 kHz in order to comply with the CENELEC standards.

The impulsive noise is classified under three titles: asynchronous impulsive noise, periodic impulsive noise synchronous to the mains frequency (harmonic noise) and periodic impulsive noise asynchronous to the system frequency. The impulse noise is monitored in time and frequency domain. Besides, the three main characteristics of the impulse noise (impulse duration, interarrival time and impulse amplitude are measured).The data acquisition time is kept long enough to avoid the disturbing effects of a long impulsive noise. Similarly; a second data acquisition is performed about 500 ms after the previous one to check the stability of the channel frequency response after an impulsive noise. The asynchronous impulsive noise and periodic impulsive noise asynchronous to the system frequency are analyzed in time and frequency domain. The periodic impulsive noise synchronous to the mains frequency (harmonic noise) is logged in time domain and the output is converted to frequency domain using Fast Fourier Transform (FFT) in order to monitor the fundamental component and the dominant odd harmonics. Finally, the narrow band noise is observed over the specified intervals of the entire frequency band.

The outline of the thesis is as follows. In the second chapter, power line communication applications in automatic meter reading are explained. The third chapter includes the power line communication examples in Europe and Turkey with present situation and future projections. The fourth chapter involves the advantages and disadvantages of PLC technology as compared to alternative communication media. The fifth chapter describes the major characteristics of the PLC system. In sixth chapter, the noise and disturbances in the power line network are theoretically defined. The seventh chapter investigates the experimental results of the classified noise types for power line channel. Finally, the eighth and last chapter provides the conclusion of the thesis with remarks and points towards future work.

1.2 COMMUNICATION STANDARDS FOR PLC

The power line has been broadly studied as a communication media for high frequency signals in the recent years. Until recently, most home and building automation were depending on communication systems that required special wiring such as twisted pairs, coaxial and fiber optic. In the last decade, the major developments in the PLC technology have started the emergence of devices that use the power line to transmit control signals with an acceptable degree of reliability.

However, there are still some concerns on this issue, as the low voltage power grid is initially designed for transmission of power at 50-60 Hz and at most 400 Hz. In addition, power line is a highly electronically contaminated environment with high signal attenuation at the frequencies of interest. As a result of these physical drawbacks, the installation of repeaters is necessary. Moreover, if data transmission is intended to pass behind the distribution transformer, bridges over distribution transformers are also necessary.

Another major difficulty for PLC technology is the lack of standardization. There are different standard for different parts of the world, differentiating mainly on the maximum transmitted power and allowable bandwidth limitations. Figures 1.1 and 1.2 indicate the frequency spectrum limitations for two different PLC markets; Europe and North America [2].

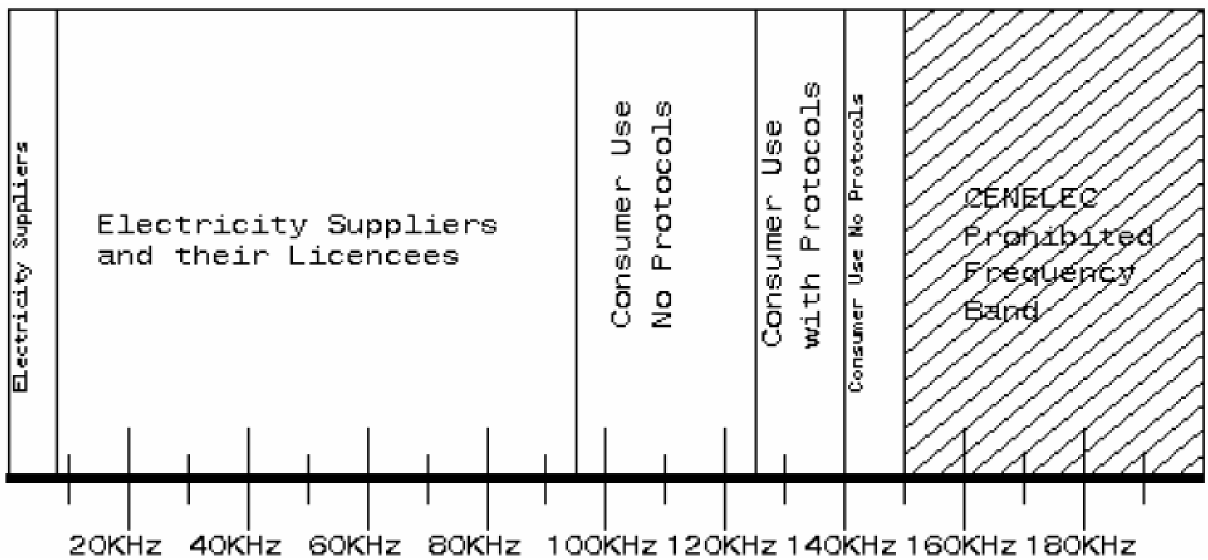


Figure 1.1: CENELEC Frequency Band Allocation for Europe [2]

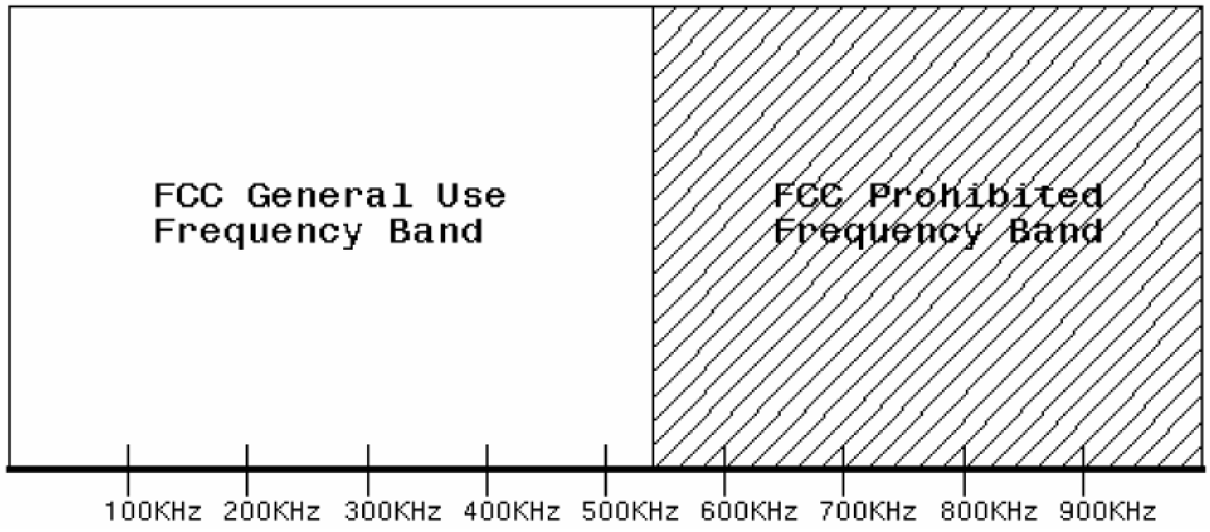


Figure 1.2: FCC Frequency Band Allocation for North America [2]

In Europe, the communication standards for PLC are defined by CENELEC (Comité Européen de Normalization Electrotechnique) which is an organization that is composed of the national electrotechnical committees of some 18 European countries. CENELEC (Comité Européen de Normalization Electrotechnique), the E.E.C's (European Electrical Committee) electrical standardization body published the standard EN50065 on low voltage mains signaling [3], [4]. According to those regulations, power line communication over the low voltage lines is restricted in the frequency range between 3 kHz to 148.5 kHz. This standard describes some characteristics of PLC such as the frequency bands allocated to different applications, access protocol for different users, limits for the terminal output voltage in the operating band and limits for conducted and radiated disturbances. In addition, it also includes the test conditions and the methods for measurement. For European standards the upper limits of the frequency band is 148.5 kHz. However, the upper limit for the frequency band is considered to be extended for the sake of compatibility with the USA standards. Still, for the rest of this thesis work, those narrow bandwidth limitations of the European standards will be taken as a basis.

As seen Figure 1.3, this standard specifies the frequency bands allocated for applications, access protocols for various users, limits for terminal output voltage, limits for the conducted and radiated disturbance and the test conditions and methods for measurement of devices. In the technical report of IEC 1334-1-4 [6], the data transmission parameters such as the impedance, the transfer function and the noise of low voltage and medium voltage power lines are defined as a function of the operation range, frequency and time. Further information can be taken from the related IEC standard published.

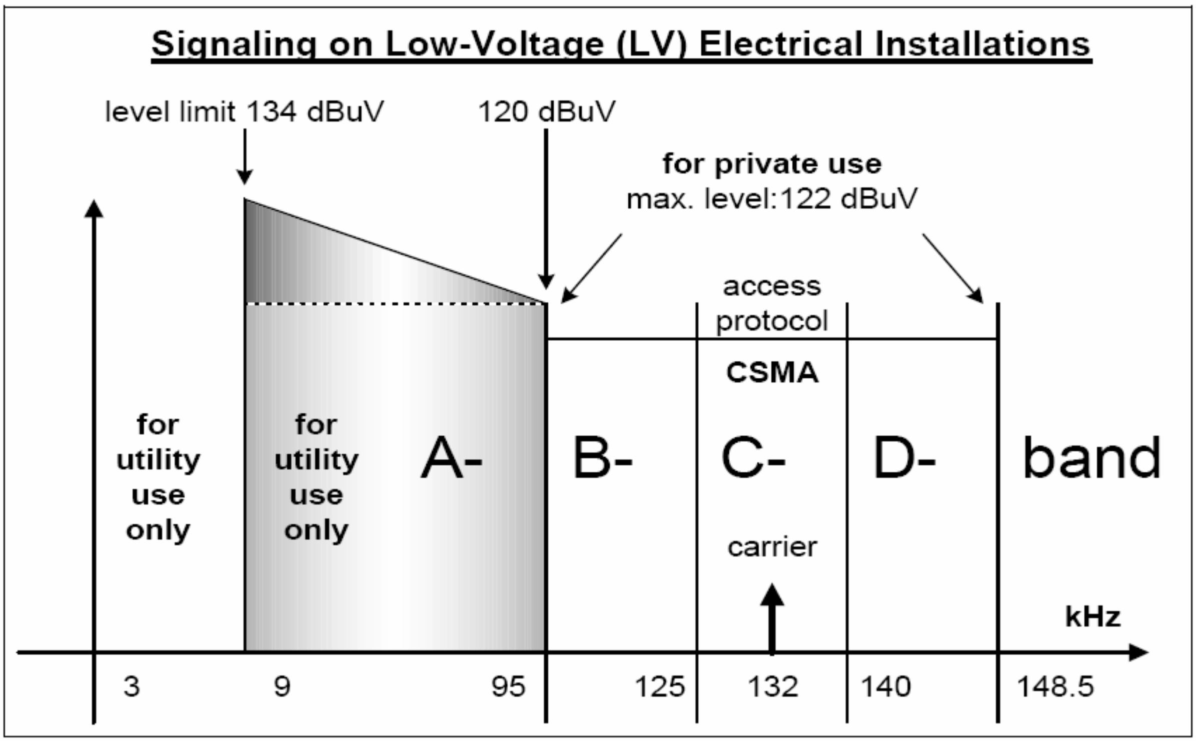


Figure 1.3: Frequency ranges and PLC signal level limits specified in EN 50065 [5].

1.2.1 Regulatory Standards for Power line Communications

Also the CENELEC Standard 50090, which has a lot of similarities with the CEBus standard used in the USA, describes the details of networking at homes and buildings with some communication media such as coaxial cables, fiber cables, power lines, twisted pair wires and RF medium [7]. The standard mainly aims to provide the multiple user efficiency and interoperability between the various system designs of different PLC technology developers by defining the access techniques, protocols, modulation and coding techniques and data rates. Another concern is avoiding the interference with ripple control systems.

EN 50065 standards, which allocates the frequency band between 3 to 148.5 kHz for PLC system operations, provides detailed regulations on parameters such as frequency range, transmitting power and signal strength. In brief, the utilities operate below 95 kHz and the private users over 95 kHz [8], [9]. For any case, the signal level can not exceed 2V. In practice, the measurements indicate that the optimal frequencies are in the range of 50 – 90 kHz where the noise levels are relatively low. Also note that, the relatively high frequencies yield a considerable decrease in the size and costs of the capacitances and inductances used for the filters and coupling devices. Furthermore, this standard identifies some requirements both for immunity of PLC system to interference from other PLC systems and for interference produced by the system itself. The lower frequency boundary is set to 3 kHz in order to avoid interference with the ripple control systems that operate around these frequencies. Similarly, the upper boundary is set to 148.5 kHz to prevent the interferences with medium wave (MW) and long wave (LW) radio broadcasts. EN 50065 standards, which are separately explained for utility and end user, also specify communication protocol, equipment impedance (to avoid excessive signal attenuation) and faltering specifications for carrier removal [10].

The frequency band between 9 to 148.5 kHz is divided into several categories:

- The A-band is between 9 – 95 kHz and is allocated for electrical utility applications such as automatic meter reading. In this frequency band access protocol is not applied.

The rest of frequency band (95 – 148.5 kHz) contains B, C and D frequency bands that are allocated for end-user applications. The frequency band was divided into 3 different subcategories according to the regulations in protocols used.

- For B band that spans the range from 95 – 125 kHz, there is no requirement to use access protocol. However the lack of access protocol jeopardizes reliability of the communication by making it possible for two systems to transmit at the same time on the B band. As collision risk is highly available, this range is allocated to less critical applications such as baby monitors and intercoms:

- The C band covers the frequency band between 125 – 140 kHz and contrary to B band, requires access protocol, preventing simultaneous message transmission. For various systems that operate in this region only one transmitter can operate at any time. Intra-building computer communications are common applications that operate in this band.

- The D band comprises the frequency band between 140 – 148.5 kHz and does not require access protocol similar to A band. Consequently message collision is a probable problem.

Moreover, the limitation of the transmitted signal behavior for PLC is a matter of electromagnetic compatibility (EMC). As stated in Fig above, the maximum signal voltage level for 9 kHz is 134 dB(µV) (or 5V), where 120 dB(µV) is determined as the maximum signal voltage level for 95 kHz. Similarly, for D band the maximum transmitted power is limited with 500 mW. Practically for indoor applications the transmission signal amplitude is limited to 630 mV within a bandwidth of 50 kHz. Consequently, for outdoor PLC applications such as AMR, the upper limit for the transmission signal strength is 5V within the predetermined 95 kHz frequency threshold [11], [12].

As stated before, between 3 kHz to 148.5 kHz the European Standard published by CENELEC standardizes the transmitted power limits. Beyond 150 kHz EMC aspects come into the picture. The related standard defines the radio disturbance limits for higher frequencies. The limitations for conduction-bound noise signals are described up to 30 MHz. Beyond 30 MHz, the restrictions for maximum electromagnetic field strength in a default distance is identified [13].

Finally, the regulatory limits for maximum transmit voltages for the frequencies below 148.5 are represented in Figure 1.4. For the frequencies above 148.5 kHz, the standard defines the properties of the time domain signal, not the power spectral density spectrum.

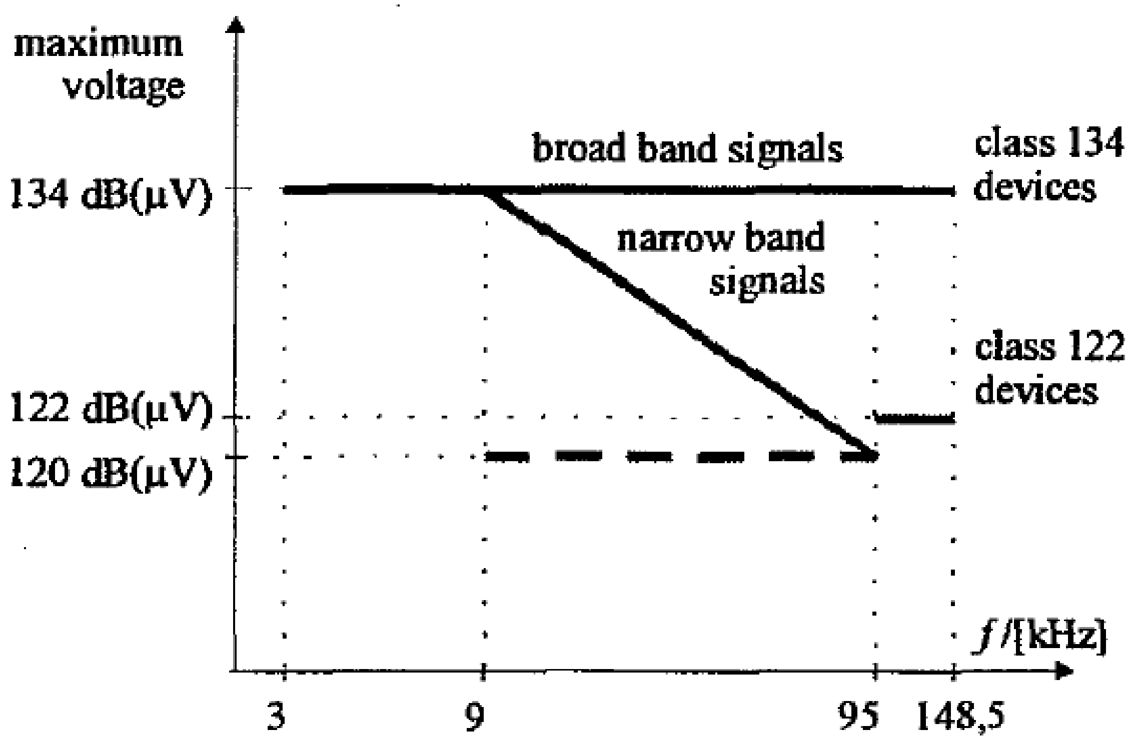


Figure 1.4: Regularity limits for maximum transmit-voltages [12]

1.3 BRIEF HISTORY OF PLC

The idea of sending communication signals on the distribution grid is not a recent idea. However the number of devices connected to dedicated wiring is far more than the devices installed to AC mains wiring. But the reason for this is the underestimated communication benefits of PLC. Only in the recent several decades the transmission advantages of PLC such as reliability, being less susceptible to hazards, economical architecture for long transmission lines and convenience for maintenance at the transmission terminals are realized and benefited.

In the 1920's two patents were issued to the American Telephone and Telegraph Company in the field of "Carrier Transmission over Power Circuits". Furthermore, in 1924 United States patents with the numbers 1,607,668 and 1,672,940 prove systems for transmitting and receiving communication signals over three phase AC power wiring [14]. In Europe, PLC initiated with the outspreading mains supply about 80 years ago. The first carrier frequency systems (CFS) came into service at high tension voltage in the frequency range between 15 – 500 kHz in year 1922 [15].

High voltage lines are favorable carriers for RF energy, considering that open-wire equipment with cross connections are rare. A transmission power of 10W is usually sufficient to transmit over distances of more than 500 km. In the late 1920's, PLC was applied in teleprotection when the PLC system was not subject to licensing. The PLC was smoothly operated in the frequency band from 10 to 490 kHz. There were only some limited cases of radio interference reported. Moreover, the PLC equipment was effectively isolated from the mains frequency and the noise components around the mains frequency. However the line coupling losses and the line attenuation losses were still vast [16].

In the past and today, the primary purpose of CFS for the utility companies (UCs) is the proper operation of the distribution system. However with the recent developments in digital modulation and coding schemes, an enhancement of bandwidth efficiency can be possible for future CFS applications. As stated earlier, UCs preferred to build their own communication network, neglecting the already existing telecommunication networks for remote measuring and control tasks because of their slow rate of penetration and lack of real-time operation. Still the power distribution wirings were referred as a promising medium for UCs as almost all the end point users were connected to the mains line. For medium and low voltage lines the load management was the primary task in means of communication. However the information flow was limited and unidirectional from the UC to the customer.

Ripple carrier signaling (RCS) was introduced in year 1930. The earliest form of AMR systems developed were fixed carrier, analogue systems that was first put to trial in the 1950s using the ripple control signalling method [17]. Differently from CFS, RCS was designed for medium voltage level (10-20kV) and low voltage level (240/415V) distribution systems. CFS was abandoned because of some difficulties such as high number of cross connections and various conductor types (open-wire and cable). In addition, the long distance RF signal propagation was unfavorable because of impedance matching problems and high attenuation. In order to surmount the impairments, large scales of RF transmission power needed to be used and this was causing some electromagnetic compatibility (EMC) problems. Thus, the frequency range for RCS was reduced below 3 kHz to 125 Hz. Moreover the transmission powers needed in the range from 10 KW to 1 MW as the impedance of the loaded distribution network was very low. In those days, typical telegram was consisting of 10 to 60 packets adding up to 20 to 120 bits with some time delays and the total length was around 0.5 to 3 minutes. The Ripple Control Signaling was used in the power grid at low frequencies. It required high transmitter power but provided low bit rate. RCS was a one way communication and used mainly for applications such as management of street lights, load control and tariff switching. The RCS was later abandoned despite its high reliability because the improvement and extension capabilities of this method were insufficient for the new technologies developed [15].

Another candidate application for the purpose of moving the PLC to the main stream was a commercialized version of military spread spectrum technology. The research and product development companies concentrated on commercial spread spectrum, which was assumed to overcome the unstable and unpredictable characteristics of power line, since the beginning of 1980's. However until today the spread spectrum technique could not generate promising products for deployment of PLC [14].

Finally, in the mid 1980s, the utility companies began to invest on R&D studies and contributed to the further development of PLC. The major driving factor for these studies was the implementation of the Supervisory Control and Data Acquisition (SCADA) systems. The R&D departments of some specific utility companies and the working groups sponsored by these utility companies, located in both US and Europe, investigated the electric grid as a medium for data transfer. The signal noise levels and the attenuation of the signal through the grid were measured. These systems offer a slightly higher data transmission rate. Then investigations were made in the mid 1980s by several utility companies to analyze the characteristic properties of the electric grid as a medium for communication. Signaling frequencies in the range of 5 – 500 kHz were investigated. Main areas of investigation were the signal-to-noise ratio levels affected by the power line channel, as well as the attenuation of the signal by the transmission grid. As a result of these intense research activities, bi-directional communication in the power grid was developed through the late 1980s and the early 1990s. The present systems came onto the market during this time frame. The main difference in the newer systems was the use of much higher frequencies (the wideband frequency range, often in MHz range) and a substantial reduction in the signal levels. As a result of this development two-way communication became realistic [18].

Today advance protocol techniques are employed to make them adaptive to network changes and to achieve better management of data transmissions. Some modern PLC solutions operate in the carrier frequency range of 1-30 MHz. The foreseen future development will utilize the frequencies in the GHz range with a much higher bandwidth and a high data throughput, possibly in the order of megabit/second speed range [19].

CHAPTER 2

PLC APPLICATIONS IN AMR

2.1 WHAT IS AMR?

Automatic meter reading, or AMR, is the technology of automatically collecting data from energy metering devices (water, gas and electric) and transferring that data to a central database for billing and/or analyzing. In other words, like the name implies, AMR refers to the collection of data from electronic meters and transmission of the collected data via communication links without any human intervention. This saves employee trips, and means that predictions about next months billing can be based on actual consumption rather than on an estimate based on previous consumption, giving customers better control of their consumption [20], [21].

2.2 BRIEF HISTORY OF AMR

First AMR tests were conducted in 1967 by AT&T in cooperation with a group of utility companies and Westinghouse. As a result of these experiments, AT&T introduced its phone based AMR service with a cost of $2 per meter which was four times more than the cost of manual reading at these times. Therefore, the solution was economically unfeasible. Several years after that, in 1972, the General Electric Corporate Research Centre, in conjunction with GE Meter Department in Somersworth, New Hampshire initiated an R&D effort to implement a remote metering system for centralized TOU (time-of-use) metering referred as AMRAC. Moreover, in 1977, a Utility Communication Division was established at Rockwell International to develop distribution carrier communication systems. Later in 1984, General Electric acquired an exclusive license from the Rockwell International to commercialize the distribution line carrier product designs and related design and technology.

In 1985, the implementation of several full scale projects initiated the modern era of AMR. Hackensack Water Co. ad Equitable Gas Co. implemented the first full scale AMR project for water and gas meters respectively. Following that, in 1986, Minnegasco established a 450,000 point radio based AMR system. In 1987, Philadelphia Electric Co. managed to reach to a large number of inaccessible meters by installing thousands of distribution line carrier AMR units. Today, the advances in solid state electronics, microprocessor components and low cost surface mount technology assembly techniques enables the production of reliable and cost effective products that rationalize the use of AMR systems on a large scale [21], [22].

2.3 AMR APPLICATIONS METHODS USING PLC

2.3.1 An overview of the common aspects of conventional automatic meter reading methods

Independent from the type of communication system employed, every automatic meter system is composed of some specific units. The transmission between the elements should be clearly defined. Each unit should be distinguished by a unique identification code, should be able to communicate to the other units directly or via one or more intermediate units and should be able to receive and transmit data to and from other units. The Figure 2.1 below briefly illustrates the AMR units.

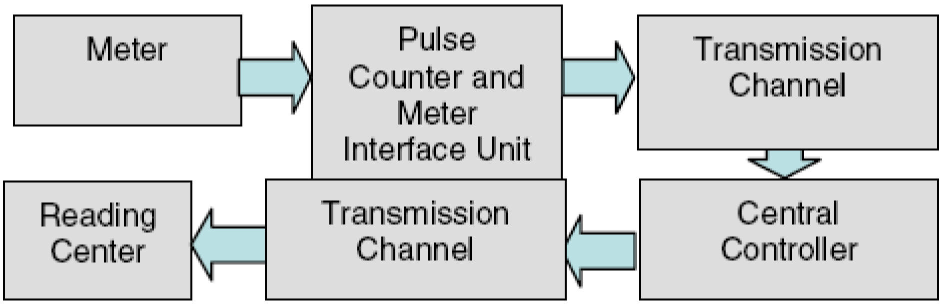


Figure 2.1: Optimal topology of AMR using PLC [3].

The meter simply reads the consumption data either using an analog or digital measurement system. Pulse counter produces electric pulses according to the amplitudes and time values of the consumption data supplied by the meter. Meter interface unit (MIU), which detects, counts the output pulses of the pulse meter, is located next to or into the meter. The pulse data is also stored in the MIU's memory to be transmitted to the central controller via the one directional or bidirectional transmission channel to execute the reading center commands [23].

Central controller, which is referred as data collector unit (DCU) in most literature, includes a processor and memory to receive the pulses from the pulse meter interface unit, converts them into the required format in accordance with the reading center requests and transmits them through the communication channel. It also executes the reading and on/off commands from the reading center. As a result of this data flow, the essential information about the consumption characteristics of the consumers are transferred to distribution companies network.

The communication channel, which serves as the link between the individual data collection and processing units, is mainly the medium of data and command transfer of the automatic meter reading system from reading center to the meter. The reading center primarily acts as the decision center and sends the commands to be executed such as reading, transmitting and so on. Moreover it reads the data to the central controller, controls and stores the meter data. Additionally, the reading center executes the operation to calculate the consumption value and bill preparation.

2.3.2 PLC Reading Technology

In the context of the automatic meter reading system using PLC studied in this thesis work, the communication channel between the meter interface unit and the center controller is the LV power line. There are various alternatives for the communication channel between the central controller and reading center such as GSM, GPRS, radio, telephone lines or MV power lines. The maximum distance that is convenient for transmission between the meter interface unit and central controller (data collector unit in our case) depends on different parameters such as power line impedance, wire twisting and vicinity, quality of nodes and the power line, underground or overhead lines and even the wind direction. The practical maximum distance between a MIU and DCU is considered to be around 150 to 300 meters; however this limit can be exceeded by employing MIUs as metering devices and/or including repeaters with an effective distribution [24].

A PLC modem is occupied on both sides of the communication channel between the meter interface unit and the central controller. A multi frequency modem may be used rather than a single one to make use of various frequencies to communicate between the AMR units and to avoid signal interference. For multi layers systems, one frequency can be allocated for the communication between the upper layer (reading center) and the middle layer (DCU) and another frequency for the communication between the middle layer and the lower layer (MIU).

For the wired communication system, as the transmitted signal is added on the power signal, the choice of modulation is critical in order to avoid the disturbance. Moreover, for long communication distances, the signal can not be transmitted in the digital form because of the resistive and inductive losses. In order to avoid these losses and disturbances, FSK modulation can be used. Due to the sinusoidal signal of FSK, the power line and the passive elements may cause signal attenuation but the consumption data is still preserved uncorrupted. Additional benefits of FSK are its ability to transmit in high frequencies and its reliability [25].

2.3.3 Integrity and Topology of PLC Network

The difficulties, such as data transmission security and accuracy having priority over the communication speed for the functionality of an AMR system and the high line losses in low voltage, promote lower baud rates to increase data reliability and precision. Lower baud rates also enable higher transmission distance range. Theoretically, considering various parameters such as the distance between the MIUs and DCUs, the number of MIUs under a MIU, attenuation and line losses, the optimum baud rate can be chosen as 600 bps.

Another issue is the integrity. In an AMR structure, all of the system units should communicate with each other in an integrated manner. Considering the network topology, consumers that are further away from the DCUs suffer from the PLC signal distance range threshold. DCUs might not be able to directly communicate with all the MIUs under its branch. Also the MIUs under a substation might not be able to see all MIUs in its network.

Collision is a common problem of all communication media. Due to the common carrier frequencies used by all units for injection, audit and control procedures should be put into service in order to avoid collision originating from the simultaneous injection of two different units. Collision takes place in the case when two devices can directly communicate with each other and send data at the same time. For the implementation of collision detection topology the transmitting units can not identify the carriers of each other, another intermediate device is needed to identify the signals of both sides. In this case if two devices inject data at the same time, the collided data is received by the third intermediate unit and considered to be invalid Consequently, several key points to prevent collision are listed below:

1- There should be only one DCU under a substation network operating as the master. The line management and control of data transmission traffic should be this DCU’s responsibility.

2- Each consumer should be given a unique ID to discern it from other consumers.
3- Collision detection and prevention software should be implemented to avoid simultaneous signal injection.

One of the most widespread protocols that satisfy the above conditions for low speed PLC channels is MODBUS.

2.3.4 PLC Reading Network Protocol (MODBUS)

Modbus is a serial communication protocol that is frequently used to transmit data in LV and MV distribution lines. It is a simple implementation of master/slave logic for serial interfaces. Modbus is suitable for applications with few communication stations and short transfer time because of its limited transfer rate around 38.4 kBaud.

Modbus protocol uses the 9-148.5 kHz frequency range in accordance with the CENELEC (EN 50065-1) standard which is applicable for the devices operating with carrier frequencies in the range of 3 kHz to 148.5 kHz for LV power line transmission. According to this standard, different frequency bands are allocated to specific applications in order to diminish the mutual effects of communication signals transmitted by the various units in the system and to reduce the disturbing effects of power line communication on various sensitive electronic devices.
As stated below the structure is composed of a single master and several slave stations controlled by this master. There are two alternative communication mechanisms that can be employed in the context of MODBUS: [26]

1- Request/Respond (Polling) Mechanism: Master stations sends a request message to the slave stations and the slave stations respond back with acknowledge message.

2- Broadcast mechanism: Master sends a global command to all the slave stations and the slave stations execute the command without sending acknowledge.

For the MODBUS application studied in the scope of this thesis work the frequency band between 125 kHz to 140 kHz is allocated. Also the power line signal transmitted in this frequency range is subject to access protocol. Accordingly, if the communication medium is shared by several systems, the following requisites are to be fulfilled. Firstly; all devices connected should use a frequency for data recognition. Secondly; the line access time for a transmitter should not exceed one second and should not be less than 125 ms in order to be considered as a valid transmission. Moreover, the maximum interval between signal series in a sending stage is limited to 20ms. The carrier detection algorithm is employed to detect the frequency band occupancy. As a result, each element is allowed to inject a signal only if the line is detected to be idle.

There is no specific procedure to select a master node. However, high density signal points are better candidates. Again note that in each network only one unit can be determined as master and each node is given a unique ID. Furthermore; the route of data interchanges starting from the master node, including the intermediate nodes (if the destination node is not directly accessible by the master node) and ending with the destination node, is identified in the message format.

After injecting the packet, the master node waits for the acknowledge message from the destination node. The destination node converts the sent message to acknowledge message and gives it to the line after executing the command specified in the sent message. The destination node reverses the direction of the direct path to find the return route. The PLC modems in both sides of the communication medium between the MIUs and DCUs convert the data into a particular format to avoid the reception of invalid signals from the disturbance sources. This should be a unique format for all the units so that every node adopts the packet. After receiving the packet each node checks the data format and accepts if it is in known format or rejects if it is not in proper format. Then if the format is appropriate, the node checks whether it is the destination node or intermediate node. If it is the intermediate node, the packet is transferred to the next node. Finally when the packet arrives to the destination node and the node verifies itself as the destination node by checking the pointer in the package, the command is executed and the packet is put back to the return path in the form of acknowledge packet. Considering that each packet is designed so as to be received by only one destination node, an additional indicator is needed. A pointer is inserted into the packet format to indicate the current position of the packet on its route to the destination node. An intermediate node reacts to a packet it received only if the pointer register is in accordance with the position of this specific node in the route. All the other nodes that do not match with the pointer ignore the packet. Thus each time a packet is transmitted to adjacent nodes, only one node responds to the packet and the collision is avoided. This data flow is expressed in Figure 2.2. The algorithm explained above is common for every network that uses power line as a communication channel. The packet design is flexible and can be modified according to constraints of the protocol used.

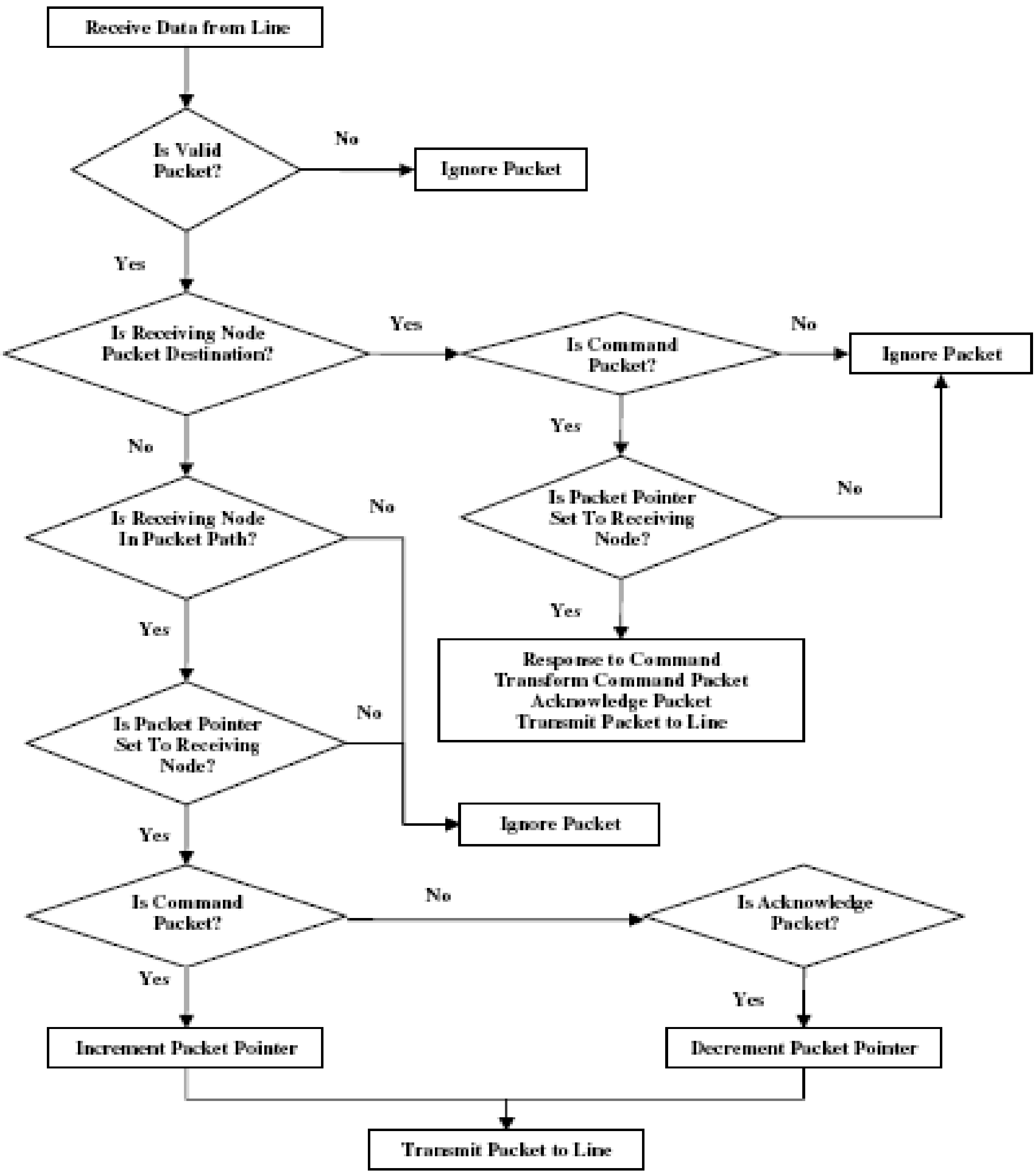


Figure 2.2: The operation flowchart of each node in case of receiving a packet [23]

2.3.5 The Transmitted Packet Format

Figure 2.3 is the standard format for a command packet from DCU to MIUs or an acknowledge packet from MIUs to DCU. Packet length is specified in a separate register. The mix byte includes the packet type (command or acknowledge), command type (reading or writing), path length and the path pointer. The pointer is again crucial for a reliable transmission so that when the destination node receives the packet it confirms the path by checking the pointer. The destination node should have the same address as the destination ID and the pointer should be equal to zero when the packet reaches the destination node.

Table 2.1: The transmitted packet format [23]

Synchronizer	Packet Length	Destination ID	Mix Byte	Packet Body	Packet Path	CRC

The packet body includes the consumption value. It should be noted that only meter consumption value returns to the DCU, other information such as tariff and demand can be calculated in MIU or other middle layers and transferred to the reading center.

As mentioned under MODBUS protocol specifications, the line access of a unit is limited by a maximum duration of one second. Taking into account the PLC modem used and the delay time between transmitting two bytes and the software delays, the maximum packet length can be calculated. The packets whose lengths exceed this amount should be transmitted in multi packets. As stated before, the line access time for a transmitter should not exceed one second and should not be less than 125 ms in order to be considered as a valid transmission.

2.3.6 Routing Algorithm

In order to route the best path to each MIU, the DCU initially tries to read all the MIUs under its branch directly by sending a command to each MIU and waiting for a response for a specific time. Then DCU makes the list of MIU from which it receives the acknowledge packet. Secondly; DCU tries to reach to the other MIUs by using the direct path MIUs as intermediate unit and again makes another list of the second stage MIUs that can be reached via the direct path MIUs. DCU repeats this procedure for a particular number of times and keeps the list of the founded MIUs in each stage and also records the number of intermediate MIUs used to reach them. Finally, DCU assigns weights for each route that can be used to reach every single MIU, selects the three paths with the maximum weight (minimıum number of intermediate MIUs) and stores them in the routing list of this specific MIU. The DCU tries to reach the MIUs by first trying the route with the maximum weight and uses the alternative routes with smaller weights if it fails.

2.3.7 Carrier Sense Multiple Access with Collision Detection (CSMA/CD)

Carrier Sense Multiple Access with Collision Detection is a networking protocol in which a carrier sensing scheme is employed. If a transmitting data station detects another signal while transmitting a frame, stops transmitting that frame, transmits a jam signal and then waits for a random time interval [26]. Collision detection is used to improve CSMA performance by terminating transmission as soon as a collision is detected and by reducing the probability of a second collision on retry [27].

Methods for collision detection depends on the media used, however on an electrical bus such as Ethernet, collisions can be detected by comparing the transmitted data with received data. If they are different, another transmitter, this points out that another transmitter is overlaying the first transmitter's signal (a collision exists), and transmission terminates immediately. Following that, a jam signal is broadcast and all transmitters back off by random intervals, reducing the probability of another collision resulting from a retry attempt.

CSMA/CD MAC sub layer monitors the physical medium for traffic by watching the "carrier sense" signal provided by the PLC (physical layer signals to MAC layer), even for the instants when there is no packet to be transmitted. When the medium is busy, the CSMA/CD MAC gives the priority to the passing frame and delays its own pending transmission. When the last bit of the passing frame leaves the channel and the "carrier sense" signal changes from true to false, the CSMA/CD MAC continues with the proper transmission [28], [29].

"Collision detect" signal provided by the physical layer is monitored to detect collisions. When a collision is detected during a frame transmission, the transmission is not immediately terminated. Instead, the transmission continues until additional bits (counting from the time "collision detect" signal is generated) determined by "jam size" have been transmitted. This collision enforcement or jam is applied to guarantee that the duration of the collision is sufficient for the all transmitting stations in the network to detect the collision [26].

2.3.8 The Token Bus MAC Protocol

The token bus MAC protocol is an alternative communication protocol for the Carrier Sense Multiple Access/Collision Detect (CSMA/CD) methods.

As described in details in the Chapter 6 , the power grid is exposed to various sources of transmission loss such as power line noise, frequency dependent signal attenuation and frequency dependent power line impedance. Until the utilization of spread spectrum techniques, power line was only used for noncritical, low level control and data transfer applications. Today, power line modems using the advance modulation techniques can be employed to establish power line local area networks (PLLAN) for reliable data communications in high data rates [30].

The physical layer of the PLLAN employs the spread spectrum techniques for the data transmission over the mains line. The MAC that operates on the physical layer regulates access to the power line utilizing a token passing scheme based on IEEE 802.4 token bus standard.

The token bus protocol has some considerable advantages compared to CSMA/CD protocols

- A token is used to determine transmission priority and regulate the access to the bus. Thus, the nodes do not have to contend for the allocation of the bus as it is the case for other protocol such as carrier sense media access with collision detection (CSMA/CD)

- This protocol executes smoothly under medium and heavy load traffic conditions which is a common situation for power line channel transmission.
- The token bus protocol is suitable for the peer to peer network in the sense that each node is guaranteed to have access to the bus and allocated a fair share of the network bandwidth.
- The failure of a node on the logical ring can be determined with minimum overhead

2.3.9 Functions and Operation of MAC

MAC performs the main tasks of the data link layer. MAC determines the timing to place a frame on the bus, coordinating with the other nodes' MACs to control access to the shared bus. Besides, MAC provides the initialization, development and maintenance of the logical ring and addition of new nodes to the logical ring. Moreover MAC has additional responsibilities such as fault detection and recovery [31].

MAC constitutes the logical ring for the data transmission on the bus according to the numerical ordering of the node addresses. The token, which represents the permission to use the line, is handed on from one node to the successor node in ascending order of the node addresses. The node resides in a particular node only during a predefined token holding time which is equal to the time required for the transmission of one packet. Once a node completes the transmission of any data frames, it hands on the token to the successor node by sending a token control frame. The related packet format of the token bus protocol is shown in Table 2.2. The header information is added to data that is passed to the MAC that operates in the physical layer and handed on to the physical layer controller that adds the preamble and postamble and the CRC code to the data for actual physical transmission. In case of any failure of transmission, the physical controller sends the transmission failure message to the MAC which employs an adaptive retransmission policy to decide if the entire packet is to be resubmitted to the physical layer controller for another transmission attempt.

Table 2.2: MAC protocol packet format [32]

1 byte	2 bytes	2 bytes	2 bytes	1~992 bytes
Primitive Number	Destination Address	Source Address	Number of Data Bytes	DATA

As stated before, MAC has addition functions such as network initialization, addition of new nodes, deletion of nodes, new token generation and recovery form duplicate tokens.

2.3.9.1 The network node list

The network list that contains the address of all other nodes on the network is formed at each node for the PLLAN management. The network list that is formed in the numeric order of the node addresses is updated at regular intervals. The node uses the network list to determine its successor node [30].

2.3.9.2 Addition of new nodes

The MAC protocol periodically searches for new nodes to add to the logical ring. The token holding node polls the nodes that are addressed between itself and the successor node. The token holding node tries to pass the token to the polled nodes until an active node is reached. The token is passed to the successor node if an active node could not be located. If the token holding node finds a new node, new node broadcasts its address to all listening nodes and passes the token to the predecessor node which is the token holding node now. The listening nodes accordingly update their network node lists when they receive a broadcast message. The token holding node assigns the new node as its successor and passes the token and its network list to the new node. By this way, the new node becomes a part of the logical ring [33].

2.3.9.3 Deletion of failed nodes

Due to some troublesome power line conditions or node failures, if a node can not successfully transfer the token to the successor node, this node is considered to have failed. Then the token holding node sends a network command to all the nodes to remove its successor node, which it could not deliver the token, from their network lists. After that, the token holding node finds a potential successor from its network list and passes the token to that node. In case of another failure, the previous step is repeated. After several trials, if no node remains in the network list, the token holding node assumes that no other potential successor exists and the network initialization process is started [33].

2.3.9.4 Network initialization

Each node listens to the network for a predefined time (according to the address of the node) waiting for a network activity. Unless the node detects a network activity during this fixed time, it generates a token and assumes master status which means that now it has the responsibility to initialize the ring. To begin the initialization process the initial network master incrementally polls the network address, trying to pass the token until an active node is determined. The located node broadcasts its address to the entire network and then passes the token to its predecessor node which is the network initializer. The listening nodes update their network lists according to the broadcast message from the second node. This is how a network composed of two nodes is established. Note that the procedure for the addition of nodes is described in the previous section.

2.3.9.5 New token generation

New token generation is necessary in case of a lost token condition. If a physical layer control determines a lost token condition, the node's firmware warns the related MAC after a predetermined time out period. Then, this node assumes master status and begins the network initialization procedure. At the mean time, the physical layer controller constantly monitors the network to avoid another node to operate as a master. If this is the case such that two nodes simultaneously generate a new token and assume master status, the physical layer control of on of these nodes will immediately drop the token as soon as it detects the error condition. Thus, only one master node remains. Also if the two nodes drop their token at the same time, then the network initialization is initiated again.

2.3.10 Other Physical Layer Protocols

There are several physical layer protocols available from various PLC manufacturers. These protocols are briefly described as below [34], [35].

2.3.10.1 X-10

X-10, which is one of the oldest power line communication protocols, employs Amplitude Shift Keying (ASK) modulation. Simply, a 120 kHz AM carrier signal is superimposed to the ac power line at zero crossing to minimize the noise interference and the information is coded according to the bursts of this signal. To ensure the communication reliability, every bit is sent twice and consequently the transmission takes a full line cycle. As a result the transmission rate is limited to 50 BPS for a 50 Hz mains frequency. X-10 command is composed of two packets with a 3 cycle gap between them. As stated above, each of two packets carry two identical messages of 11 bits. That adds up to a 48 cycle command length with a duration of 0.8 second [2], [36].

Although the initial X-10 applications were unidirectional, later some bidirectional products are also manufactured. Mostly, the control signals from the X-10 controllers are transmitted to the simple receivers are used to control lighting and similar appliances. X-10 has quite poor bandwidth and the transmission reliability is in considerable distress because of the unfriendly and noisy transmission environment.

2.3.10.2 CEBus

CEBus protocol employs peer to peer communications model. CEBus provides protocol standards for RF, twisted pair, PLC and some other home networking methods. For CEBus, a binary digit is represented by how long a frequency burst is applied to the channel. For example, if a binary “1” is represented by a 100 microsecond burst, a binary “0” may be represented by a 200 microsecond burst. Consequently, the CEBus transmission rate depends on the number of “0” and “1” characters transmitted [37].

In CEBus protocol, every node in the network has access to the communication media every time. As a result collision is probable. A Carrier Sense Multiple Access/Collision Detection and Collision Resolution (CSMA/CDCR) protocol is utilized to avoid collision. As stated before when the CSMA/CD protocol is explained, according to this protocol, a particular node waits for the line to be clear and makes sure that there is no other nodes transmitting before it sends a package [37]. The objective of this protocol is the optimum allocation of communication channel in the sense that as many nodes as possible can use the medium without interfering with each other. The physical layer of the protocol is based on spread spectrum technology. The packet format includes the mandatory sender and receiver address and is transmitted over the media at about 10 Kbps [38].

CEBus is a commercially owned protocol so its applications require registration fees. Generally, currently commercially available CEBus protocols are simple systems designed for home automation. Still, there are some high capacity systems that are developed in some research institutes.

2.3.10.3 LonWorks

Similar to CEBus, LonWorks is also based on peer to peer connection by implementing Carrier Sense Multiple Access (CSMA) protocol. Differently from the CEBus, LonWorks utilizes narrow band spread spectrum modulation scheme (125 –

140 kHz, BPSK) with a multibit correlator to protect the data against the interference noise by using a patented impulse noise cancellation scheme. As LonWorks uses a narrower transmission band, the levels of distortion of the transmitted signals is considerably lower than that of wide band spread spectrum [39].

2.3.11 A COST EFFECTIVE ALTERNATIVE REMOTE METERING SOLUTION: THE AMPMETER SYSYTEM

Coming into picture as an improvement for the optimal topology of AMR solution described above, the Ampmeter systems shares most of the common units of the optimal topology of AMR and has some additional specialties [40].

Especially for premises such as apartment complexes, university dorms and military complexes with high turnover of residents, manual reading is an expensive application that needs multiple trips to the customer premise. AMR can be employed at these kinds of applications for the automated billing and remote control and management of the meters.

Ampmeter is a bidirectional AMR that integrated PLC and GSM/GPRS technologies to enable utility company to remotely connect and disconnect energy measurement services, activate load balancing and cost control. The design of the AMR system without the need of additional wiring is illustrated in Figure 2.5.

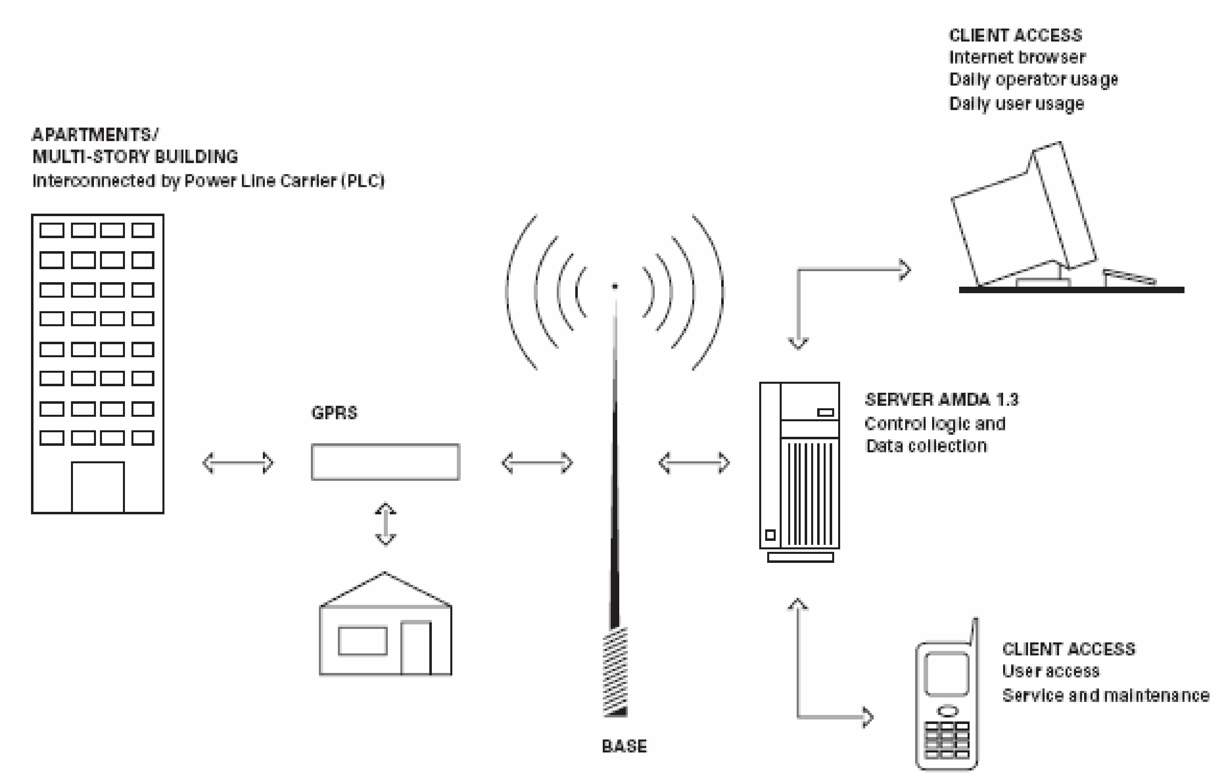


Figure 2.3: The schematical representation of Ampmeter AMR system [41]

Similar to the optimal topology described above, the Ampmeter consists of three parts: the meter interface module, the data concentrator system and the central computer system. The illustration of the proposed architecture is given in Figure 2.4.

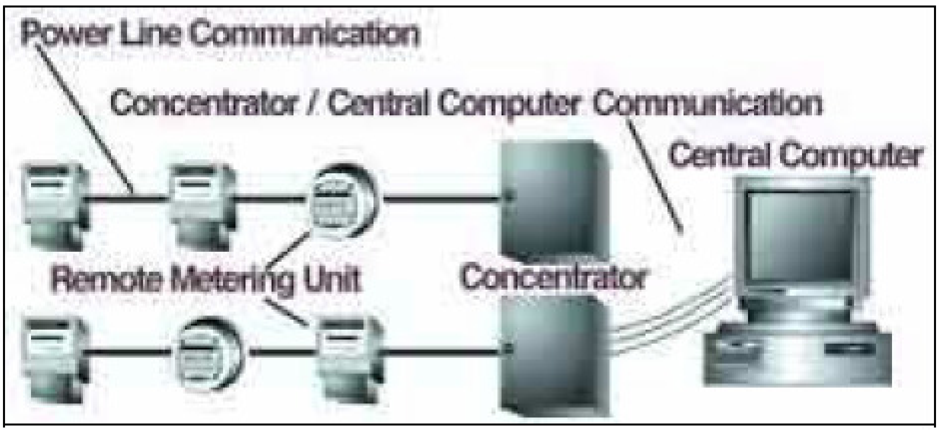


Figure 2.4: Major components of the Ampmeter system architecture [42]

The parts of the system are not to be defined in details as most of the parts have the same functions as the optimal topology design. In short, the meter interface consists of a backup power supply accompanied by the meter sensors, controlling electronics, memory for storing data and a communication interface that facilitates the data transfer from this remote device to the central computer. As stated also for the optimal topology, the Ampmeter system is also bidirectional, enabling the central computer signals to be received by the remote metering unit and vice versa. The data concentrator, which acts as a bridge between the central computer and the meter interface unit, is employed for the transmission of data and control signals between the meter interface unit and the central computer. In this particular system, the link between the remote metering unit and the concentrator is a low voltage power line. On the other hand, a GPRS system is used for the link between the concentrator and the central computer which is composed of the host computer and the GPRS modem for the link to the concentrator.

The main functionality of the units can be summarized according to the diagram in Figure 2.5

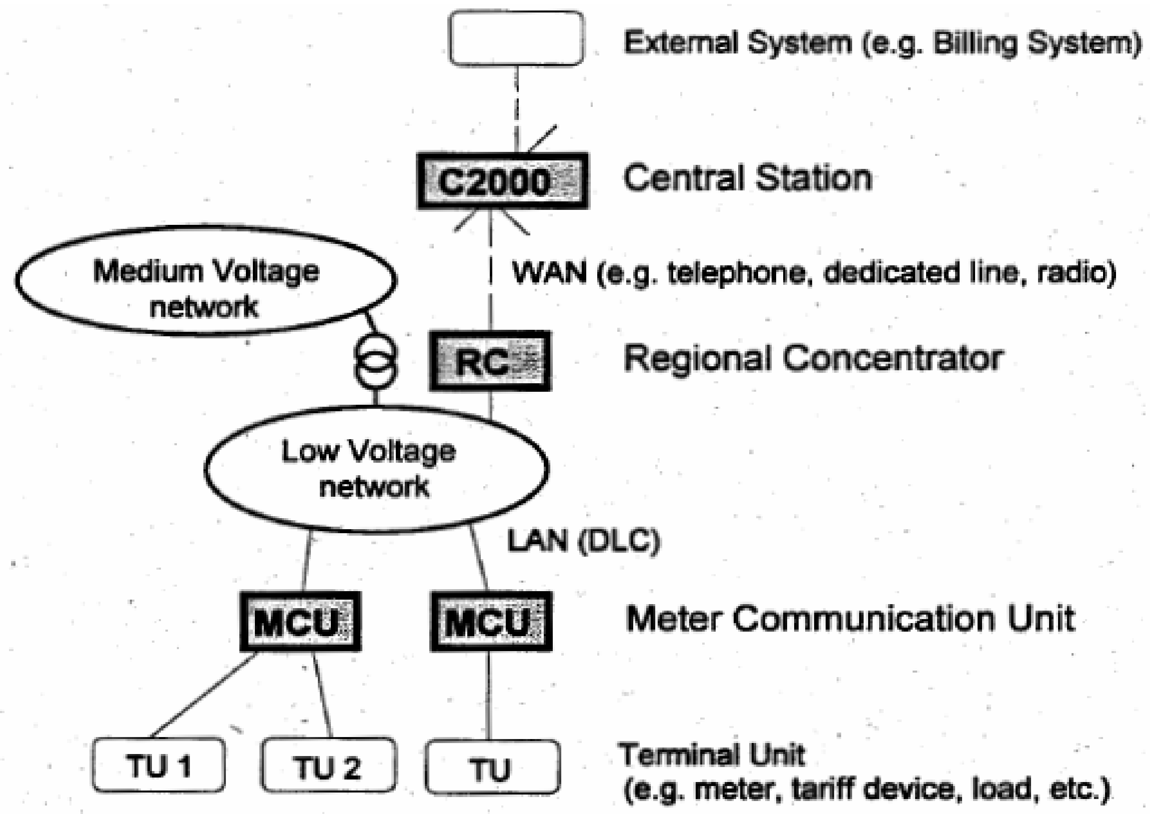


Figure 2.5: Architecture of the Ampmeter system for a single phase [43]

2.3.11.1 The main components of Ampmeter system

2.3.11.1.1 Central station (Central computer)

Central station provides the administration, configuration and operation of automatic data acquisition, processing and transmission over the man machine interface (MMI). The database included stores the configuration, operation and acquired data and the scheduler performs the periodic tasks automatically. At the central station, the meter data is converted and transmitted to the utility company's related departments to be stored as a historical database [43].

2.3.11.1.2 Regional Concentrator (RC)

The Regional Concentrator functions as the master and administrator of the low voltage network. RC communicates with the meter communication units over the low voltage power line and with the central station via the GPRS using the standard transmission protocols.

The RC is assigned as a slave for the Central station to carry out the consigned tasks automatically. It also controls the connected MCUs and stores the data read at by the MCUs in the nonvolatile inbound buffer to the central station until the data is collected by the central computer. The intelligent memory of the regional concentrator enables it to execute the downloaded tasks independently without the necessity to build a permanent connection with the central computer. The regional computer keeps a task list for the commands that have to be executed at a specific time of the day, at specific intervals. Moreover, the regional concentrators carry out the automatic synchronization of the real-time clocks of the meter communication units [43].

2.3.11.1.3 Meter Communication Unit (MCU) or Meter Interface Unit (MIU)

The meter communication units fulfill the simultaneous reading of consumption values from the energy meters and transmission of data to the regional concentrator. MCU can execute according the tariff and load control according to the commands from the central station and can also execute the locally stored programs downloaded from the central computer. Besides, as stated before, each MCU can act as a repeater to strengthen the communication between the other distant MCUs and the regional computer. The conditions for which the MCU is entitled to behave as a repeater are defined and adapted by the central station according to the characteristics and the topology of the low voltage network [43].

As stated before for PLC based AMR systems, the data signals are superimposed on the power transmission lines. The point of signal injection is normally in the zone substation bus bar. The outline of the Ampmeter system for a 3 phase distribution network is as follows [44].

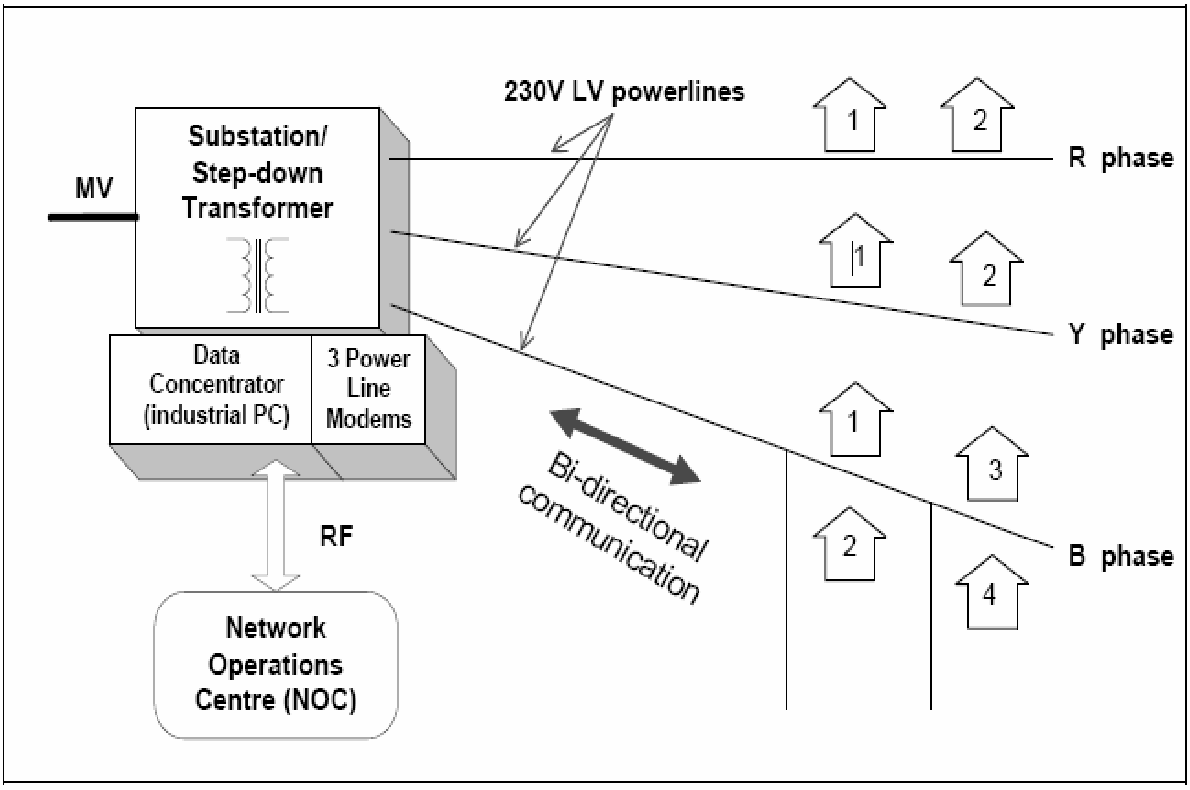


Figure 2.6: A typical AMR system using power line carriers [45]

As indicated in the diagram of Figure 2.6, PLC access networks are connected to the backbone communication via a transformer station in the network. There are several network sections from a transformer with different topologies. Still, independent from the PLC network topology, communication between the end users and the wide area network is carried out by the base station located in the transformer unit. The AMR meter interfaces are installed for each customer premise in the power distribution areas of the distribution transformer that steps down the MV to LV. Each metering unit has its unique ID and stores the consumption data in the intervals that is defined according to the network operation center (NOC) preferences. Besides, each AMR node has the capability to function as a communication relay (in the same way as a repeater functions in a telecommunication system) to transmit the data over a noisy path between another AMR meter and the concentrator that struggles to send or receive information to that problematic AMR meter.

Considering Figure 2.6, the data concentrator, which is normally located at the distribution transformer, is composed of a PC and three power line modems for each phase (R,Y and B). Besides, for each isolated section of the low voltage network, a new data concentrator should be located. Because the carrier frequencies of the AMR system is significantly higher than the mains frequency and the distribution transformers act like a low pass filter at the low voltage boundary, forming a restricted section for this specific low voltage sub network. The Ampmeter system also uses the same master/slave approach same as the optimal topology solution. Again the data concentrators are the masters and the AMR metering units are the slaves. As the data concentrators are on the LV side of the distribution transformer, the communication and control signals are simply transmitted over the power line between the concentrator and the metering unit. For the communication between the concentrator and the network operation center (NOC), a GPRS link by the use of GPRS modems is employed. Depending on the geographical position of the system installed and data transmission rate requirements, GSM, direct fiber optic, copper links or Ethernet protocol 802.11b can be utilized for the link between the NOC and the concentrator [46].

2.3.11.2 The Functions and the benefits of Ampmeter

As stated before the main functions of the Ampmeter is Automatic Meter Reading, remote connection of services and e-billing. Moreover, it enables the utility company to monitor the electrical network profiles of the customers. On the customer side, multi-tariff structures and increased cost control are added benefits. It provides both browser access over the Internet and cellular access over GSM. In addition, fraud management and complete logging of the customers' consumption values are included.

The Ampmeter system provides savings and improvements in the following ways:

- No additional cables required, GPRS is a wireless technology and PLC uses the existing cables
- The utility company benefits short deployment time, fast learning curve and a low total cost of software ownership and usage.
- Modest annual operating costs. GPRS is one of the most inexpensive wireless technologies and PLC requires almost no operating cost.
- The human intervention is avoided by abandoning the manual reading. All the utility meters are read automatically and transferred to the billing system.
- The utility company can keep track of the consumption profiles of the customers in real time. The Ampmeter application server is connected online with each individual Ampmeter module to read the meter information and execute the control commands.
- The utility company can easily monitor the consumption above the prepaid amount and the unpaid bills. If necessary, the consumer can be removed from the utility grid remotely. Moreover, additional cost savings can be achieved by detecting the tampering of meters with methods such as reverse rotation, meter slowing and bypass. The bidirectional communication of Ampmeter enables the utility company to check the current meter data against the historical data in case of any suspicion.

Besides, the functions of the PLC based Ampmeter can be summarized as follows:

- All the utility meters are read automatically and remotely on request via a browser based interface provided to the utility company. The consumption values are transmitted to the billing system which reduces the operational costs and increases accuracy. Similarly, the final reading due to residence changes is performed very quickly, reducing the operational cost. So as to say, on-request, scheduled and final readings are performed easily and accurately
- The proposed solution also enable the sub-metering of building complexes such as a construction site or a shopping centre, providing the electrical

network profiles and energy consumption information of the users, distributing the internal cost to monitor each individual load.

- The system offers appliance and utility control. In addition the network demand and supply management reduces the risk of power outages due to over consumption.
- The remote control enables the utility to cut off the energy to the illicit user or the customers who exceed the prepaid amount.
- The system offers logs and statistics over a browser based interface to the user, indicating the historical consumption profiles.
- The system offers interoperability to enterprise resource planning (ERP) and geographical information systems (GIS).
- Multi tariff structure, e-billing and prepaid cash solutions are available

2.3.11.3 Modeling the Ampmeter Network Structure

It is not always possible to obtain a direct communication between the data concentrator and a meter communication unit (MCU) because of the some channel impairments and high signal attenuation. As a result, the MCUs that are not directly reachable by the data concentrator has to communicate with the concentrator with the help of communication relays that operate as intermediate devices both to boost the transmitted signal voltage level and to collect and temporarily store the metering data from the MCUs that are not directly reachable. According to this approach, the network topology is divided into a hierarchical structure based on the ability of the MCUs to receive a direct signal from a source and transmit it to a destination without the need of using a relay on the way to boost the signal voltage level. So, the MCUs that can directly communicate with the concentrator are defined as Level 1 meters. The grouping of these MCUs forms the Level 1 of the hierarchical network. The MCU to be chosen as a relay should be considerably far away from the concentrator but still has to have a fairly stable and dependable communication link status. Only by this way, the relay MCU can boost the received signal and send it far in the rest of the network. Similarly, the MCUs that cannot communicate with the concentrator directly but can communicate with the relay in Level 1, are called Level 2 meters.

This procedure is broadened until all of the MCUs in the network can communicate either with the concentrator or with the relays. The figure 2.7 illustrates an AMR network in hierarchical structure.

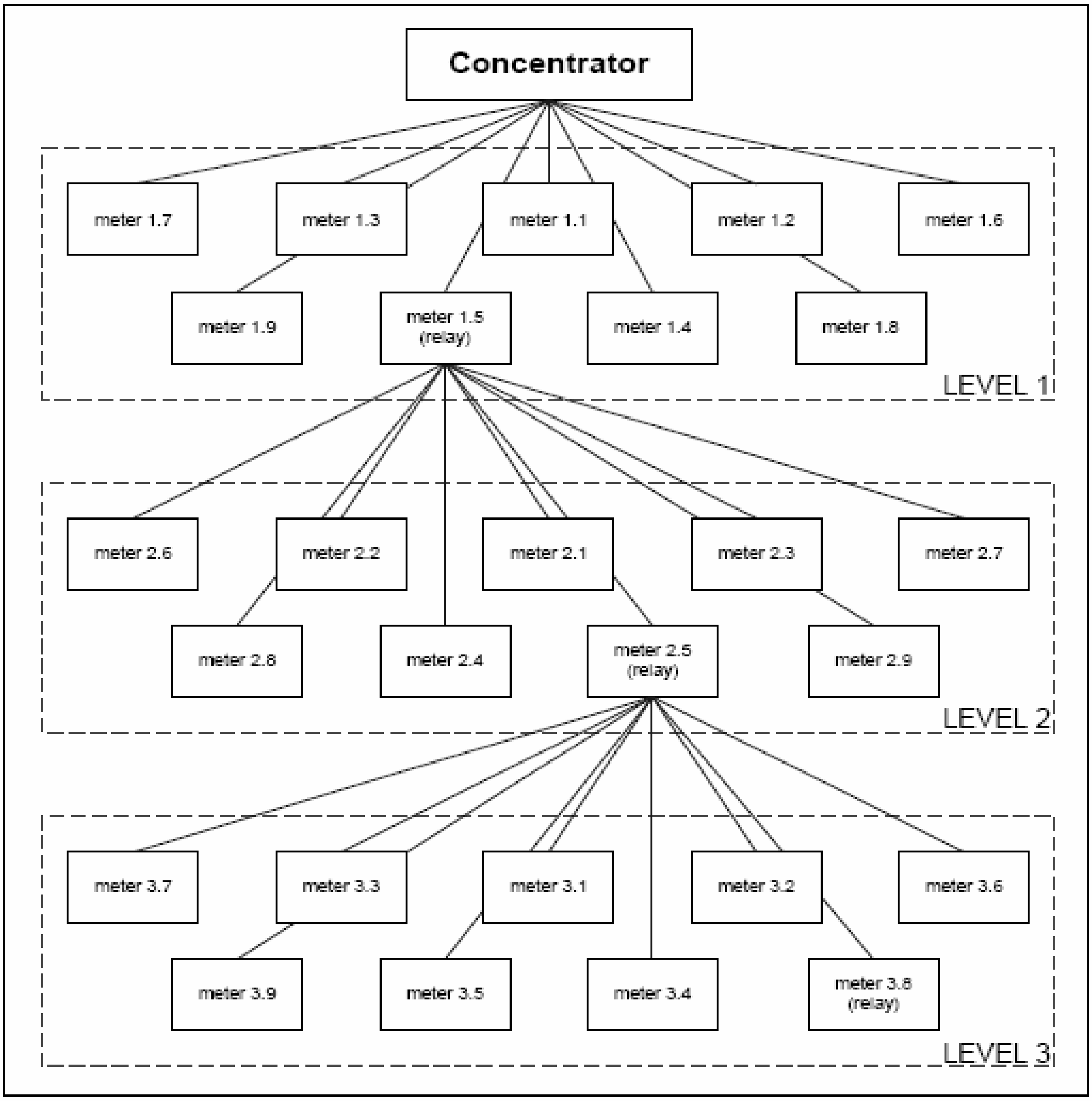


Figure 2.7: Implementing the AMR network in a hierarchical structure [45]

Also note that the locations of the MCUs in the above diagram are not done through logic. As stated before, for the procedure of the hierarchical structure, the MCUs are labeled systematically according to their distances to the concentrator. The actual logic is that when the concentrator broadcasts the hello packet during the initialization, the MCUs are registered to the network one after another according to the order of their reply packets which is called the hello confirm. Logically, the reply packets of the MCUs that are nearer to the concentrator will reach the concentrator faster and the closer MCUs will be given earlier network addresses. However, this first come first serve principle is not always applicable in practice. The reason is that in spite of the noisy environment and the channel impairments, the transmitted signals travel very fast in the channel, leading to a very short total transmission time. Actually this transmission time is much shorter than the time it takes for the concentrator to process an incoming packet especially from the MCUs that are nearer to the concentrator. As a result in this processing time, a lot of incoming packets are processed all together, and concentrator is unable to distinguish the real arrival order of the packets, causing an unreliable address assignment for the related MCUs. This phenomenon is called signal jamming [47]. There are various solutions to this problem but the simplest one for the AMR applications is to randomly delay the transmission time of the packets from the concentrator. Principally, the concentrator randomly adds a delay period to the packets that are sent out to the MCUs. Thereby, the concentrator sends out each packet at a randomly delayed time interval and records the time difference. By this way, the signal jamming is prevented to some extent and transmission collisions are decreased.

2.3.11.3.1 Basic Parameters of the Model

The meter ID, the different data packet formats and the database of the model is the described below. Note that although for the logic design and the microprocessor controlled algorithms, binary numbers are used to store and manipulate network address, in this chapter of this thesis work, decimal numbers are used for the representation of the network address to make them more understandable.

2.3.11.3.1.1 The Meter ID

Basically, the ID or network address of a MCU uniquely identifies the meter and indicates the meter location in the network. The format of the meter ID is as follows.

Note that for the phase bit the phases R, Y and B correspond to the 1, 2 and 3 respectively.

Table 2.3: The Electronic ID [45]

Network No.		Phase	Level No.	Sequence No.		
0	1	1	1	0	0	1

Every meter manufactured has a unique identification number issued by the manufacturer. This identification number is the electronic ID of the meter. After the installation of the meter at the customer premise, this identification number is registered to the customer's database. This ID is also manually recorded to the EPROM of the AMR meter in the customer site. As a result, all the information about the related customer such as the address of the premise, the consumption data etc. can be reached by searching with this identification number. Moreover, this meter ID can be added to the data packets sent out from a particular meter, specifying the location of the meter in the network. The uniqueness of the meter ID is important to link a particular meter on the AMR network to the meter's actual physical address. Moreover, it enables the model to share network topology information to be employed to construct the overall network structure [47].

2.3.11.3.1.2 Data Packet Design

The typical packet design for the proposed AMR network is illustrated in Table 2.4

Table 2.4: The 10 message types designed for the AMR system protocol [45]

M1	M2	M3	M4	M5	M6	M7	M8	M9
Message Type	**Source ID**	**Destination ID**	**Electronic ID**	**Relay Designation**	**Signal Level**	**SIR**	**Metering Data**	**Meter Status**
Hello (1)	✓	✓						
Hello confirm (2)	✓	✓	✓		✓	✓		✓
Assign address (3)	✓	✓	✓	✓				
Assign address confirm (4)	✓	✓	✓	✓				
Data request (5)	✓	✓						
Data send (6)	✓	✓					✓	✓
Repeat data send (7)	✓	✓					✓	✓
Relay report (8)	✓	✓	✓					✓
Relay report confirm (9)	✓	✓	✓	✓				
Alert (10)	✓	✓						

For a packet transmission both the Source ID and the Destination ID are needed to specify where the packet comes from are where it is sent to. Each MCU's unique network address that indicates its location in the network can be used as source or destination ID. Nevertheless, some default value may need to be assigned to the Source or Destination IDs in predefined cases:

- For packets sent from the concentrator, by default the source ID is 1111111.
- For packets sent to the concentrator, the destination ID is 1111111.
- For broadcast packets sent to all MCUs in the network, the destination ID is 0000000.
- For a hello packet sent from a MCU whose address is not yet assigned, by default the source ID is 0000000.

The hello packet is used for the initialization of the network for the purpose of registering the slaves to the network. This process can be resembled to sending a message saying "hello, can anybody hear me?" Every MCU that can receive the message properly will reply back with a hello confirm packet which includes the network address of the MCU and the electronic ID. In addition the signal to interference ratio (SIR), which is used for the determination of the communication relays, is also sent. Note that, the signal to interference ratio (SIR) in dB is calculated according to the formula;

$$SNR(dB)= 20 \log10(VR/VT). \quad (2.1)$$

Similarly, the functionality of a particular MCU can be controlled by making the MCU send out hello packets periodically. In this way, the communication links of the MCU to the surrounding MCUs can be checked. The meter status register indicates whether the MCU is functional or not. The register is set to 1 if the meter is functional. If the meter is removed from the system or the customer has ended the contractor with the utility, the register is set to 0. Similarly, if the meter is damaged and the communication with the meter is lost, the status register is set 0. At this stage, if the MCU does not respond after a preset number of hello messages, the customer database is checked at the network operations centre to determine the location of the damaged meter. Then, a technician is sent to the physical address of the meter to see if the meter is damaged or removed from the system. The hello and the hello confirm packet formats are as follows:

Table 2.5: The hello packet format [45]

Message Type	Source ID	Destination ID	Electronic ID	Relay Designation	Signal Level	SNR (dB)	Reading Data	Meter Status
1	1111111	0000000	xxxxxxx	x	xxx	xx	xxxxxxxxxxxx	x

Table 2.6: The hello confirm packet format [45]

Message Type	Source ID	Destination ID	Electronic ID	Relay Designation	Signal Level	SNR (dB)	Reading Data	Meter Status
2	0000000	1111111	2312015	0	3.45	34	xxxxxxxxxxxx	1

The third packet type, assign address packet, is used by the concentrator to assign network address (meter ID) to the meters. Obviously, when the meter receives this packet, it replies back with the assign address confirm packet. Another message type called the relay designation field determines if the related meter is defined as a relay or not. Apparently, if the meter is assigned as a relay in the hierarchical network, the register is set to 1, otherwise it is 0. Moreover, the data request packet is sent to collect the meter readings. The concentrator sends the data request packet to a meter to receive its meter readings. The meter responds back to this message with the data send packet containing the required information.

Furthermore, the repeat send data packet is used by a relay or concentrator to confirm that the receiver has properly decoded the data sent message. When a relay or concentrator receives a data send packet, it replies back to the sender of the metering data with the repeat data send packet that includes the same information as the data send packet. This entire process is employed to check the data integrity.

The eight packet type, the relay report packet, is composed of the routing information of a particular level in the network. Relay report packet is sent by a particular layer containing the topological data of the meters that are one level down from this relay to the concentrator. As expected, the relay confirm packet is sent from the concentrator to the relay that has sent the relay report packet for the purpose of informing the sender relay that the relay report packet is received. The last packet type, the alert packet, is used to send an alarm message to the network operation center in accordance with the alarm monitoring service of the AMR utility company. The alert packet, which is an integral part of the AMR’s value added service, has the highest priority and all the other transmission is stopped to make the alarm signal be transmitted to the destination. Nevertheless, the alarm signal should be short compared to other message types for the purpose of minimum transmission time and immediate respond or reaction.

2.3.11.3.2 Proposed Database Structures

The vital information about the network architecture and functions are stored in the concentrator database. The information about all meters is accumulated in this database and has a sample format as in Table 2.7.

Table 2.7: Sample concentrator database [45]

	Meter ID	Electronic ID.	SIR (dB)	Metering Data
Level 1:				(Reading/Time/Date)
Relay	01 1 1008	12 1 1 008	18	12345 23 55 31 08 03
Meters	01 1 1001	12 1 1 001	78	23456 23 55 31 08 03
	01 1 1002	12 1 1 002	70	34567 23 55 31 08 03
	…	…	…	…
Level 2:				
Relay	01 1 2005	12 1 2 005	18	45678 23 33 01 09 03
Meters	01 1 2001	12 1 2 001	35	18659 23 33 01 09 03
	01 1 2002	12 1 2 002	25	17325 23 33 01 09 03
	…	…	…	…
Level 3:				
…	…	…	…	…

On the other hand, the relay database has a similar structure to the concentrator database except the fact that the relay database does not store the information about all of the meters in the network but it keeps the information for the meters that use it as an access point and send data through it. Note that for the sample relay database in the Table 2.8. The meters listed under the relay database are one level below the level of the relay.

Table 2.8: Sample relay database [45]

	Meter ID	Electronic No.	SIR (dB)	Metering Data
Meters	01 1 2001	12 3 2 110	25	01234 23 33 01 09 03
	01 1 2002	12 3 2 111	30	12345 23 33 01 09 03
	01 1 2003	12 3 2 110	22	23456 23 33 01 09 03
	01 1 2004	12 3 2 111	31	34567 23 33 01 09 03
	01 1 2005	12 3 2 110	45	45678 23 33 01 09 03
	01 1 2006	12 3 2 111	40	56789 23 33 01 09 03
	…	…	…	…

Similarly, the meter database holds the locally stored information about the meter such as meter ID, electronic no., SIR value and the up-to-date meter data in its storage memory. Furthermore, each meter checks the noise level in its nearby communication environment at periods of 100 ms.

2.3.11.3.3 Communication Relay Designation

Practically, starting from the outermost meter i.e. the meter with the largest network address (according to Table 2.9, the meter with the network address 1060), 10 consecutive active (communication status register value equal to 1) meters are chosen. These meters are signed with a circle in Table 2.9. After that, the Dijkstra algorithm is applied on these 10 consecutive meters with the metric calculated as the distance from the meter to the main distribution line. The details and algorithmic logic of the Dijkstra algorithm can be seen in Appendix A. One of the meters among these 10 meters is chosen as the communication relay for the meters in this level, depending on the Dijkstra algorithm.

Table 2.9: Selecting 10 consecutive meters with communication status of "1" [45]

Address	Distance	Noise Level	SNR	Com Status	Relay
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
1042	663.5	0.86003	14.571	1	0
1043	663.82	1.0982	9.6641	0	0
1044	667.43	0.98999	11.541	0	0
1045	667.5	0.55886	22.974	1	0
1046	667.64	1.1173	9.1093	0	0
1047	667.83	0.10342	56.697	1	1
1048	669.02	0.55443	23.049	1	0
1049	669.2	0.83104	14.944	1	0
1050	669.44	0.58841	21.835	1	0
1051	669.69	0.33592	33.033	1	0
1052	673.55	0.54345	23.197	1	0
1053	673.62	0.28523	36.086	1	0
1054	675.18	0.14889	49	1	0
1055	675.2	0.68246	18.549	1	0
1056	675.74	0.18894	44.204	1	0
1057	679.41	1.0647	9.4162	0	0
1058	679.66	0.29435	35.115	1	0
1059	679.89	0.4345	27.313	1	0
1060	679.92	0.88269	13.136	1	0

From the outermost meter (address 1060), count 10 consecutive meters with communication status equal to "1".

As seen in Table 2.9, the meter with the network address 1047 has 1 in the relay register as it is chosen as the communication relay. In addition to the communication relay three other relays are chosen as the backup relays because of the noisy channel conditions of the LV power line. However, in the further trials, it was observed that the distance metric methodology is not suitable as it is based on the transmission time of arrival, resulting to signal jamming problems.

A more realistic variable was searched to optimize the relay designation. According to the signal to noise ratio equation, the received signal strength and also the SIR value is reversely proportional to the distance due to the cable attenuation factor. For that reason, omitting the other variables, a meter's SIR value can be expected to decrease as the meter is further away from the concentrator. As the purpose is t o select the meter that is considerably distant from the concentrator (to have a broad range of meters in its vicinity) but still has a sufficient signal strength and a dependable connection status to the concentrator, it is logical to select the meter with the smallest SIR value which is still above a specific preset SIR threshold as the communication relay. However, considering the unfriendly and unpredictable nature of the power line, it is always possible for a meter with a SIR value slightly above the threshold to experience communication problems due to rapidly changing communication channel conditions such as a sudden impulsive noise or multipath interferences coming out as a result of load changes. For the model described above, a 6 dB SIR margin is added to the threshold value of 11 dB, yielding a total SIR of 17 dB. The meter with the SIR value closest to 17 dB is to be selected as the communication relay with the suitable communication range and a reliable communication status.

As stated before, the primary intention for this model was to select three backup relays. However as the backup relays chosen will have SIR values very close to the original communication relay, it is probable that these backup relays might also be at the edge of failing. Thus, the final decision is not to choose any back up relay. When a selected communication relay fails to respond to a packet, depending on the transmission direction of the packet, the relay either one level up or down the communication relay will be able to detect that this particular relay has stopped transmitting. Following that, the functioning relay starts to send out hello packets, collecting the SIR values from the meter that respond with the hello confirm packets. According to these new SIR data, the functioning relay is to select another relay as the new communication relay in this particular level.

2.3.11.3.4 Network Topology Update

For the proposed AMR model, the topological database of the system is updated periodically to guarantee that the system regularly adapts its routing topology in accordance with the network changes.

The process starts with the concentrator broadcasting hello packets throughout the network in a periodical basis. Naturally; all the meters located in the Level 1 respond to these packets with the hello confirm packets. Similarly, the currently chosen relays on all other levels of the network send hello packets to the meters that are located in the lower level in network hierarchy. As all those meters are assigned their network IDs, the assignation process is omitted. Only the relay report and the relay report confirm packets are communicated between the concentrator and the relay of each corresponding level. In this way, the update of the entire database is completed with the meters registered with their up to date addresses and information in the concentrator database.

2.3.11.3.5 Routing Techniques

2.3.11.3.5.1 Adaptive Routing

Obviously, low voltage is an unfriendly communication environment because of various channel impairments. The noise levels are highly variable and dependent on the load types connected to the line. Besides, the changing load impedance and high attenuation develop the need for multiple and alternative paths for signal transmission. So as to say, no signal transmission path is reliable enough for continuous and uninterrupted transmission.

Adaptive routing (referred also as dynamic routing) is employed as a routing technique that can adapt the transmission channel to the changes such as traffic patterns, equipment failures, channel availability and circuit expansions such as addition or removal of some nodes or new area development. Adaptive routing protocols are effectively used for network configuration of AMR systems as the LV network is a dynamically changing network. The main benefits of the adaptive routing are improving network performance and increasing the fault tolerance by offering multiple routing paths [48].

The adaptive routing protocols are favorable as the cost for signal processing decreases and better communication performances are observed. Besides, considering the rapidly and unexpectedly changing communication environment of the PLC based AMR networks such as new housing area developments and land transformations, the adaptive routing protocol's potential to adapt future changes is important [45].

Several networking protocols exist in the literature that are applicable for PLC based AMR networks. The Adaptive Token Passing Protocol and the Open Shortest Path First (OSPF) Routing Protocol are the two most widespread protocols.

Adaptive Token Passing Protocol and Open Shortest Path First (OSPF) Routing Protocol

Token passing protocol is an algorithm that is based on passing a token around a ring or nodes according to a logarithmic, binary search methodology [49]. Fundamentally, the token represents the access right to the communication medium, which means that the node that possesses the token has the momentary allocation and the control over the channel. The token is circulated among the participating nodes and the by the use of this token, a logical ring is established.

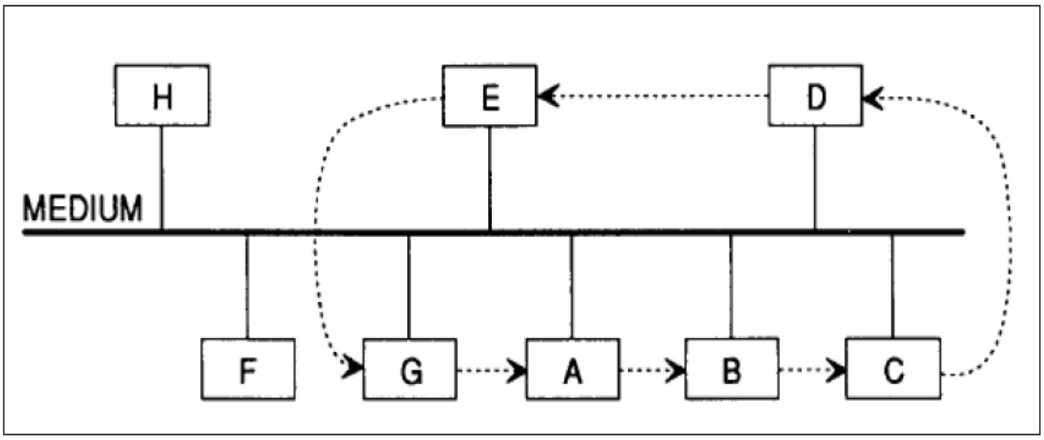


Figure 2.8: Logical ring formed on the physical bus [49]

The steady state operation of the protocol consists of two stages; token transfer phase and the data transfer phase. The other operations involved are ring initialization, addition or removal of a station, lost token recovery etc.

The adaptive token passing method can be employed for AMR network initialization such that each logical ring established during one complete process of token passing algorithm is to be defined as a hierarchical level of the AMR network. However, in practice this method has some disadvantages. As stated before, there are two stages, token transfer and data transfer, which lead to too much overhead resulting from passing the token around the tree structured network. Moreover, the constant maintenance of the network (addition and removal of nodes, new token generation etc) may incur additional overheads [50].

Considering the limited transmission rate and channel capacity of the narrowband AMR system described, algorithm that can occupy the channel less are more favorable. That is why, some network designers prefer to use the Open Shortest Path First (OSPF) Routing Algorithm that broadcast routing information only when changes occur in the network architecture such as a failed communication link or an additional meter being installed to the AMR system. Furthermore, OSPF has no limitations on the number of nodes (or meters for AMR), OSPF supports hierarchical network structures. Besides OSPF employs IP multicast routing which means less processing on router units for the units that are not listening to the network. Finally, the updates are sent only in case of routing changes and not periodically. This leads to an effective usage of bandwidth [51].

2.3.12 DLMS: The application protocol for communicating meters

DLMS, which aims for the standardization of the messaging system, represents the Distribution Line Message Specification. In some literature it is also referred as Device Language Message Specification. This standard ensures the non-proprietary, internationally standardized communications protocol for PLC. The initialization and the evolution of this standard resemble the standardization studies for the Telecom Industry when new applications and devices were coming forward but were isolated from each other without interoperability. The telecommunication companies quickly realized that this lack of interoperability stands in their way to expand the telecommunications market. So as to say, the companies were settling for a share of a small market rather than developing together a bigger market. This ambition leaded to an international effort to develop the Open System Architecture (OSI) Model which was published by ISO in 1984. Most of the communication standards including the Internet Protocol Suite depend on the layered model of OSI. Eventually today, telecommunications market is considerably big and the telecom service providers, manufacturers and the end users are getting their shares from this big market [52].

The communication systems are commonly used by utility companies for management of energy production and supply under the name of Distribution Automation applications. Moreover, Customer Automation applications such as remote meter reading and tariff control also make use of communication systems. However most of the emerging technologies in this field are also use proprietary protocols and stand as isolated, non-interoperable applications. On this account, International Electrotechnical Commission (IEC) is working on standardizing DLMS to introduce a common language for all kinds of communication systems employed in energy industry. The target of DLMS studies is to guarantee the interoperability of the all the metering communication equipment (meters, data concentrator etc.) The proposed solutions are aimed to be simple enough and independent on metering application or the communication medium.

2.3.12.1 The DLMS Object Model

DLMS, which is an object oriented application model, employs object oriented modeling to describe the DLMS device model and service procedures. In the scope of DLMS, the operations and characteristics of the abstract object types are described.

The DLMS model is represented by five object types. The outmost object type is the Virtual Distribution Equipment (VDE) which models a real application. The other four objects are located in the VDE. The four objects are classified under two categories:

- The resources of a real device are represented by the virtual objects including data set, task invocation and variables.
- The Virtual Application Association Object specifies the communication aspects.

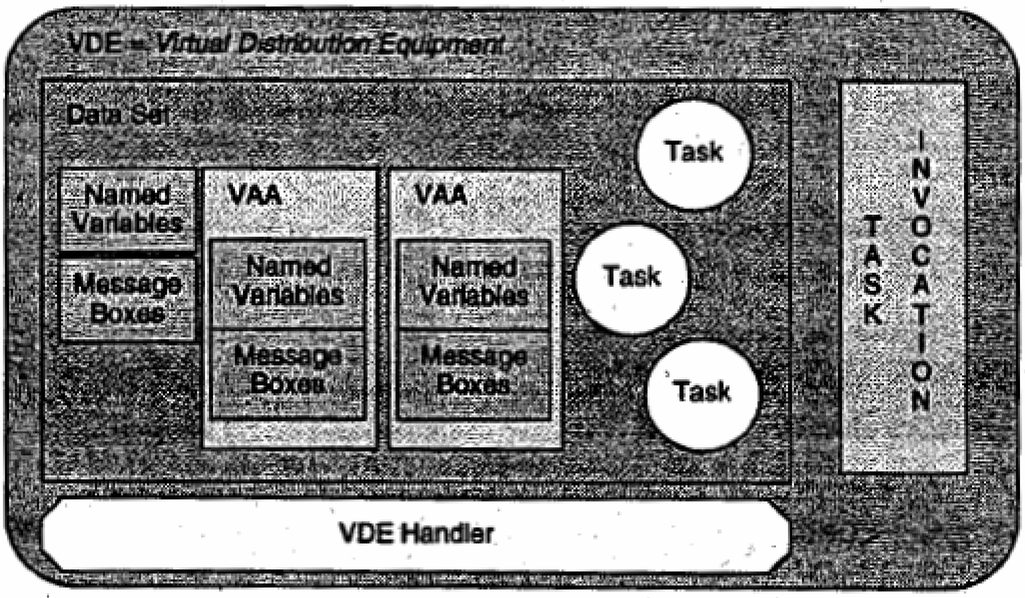


Figure 2.9: The virtual distribution equipment [53]

All the objects above are interface objects that model the real device in an external point of view. To ensure independence from the real application, the DLMS objects do not interfere with the modeling of the real objects. All the real appliances such as meters, concentrators etc. are indicated as virtual distribution equipments to which external observes have no direct access.

2.3.12.2 DLMS as an Application Protocol

In scope of the DLMS model, different object instances are defined and the operations of these object instances are cited remotely. In the context of the OSI reference model, this type of remote citation stands for the application protocol. Note that, the DLMS model is not a communication protocol but is used as a basis for communication protocol because it represents an abstract structure for all communication related functions. The main benefit of OSI reference model is the decreasing the complexity by logically fragmenting the entire communication system into smaller functional models, referred as layers [53].

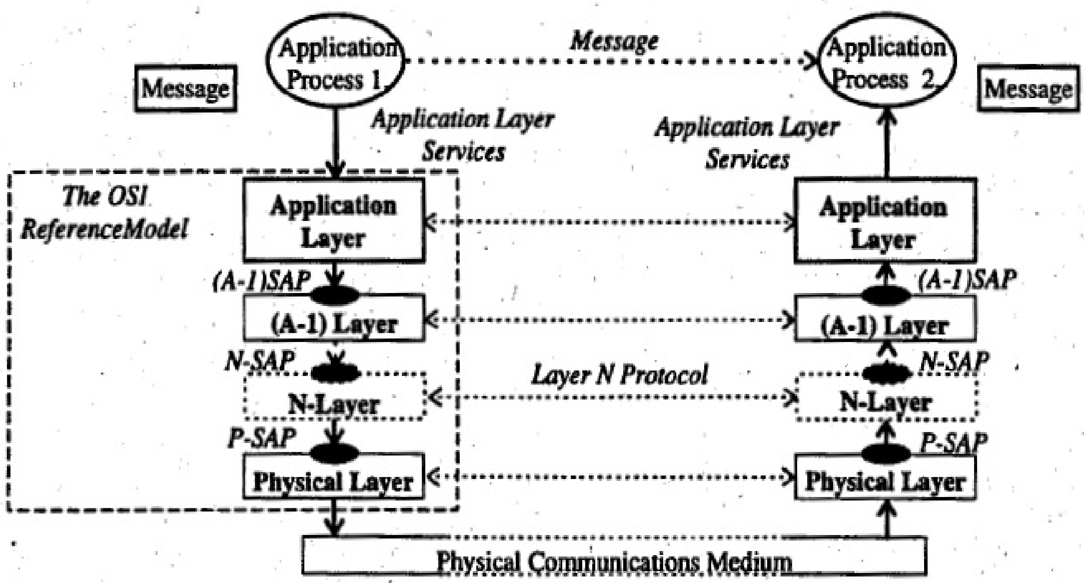


Figure 2.10: Communications within the OSI reference model [53]

The layers of the OSI protocol are divided into two groups. From bottom the top, the lower layers are:

1) Physical
2) Data link
3) Network
4) Transport

And the higher layers are:

5) Session
6) Presentation
7) Application

According to OSI protocol communication illustrated Figure 2.10, the consequent application processes that are outside the layer protocol transmit their messages via the communications functions distributed in the layers. Obviously, application processes can only be in contact with the closest layer which is the application layer. Similarly, the application layer contact with the next layer and this process goes down to the physical layer which has no other layers but the real physical communication medium with the real world signals.

Note that each layer isolates its communication aspects from the layer below. In this particular approach, the application layer provides the system with a communication channel independent specification for the message exchange in the application process and an interface to the communications support supplied by the other layers.

In order to activate the operations of the DLMS objects, a message is transmitted from a client that uses the application process of the DLMS model to another client that employs the same application process which contains DLMS objects. The DLMS application protocol is used to specify these messages and to execute these messages in the Application Layer. Following the OSI Application Layer conventions, the supported message formats referred as service syntax and the dynamic behavior which consists of the regulation for the way the services are executed. The service syntax for DLMS services is determined according to the ISO standard Abstract Syntax Notation No.1. On the other hand the dynamic behavior is described by the help of state transition diagrams and time sequence diagrams [54].

2.3.12.3 The Current Status of DLMS and the Upgrade Path

DLMS protocol was developed primarily by Electricity de France in cooperation with Landis&Gyr. DLMS was intended as a simpler messaging system alternative for the already standardized Manufacturing Message Specification referred as ISO 9506-1 and 9506-2. Moreover, the protocol is named as DLMS as the first complete communications protocol that makes use of DLMS was an application of power line carrier technology called Power Line Automation Network (PLAN). Accordingly, the Working Group 9 of the IEC TC57 completed the standardization of the DLMS and named it as IEC 1334-4-41. This international standard defines the DLMS Object Model and defines DLMS as an application protocol in terms of protocol and services. Again, the same working group had some studies on DLMS based communications in the scope of PLC communications and other elements of the OSI protocol's higher layer application such as transfer syntax, association control service element, etc. The group also came up with three PLC communication profiles and proposed them to be standardized [54].

The DLMS is also attractive for different types of utilities and other standardization bodies of the meter communications domain as it can be used as the basis of all Application Protocol for all meter types. Furthermore, another working group, IEC TC13/WG14 has some studies on DLMS communications profiles for other communications media such as twisted pair, PSTN, etc. Similarly, CEN TC294 has some studies on DLMS based communication protocol for other utility meters such as water, gas, heat etc.

On the other hand, the user of the DLMS model should be able to identify the relation between the DLMS model which is the solely identified visualization of the model by the client and the real objects defined by the DLMS model. The logarithm and the real life counterpart of the objects defined should be clear to the client. For example an integer value returned by the protocol's logarithm can represent the power fails since the last reading, the current tariff rate or any other parameter defined in the model concept. The link between the objects created and their real life equivalents should be perspicuous. It is the companion standards that define this relationship between the DLMS attributes of the objects created within DLMS model and the real objects. Thus, interoperability can be attained by clearly defining both the DLMS protocol and the related companion standard.

In conclusion, DLMS is at the development stage of its life cycle compared to some other multimedia metering systems that is composed of meters that can serve several types of utilities (electricity-gas or electricity-water) by working over several communication media at the same time. Besides, these multimedia meter systems including the multivendor meters are more favorable in means of interoperability. To close the gap, there are several developments that DLMS should focus on:

- The open technical issues should be resolved.
- Complete metering systems such as industrial DLMS client systems should be developed
- Standard communication profiles should developed for communication media such as PSTN, twisted pair etc.
- Similar standards for other energy distribution equipments other than the meters only, should be generated

Only after these steps, the DLMS protocol can be the common language for metering communication systems providing the simplicity, flexibility and ubiquity.

2.3.13 ATICON’S Low Cost Power Line Modem for Domestic Applications

Obviously, the installation costs of the PLC technology are relatively low compared to its rivals, as there is no need of any additional wiring. This low cost aspect is important for the consumer market. The system is composed of the power line modem, power supply, line interface, application protocol and an opto-galvanically separated I/O interface [55].

Besides, the utility applications such as AMR, PLC can also be employed for home automation systems, enabling the individual stations to communicate and exchange information with each other as a way of linking the domestic appliances to the global world. Some example application fields are energy management and reduction of peak power consumption of white goods. As the household devices do not need power continuously but only for a certain period of time, the peak power consumption can be reduced and the energy price can be lowered if these consumption periods can be interlaced. Some other potential application areas of PLC for home automation are remote control, entertainment (audio, video), security (burglar alarms), safety (water leak detection) and HVAC [56].

The PLC based home automation systems are also compatible with CENELEC EN50065-1 standards defined for the transmission on low voltage installations. As stated before for the definition of CENELEC standards, the frequency band allocations are as follows:

- A band: 3 – 95 kHz is allocated to energy suppliers.
- B band: 95 – 125 kHz can be used by any application without the need of an access protocol
- C band: 125 – 140 kHz is reserved for home automation products. CSMA (Carrier Sense Multiple Access) algorithm is required to be employed to provide the co-existence of different systems in this frequency band.
- D band: 140 – 148,5 kHz is reserved for alarm and security systems without the necessity of using an access protocol [57].

2.3.13.1 EHS – a Common European Standard

As stated before to increase the penetration rate, adding value to the acceptance of home automation technology and the interoperability and the compatibility are targeted by several projects such as EUREKA and ESPRIT. [58] Some major European companies such as ABB, AEG, British Telecom, Electricité de France (EdF), Electrolux, GEC, Philips and Siemens are involved in the development of these projects resulting in European Home System Network (EHS). The EHS is applicable over six different physical medium for the information transfer to and from the domestic appliances. These are: twisted pair (9.6 kBaud), twisted pair 2 (64 kBaud, ISDN), coaxial, infrared and radio frequency.

EHS also enables the plug&play installation mechanism for the power line. The network addresses of the nodes are automatically assigned (registration) and the application links are established (enrolment). Thus, there is no need for a technician for the installment process. Last but not the least, the standardized command language of EHS provides the flexibility for the applications from various manufacturers.

2.3.13.2 EHS Power Line Medium

Power line channel is a standardized medium of the EHS specification. The communication is established via a 2400 half duplex protocol with FSK (Frequency Shift Keying) modulation in accordance with the CENELEC EN 50065-1 standard over the C band using CSMA (Carrier Sense Multiple Access) collision avoidance. The centre frequency is 132,5 kHz and the frequency deviation for data transmission is $\pm$0,6 kHz. Thus, the logical “1” is represented by the lower frequency (131,9 kHz) and obviously the logical “0” is represented by the upper frequency (133,1 kHz) Finally, in accordance with the CENELEC C band limitations the output level of the power line transmitter can not exceed 116 dB(μV). The figure 2.20 below is the schematic of the EHS Power Line Diagram.

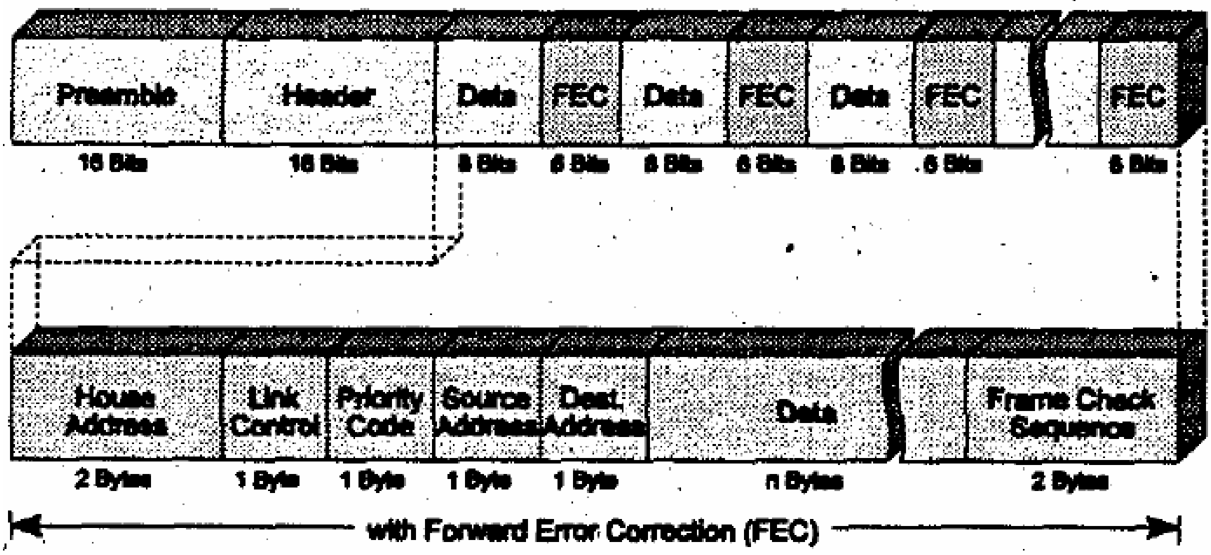


Figure 2.11: EHS Power-Line Datagram

For EHS, differently from the conventional common serial data protocols, there is no start or stop bits for every data byte. A 16-bit preamble consisted of 8 falling and 8 rising edges are employed for the synchronization of the receiver and the transmitter. The following 16 bit header code is used for the recognization of the EHS datagrams or EHS acknowledges in case of loss or destruction of bits due to a noise in the network. For the purpose of 6 bit Forward Error Correction (FEC), each byte of the following sequence (every 8 bits) is extended to 14 bits. The generator polynomial for the FEC is $x^6+x^5+x^4+x^3+1$ and at maximum three succeeding bit errors can be corrected within 14 bits. This error correction algorithm is suitable to avoid the disturbing effects by the switch mode power supplies or light dimmers in the form of impulse noises that can last approximately 1 ms, mostly repeated every same phase angle. As mentioned before, the EHS power line packet can be a datagram or an acknowledge packet. The datagrams are used for the transmission of control information while the acknowledge packets s are for the confirmation of the reception of a diagrams by the receiving node.

2.3.13.3 The components of Aticon's Low Cost Power Line Modem

2.3.13.3.1 Power Line Modem

In brief, power line modem generates the FSK-modulated signals, supervises the CSMA collision avoidance protocol and provides the clock, reset and watchdog to the system [59].

2.3.13.3.2 Power Line Interface

The power line interface acts as the coupling circuit between the power line modem and the mains line. The power line modem modulates the signal at the sender side and the sender power line interface feeds the modulated signal to the line. At the receiver side, power line interface receives the signal and passes to the power line modem for demodulation. For the cost concerns, no inductive signal transformers are used for galvanic isolation. Thus, the system is not galvanically isolated from the mains. The primary component of the power line interface is the high voltage coupling capacitor that has a low impedance at the centre frequency of 132.5 kHz. Furthermore some analog filters are also employed in addition to the coupling capacitors to improve the quality of the receiving signal. Additionally, a varistor is also used to protect the line interface against potential damages of the transients in mains line [59].

2.3.13.3.3 Power Supply

A switch mode power supply is employed for voltage conversion. The power supply firstly divides the mains voltages up to 250 V into short sections and then smoothes these divided portions to DC voltage. The switch mode power supply provides two different voltage outputs: 10V for the power line modem with a current rating up to 200 mA and 5V for the microcontroller with a current rating up to 100 mA [59].

2.3.13.3.4 Application Processor

The application processor used is a cost efficient Intel-8052 compliant microcontroller with 256 bytes of internal RAM. In addition to that, a serial EEPROM of 256 bytes memory can be added to the system. Finally, the serial interface of the microcontroller is connected to the opto-galvanically separated I/O interface with a connection speed of up to 19200 bauds over full duplex asynchronous data transmission [59].

2.3.13.3.5 I/O Interface

The power line node is connected to the outer world over the I/O interface. Two inputs and the two outputs are supplied with an isolation voltage of up to 5300 V AC and the maximum switching frequency of the optocouplers is 20 kHz [59].

2.3.13.3.6 Software

The triple bit scanning algorithm with majority decision yields a high noise rejection capacity. The carrier detection provided by the software enables the reception of signal below 5mV. The EHS protocol, which defines the commands for various applications such as heating, air conditioning, security, safety etc, increases the system flexibility. As stated before, the structure of the EHS protocol stack implementation complies with the OSI model, omitting the layers 4, 5, and 6. According to the regular protocol algorithm, a unique network address is assigned to each device (registration), and then each device begins to search for the communication partners in its surrounding network (enrollment). Finally, the network addresses and the defining properties of the nodes are stored in the Application Title Directory [59].

2.3.13.4 Conclusion

After the rapid development of signal processing and semiconductor technologies, the transfer rates for the PLC devices described are able to reach to speeds above 100 kbps. Comparing all the PLC alternatives described in this thesis work, no single solution is a clear winner above another one. But the coexistence of each of them in this unfriendly communication environment is a more realistic conception.

2.3.14 An AMR Application Example: Automatic Remote Meter Reading Using Power Line Carrier Systems in UK

The low voltage distribution network that is also functioning as a communications medium has the delivery of electricity functionality at 230 V and 50 Hz. An integrated remote metering communication and information system infrastructure is needed not only for the cost effective tariffing structures but also for the fact that the communication path from the supplier to the end user can involve multi parties and can have a complex structure.

Depending on the previous experiences in meter reading business, the utility companies realized that to satisfy the potential customers of a fully automatic remote meter reading system, the implementation of an accurate system that has less faults and faster repair times is crucial. Moreover the system should be resilient and should be able to interface with the various communication technologies available. Needless to say, the various customer infrastructures that can be interfaced with the AMR network should be further investigated as the type and size of customer infrastructure affects the amount and type of data that can be transmitted over the system [60], [61], [62].

After the deregulation of the UK Electricity Supply Industry a three tier model was developed. Tier 1 is for the customers with requirements of 1 MW and above, tier 2 is for the customers with requirements of less than 1 MW but greater than 100 KW and tier 3 is for the customers with less than 100 KW.

Another aspect worth noting for the load requirements of the customer systems and the related customer infrastructures is the time periods that the peak consumption of loads occurs. Within the day time, the load variations occur between the hours 06.00 - 09.00, 12.00 - 14.00 and 16.00 - 21.00. For example, for industrial premises, the utility load requirements are expected to decrease at 18.00. Besides, some fluctuations also occur in weekends and holidays. The seasonal variations should be also taken into account. Therefore, the best time for the PLC based meter reading to read the domestic and residential consumption can be between the midnight and 07.00 in the morning when the human activity is limited. For the residential reading the readings can be also switched to the hours between 10.00 and 15.00 when the people are at work. Hence, the human interference to the PLC systems as noise sources is minimized. Similarly, for factories an appropriate time of the day for readings is the evening hours when the production is stopped. For all these applications, the physical interface needed to execute the transmission, the volume of the data sent, the complexity of addressing, protocols and control mechanisms are core elements to be decided [63].

2.3.14.1 The Proposed Remote Meter Reading Protocol Architecture

For AMR purposes, CENELEC defines a protocol stack of Low Voltage Distribution Networks that is composed of 3 layer DLMS model, derived from a the well known OSI 7 layer model. See Figure 2.12 for the 3 layer DLMS model.

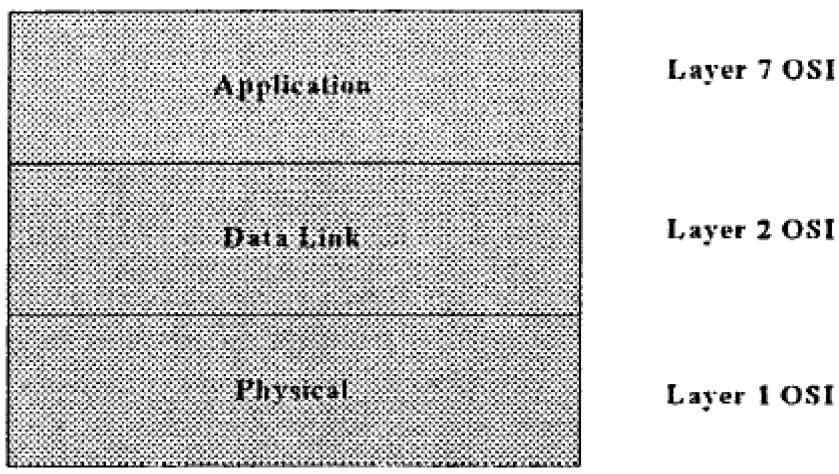


Figure 2.12: Layer DLMS model [63]

The top level which is the application layer is independent of any communication media to have a clear and unique view of all meter configurations. Oppositely, the layer 1 and 2 depend on the communications media employed. The related configuration is shown in Figure 2.13. The application layer is divided into two parts: the distribution line message specifications (DLMS) and the logical link access control (LLAC). DLMS was initially developed by Electricity de France (EDF) for PLC applications by modifying the Manufacturer Messaging System (MMS) which was defined as an International Standard by IEC TC 57.

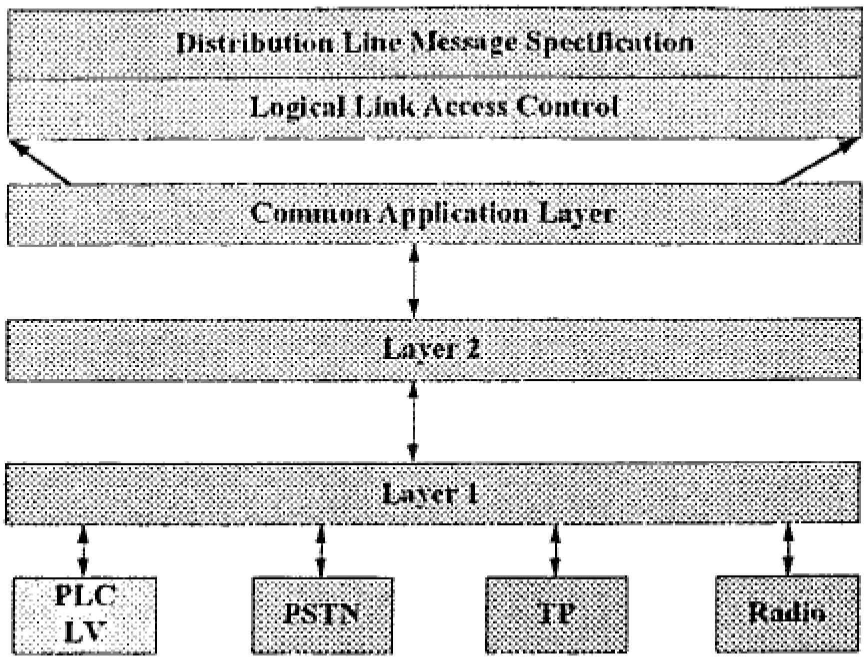


Figure 2.13: IEC protocol architecture. [63]

In addition to the DLMS standards and for the purpose of adapting the DLMS metering applications, a common Companion Standard (CS) that is composed of additional rules to ensure the interoperability and compatibility with the semantics and the syntax of the DLMS kernel is defined. CS can be specific for the individual meters manufactured by various companies and reflects the capabilities of those meters. The CS can not be represented as a independent and transparent presentation of a meter rather than an Application Layer Companion Specification. The related development scheme of a Companion Specification is illustrated in Figure 2.14.

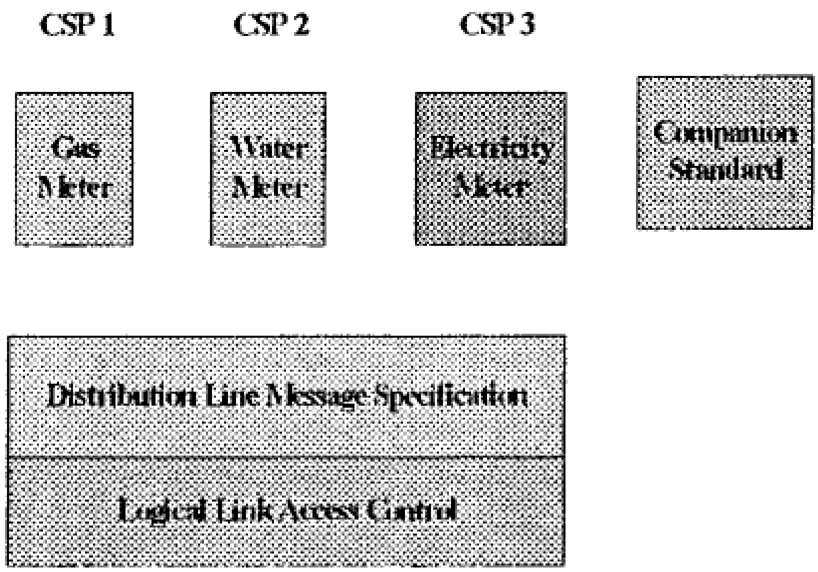


Figure 2.14: A companion specification [63]

DLMS has common elements for all meters such as ID, encryption key, address of the node, and billing. Still, every manufacturer can differentiate its metering capabilities within the terms of the standards. Apparently, definition of the objects is an integral part of the Companion Specification of a meter since these objects determine the meter's aspects and behaviors in the communication link's perspective.

Companion Specification indicates the physical devices such as meters and meter interface units as individual or multiple Virtual Distribution Equipments (VDEs). Each VDE defines another function of the device. For example, a single VDE, which is called Management VDE, can be attributed the task of representing the information of the physical device itself. Thus, even the simplest MCU in the remote meter reading configuration will include the Management VDE, while on the other hand a metering node includes both the Management VDE and the Metering VDE. Similarly, for a more complex remote meter reading architecture specific nodes can include not only Management and Metering VDEs but also Supervision and special application VDEs [64].

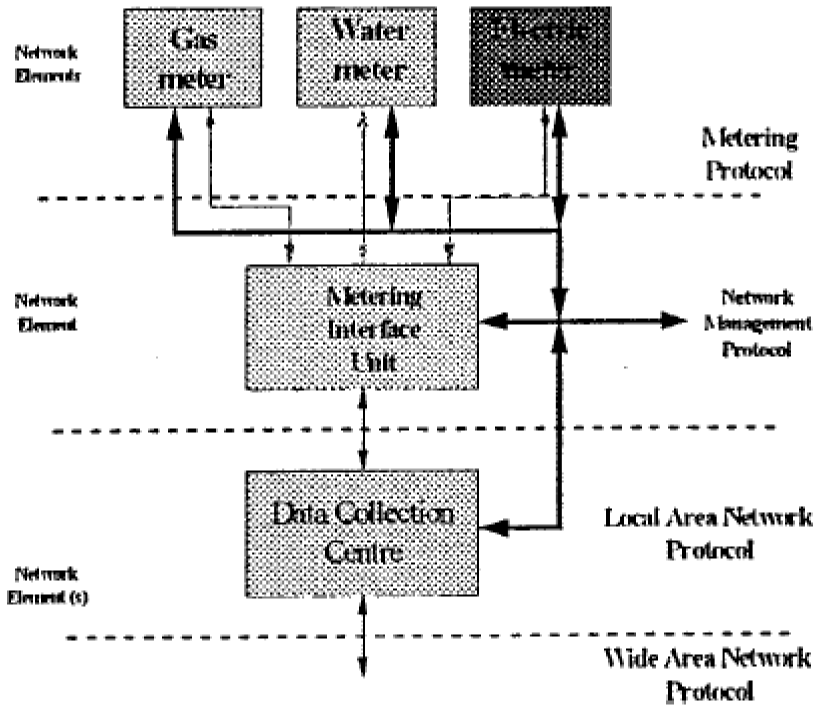


Figure 2.15: Proposed protocol architecture for remote meter reading system [63]

As indicated in Figure 2.15, remote metering system architecture is consisted of four separate protocol interfaces and can employ different number of protocol for each interface. Fig represents an architecture where one protocol is used for metering communications. The second protocol is used for local area communications and the third protocol for wide area communications. Finally, the fourth protocol is employed for Network or Equipment management. For a standard application, a metering protocol in compliance with European Standard EN 50065-3 can be used for metering communications. On the other hand, standard LAN protocols can be used for local area communications as defined in the DLMS or IEEE 802.3 standards. Correspondingly, TCP/IP can be employed for wide area network protocol and SNMP/IP can be used for the Network Management Protocol.

2.3.15 Enterprise Wide Benefits of the PLC Based AMR

For T&D companies there are various business drivers that AMR is related and can contribute to. For the effective management of utility costs, customers and financial returns, the key elements are T&D operations, asset management, customer service and energy efficiency. The definitions and the primary objectives of these business drivers are as follows:

T&D Operations: AMR contributes to the effective planning, design and execution of T&D infrastructure. The timing and the cost efficiency of the T&D infrastructure construction, facility maintenance and inspection, customer field service, outage management, metering operations and supply chain are the main areas of contribution.

- Asset Management: Asset management aims to meet the target levels of reliability and safety at acceptable levels of cost and risk by means of balancing the financial and operational performance.
- Customer Service: Customer service includes all the work to provide the utility customers with faster and diversified service and more accurate information through customer communications, account management, service request, trouble response, metering, billing and collection.

- Energy Efficiency: Energy efficiency covers all the tasks related with minimizing the overall cost of energy, diminishing price risks and attaining a suitable level of energy supply reliability by controlling alternative resources such as distributed generation, load management and demand response [65].

2.3.15.1 Enterprise AMR Applications

The meter reading techniques can be mainly divided into two categories: in-field and centralized meter reading. Briefly, for the in-field reading, the technical personnel go to the actual site to obtain the metering data while for centralized meter reading no personnel is dispatched to collect the data, the data is transmitted to control center. Enterprise AMR applications can be grouped into three broad categories:

- Billing and customer service: The simple and complex billing applications include demand response, dynamic pricing, change of party (move in or move out of the customer), bill inquiry, outage complaints, virtual and/or physical service connect and disconnect.
- Revenue Protection: Revenue protection includes the load, site and meter integrity monitoring, energy diversion, illicit energy utilization detection and rate validation.
- T&D Operations: T&D operations are composed of the tasks such as outage and restoration notification, system planning, leak detection, rate design, maintenance and operations.

2.3.15.2 The Practical Enterprise Benefits of AMR

The enterprise benefits of AMR are crucial in the basis of the core business drivers of the T&D business that AMR can contribute to. As stated before these are T&D Operations, Asset Management, Customer Service and Energy Efficiency. Smart Grids and AMI: Understanding the big pictures Areva T&D official website intranet documents [66].

In the context of T&D Operations, AMR adds value to the meter reading operations by increasing the accuracy and the frequency of meter readings. AMR increases the number of physical meter reading per billing cycle while decreasing the total cost of reading a meter and the probability of field personnel injuries. Complex billing data that provides detailed information on the real load patterns contributes to the distribution system planning and design, transformer load management and load forecasting. The effective and comprehensive use of this information can reduce the asset intensity and capacity requirements of T&D companies. Besides, the distribution losses are reduced and the network reliability is improved. The continuous monitoring of site, meter and load contributes to the equipment protection. Furthermore, the energy diversion is more rapidly detected and avoided. In case of outage or restoration, the on-demand data in association with the outage and restoration notification data, enables the fast and accurate outage localization and restoration activities and eases the crew utilization and mobilization. All of the mentioned improvements add value to the service reliability and efficiency.

CHAPTER 3

PLC IN EUROPE AND TURKEY

3.1 CURRENT STATUS IN EUROPEAN METERING MARKET

Electricity is supplied almost all the households and businesses in the Europe. Thus, metering is a primary business aspect for the utility companies. As of beginning of 2006, there were approximately 244 million electricity meters in the EU region plus Norway and Switzerland (EU23+2). With the liberalization of the European electricity distribution market, the metering applications are experiencing substantial changes and the utility meters are required to be connected to the data communication networks [15]. The basic structure of Automatic Meter Reading was explained in the previous chapters. Automatic meter reading can be referred as the collection of intelligent metering services depending on bidirectional data communication.

Manually read electricity meters are in use since the beginning of utility industry in the late 19th century. Since the 1980s the automatic meter reading has went into the melting pot especially in the US where radio based AMR applications are in high demand. The simple reading benefits of the metering technology are expanded with added value services enabled by two way real-time data communication.

The fluctuating energy prices promoted the energy markets reforms and supported the public interest in energy conservation As a result, the AMR solutions are in great request especially in Western Europe. Based on the previous calculations of the utility companies, upgrading all the energy meters in Europe would cost € 40 billion.

Among all the EU 23 countries, Italy is the leading country in means of the number of customers equipped with advance metering systems. Sweden will make all the infrastructure compatible to AMR after the new national metering regulation comes into effect at the end of 2009. Moreover, the expansion in Sweden is expected to trigger the AMR coverage in Denmark, Norway and Finland. The Dutch authorities are planning to promote AMR by the aid of legal legislations. [15]

Specifically, at the beginning of 1999, Enel S.P.A of Italy, the largest publicly traded utility corporation in the world, initiated the adaptation of Echelon's AMR network infrastructure to convert the Italian national power grid to an intelligent services delivery network. The bidirectional communication and data transmission system is called SITRED. The distribution network is designed to provide a data transmission line in each distribution installation (power substation or distribution transformer) and at each customer or industrial premise, making use of only the existing distribution infrastructure. The applications specific to ENEL infrastructure was included in SITRED, such as remote control of power distribution network, remote reading of consumption data, MV and LV customer service automation. This project costs around € 2.2 billion with a five-year payback period for the ten million meters installed. The average cost per connected meter was around $85. The Enel project was perpetuated by regional utilities such as ACEA of Rome [45], [67].

After the introduction of Enel's project, similar applications were initiated by other European utility companies. For example, in 2002 Vattenfall started to employ remote meter reading applications in Sweden and Finland. In 2003 the first round of AMR was installed in Sweden by E.ON. The other companies such as the Nordic energy groups Fortum, Skagerak Energi and the companies taking part in the Swedish SAMS buying consortium followed by introducing AMR applications. The Dutch company, Nuon introduced AMR deployments according to future regulation expectations in Netherlands.

Approximately 3.5 billion euros are expected to be invested to the intelligent metering solutions by the year 2010. As seen in Figure 3.1, the penetration rate for remote meter reading is estimated to rise from 16 to 19.7 percent by the end of 2010. Moreover, the annual shipments of smart meters will be around 3.7 million units. According to the calculations of the national utility companies, a capital investment of € 40 billion is involved to upgrade all electricity meters in the EU to remote meter reading systems.

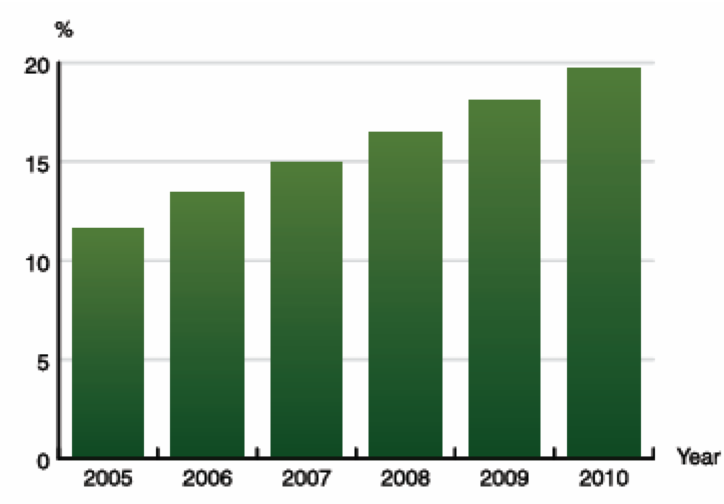


Figure 3.1: Penetration rate for remote electricity meter reading in EU23+2 [45]

Macroeconomic parameters such as energy consumption patterns, tax policies and the competitive and regulatory structures of different countries, affect the expansion of AMR in the European domestic markets. Technological developments, rising electricity consumption and electricity prices are the additional driving factors for AMR deployment. The European countries with the highest deployment of the AMR are the ones with the highest electricity consumption per capita (such as Sweden, Finland and Norway) and the ones with the highest electricity prices (Italy, Denmark and the Netherlands). Following those countries, the AMR solutions are growing rapidly in Western Europe as a result of the energy market reforms and increasing public interest in energy consumption because of the rising electricity prices.

3.2 PLC APPLICATIONS IN EUROPE

The European market became a convenient environment for true competition after the considerable completion of the telecommunication and energy market deregulations. The electric power wiring that already exist in the form of distribution infrastructure can cover the need of alternative cable links to customer premises in order to activate the competitive market [68].

According to the current R&D studies, the data transmission rates up to several megabits per second and transmission frequencies around 20 MHZ are attainable for European power distribution infrastructure. Nonetheless, the power distribution grid characteristics are considerably different from the other communication channels such as telephone cable or radio links. Figure 3.2 designates typical topology of European power distribution grids. The typical European distribution gird topology is star shaped. In general up to ten cables are fed by a single transformer and each transformer supplies between 30 to 40 households. Thus approximately 300 to 400 customers are connected to a transformer station [15].

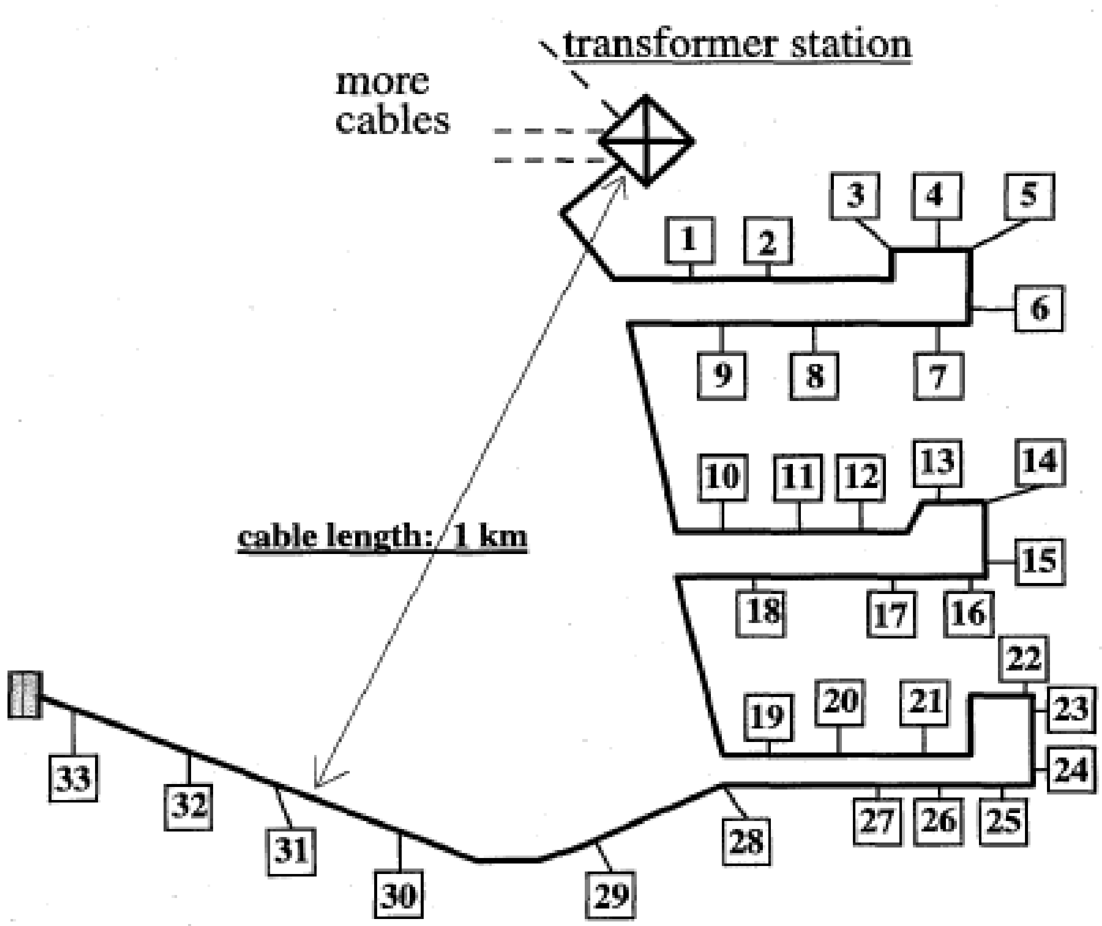


Figure 3.2: Typical topology of a residential distribution grid in central Europe [68]

The development and standardization in bidirectional signaling is expected to introduce enhanced value services (EVS). For the moment, EVS includes some functions such as load management, tariff switching, control and supervision of the customer's premises and remote metering [69], [70]. Considering the European standards and norms such as CENELEC EN 50065 which described was in detail previously, bidirectional signaling at data rates up to several thousand bits per seconds is applicable. The maximum transmission limits and user dedication was also indicated in CENELEC EN 50065 which differs considerably from American and Japanese norms for which the frequency range is extended up to 450 kHz and transmission over the protection earth line is allowed where interference levels are much lower [15], [68].

3.2.1 Automatic Meter Reading and Energy Management

The leading example of PLC applications is the AMR system installed by Iberdola in the entire village of Zarauz in Basque region of northern Spain. The project was a consortium between Ikusi, a Spanish systems integrator, and Iberdola, the largest utility company of Spain.

The system, which is composed of in-home customer display units, metering devices, and the power distribution medium, monitors real-time consumption, time of day energy rates, overall system demand, peak consumption times and performs invoice period comparisons. In the scope of the project, almost 10 km of power line was retrofitted for automatic meter reading. The products of Adaptive Networks which is a Brighton, US based company, were employed. 50 concentrator units were installed at transformer stations and approximately 1500 customer display units were installed in customer residences. The throughput of the power line system established was measured as 19.2 kbps. The data rates on the order of a few hundred bits per second were obtained in the secondary parts of the distribution transformers. In accordance with a usual AMR design, the meters and the customer displays were networked to the concentrators (MIUs) and the concentrators were connected to the central control (DCUs) and monitoring centers via telephone lines, radio or fiber links due to the geographical limitations. The customer display units yield the information on elapsed consumption and cost, sales rate at current time of the day, alarms and messages form the utility and allow load control for energy management, making it possible for the customer to take conscious decisions.

3.2.2 Indoor Applications for Building Automation

Fundamentally, CENELEC B or C bands can be used for “smart home” applications by using the existing power wirings. Smart home application examples are sensors and actuators for air-conditioning, heating and illumination systems that are remotely controlled and security systems such as fire or burglar alarms. However in the recent year there have been inadequate improvements in this field mainly due to lack of understanding of the power line characteristics and models.

One of the remarkable research and development works in this field was conducted at the University of Karlsruhe in order to model the power supply networks as a communication medium. The prototypes that were designed as a result of these studies were later proceeded into series production in industry and these systems have reached maturity in the market. In year 1996 a building automation system called Powernet-EIB, which was able to establish a network with intelligent appliances and electrically powered building equipment such as air-conditioning and illumination was introduced. The critical disadvantage of the EIB system is the necessity for using a separate two-wire bus. Nonetheless, Powernet-EIB benefits the advantage of using the existing supply wiring and is a good candidate to expedite the competition in the market.

3.2.3 Outdoor Applications, Enhanced Value Services (EVS)

Needless to say, the power line communication applications are not confined to indoors. Every indoor power network is in connection with the neighboring indoor network and at least one distribution transformer. The properties of power wiring are subject to big changes in frequencies other than the mains frequency. The more the frequency is, the more electrical and magnetic losses are. In addition the electromagnetic field propagation should be taken into account as the transmission distance can exceed 1 km. Looking on the bright side, the know-how collected through indoor PLC applications can be transferred to outdoor applications and the system designs that proved to be successful for indoor channels can be modified for their outdoor counterparts. For instance, there have been some ongoing studies to modify the Powernet-EIB technology to utility distribution networks.

3.3 ADDED VALUE INTRODUCED BY THE PLC APPLICATIONS TO THE TURKISH MARKET

To begin with, despite some technical deficiencies, the entire PLC infrastructure of Turkish interconnected network is already present; connections to all the consumer premises exist and are active. Thus starting costs are considerably low and consists of mainly the transmitter and receiver units. The low voltage network in our country can generally be classified as a meshed network. In case of any failure or fault, a consumer can be reached from several medium to low voltage distribution transformers. With the introduction of transmission and distribution market deregulation, PLC is expected to initiate a new power market model.

3.3.1 The reregulation of the power industry and PLC applications

The process of opening the power markets for competition is usually referred as deregulation in most literature. However considering the necessity for careful monitoring of network costs, the evolving power markets should be even more regulated than the traditional power markets. Thus, in this chapter the term "reregulation" will be used in place of "deregulation" to describe the free competition power markets [71].

The reregulated market structures for different domestic markets differ slightly. However, Figure 3.3 is a quite generic and explanatory representation of a reregulated power market. In a monopolistic market, a single authority or company is responsible for the generation, transmission and distribution of electricity. As the power is purchased from a power utility, there is no need to separate generation from transmission and distribution either at the supplier side or customer side. As a result, in the traditional monopolistic power market model, the customer has no choice of power supplier.

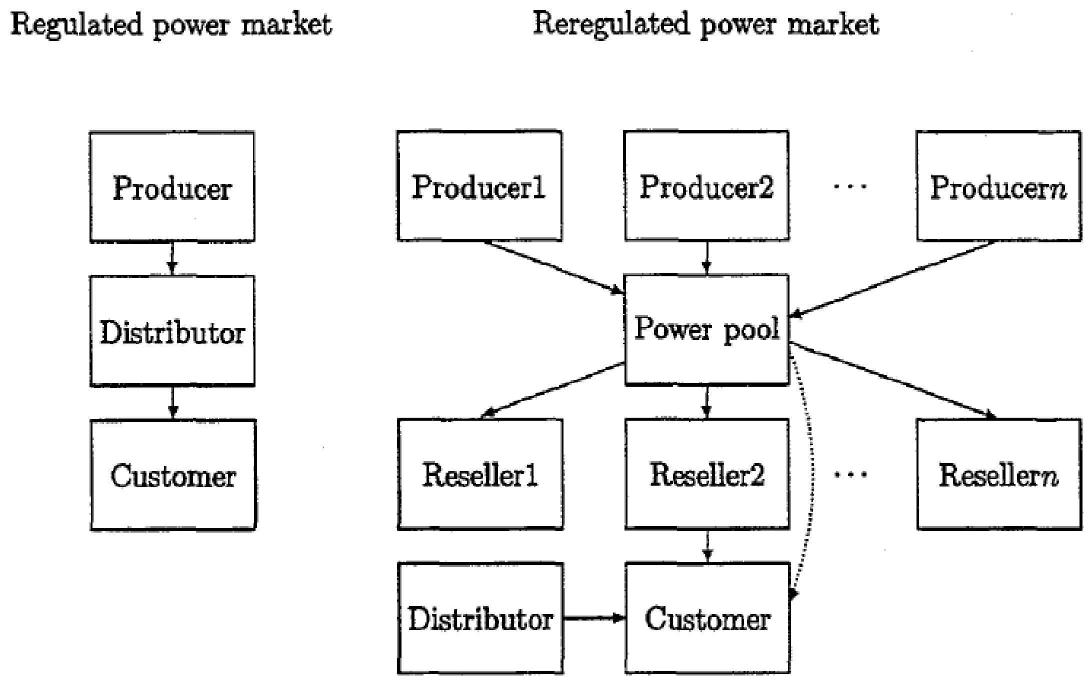


Figure 3.3: The reregulation of the power industry [71]

On the other side, in a reregulated market, the power is sold through a power pool in means of bilateral contracts. Alternatively, some countries enact the power production to be sold to a power pool. In either case, the buyers of the power pool are power resellers or high demand, large customers. Transportation is separated from the generation both at the production and consumption side. The non-competitive transportation costs are paid to the transmission and distribution company by the reseller and the reseller charges the consumer for the transportation when the electricity is actually sold.

The efficiency of power market reregulation can be further increased if the customers can buy the power directly form the power pool or even directly form the producers. As a result, the resellers can be bypasses from the process in a way similar to how resellers are bypassed in music or travel industries. Instead of directly bypassing the resellers, one can think of adopting slimmed energy resellers, operating by the IT substantially for functions such as electronic billing and consumption forecast. Alternatively, there might be some companies whose core business is in another area but they might also sell cheap electricity as bi-product or extra service. However, the aimed application is for small and medium to trade electricity directly from a power pool without reseller interference. Although this chapter concentrates mainly on trade between small customers and the power pool the concepts described can substantially be applied to the bilateral trading with producers.

3.3.2 The Open Electric Power Pool

3.3.2.1 Local computations and communication

Considering the trade in power pools, it is not possible to predict the exact future consumption and as a result the long term selling is not logical. The future predictions about the energy consumption should be made in shorter time intervals. Also the added value of purchasing from a power pool rather than a reseller is not big enough for making a daily purchase profitable. So as to say, the purchase process should be handled by software, acting as a representative of the customer. The so called “software agent” will continuously check the demand vs. supply and make purchasing decisions according to immediate calculations. This software agent used for electricity trading, called HOMEBOTS, will not be described in detail [72]. Only the related benefits and intended uses of the software will be described

In order to implement the data flow that this software needs to process PLC is a good candidate because of its wide coverage. Also considering that, for electronic power line markets the bandwidth is not an important criteria, PLC is a powerful alternative to fast telephone lines and fast Internet. The wide availability and coverage overcomes the speed requirements.

3.3.2.2 Contract responsibility

For the case of reregulated power markets, the time elapsed between two consequent data communications is in the order of an hour or 30 minutes. The energy trade takes place in advance of the related period and when the trade is set to a deal, the customer and the producer are committed to the purchased amount, called contracted amount. Variations from the contracted amount induce considerable fees or penalties. For the conventional and large scale reregulated power markets, estimating the consumption values are more straightforward due to the statistical equalizing techniques and other resources and methods for estimation. Moreover, in most of the time, there is a possibility to match the demand and supply in a way to meet the mutual responsibilities.

On the other hand, for a small customer i.e. an individual household, the software agent can not control the demand or supply. Thus, even a small deviation or unplanned activity might destroy the estimations. This problem can be solved by decreasing the estimation time intervals. Hourly measurements might be considerable for manual power trade applications. However for automated electronic trade, the resolution of minutes is perfectly achievable. Note that, this does not bring on a necessity to increase the metering resolution as limited bandwidth is a major problem. Instead an improvement is software make up for this deficiency.

Note that, the binding force of the contracted amounts will be void of interest, if the time between consecutive measurements is decreased. So as to say, if the time between successive trades approaches to zero, the deviation from the contracted amount also approaches zero. Considering an extreme example, if the time between the trade can be executed every second, a household uses a fuse of 16 A, the maximum deviation from the contracted amount can not exceed 0.001 kWh.

Looking at the big picture, with the introduction of more automated trading agents that are able to trade in short time intervals and that can represent controllable loads, the difference between the spot prices (determined in advance) and regulating prices (instantaneously determined on-line) can be expected to decrease.

The most comprehensive examples for a reregulated market are the Nordic countries despite being still not as developed as the model described above. In this market structure, the short term market is controlled by the grid operator and only the producers can place bids that affect the decrease or increase of production in the market. Again the grid operator selects bids in case of a perceptible mismatch between supply and demand [71].

3.3.2.3 Grid Operation

Grid operation is still a monopolistic and highly regulated aspect of the power market. So as to provide grid stability and security, the power grid operation is restricted with some constraints and not all possible combinations of consumption and production are allowed. In addition, too sudden or extreme fluctuations in the allocation should be avoided, even if the initial and final allocations are stable. The resistive losses on the power line incur transportation costs in addition to the investment costs. The problems identified vary from one country to another. For example, the related losses are more critical for US than for Nordic countries. So as to say, the grid stability, security and cost management should be carefully considered for a power market. The main reason that the electronic power markets model is still not adapted to all electricity trading markets is the difficulty of integrating grid operation to a competitive environment. Moreover, the fact that the allocations might change severely between regions violates the stability and security of the grid. However still there are some logical reasons to think that a more detailed electronic power market agent with smaller measurement intervals would decrease the difference between the demand prediction and the actual demand. Some of these reasons are that the customers will trade directly against dynamic prices; they will use their incentives to adjust their demand accordingly and control their loads. Considering that there will always be some fee for a transaction, the customers will be willing to compensate the variations locally as the cost of transaction between agents that are close to each other is lower. The power line communication for the agents that can reach each other via a common power line will be cheaper than those that are geographically distant from each other. As a result, the variation of compensation among the neighbors will be more preferable than the compensations from the agents of other areas [71].

3.3.2.4 Changes in Market Conditions, Legal and Technical Environment

In order to be able to integrate PLC into the energy and telecommunication applications, it should be considered that the current developments are dragging the market to a highly dynamic and uncertain environment, where sector boundaries are shifting, and crucial financial power is obtained through mergers and acquisitions. As a result, in all dimensions of the distribution and generation market competition is increasing. On the other hand, the legal legislations are redesigned, local and international companies are approaching Turkish market as new entrants. Consequently, new operational and business strategies are needed to be developed according to the rapidly changing market conditions.

3.3.2.5 Electricity sector liberalization

The emerging expectations of privatization, liberalization and open competition in electricity generation, distribution and transmission businesses are evoking radical changes in corporate structures, organizational cultures, business goals, market expansion strategies and customer orientation [72].

Moreover, the electricity transmission, distribution and generation businesses are experiencing consistent financial struggles in means of their fundamental operations. According to Nuclear Energy Information Platform's study, dated January 21st 2008, the total electricity production of Turkey increased by %8.4 in 2007 compared to 2006 and reached to 191.2 billion kWhs. In the same period, national electricity demand increased 8.6% ad reached to 189.5 billion kWh. In Table 3.1 below, the instantaneous peak time power demands and the power demand increase values are listed. For 2005, the peak time instantaneous power demand was 25174 MW where as the minimum instantaneous power demand was 10120 MW. Similarly, for 2008, the peak time instantaneous power demand was 27594 MW and the minimum instantaneous power demand was 10545 MW. The energy demand values for years between 1997 and 2006 are also listed. Except 2001, (the year when a big financial crisis occurred) the annual demand increased around 6.5 – 8.5 %. Most recently, the energy demand suffered again from a global financial crisis as of 4th quarter of 2008. The profit margins of electricity companies also shrunk considerably.

Table 3.1: The realized peak time instantaneous power demand and energy demand values in Turkey between 1997 and 2006 [73], [74], [75].

YEARS	**Instantaneous Peak Time Power Demand in MW**	**% Increase**	**Energy demand in GWs**	**% Increase**
1997	16.926	11,1	105.517	11,3
1998	17.799	5,2	114.023	8,1
1999	18.938	6,4	118.485	3,9
2000	19.390	2,4	128.276	8,3
2001	19.612	1,1	128.871	-1,1
2002	21.006	7,1	132.553	4,5
2003	21.729	3,4	141.151	6,5
2004	23.485	8,1	150.018	6,3
2005	25.174	7,2	160.794	7,2
2006	27.594	9,6	174.230	8,3

According to the same study by Nuclear Energy Information Platform, dated January 21st 2008, the energy demand for the next 10 years was projected as in Table 3.2. However, considering the recent financial situation around the Europe and rest of the world, this demand estimation should be revised.

Table 3.2: The estimated instantaneous power demand and energy demand between years 2007 – 2016 prior to the global financial crisis in 2008 [73], [74], [75].

YEARS	Peak Time Power Demand in MW	% Increase	Energy Demand in GWs	% Increase
2007	29.829	8,1	188.348	8,1
2008	32.275	8,1	203.787	8,2
2009	34.954	8,3	220.701	8,3
2010	37.855	8,3	239.019	8,3
2011	40.997	8,3	258.858	8,3
2012	44.359	8,2	280.084	8,2
2013	47.908	8,3	302.491	8,2
2014	51.692	7,9	326.388	7,9
2015	55.724	7,8	351.846	7,8
2016	59.904	7,5	378.234	7,5

However, still, the regional and national utility business offer stable, low risk and high quality revenue streams for potential investors. The ongoing competition in supply business is inspiring companies to develop strategies to differentiate themselves with value added services and gain competitive advantage in the market.

3.3.2.6 An example of liberalization: Telecommunication sector liberalization in Europe

The liberalization process of telecommunication sector started long before the electricity supply and utility business all over the Europe. The common approach across Europe is the participation of power utility sector to telecommunications operator business. Across Europe, almost all second national telecom operators have participation from the respective former power transmission & distribution or generation companies. The Figure 3.4 below summarizes the combined business ventures in Europe.

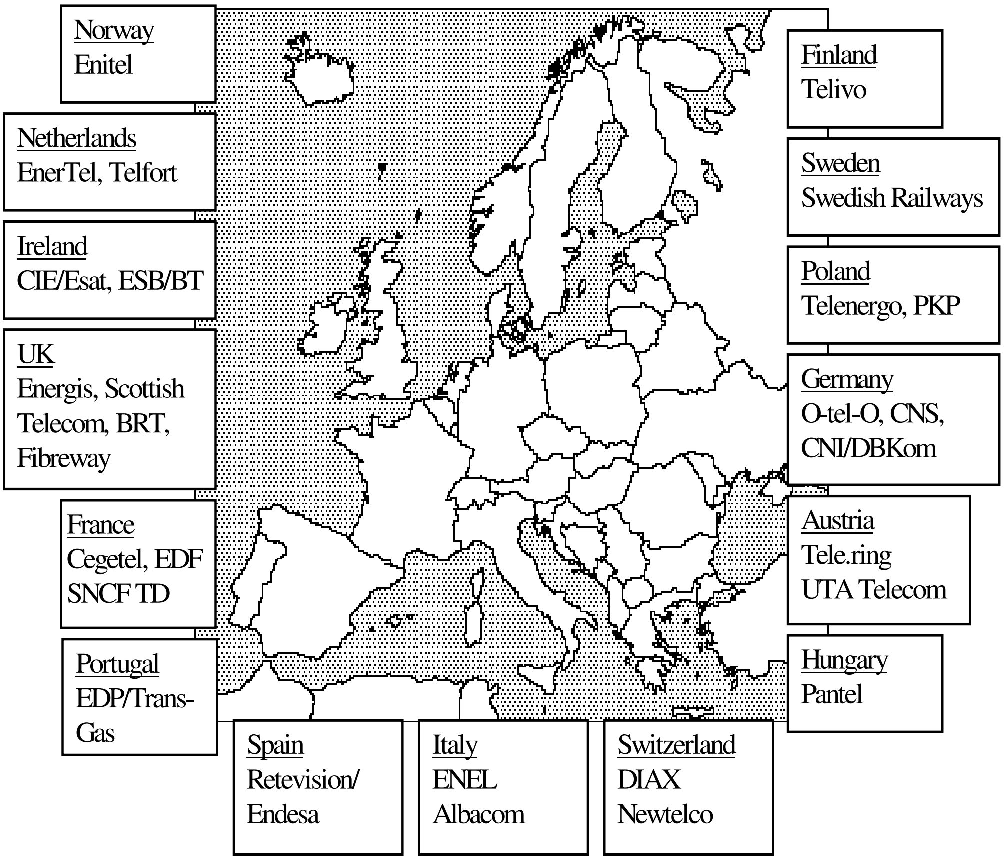


Figure 3.4: Key utility operator ventures in Europe [76]

This joint structure triggers the extensive employment of PLC technology for a more cost effective and ubiquitous communication infrastructure. Furthermore, for those power utilities that look forward to participate in telecom services directly, can commercially make use of PLC to have network access to telecom operators.

3.3.2.7 The significance of power line in telecommunications

The PLC can be a solution to the bottleneck of local loop or last mile to the customer problems that telecommunication sector faces. The PLC can help the development of telecom services over a high speed communication medium and can gain the upper hand on the other alternatives such as copper wires, cable networks or fiber networks. There are several reasons why copper wires and cable networks could not accomplish the high speed information network.

a) The limitations of existing copper wire infrastructure of the national telecom operator: This infrastructure can only support one or two lines of basic telephony. These networks can support at most the ISDN with some network upgrades. This is insufficient for high speed interactive services without a considerable amount of capital investment.

b) Similarly the cost of additional investment required to construct an alternative network for high speed interactive services is also drastic.

To sum up; presently the internet services offer to public is limited to slow speed and poor quality, employing the telephone wires and cable networks. Moreover, the limited capacities and inadequate availability of these networks damage the development of new interactive applications and value added services. As a result of all the factors described above, the PLC investments can lead to very optimistic and promising results in means of energy and telecommunication applications [72].

3.3.2.8 Conclusion

The electronic power markets, which serve the small and medium size customers to trade electricity directly with power pools, compose faster acting market structures that can react quickly to price changes in rapidly changing conditions. Note that for small and medium scale customers to benefit from these agents, the local computation and communication equipment is supposed to be relatively inexpensive. Only by this way, the power line communication that has the highest potential of reaching the "last mile" customers will overcome the broadband communication technologies despite its obviously limited bandwidth. As such, power line communication can be the most favorable communication alternative for power markets.

With the deployment of a PLC network with low cost network nodes, utility companies will have the opportunity to enhance their basic service with communication aspects of power line. Power line communications operating at higher data rates will help the utility companies to develop some added value services such as energy management, telemanagement and broadband internet access.

After the adaptation of deregulated market rules, the real-time information from the meters will be crucial resources for the utility companies to compete for customers who will look for additional benefits from the utility companies such as saving plans, security and energy management. This competition will be similar to the competition that is present between the GSM providers today. Both the utility companies and the customers, who can make informed decisions about their consumptions, will reap lasting benefits from a high speed, bidirectional, secure and reliable PLC network.

3.3.3 Remote Detection of Illicit Electricity Usage via Power Line Communications

3.3.3.1 The illicit utilization in Turkish Electricity Market

In the previous section, the benefits of PLC for automated electronic trade were explained. The reregulation, competitive open market conditions and varying customer profiles triggered Automatic Meter Reading (AMR) applications in the energy supply sector. As stated before, PLC with the ”last mile connectivity“ advantage has many service possibilities to offer to customers without additional investment for infrastructure. The additional benefits of AMR systems using PLC are monitoring of real time energy consumption via remote readings and the detection of illicit electricity usage. [77]

The illicit energy utilization is a major problem of Turkey for years. According to the statements of Energy and Natural Resources Ministry, 19% of total electricity consumption in Turkey was illegal as of year 2003. This amount is almost 16 percent as of end of 2008. Considering the frequent blackouts and the inadequate power investments in the recent years, prevention of the illicit utilization of electricity is an unavoidable precaution for Turkish power market. Considering the privatization of distribution sector, the legal legislations for the sake of preventing the illicit electricity usage are becoming more important recently. This has been emphasized in a lot of press statements of the Energy and Natural Resources Ministry in the last years. The deputy director of TEDAŞ (Turkish electrical Distribution Company) stated that unless Turkey can make use of the energy investments executed with limited resources in a more efficient manner, the energy prices will continue to rise. [78] As of September 2006, the debt of municipalities to TEDAŞ was 2,710 billion YTL, the debt of industrial organizations was 325 million YTL, the government offices' debt was 1,286 billion YTL, the debt of the residences was 1,175 billion YTL, and the debt of business establishments was 817 million YTL. As the debt of the other parties and organizations are added, the total debt adds up to 8,350 billion YTL. [79]

In addition to these debt figures the illicit utilization of electricity is around %17 as of 2007. Apart from other losses, the illicit utilization not only threatens the current national economic situation, but also makes it difficult to make plans and predictions about energy consumption (and consequently the amount of investment required) in the following years. Until now, the methodological precautions such as manual reading, optical reading of the energy meters, the creditable utilization of electricity and the legal precautions such as intervention of government forces did not yield successful results.

PLC comes into scene at this stage, offering a relatively inexpensive, reliable and widespread last-mile solution to monitor the consumption values and prevent the illicit electricity utilization.

3.3.3.2 Detection of Illegal Electricity Utilization

3.3.3.2.1 The Methods of Illicit Utilization

The following are some common examples for illicit utilization: [79]

i) Mechanical objects: The illicit user can place some mechanical objects to reduce the revolution speed of the meter disk which is used to measure the consumption. By this way the disk speed is reduced and the recorded consumption is undermined.

ii) A fixed magnet: A fixed magnet can be used to manipulate the electromagnetic field of the current coils. The recorded energy is also altered as it is a proportion of the electromagnetic field.

iii) Bypassing the line with an external phase: An external phase can be used to bypass the mains line to obtain measurement-free energy. [80]

iv) Switching the energy cables at the meter connector box: The current passing through the current coil is blocked. No consumption is recorded.

All four methods can be applied to electromechanical meters. However, only the last two are valid for the digital meters. The following system offers a detection and control system to solve this problem.

3.3.3.2.2 AMR, Detection and Control System

The proposed detection and control system is schematized in Figure 3.5. The low voltage side (220 VAC) of the distribution transformer is integrated with an AMR system via PLC technology. The transmission is executed among the host PLC unit and two PLC modems for each customer. In Figure 3.5, the host plc modem is located adjacent to the distribution transformer. The modems labeled PLC1A … PLC1N are employed for AMR functions. The primary function of these modems is to communicate with each other and to transmit the data measured in the kWh meters to the host PLC unit. In addition to those, in the connection point of the mains line and the customer premise line, another PLC modem, labeled as PLC1B … PLC1N and an energymeter chip are installed for each customer. The illicit utilization is determined by comparison of the two consumption data from the PLC modems next to the energymeter (PLCnA) and the PLC modems in the connection point (PLCnB). This connection point is closed to interference as it is normally underground or in air [81].

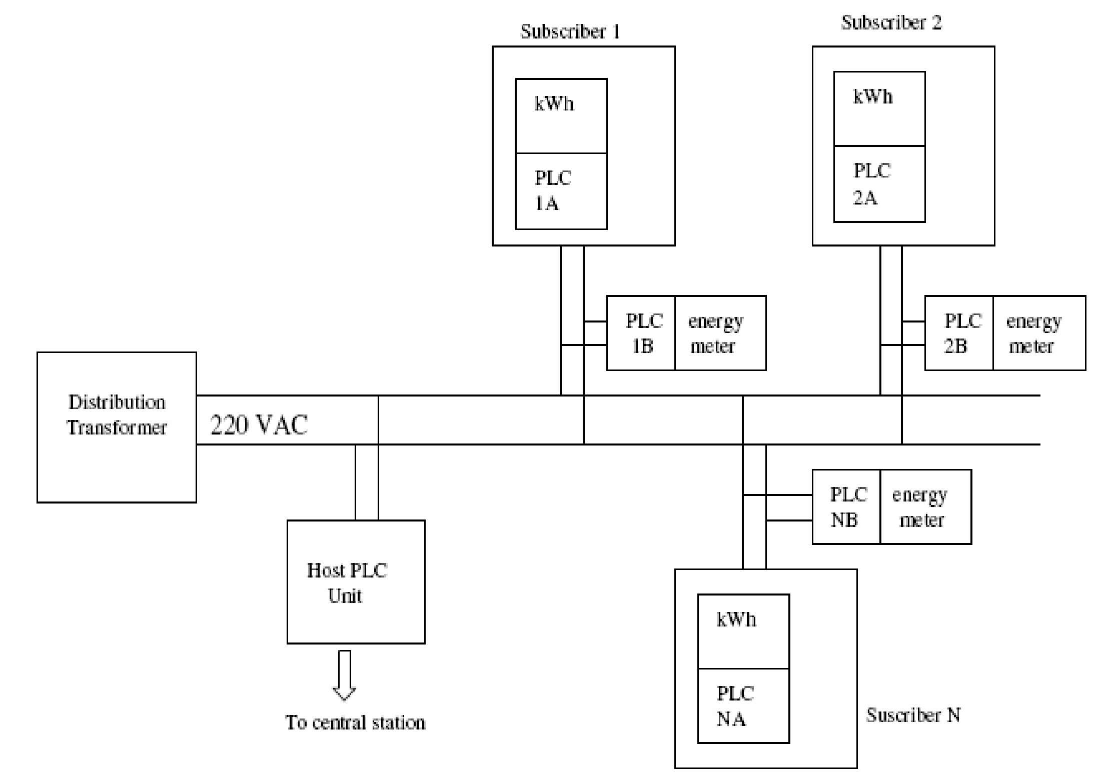


Figure 3.5: The schematical illustration of detection system of illegal electricity usage [79]

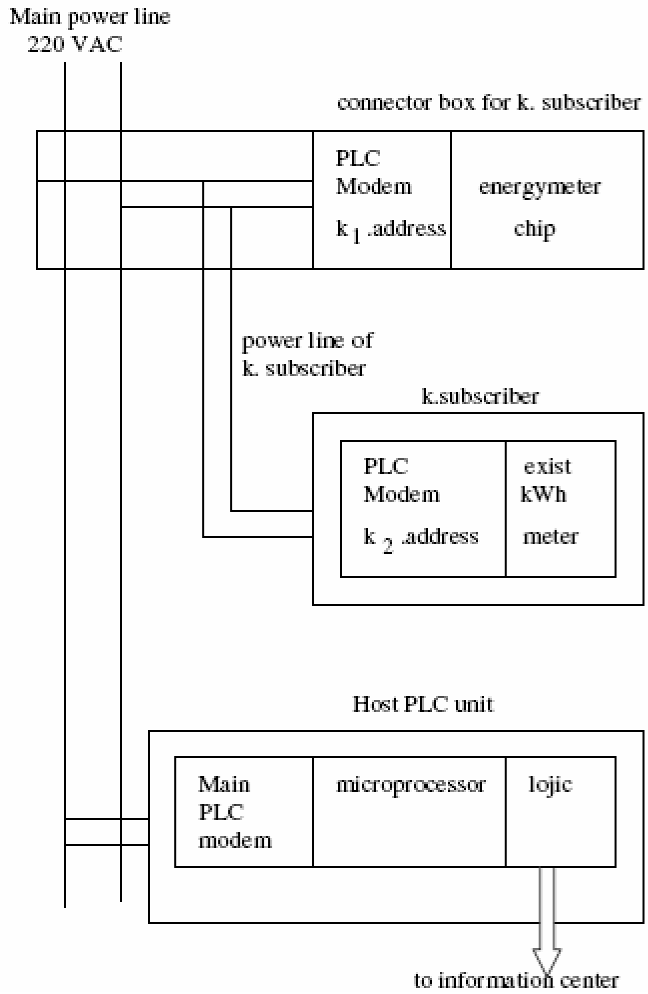


Figure 3.6: Illegal detector system for one subscriber [79]

As stated in the Chapter 1, power line communication is realized according to the CENELEC EN-50065-1 standard. Remember that, the frequency band between 3 – 95 kHz is allocated to the usage of electricity suppliers and 95 – 148.5 kHz is allocated to the consumer utilization. Basically, the signaling level for PLC is limited to 116 dBμV (referred as Class 116 equipment) and for particular applications such as industrial appliances, the signaling level is restricted to 134 dBμV (Class 134 equipment). The recorded data in kWhmeter of each customer is transferred to the host PLC unit via PLC modems coded PLCnA located at the customer premise. On the other side, the energymeter chips assembled in the connection points of the mains line and the customer line also read the energy consumption in kWhs and transmit these data to the host PLC unit via PLC modems coded as PLCnB. Eventually; the host PLC unit compares two corresponding data for each customer (one from the AMR modem called PLCnA and one from the PLC modem in the connection point referred as PLCnB) and generates an error signal if these two data do not match. In case of inconsistency of these two data, an illicit utilization is proven. Following the detection, the related customer's IP address and error signal are combined and transmitted to the central control unit. Optionally, a contactor can be added to the system to remotely turn off the energy flow to the illicit user [82].

3.3.3.2.3 The Overview of the Proposed Detector System

The proposed AMR system includes PLC nodes, energymeters, control logic parts, and the system software. The host unit modem and the target modems (PLCnA's and PLCnB's) are employed for bidirectional communication between the host station, the customer premises and the control stations at the connection points of the mains line and customer line.

In the connection points, the energy meters are composed of energy meter chip and related circuit elements. The host PLC unit includes control and logic units to compare the dual data and generate error signal in case of inconsistency. The system software is composed of an assembler program for the microcontroller and operating software for executing the system management that is included in a PC in the main system center.

To sum up the main functions of the proposed system is as follows:

1) An energy meter is installed in the connection point between the customer line and the mains power line.
2) Host PLC unit is installed in the distribution transformer's vicinity and the transmission data packet format is designed accordingly to meet the system requirements.

3) Two PLC modems are allocated for each customer. One of them is for the AMR data transfer and one is for the transfer of data from the energymeter chip in the connection point.

4) The related address of the each AMR module and each energymeter are defined at the host modem's logic controller.

5) Operating software registers every customer in every subnetwork by using the number, address, billing and etc.

6) The logic unit of the host compares the two consumption values from the energymeter and AMR module and generates an error signal if necessary.

7) The proposed system is for a single distribution power network with a single host PLC unit. This system should be repeated for several host PLC units of the corresponding distribution transformers to form a wider power network. The host units of the different distribution transformers are supposed to be connected to each other and the main center station via power lines, fiber optical cables or RF links [84].

The cost of the system subnetwork system including PLC modems, energymeter chips, PLC modems and the energy meters is approximately $20-25. To sum up, considering the total amount of economical loss resulting from illicit utilization, the proposed PLC based AMR system is an economical and reliable solution to prevent illicit utilization and obtain real time consumption data of the customers [85].

3.3.4 Broadband over Power Line (BPL)

Traditionally, power line carrier is a communication method that uses the existing infrastructure to send information in the carrier signals over the power line. Power lines are extensively used by utility companies, on the order of transmission frequencies of 10's of kHz, for the purpose of controlling the switches and relays on electric power transmission system. In the recent years, by the help of digital signal processing (DSP) techniques, Broadband over Power Line transmissions make use of digitally modulated carriers in the frequency range of 2 - 80 MHZ. PLC has used for pure communication applications rather than the limited traditional usage as control medium of home automation or utility protection systems. Broadband over Power Lines (BPL) which is also called power-line internet or power band is described as the usage of PLC to provide broadband internet access over power line cables. The ease of usage is a main advantage of the application. A consumer only needs to plug a BPL modem into an outlet in an equipped building to access to high speed Internet. Moreover, as emerging PLC modem technologies come into scene, the data transfer over power line in the home and office at the speed of more than 1 Mbps is becoming available. Thus, PLC has become a competitor of Internet communication medium against traditional phone line modems, digital subscriber line (DSL) and wireless Internet.

In the PLC modem market, Inari recently introduced a high rate home networking solution using high data rate PLC communication for Internet, PC and printer sharing for home and small office/home office (SOHO). Inari's design employs 350 kb/s power line modems. The company also introduced a new power modem with 1 Mb/s speed. On the other hand, an Israeli company Itran Communications has recently introduced a 10 Mb/s PLC modem by the end of this year. Obviously, the data transfer demand and availability of the Internet is rising and the PLC modem should be able to meet higher frequency requirements. For the communication rates over 1 Mb/s, the low frequency band is evidently inadequate.

A communication device can transmit the data over a band of the spectrum around the nominal frequency which called as bandwidth. Sending information at a higher rate requires a wider bandwidth. The channel capacity or the bit per second (b/s) rate represents the relationship between the bandwidth needed and the data rate that can be attained within the band. To meet the channel capacity of 1 Mb/s rate, PLC applications should use higher than a 2-3 MHz high frequency band [86].

In the United States, the various application fields of BPL are residential BPL, BPL on 120/240 V power lines, BPL on 1,000V to 40,000V power lines. The topology of BPL illustrated in Figure 3.7 mainly consists of the following elements: (1) PC, (2) modem, (3) transition from the residential or commercial power line to the a single phase of the medium voltage system that supply the residential or commercial premise (4) injector (5) extractor (6) repeaters (7) transition from the single phase of MV line to the fiber optical link.

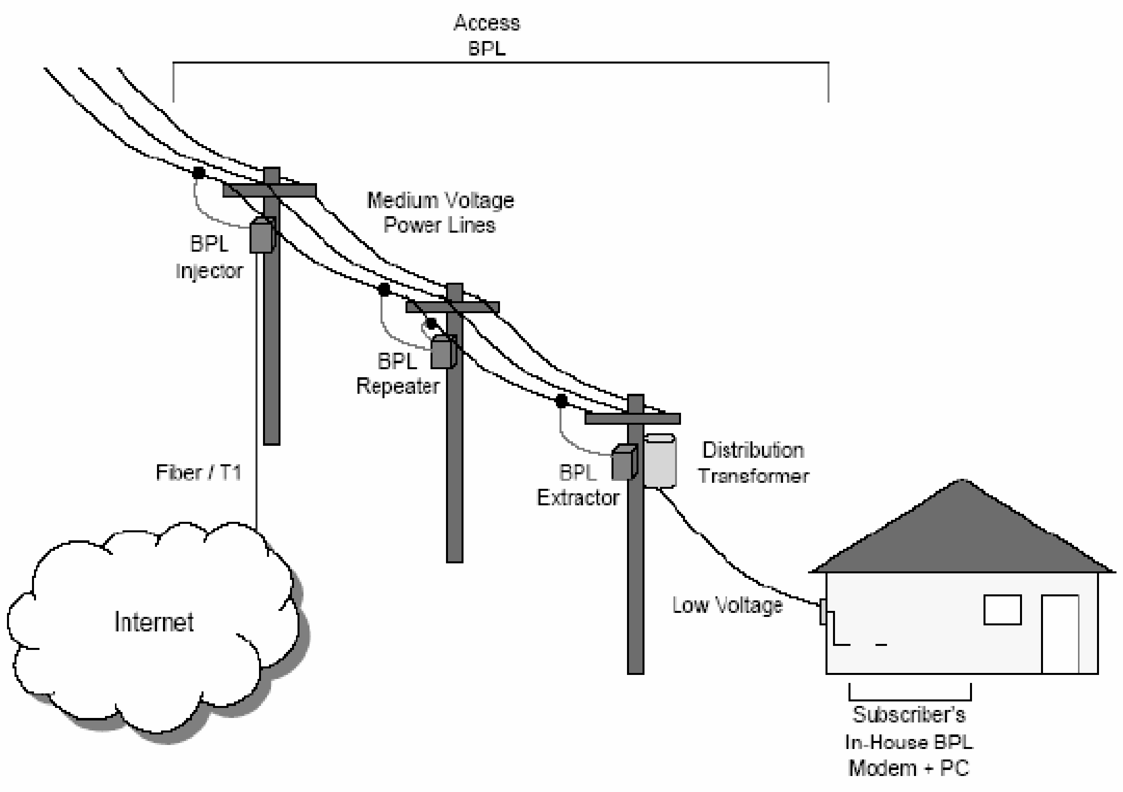


Figure 3.7: Basic BPL-System [87]

The connection of the internet backbone to the MV single phase is established by the BPL injector. Fiber optic lines that are feed in from the BPL service area are employed for the connection between the internet backbone and the injectors. The three phase MV lines are initiated from the distribution substations and one or more of three phases can be used to service the customers. The attenuation, distortion and noise are the most important problems that jeopardize the signal strength and the reliability of the power lines. The repeaters are occupied between the BPL injectors and the BPL extractors to cover the attenuation and losses. The extractors are the interfaces between the MV infrastructure and the customer's local area network, modem or PC. BPL extractors are conventionally located at each low voltage distribution transformer, feeding the customer premises or residences.

Orthogonal Digital Frequency Multiplexing (OFDM) is the conventional digital modulation method for BPL applications. In the context of OFDM, multiple carrier frequencies that are orthogonal to each other are used to digitally modulate the data. As a property of orthogonality, the correlation of the carrier frequencies is zero. The BPL modem on the customer side, converts the serial data stream into successive parallel streams that digitally modulate one of a group of orthogonal carriers. There are two solutions to transmit these modulated orthogonal carriers from the LV line to the MV phase line. For this purpose, the first method is an inductive coupler, bypassing the transformer. The alternative method is placing a Wi-Fi transponder and a modem next to the PC, transmitting the data signal to a transponder on the utility pole that is connected to the phase through and inductive coupler. As indicated before, the repeaters are also employed to stimulate an amplified BPL signal to surmount the disturbing affects such as noise, losses and attenuation. The BPL service provider controls the amplitude, the orthogonal carriers utilized and notched out signal components of the BPL signal [87].

The benefits of this new technology to the Turkish electricity and telecommunications markets can be summarized under two main titles:

1) Greater competition and evidently lower prices in the Turkish broadband market: BPL can motivate DSL and cable operators for higher transmission quality and higher market penetration [88].

2) Ability to offer broadband access to rural and country areas without DSL, cable, wireless and fiber optic internet access: The extensive infrastructure that is already present will allow these people in remote locations to have internet access with little equipment investment.

There are some major disadvantages of BPL over DSL and cable. The most important ones are unstable physical characteristics of the electricity network, the lack of IEEE standards and relatively limited bandwidth compared to cable, DSL and wireless.

3.3.5 Existing and Foreseeable Complications of PLC Applications in Turkey

There are several reasons why the PLC employment has been limited to narrow band applications such as automatic meter reading in Turkey.

a) PLC technology is in the development stage of its life cycle. It is still very young and the capabilities need further improvement. Only in the recent years, complex modulation techniques have been developed to attain high speed services.

b) For every communication medium standardization and interoperability is crucial for further development with the contributions from different technology developing companies. The CENELEC standards that restrict the frequency of PLC application to the upper limit of 148 kHz are not enough for the development of modern voice or data systems. This limitations discouraged lots of independent researchers and technology companies to invest for higher value PLC systems.

c) As stated above, PLC applications was limited to narrow band applications. The main reason for this was to be able to reduce the operational costs of utility supply. Moreover, for this kind of limited applications, there exists some other obstacles such as continuous market, legal and technical uncertainties [72].

Indicating the potential complications, let us focus more on the automatic meter reading (AMR) which is the first widespread application area for PLC. It was stated before that after the reregulation (or deregulation as called in some other literature), automatic meter reading has become an important service for distribution companies. The measurement intervals were fixed around 0.5 – 1 hour and the utility companies made their own experiments in limited bandwidth and without interoperability obtained. Still, the results were satisfactory. The uncertainty was mainly resulting from the following factors: [89]

- The vague effects of future reregulation in metering market
- The uncertainties about information security. This information will be protected and limited to the distribution company.
- The return of investment of added value services such as AMR should be carefully calculated for a cost - benefit analysis. Bundled services rather than singular applications can be more effective in means of adoption and penetration of PLC.

The implementation of bundled PLC applications require integration of relatively distant disciplines such as telecommunications, power engineering, advanced software applications, related hardware and market research. These disciplines are different from core competencies of telecommunication and electricity distribution business. Thus, telecom and utility companies should make use of external collaborations with their experienced counterparts in Europe [90].

So as to say, the relatively cumbersome adaptation process of PLC should not discourage the potential investors. The penetration rates of the existing communication technologies were not rapid either. For the fastest spreading technology, Internet, it took five years to reach 50 million people worldwide. For broadcasting radio system the same figures were reached in 38 years and for TV it took 13 years. In conclusion, the PLC can follow this pattern in means of expansion. The expected combined efforts of telecommunications and utility companies after the completion of privatization process and the higher adaptation capabilities of the Turkey's young population are promising factors for effective implementation of PLC.

3.4 CONCLUSION

PLC initiates a lot of new business opportunities related to added value services for both the energy and telecommunication sectors.

The power lines are basic components of the rising Information Society for two main reasons:

a) Power line as electricity carrier: It is self-evident that the primary purpose of the power lines is to supply electricity. In the same way, all equipments and functions of the Information Society necessarily depend on a cost-effective and reliable electricity grid.
b) Power line as information carrier: As we stated several times before, latest advance in telecommunications enabled the power lines to be large-scale, moderate speed, reliable information carriers under the name of Power Line Communication (PLC). PLC offers the power line as an Information Society telecommunications infrastructure along with the well known alternatives such as copper wires, fiber optical cables, wireless networks and satellite networks.

Making a brief SWOT analysis, the PLC has some obvious and unique strengths to be important elements of the future Information Society Infrastructure.

3.4.1 Strengths

- Ubiquity: The low voltage power network is already a widespread networked infrastructure reaching out to billions of private and business premises. Crossing the boundaries of the buildings, PLC accesses the wall outlets, all electrical appliances and industrial equipments.
- Last mile connectivity: Considering its alternatives in means of data communication, last mile connectivity is not a uniquely distinguishing characteristic of PLC. Still, PLC offers permanent access, always online and bidirectional connection to the customers.
- Strong growth potential in means of data transmission based services: Although it is a newly developing technology in our country, with limited number of examples, PLC is a promising technology in means of telecom capabilities and commercial equipment cost reductions. The already achieved

transmission speeds support innovative applications. The value added services described throughout this thesis work is achievable around kbps range. This is considerably attainable limit, considering that the current PLC speeds are on the order of 1 Mbps and speeds up to 100 Mbps are foreseeable in the near future. [91]

3.4.2 Opportunities

There are various driving factors originating from related business areas of PLC in telecommunications and electricity sectors.

- Privatization and liberalization of electricity supply sector triggering investment to increase efficiency in transmission and distribution business.
- The relatively flat growth and net margins are compelling the power utilities to offer more value added energy services. The great portion of these value added services are the related to communication technologies.
- PLC is the most cost effective and reliable solution for the local access and availability problems in the telecom service infrastructure. For developing countries such as Turkey, PLC can improve coverage and density in a cost effective and speedy way.
- Besides the AMR and control benefits, PLC can offer high speed access and broadband applications to support the development of interactive information era.

Moreover the services listed below can be offered through PLC in combination with the telecom and energy aspects in order to expand the service range and enrich the individual choices.

- Energy services in the recently expanding sector boundaries and features. Some examples are automatic meter reading, remote billing, demand side management, remote control and distribution automation.

- PLC based telecommunication services such as broadband over PLC, PL based telephony, voice and video transfer services.
- Added value services beyond the current sector boundaries such as PLC based energy and equipment cost saving services, agent enabled personal comfort services, smart home automation and security applications, content oriented electronic services in electronic commerce, education, information and entertainment.

CHAPTER 4

ADVANTAGES AND DISADVANTAGES OF PLC TECHNOLOGY AS COMPARED TO ALTERNATIVE COMMUNICATION MEDIA

4.1 INTRODUCTION

As stated before, the power line carrier communication is a method of data transmission using power lines as the communication media. Recently, PLC has become a flexible communication alternative to implement low cost, reliable, widespread and highly accessible network in the domestic environment. PLC can provide new information services in energy and telecom [92].

On the other hand, PLC is still a developing and evolving method, targeting the employment of the electricity power lines for data transmission. Needless to say, for a communication technology to be favorable, the geographical coverage and the maximum number of users it reaches are important criterions. PLC is one step ahead in this manner compared to wire, cable, fiber, wireless and satellite solutions. As stated before, power grid reaches every customer and industrial premise and the coverage of this wiring cannot be compared with any other communication media such as copper PSTN or cable TV network. As a result, PLC offer mass provision of local access at a reasonable investment and utilization cost. PLC is highly attractive compared to other local access technologies in terms of capital expenditure and implementation requirements. Moreover PLC offers various distinguishing added value services such as automatic meter reading, energy management, home automation etc. [72], [93].

The listed features of PLC technology are important for the integration and incorporation of telecommunication and energy businesses. PLC can introduce a great variability of new information dependent services to the electricity distribution market.

4.2 COMPARATIVE ANALYSIS OF PLC WITH THE ALTERNATIVE COMMUNICATION MEDIA

PLC competes with different communication technologies such as PSTN, LAN systems, radio based systems (DECT, GSM, ISM-band modems) and wireless LAN. All of these technologies are successfully implemented in the related fields and they reached to economies of scale as a result of the large scale production. Still some radio based systems, such as GSM, require an infrastructure which makes the system relatively expensive compared to others. Thus, the PLC applications over the LV mains line, can take the advantage of its cost effectiveness and ubiquity for the cases where radio based systems are unfeasible or expensive [94], [95].

So as to say, various communication technologies offer different solutions for the coverage and local access issues. The market is expected to be a combination of all these technologies operating simultaneously and methodically. Figure 4.1 illustrates a hypothetical model for the integration of these communication media.

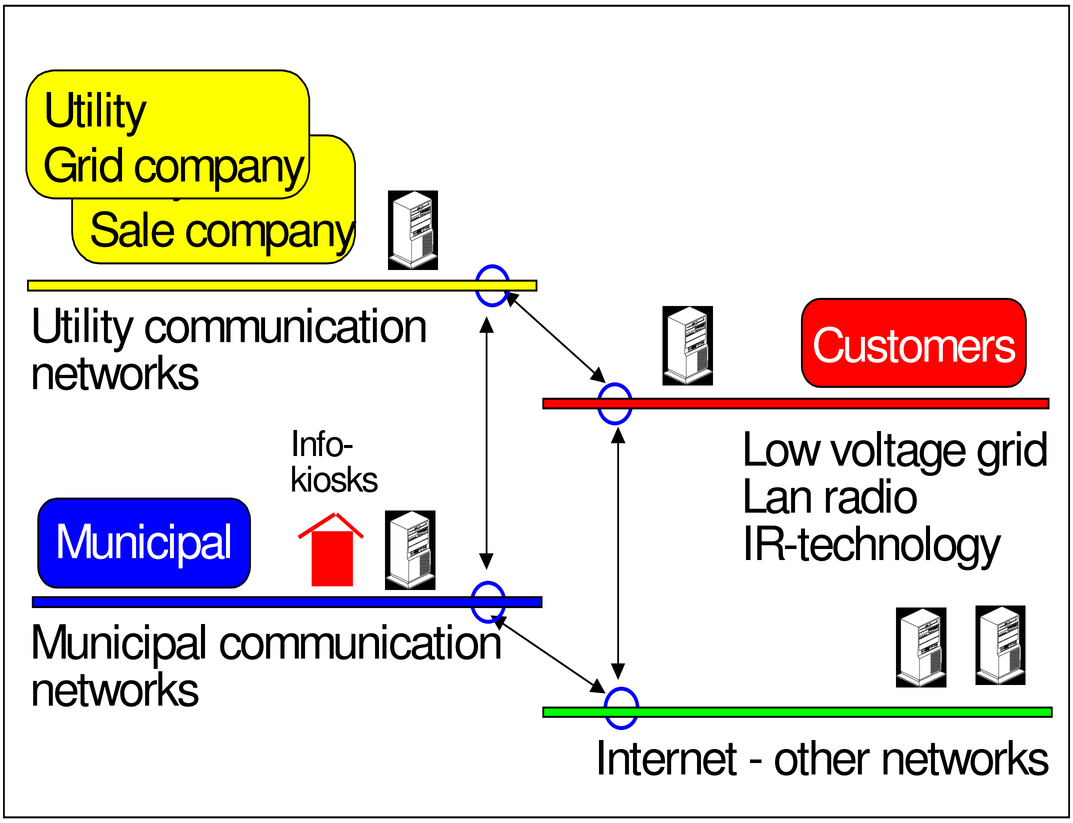


Figure 4.1: The integrated energy distribution market infrastructure (source: EnerSearchAB) [72]

Additionally, Figure 4.2 demonstrates a state-of-the-art comparison of PLC and other candidate technologies for local access infrastructures and services.

Copper / PSTN

+ Mature and robust
+ Good installed base
+ Wide choice of product
+ Easy to install / use
+ Relatively cost effective

– Relatively slow
– On demand only

ISDN

+ Mature and robust
+ Widely available

– Expensive for consumer market
– On demand only

Cable Modems

+ Excellent performance
+ Permanently on line

– Limited geographical coverage
– Currently only available in limited trials
– Contention based

Copper / ADSL-Lite

+ Good Performance
+ Currently at the trial stage
+ Permanently on line

– Immature
– Length of local loop affects performance

PLT

+ Good Performance
+ Permanently on line
+ Good geographical coverage

– Still at the developmental stage
– No installed base
– Distance limited
– Possible problems in meshed power networks

Figure 4.2: The comparison between PLT and other relevant technologies for the provision of Information Society access infrastructure and services (source: Mason Communications Ltd) [72]

However, comparing these communication media should not be constrained to the state of the art today. The ease of development and the possible upgrade and improvement paths are also crucial.

Customer Bandwidth

	COPPER / PSTN 1)	CABLE TV NETWORKS 2)	FIXED RADIO (WLL) 3)	PLT 4)
Broadband > 1 Mbps				Requires compression ?
Wideband 128 kbps–1 Mbps	Introduction of ADSL	Introduction of cable modems	Introduction of broadband radio	+
Midband up to 128 kbps	–	–	–	+
Multi-line telephony (minimum data)	Requires additional build	Requires additional build	Requires additional build	+
Telephony (minimum data)	+	+	+	+

1) Copper twisted pair
2) Hybrid fibre coax with copper termination for telecoms
3) NORTEL proximity-1 radio system
4) Based on an OFDM implementation protocol

Figure 4.3: Comparison of access technology upgrade paths (source: Spectrum) [72]

Note that, considering the capital expenditure and implementation requirements; PLC is considerably favorable compared to other local access technologies. In addition, PLC can offer gradually increasing bandwidth availability to the market as the demand increases in time.

4.3 THE SWOT ANALYSIS FOR PLC

4.3.1. Strengths and Weaknesses

The most noteworthy strengths of PLC can be listed as follows:

- PLC offers a permanent online connection without the burden of extra employment costs which is still valid for most conventional switched systems.
- PLC requires no additional wiring.
- PLC offers easy installation and expansion. The terminal of the communication systems are already connected to power lines, by just putting power plugs to the new outlets, new terminals can be added to the system or the existing ones can be repositioned.
- PLC provides reasonable performance and good geographical coverage.
- PLC provides bidirectional data communication with a relatively inexpensive infrastructure investment.
- The PLC infrastructure is ubiquitous and has an attractive upgrade path
- PLC is unique in such a way that it provides both telecom and value added energy services concurrently.
- The low level of output power transmitted complies with the electromagnetic compatibility criteria. This low power level is in line with the environmental constraints for in house applications.

On the other hand some of the remarkable weaknesses of the PLC are:

- Since the power wiring system was originally intended for transmission of AC power, the power wire circuits have only a limited ability to carry higher frequencies.
- Inferior and unstable transmission characteristics causes serious degradation of error performance
- PLC is still at the development stage, there are not a wide range of installed customer bases. Report on the transmission of data over the electricity power lines
- Although PLC has a wide coverage, the distance it can transmit the data uninterruptedly is limited compared to its competitor technologies.
- Impedance of power line is usually lower than that of the connected equipment. Impedance mismatch causes transmission losses.

- Power line channel transmission can experience some possible problems in case of very heavy power fluctuations or cutoffs. Furthermore, during the day time, LV network exhibit problematic conditions such as very low impedance values and high noise levels. That's why night conditions of PLC propagation make it feasible, in contrast to the conditions observed in the early hours of the evening or midday.
- Allowed frequency range is narrow (3-148.5 kHz). Still PLC offers acceptable bandwidth, considering the low investment costs.
- As a result of the electromagnetic compatibility limits defined for different communication media, PLC network are limited with a specific signal power. Due to these limitations, PLC network become more sensitive to disturbances from the electrical supply network and the network environment itself. Besides, the error handling mechanisms employed to solve this problem, uses a part of the transmission capacity and decreases the data transmission rate. Consequently, there exists a trade-ff between the QoS (Quality of Service) requirements for the PLC and decreased data rates. This trade-off is a considerable disadvantage of PLC in its competition with the other access technologies such as DSL or cable TV.
- Non whiteness of the PLC noise complicated the modeling of power line noise. Defining counter measures for the noise is difficult because a new model has to be developed to express the PLC noise model. Statistical behavior of the man-made noise is different form the stationary white Gaussian noise which is usually used as a basis to design communication system models.

To sum up, PLC is a remarkable candidate for the last mile local access technology. However, the integration and concurrent functioning of the different local access technologies is more probable as each technology provides various trade-offs among coverage, bandwidth, noise immunity and investment and operation cost. For PLC to differentiate, it should be positioned as an interoperable and standardized local access strategy, making use of its continuous online availability and coverage advantages.

4.3.2 Opportunities for the Utility Companies

4.3.2.1 Higher Availability and Growth in Access Network

The utility company takes the advantage of a reliable and suitably scaled access technology by implementing PLC. For example the NORWEB, that is the pioneer company for the development of Digital Power Line Commutations in UK, has benefited the high bandwidth data access over the same physical cabling as that used for electricity distribution. The PLC turns the already existing cable infrastructure to an Intranet by providing a Local Area Network to the private or industrial customer. Moreover, with the added benefits of the PLC technology, this network functions over the internal building wiring, generating a ubiquitous high bandwidth data infrastructure for the communication of PLC based electricity distribution network. Some emerging applications are a network of computers plugged into the mains line, forming a high bandwidth data network. All end devices connected to this network such as TV sets, PCs, domestic home appliances or building control monitoring systems will be able to access the data transmitted over the network. Furthermore, automatic meter reading also benefits from the same network [96].

On the utility side, PLC enables the companies to offer new tariffs, prompting the customer for the sensible usage of energy by linking smart meters, programmable controllers and intelligent demand-supply management devices. Moreover, with the aid of the additional monitoring through AMR, the utility company can control the power distribution peaks. Needless to say, PLC contributes the utility company to retain its customer profile after the introduction of distribution market deregulations over the next years [97].

4.3.2.2 New Value Added Services

With the increasing availability and employment of the information services such as internet, more companies are appreciating the benefits of multimedia electronic services especially in the customer services area. This new relationship concept brings together the openness and competition, extending the limited transactional relationship between the customer and the company to an open and competitive environment. Companies, which begin to consider their customer service as their main marketing tool, are attaching more importance on multimedia and communications technology to employ automated and online customer service provisions. By this way the call center operators are filtered and the power is given directly to the customer. Supported by multimedia applications with sufficient data rates, customers can connect directly to the utility company and can receive up to date account statements, monitor their real time consumption, and electronically pay their invoices that they receive in the preferred format. The market surveys point out that the customer do not have loyalty to the printed invoices or bills but they would prefer the employment of an electronic data transfer technology. So as to say, by implementing PLC based applications, the utility companies not only grow their core business but also benefit form the online services as a marketing advantage for the company [96].

The online customer services offered via the PLC infrastructure assists the company to benefit from the one to one marketing relationships depending on the customers' preferences and profile. The multi utility approach provides a set of services for the fulfillment of customer needs. The smart cards' capacity can be used to store the user information and to enable the customers to reach their utility accounts through a PIN number. The user interface employed can also serve the user with online graphical displays of historical information about the account usage and profile. This is beneficial both for the utility company and the user. The utility company can make good predictions about the future usage profile of the customer by the use of the historical data and the customers can keep track of their short term and long term usage by the help of the historical data.

Furthermore, the proposed PLC systems can be examples for the effective transfer of directed and up to date advertising or responses to service problems of the customers. After the distribution market utilization by the employment of the multi utility environment, the customer can also benefit from the comparative analysis of a utility with the competing utilities. Moreover, cross marketing for other services can be of additional value to the customer loyalty. Finally, as stated several times in the previous chapters, AMR is employed for the transmission of meter reading values to the utility and also is efficacious for the customer to monitor their charges continuously. The customers do not have to wait to receive the bill to envisage their monetary burden. For all of these added value services to function properly, the employment of appropriate interface technology and the adaptation of the customers are key issues.

4.4 Business Aspects of PLC in the Scope of Telecommunications and Energy Markets.

PLC opens up new business opportunities for electricity and telecom industries due to its technical and economical advantages in means of ubiquity, last mile connectivity, strong growth potential of information services and cost effectiveness.

Various business and technology factors in the telecom and electricity sectors affect the PLC development through the continuous evolution of electricity business. Especially in Europe, privatization, liberalization and competition have required fundamental changes in corporate structure, organizational culture and the market.

Considering the utility monopolies these businesses deliver, low risk, stable and high quality revenue streams. Thus, the demand for technology development and the market innovation has been limited for the past decades. However, the growing competition driven by the privatization has pushed the companies to invest in technological developments and develop business strategies to differentiate their service and gain competitive advantages in the evolving market [71], [98].

While these changes are occurring in the energy markets, even more drastic developments are taking place in the telecommunications industry leading to greater competition among the participating companies. As a result of these changes, the utilities are trying to make use of the capabilities of power line communication to reduce telecom network costs and increase service availability and reach. Furthermore, the power utilities that do not directly enter to the telecommunications sector are seeking for ways to utilize PLC technologies by providing network access to telecom operators.

The current development of PLC occurs under the conditions of changing business sector boundaries, increasing competition, altered business regulations, reorganized financial institutes and redesigned global markets. Consequently, the current technical capabilities, especially the bandwidth, of the PLC technology is not limited by the physical capabilities of the power line, but rather with the boundaries defined by the regulatory authorities aiming to prevent the interference with other networks.

Over the past decades the bottleneck of local last mile access to the customer and the limitations in geographical availability, restricted the potential developments in the telecom services. The limited transmission capacity of the existing copper local network has limited the possibility of connecting all residential and commercial customers to a high speed information network. Besides, the cost of establishing an alternative high speed local access network was considerably high. Despite the high speed interactive capabilities of the copper telephony systems, cable TV networks or radio systems, the service or capacity that can be offered by these services in the local network environment were restricted.

On the other hand, PLC supplies a permanent on-line connection through a bidirectional symmetric communication accompanied by a reliable performance and very satisfactory geographical coverage. However, it should be noted that the PLC is still in the development stage and its applications are limited to narrow band applications such as SCADA based remote metering and telemetry. Moreover, there is not a widespread network of installed customer database and the commercial incentives to exploit PLC infrastructure are not defined. So as to say, the capabilities of PLC are still immature and need development.

As stated before, PLC is an alternative communication solution for the transmission of various shared service alternatives. PLC is a shared medium similar to all the other cable systems. Besides, DSL is a point to point connection with a lot of end users. To sum up, the data transmission from the data centre to the vicinity of customer premises can be supplied by traditional telecommunication methods or optical fiber. Then, the transmission from the vicinity of the customer premises to the end user can be supplied through various methods. At this point, PLC is the alternative to various access solutions such as DSL or cable modem. Alternatively, some designs use ordinary telecommunication solutions to transmit the signal to the point just before the substation or just before the distribution transformer. Another design is to employ PLC for aggregate signals but to use the wireless technology for the last mile to the end user.

Above all, the upgrade path for PLC is favorable compared to the other local access technologies by means of capital expenditure and implementation requirements. Consequently, PLC is significant last mile local access technology. Still, it should be remembered that PLC is a part of the complimentary technologies that offer different compromise between the bandwidth, noise immunity, reach and cost. For PLC to make use of its competitive advantages, it must be positioned by employing a well defined local access strategy, highlighting the benefits of it considering the geographic concentrations of users requiring common utility services.

CHAPTER 5

PLC SYSTEMS CHARACTERISTICS

5.1 IMPEDANCE

5.1.1 Power Line Impedance Characteristics

As stated before, the quality of signal transmission in power lines is significantly affected by noise and attenuation. The power line impedance that is frequency dependent and varies between a few Ohm to a few kOhm is another parameter that influences the signal quality in PLC [104].

The medium of the electromagnetic field is non homogenous and power line has various loads with different impedances connected to the line at different times. Thus, the power line impedance cannot be represented by a uniform distributed line or cable model. As a result, the channel impedance is continuously fluctuating. The overall resulting impedance of the line is the combination of all the network impedance and parallel connected loads. Therefore, the small impedances are important for determining the overall impedance and the resultant network impedances are difficult to predict. In most of the cases, the output and input impedances of the transmitter and receiver in a PLC system are suitably low to match the channel impedance. However, as the resulting network impedance is highly fluctuating, maximum power transfer is difficult to attain, resulting in the challenges for designing a coupling network.

CENELEC SC105A Working Group 4 points out this issue by implementing network impedance measurements in three European countries: France, Germany and Italy. These measurements and the results are considered to be representative of similar measurements for the low voltage distribution networks of the other EEC member countries. According to these studies, it was found out that the low voltage distribution network impedance values are rarely over 20 ohms in the frequency range of 3 to 148.5 kHz specified by EN 50065. In fact %90 of the impedance values of the low voltage distribution network was in the range of 0.5 to 10 Ω. Besides, the most frequently measured low voltage distribution network impedance values were in the order of 5 Ω. At some specific frequencies, there are peaks in the power line impedance characteristic. At these peaks, power line behaves like a parallel resonant circuit. Obviously, the results depend on the location over the power line in which the impedance is measured. Although the low voltage distribution network has a complex tree structure of phase and neutral conductors and earth lines with the power supply located at the root of the tree and the consumer loads distributed on the branches, still the impedance characteristics are highly variable. The reason for that is the fact that the actual physical layout of the low voltage distribution network varies considerably for different consumer loads that include household electrical devices, cookers, fridges, HIFI and other electrical equipment. As a result, the impedance of any cables, lines or devices is not negligible by comparison. So as to say, the transmission bandwidth is limited by the load characteristics, location (residential or industrial), the choice of modulation system and the data rate.

To sum up, several parameters such as characteristic impedance of the line, the network topology and the impedance characteristics of the connected loads affect the overall net impedance of the system. In order to decrease the attenuation impedance matching is targeted in conventional communication channels. Impedance matching is straight forward for a typical antenna or a coaxial cable, the characteristic impedance of which is defined in a wide range independent of frequency.

However for a power line channel the characteristic impedance in highly variable. For example, as a result of the impedance characteristic of the power line, several hundred watts of transmission power would be required to inject allowed signal amplitude into the network at 10 kHz. On the other hand, a signal in the order of watts might be enough to do the same injection at 90 kHz. For a power line system, access impedance typically increases with increasing frequency. In addition to the time variance and frequency dependence properties, power line also varies significantly with location. At the low voltage side of a distribution transformer the impedance values are 10 – 20 times greater than those at a normal outlet of a building [15].

5.1.2 The residential power line impedance

The residential impedance is a crucial point for the PLC system design. The residential impedance is determined by the characterization of the distribution transformer secondary windings and the entrance cables, house wiring and electric loads.

Figure 5.1 illustrates the frequency response of a typical power line examined by the Nicholson and Malack.

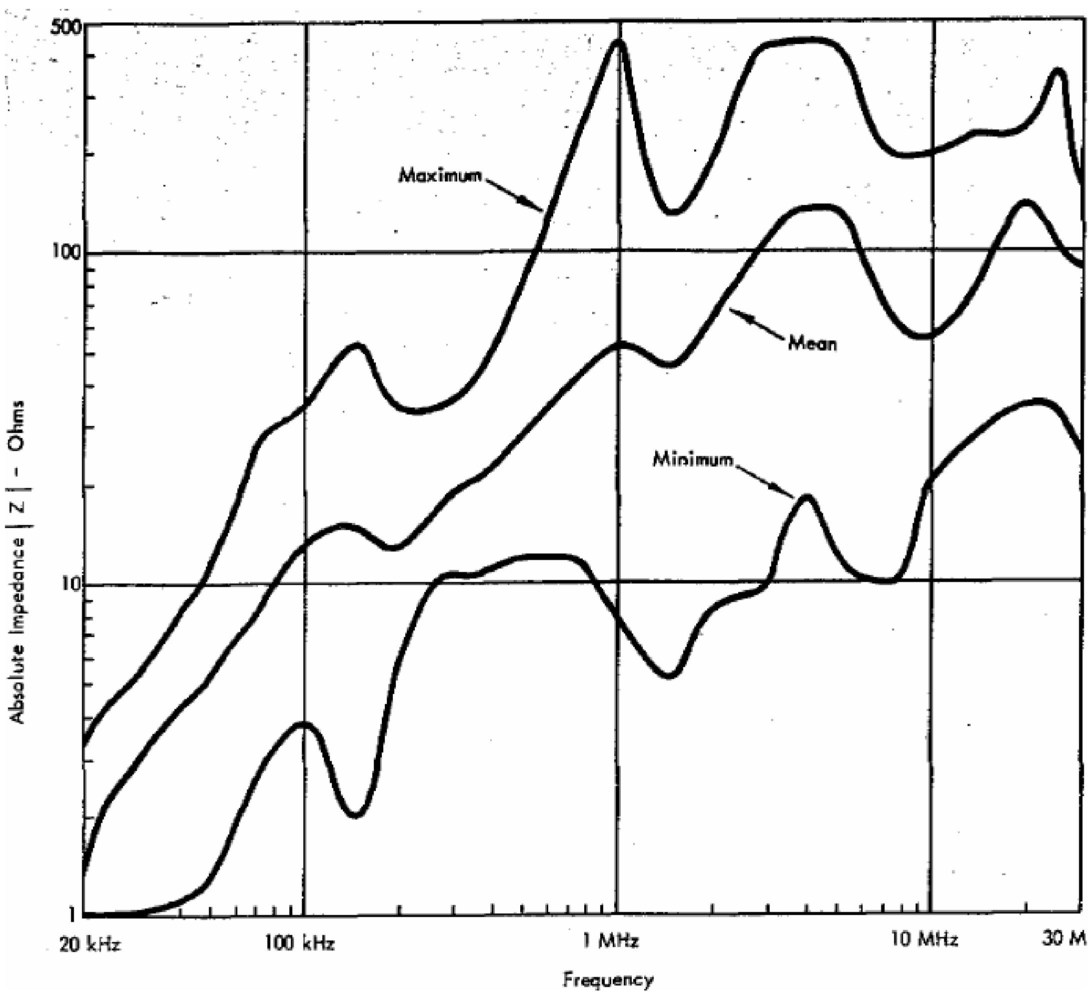


Figure 5.1: Power Line Impedance Measurements by Nicholson and Malack [103]

Nicholson and Malack measured the power line impedance throughout the frequency range from 20 kHz to 30 MHz and stated that the power line impedance increased from 10 ohms to 25 ohms in the frequency range between 100 Hz to 450 Hz [103].

In addition, Vines's studies partially confirms the results of the studies of Nicholson and Malack for the frequencies up to 20 kHz [105]. Vines feeds the voltage signal to the line via a bandpass filter at the frequency of interest and measures the voltage and current values. Vines's method is interesting because there is no need for the presence of a mains power signal (60 Hz in this case) and this simplifies the test set up. The presence of the 60 Hz signal causes some harmonic distortions but has no

significant effect on the frequencies in the order of several kHz. For different types of cables, Vines reports frequencies between 70 Ω to 100 Ω.
Vines's studies and some other studies indicate that the residential power line can be simply modeled as distributed impedance with a characteristic value of

$$Z_c = \sqrt{\frac{L}{C}} \text{ for L in mH/foot and C in mC/foot} \qquad (5.1)$$

The 120 and 240 kV residential power circuits show an inductive behavior as the impedance increases with increasing frequency. According to Figure 5.3, the power line impedance is between 5 to 32Ω at 100 kHz.

Likewise, the affect of household loads on the overall residential impedance is covered in Vines's study. He states that the impedance of most electrical loads, except the high resistive loads, is high compared to the unloaded power line impedance. In addition; some loads cause resonance with the power line impedance at frequencies above 40 kHz, which is worth considering as the protocols of interest cover the frequency range above 100 kHz. Furthermore, the EMI filtering of the switched mode power supplies (SMPS) cause problems as the capacitors used for these filters bypass the transmitted signal and PLC nodes should not be connected to these points [105].

5.1.3 Load Impedance Measurements

In his study of "Performance analysis of FSK Power Line Communications Systems over the Time Varying Channels: Measurement and Modeling", Hakki Cavdar investigated the impedance and attenuation characteristics of power line channels [85].

Load impedances are highly time variable. The studies of J. Huloux and L. Hanus[106], G. Platt and B. Cook [107], J. A. Malack and J. R. Engstrom [108] are some of the studies on load impedances for PLC applications. According to those measurements the impedances of residential power circuits increase with frequency and change between 1.5 to 80 Ω at 100 kHz.

Table 5.1 is the list of measurements for some typical loads in Turkish homes in the frequency range between 50 – 200 kHz.

Table 5.1: Impedances of typical electric household appliances in Turkey [85]

APPLIANCE	Avrg. Power (W)	RF IMPEDANCES MAGNITUDE (KILOOHMS) Frequencies (KHz)				
		50 Hz	50	100	150	200
Coffeemaker	1200	0.07	0.07	0.07	0.07	0.07
Dishwasher	1200	4.75	0.02	0.01	0.006	0.004
Mixer	127	8.25	23.5	10.4	6.43	4.91
Oven	2500	0.02	0.02	0.02	0.02	0.02
Iron	1200	0.85	0.35	0.40	0.46	0.52
Toaster	1150	3.50	0.03	0.02	0.01	0.007
Washing mac.	512	5.25	32.5	27.2	21.5	17.4
Air conditioner	860	45.0	11.2	9.75	6.35	4.45
Fan	88	11.9	27.2	18.9	12.6	8.50
Hair dryer	600	4.72	47.1	39.2	24.20	12.70
Shaver	15	30.0	11.0	8.50	7.25	6.75
Radio	70	21.2	23.3	6.66	4.28	3.15
Television	240	0.05	0.06	0.02	0.01	0.006
Type recorder	145	2.53	21.4	4.7	3.13	2.50
TV Anten. Amp	4	100	21.4	13.3	4.70	5.09
Vacuum cleaner	600	47.0	8.72	3.13	2.01	1.36
Lamp	75	0.63	0.63	0.63	0.63	0.63
Heater	2000	0.25	0.25	0.25	0.25	0.25
Computer (PC)	500	6.00	0.27	0.30	0.315	0.33

This measurements show that home appliances impedances changes with the frequency in a non linear fashion. So it is difficult to come up with an explicitly frequency dependent formula or equation for the home appliances. The impedance should be determined at the specific link frequency. At the same time, industrial and commercial power utilization varies during the day. The load changes during a period of time are called diversity. In addition to the daily variations, the weekly and seasonal diversity should also be taken into consideration for load impedance estimations. As a result of these kinds of fluctuations, the probable errors in the control signals may cause system errors. Real impedances are calculated using the load diversity of the power systems.

5.2 ATTENUATION

5.2.1 Power Line Attenuation Characteristics

The transport of the electrical energy from the power station to consumer premises is executed in three voltage levels referred as high, medium and low voltage levels. The high voltage level, which covers the range between 380 kV and 110 kV, is used for the transmission of electrical energy from the power stations to the high voltage transformer substations close to urban or industrial locations. The medium voltage network is employed for energy distribution between the high voltage transformers substations and the medium voltage transformer substations near the customers. At the medium voltage transformer substations the voltage is reduced to 0.4 kV and distributed to customer premises. On the other hand, most of the industrial customers' premises are fed directly from the medium voltage network. Medium voltage network can be composed of overhead or underground cables. The most widely used network topology is a radial net or open ring network. (See Figure 5.2) Radial network is simpler and easier to assemble. On the other hand, open ring network offers a higher reliability [109].

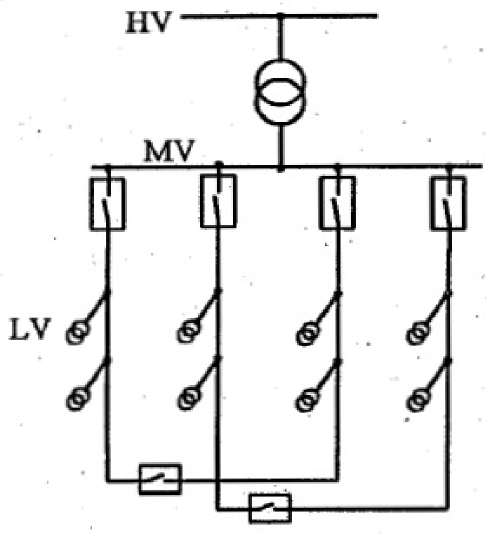


Figure 5.2: Open ring net [110]

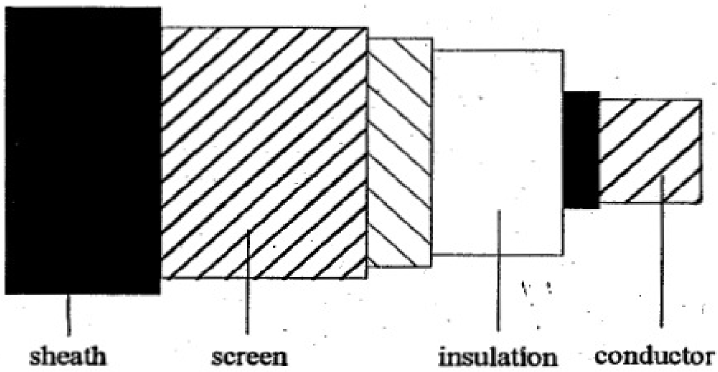


Figure 5.3: The general construction of coaxial cable from inside to outside [110]

Depending on several factors such as the consuming statistics and the geographical location, the distance between two medium voltage transformer substations is around several hundred or thousand meters. In figure 5.3, the cross sectional view of a coaxial single core cable is illustrated. The core of the cable is composed of one or more copper or aluminum wires with cross sectional areas between 35 mm^2 to 500mm^2. The semi conducting insulation, which separates the screen from the conductor, is used to limit the electrical field. The screen is composed of semi-conducting material and copper wires. The screen, which is connected to the ground, carries charging current, leakage current and ground fault current. The cable is protected against mechanical stress and corrosion by the outer sheath.

The primary transmission line parameters can be calculated by using the related formulas for coaxial cables because of the coaxial structure of the single core cable. Accordingly, the resistance per unit length is calculated by using the diameter of the outer conductor (D) and the diameter of the inner conductor (d), along with the conductor resistivities (ρ_i) and the penetration depths t_i as follows [111]

$$R' = \frac{\rho_1}{\pi . d . t_1} + \frac{\rho_2}{\pi . D . t_2} \tag{5.2}$$

Where, $t_i = \sqrt{\frac{2\rho_i}{\omega\mu_0}}$ (5.3)

for ω the angular frequency and μ_o the magnetic constant.

Similarly, the conductance per unit length is calculated as [112]

$$G' = 2\pi \frac{\omega\varepsilon_0\varepsilon_r}{\ln\frac{D}{d}} . \tan\delta \tag{5.4}$$

for the permittivity of space ε_0, the relative permittivity ε_r and the dielectric loss angle $\tan\delta$.

Moreover the inductance per unit length is,

$$L' = \frac{\mu_0}{2.\pi} . \ln\frac{D}{d} \tag{5.5}$$

and capacitance per unit length is

$$C' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\frac{D}{d}} \tag{5.6}$$

Furthermore, the secondary transmission line parameters characteristic impedance $\underline{Z}_L$ and the propagation coefficient $\underline{\gamma}$ can be derived from the primary transmission line parameters as follows: [112]

$$\underline{Z}_L = \sqrt{\frac{R' + j.\omega.L'}{G' + j.\omega.C'}} \text{ and } \underline{\gamma} = \sqrt{.(R' + j.\omega.L').(G' + j.\omega.C')} \tag{5.7}$$

Several types of power line cables were measured by to determine their characteristics. Measurements were carried out using a network analyzer with input impedance of 50 Ω. To come up with a formula, the open circuited and short circuited cable impedances were measured.

The input impedance of an open circuited transmission line can be expressed as [112]

$$\underline{Z}_{ino} = \underline{Z}_L.\cot anh(\underline{\gamma}.l) \tag{5.8}$$

Whereas, the input impedance of a short circuit transmission line is

$$\underline{Z}_{ins} = \underline{Z}_L.\tanh(\underline{\gamma}.l) \tag{5.9}$$

Using the short and open circuit input impedances, the characteristic impedance can be calculated as [112].

$$\underline{Z}_L = \sqrt{\underline{Z}_{ino}.\underline{Z}_{ins}} \tag{5.10}$$

And the propagation coefficient is derived as

$$\underline{\gamma} = \frac{1}{l}.arctanh\sqrt{\frac{\underline{z}_{ins}}{\underline{z}_{ino}}} \tag{5.11}$$

Lastly, the primary transmission line parameters are calculated as:

$$R^{'} = \Re\{\underline{z}_{L}.\gamma\} \tag{5.12}$$

$$G^{'} = \Re\{\gamma / \underline{z}_{L}\} \tag{5.13}$$

$$L^{'} = \Im\{\underline{z}_{L}.\gamma\} / \omega \tag{5.14}$$

$$C^{'} = \Im\{\gamma / \underline{z}_{L}\} / \omega \tag{5.15}$$

Note that, the real part of the propagation coefficient which is referred as attenuation coefficient and its imaginary part called the phase coefficient usually can not be measured explicitly as a transfer function because of the impedance mismatch between the network analyzer and the device whose characteristics are measured. Distorted measurements are obtained because of this impedance mismatch. In order to solve this problem, firstly the characteristic impedance should be measured and impedance transformers should be used to match the input/output impedance of the network analyzer to the characteristic impedance of the device.

5.2.2. Attenuation and Measurement of mains cables

5.2.2.1 Dependency of Attenuation Loss on Dielectric Characteristics

Regular cross sectional view of an indoor mains cable with 2 or 3 conductors is shown in Figure 5.4. The insulation material is a cable is important for determining the frequency characteristics of a cable. The insulation material of a low voltage is normally polyvinyl chloride (PVC), however the insulation material can be polyethylene or rubber for operating conditions under high temperatures.

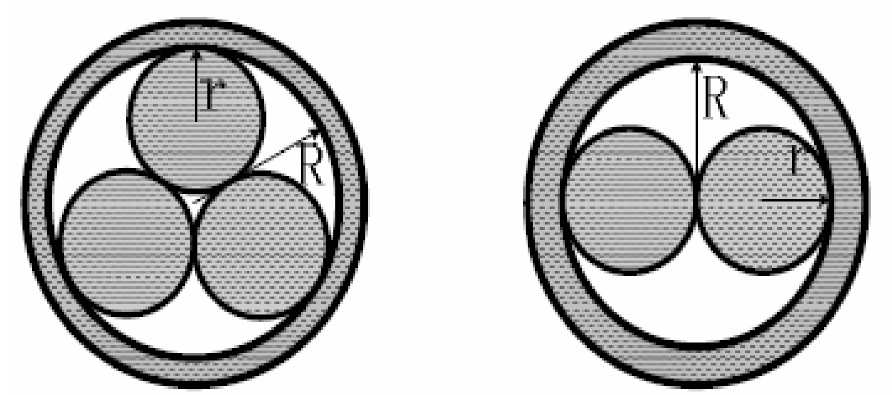


Figure 5.4: Cross sections of typical indoor power cables [113]

The dielectric characteristic of PVC depends on temperature, frequency and the composition of the insulation material. So it is not logical to attempt defining the explicit dielectric characteristics of PVC. Figure 5.5 gives a brief idea about the relationship between relative electric constant, frequency and temperature.

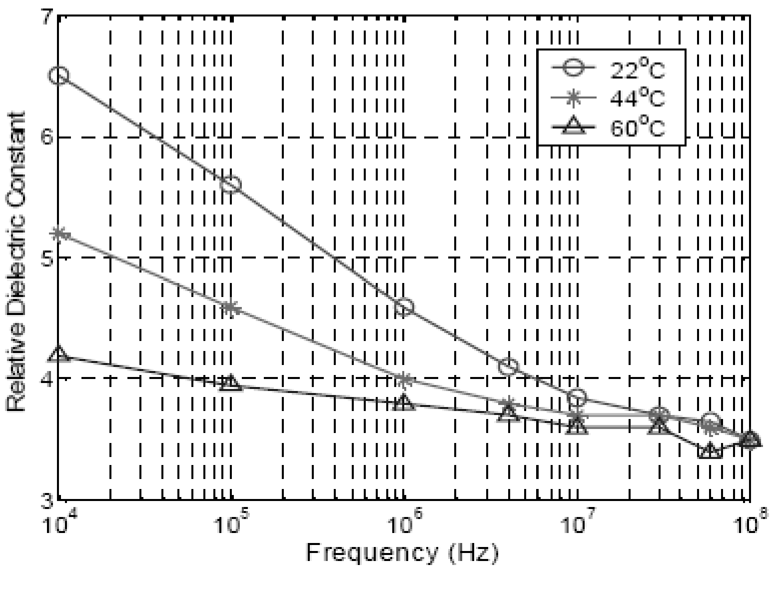


Figure 5.5: Relationship of the relative dielectric constant with frequency and temperature [114]

Some proportion of the power injected by the transmitter does not reach to the receiving end because of the non ideal characteristics of conductors and insulation materials. At the frequencies of interest for PLC, the primary causes of loss and attenuation for low voltage (220 V) power cables are the resistive losses, dielectric losses and coupling losses. [114]. Referring to Jero's studies, the transmission line theory indicates that the PLC cable can be modeled by distribute parameters R, C, L and G as follows:

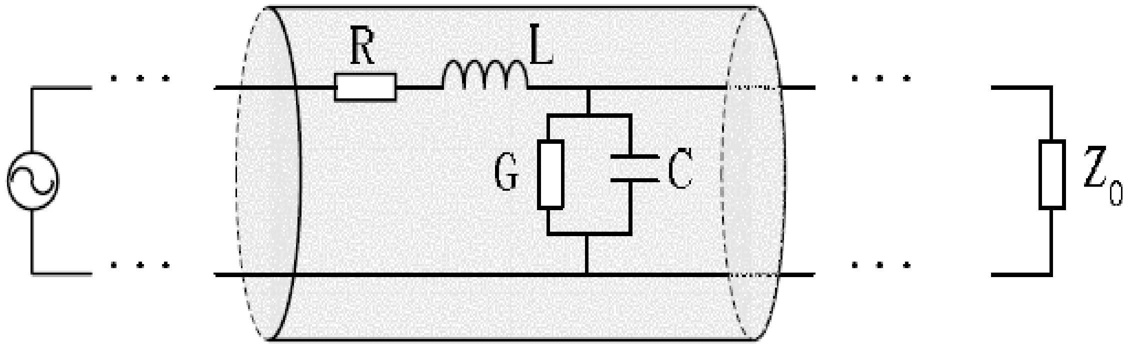


Figure 5.6: A distributed transmission line model. [115]

When the signal is fed between the two conductors, most of the electric field is confined between the conductors. Then according to Manfred and Klaus's study, the resistance per unit length is determined by the skin effect [116]. R is proportional to $\sqrt{f}$ and G is proportional to f. Following that the characteristic impedance (Z_L) and the propagation constant (γ) are calculated as;

$$Z_L = \sqrt{Z/Y} = \sqrt{\frac{R + jwl}{G + jwC}} \tag{5.16}$$

$$\gamma = \sqrt{(R + jwL)(G + jwC)} = \alpha + j\beta \tag{5.17}$$

Considering a real transmission line the effects of R and G on the attenuation is much smaller than the effect of L and C, i.e. R<<wL and G<<wC which leads to

$$Z_L = \sqrt{\frac{L}{C}} \tag{5.18}$$

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} = \frac{R}{2}\frac{1}{Z_L} + \frac{G}{2}Z_L \tag{5.19}$$

$$\gamma = k_1\sqrt{f} + k_2\sqrt{f} + jk_3 f \tag{5.20}$$

Note that, the attenuation loss (α) which is the real part of the propagation loss, is proportional to a function of f and $\sqrt{f}$. Table 5.2 below shows the measured attenuation for a bundle of indoor mains cables for a length of 20 meters.

Table 5.2 Types and sizes of the measured cables [113]

Cable Type	**Size (mm^2)**
Vulcanize rubber cable (three-wire)	0.75
Vulcanize rubber cable (three-wire)	1
PVC/PVC cable (three-wire)	0.75
PVC/PVC cable (two-wire)	0.5

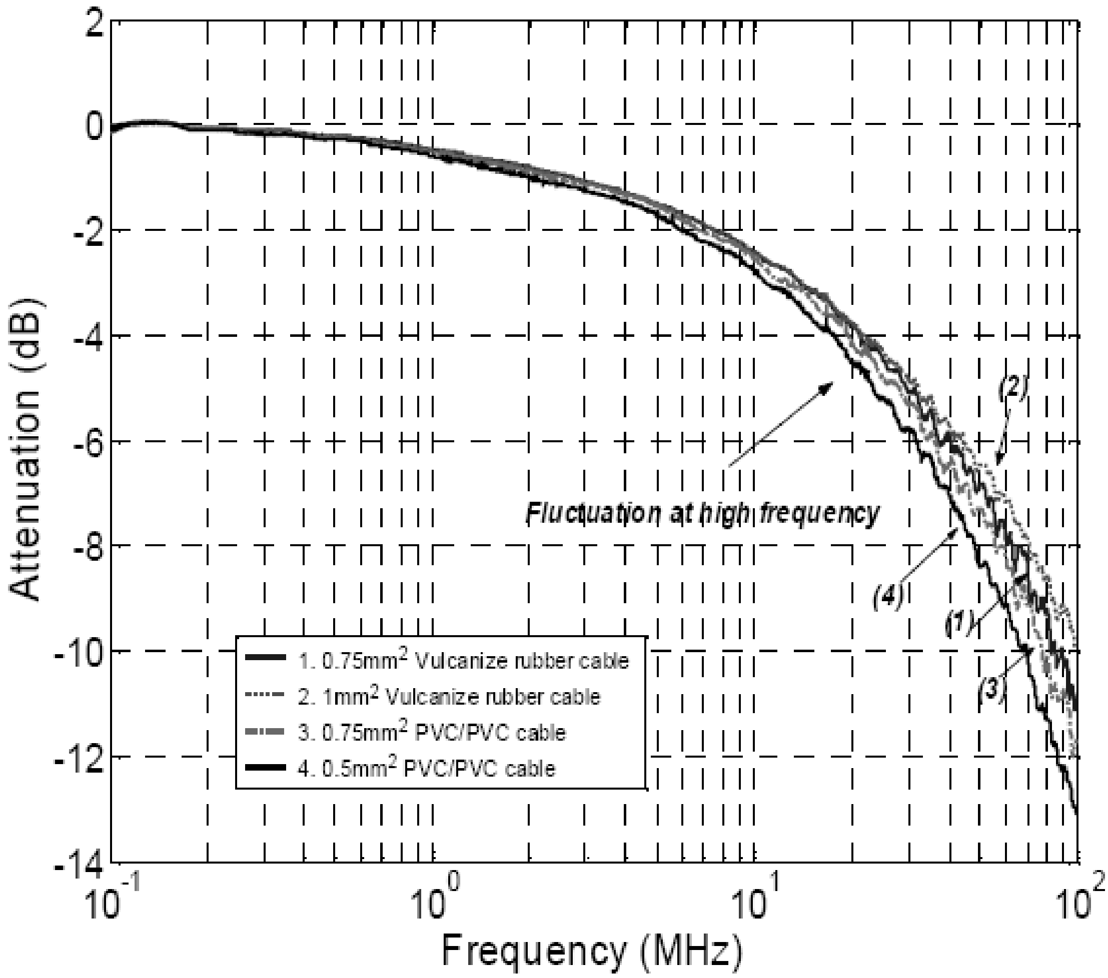


Figure 5.7: Attenuation of the measured mains cables [113]

In Figure 5.7, note that the fluctuation at the high frequency between 10 to 100 MHz is caused by impedance mismatching of coupling circuit. It is observed that the maximum attenuation difference among the mains cables is 4 dB at 100 MHz.

5.2.2.2 Attenuation characteristics modeling and measurements for mains cables

A tone signal injected to the power line at appropriate frequency through a coupling circuit is a usual cause of attenuation. In the frequency band of interest, the measurements can be conducted by applying a sinusoidal sweep signal, transmitted through a twisted low voltage line. Attenuation is calculated from the relationship between the received and transmitted signal by using a FFT based software. The real part of the transfer function reveals the attenuation. Additional attenuation, on the order of 20 dB, due to the coupling between phases (cross coupling) can occur. There are various measurements about the modeling the signal attenuation as a function of the variables that are mentioned in the introduction of this chapter (location, time, frequency, user access, load characteristics, voltage level and cable layout) [3]

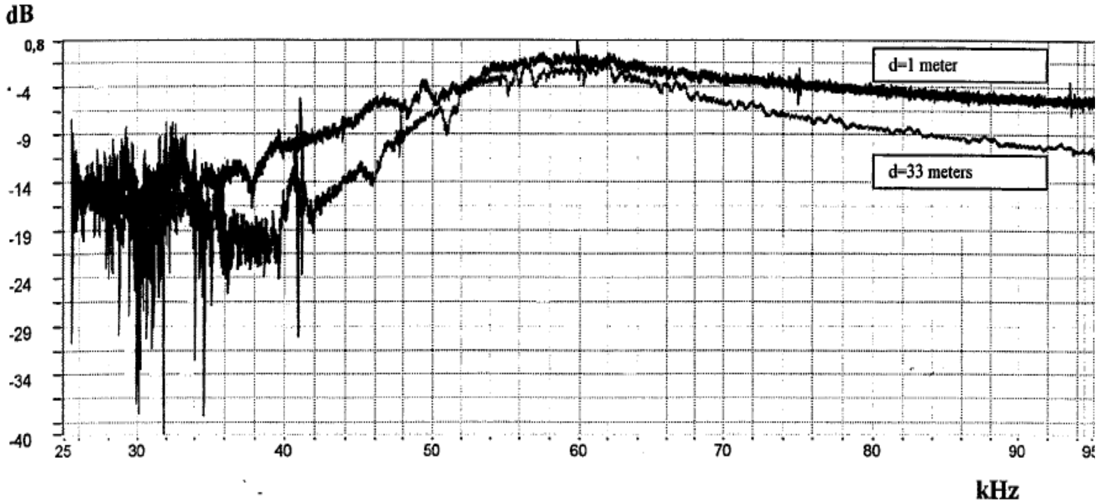


Figure 5.8: The transfer function of low voltage line versus frequency [3]

According to Hooijen's model presented in "On the channel capacity of the residential power circuit used as a digital communications medium", the attenuation frequency is independent but varies within the range between 40 dB/km and 100 dB/km.

Based on IEC's Technical Report 1334-1-4, the attenuation is simply modeled as follows

$$A = 12.6 + 0.055(d - 100) + 0.25(f - 60) \text{ dB} \tag{5.21}$$

Note that the attenuation increases with a slope of 0.25 dB/kHz for frequencies between 60 kHz and 90 kHz. Moreover distance in meters contributes to the increase of attenuation with a slope of 55 dB/km for distances between 100 and 550 km. Furthermore the time of the day has some effect on the fluctuation of attenuation. Night time attenuation usually exceed the day time [6].

For a typical low voltage distribution system, power conductors are arranged in a star shaped topology. A circuit breaker usually feeds 10 to 20 lines and each line supplies 8 to 10 outlets. The branches in the line are permitted but not common. In the case that the loads are connected to outlets, stubs occur. If extension cables are used these stubs can become very long. For lengths of stubs being less than 100 meters, no nulls are formed at frequencies less than 500 kHz. The absence of nulls points out to a considerably flat attenuation characteristic for low voltage PLC frequency of interest (100 to 450 kHz). In this case, there is no need for channel equalization.

In addition to the almost flat and constant attenuation of the power conductors, high attenuation that can obstruct the data transmission significantly is observed in some frequencies. This type of attenuation is mainly caused by quarter wavelength transmission line stubs.

Dostert indicates a 15 dB mean attenuation for a typical single phase indoor cable and 50 dB for external power lines for frequencies below 150 kHz up to 0.7 mile cable lengths. He states that the in some cases the interference signal level exceeds the transmission signal because of the signal level limitations. He indicates that these unreliable data links are also a consequence of poor performance of narrowband modulation techniques. Dostert proposes a frequency hopping spread spectrum (FHSS) communication technique to solve this problem [117]. Similarly, Chaffanjon, Duval, Menuier and Pacaud state in their studies that an attenuation of 60 dB may be observed at the end of 100m of overhead line in towns, while in rural zones the level of propagation attenuation may be in the order of 20 dB at the end of 500m of twisted overhead line [118], [119], [120].

On the other hand, Hanson measured the signal attenuation in the Engineering Building of the University of Saskatchewan and found out that the attenuation was on the order of 15 or 20 dB at a separation of 4m between the outlet and ranged from 35 dB to 40 dB at a separation of 23m.

5.2.3 In-home signal strength measurements for signal attenuation

Signal attenuation for in home electrical line is crucial for the home automation systems design. According to the study of Hakki Cavdar's study, the attenuation measurements are done between some room of a typical house such as kitchen, bedrooms, living room, bathroom and hall. [85] Power is delivered through the connectors located at the walls between the corresponding divisions of the house. In Table 5.3, the connector numbers for each branch are indicated in the parentheses. The distances for the power line measurements of Table 5.3 are between 6 – 30 m.

Table 5.3: Attenuation levels between the divisions of homes (in decibels) [85]

	Kitchen	Living room	Bedroom 1	Bedroom 2	Bedroom 3	Bathroom	Hall
Kitchen	(1) av=6 dB sd=1.5 B	(2) av=9 dB sd=2.5 dB	(3) av=8 dB sd=2 dB	(3) av= 7.5 dB sd=2 dB	(4) av=9 dB ss=3 dB	(4) av=10 dB sd=3 dB	(5) av=6 dB sd=2 dB
Living room		(1) av=5 dB sd=1.5 dB	(2) av=6dB sd=2 dB	(2) av=6 dB sd=2.5 dB	(3) av=8 dB sd=3 dB	(3) av=8 dB sd=2.5 dB	(2) av=6 dB sd=2.5 dB
Bedroom 1			(1) av=6 dB sd=2.5 dB	av=6.5 dB sd=2 dB	(3) av=8.5 dB sd=2.5 dB	(2) av=7 dB sd=3 dB	(3) av=5 dB sd=2.5 dB
Bedroom 2				(1) av=6.5 dB sd=2 dB	(2) av=7.5 dB sd=3 dB	(3) av=7.5 dB sd=2.5 dB	(3) av=5.5 dB sd=2.5 dB
Bedroom 3					(1) av=5.5 dB sd=2.5 dB	(2) av=8 dB sd=2.5 dB	(3) av=7.5 dB sd=2 dB
Bathroom						(1) av=6.5 dB sd=2.5 dB	(4) av=6.5 dB sd=3 dB
Hall							(1) av=6 dB sd=2 dB

5.2.4 Interhome signal strength measurements for signal attenuation

For relatively long distance communication applications such as automatic meter reading, remote control of home appliances and wireless ring networks, the interhome signal measurements are important. For the Turkish electricity grid, interhome signal measurements can be divided into two categories: the measurement between the flats of an apartment and the measurements between single homes using the same phase of a power line. According to the studies of Hakki Cavdar, the distances between the signal homes that share the same phase vary between 5 to 1500 m. Hakki Cavdar points out that the attenuation for the interflat signals is between 10 – 25 dB and the attenuation for the single houses that are 200 – 1000 m distant from each other, the attenuation varies between 40 – 60 dB [85]. Again the load diversities should be taken into account for complete understanding of signal attenuation.

5.3 CONCLUSION

Power communication lines characteristically have low characteristic impedance and high signal attenuation. Typically, every transmitted signal is subject to attenuation over the power supply on the way to the receiver. Attenuation values depend on individual properties of the power line such as total length of the link, frequency, location and time. In power lines attenuation can be as large as 90 dB. Average fluctuations with time are around 20 dB.

Attenuation and time related distortions degrade the efficient and reliable data transmission over the power network. Stable and high frequency carrier signals of considerably adequate power level are need for data transmission in the vicinity of noise between the required terminals. However, there is a trade-off between the increased levels of data transmission and radiation of the high frequency communication signals. The power levels should be limited to prevent counterfeit emissions from the high frequency transmitting equipment. There are internationally agreed maximum power levels for spurious emissions from high frequency transmitting equipment**.** These standards should be taken as a basis when designing the equipments in order to diminish the risk of interference to other occupants of the high frequency spectrum.

CHAPTER 6

NOISE AND DISTURBANCES IN THE POWER LINE NETWORK

6.1 INTRODUCTION

Noise and disturbances in the electrical grid can be roughly classified as follows:

i) Waveshape disturbances
a. Over-voltages, both persistent (>2 seconds) or surges (<2 seconds).
b. Under-voltages, both persistent or surges.
c. Outages.
d. Frequency variations.
e. Harmonic Distortions
f. Interharmonic Distortions

ii) Superimposed disturbances
a. Persistent oscillations, either coherent or random.
b. Transient disturbances, both impulse and damped oscillations

The waveshape disturbances have limited effects on the PLC systems. Transceivers are usually able to decompose minor overvoltage and undervoltage disturbances. Evidently, when overvoltages occur, total line outages make information transmission impossible. However, sometimes the outage of a particular device may not affect the performance of the entire domestic PLC system. The harmonic disturbances are much frequented sources of noise. The triacs or silicon controlled rectifiers such as light dimmers or photocopiers are examples for the sources harmonic and interharmonic noise. The typical spectrum of this type of noise includes a series of harmonics of the system frequency. As the order of lower harmonics between 3 to 10 kHz is lower than the PLC transmission frequencies, they have no direct impact on the PLC receivers. However, these harmonics produce a resonance source in the PLC system and affect the overall PLC system operation by resulting in the saturation of PLC components with ferromagnetic cores. As a result of this saturation, local harmonics are generated in the PLC frequency range. Still, it is good to know that the harmonic disturbances occur at frequencies below PLC transmission range defined by the regulations [124].

On the other hand, since many PLC systems depend on the system frequency sine wave (carrier wave) for the system synchronizing the transmitter and the receiver, the frequency fluctuations and variations in the carrier wave may cause transmission errors. Abandoning the dependence on main carrier for synchronization between the transmitter and the receiver can solve this problem. Additionally, the interharmonic noise is the type of noise with a frequency at the noninteger multiple of the power system frequency. The modulation schemes that can avoid these interharmonics can be employed to filter out these noise components by using accurate notch filtering [105], [125], [126].

The persistent oscillations include the noise type with a smooth spectrum. This type of noise is usually caused by universal motor. The transient disturbances are impulse noises and the non synchronous noises. The impulse noise is generally caused by switching devices. It affects the whole frequency range for a short period of time and can be eliminated by using error correcting codes. The non synchronous noise occurs at frequencies other than the system frequency. The different standards of television and computer scanning with different radiated noise components are the examples for this type of noise. The non synchronous noise can be eliminated by avoiding the transmission at certain frequencies and by using a frequency diverse modulation scheme that can avoid the non synchronous noise at any foreseen frequencies.

Looking at the big picture, the noise in power lines can be discussed starting from the producer to the very end user. So the journey from the output terminals of a generator to the power plug of a consumer premise is a long path that is worthy of a detailed analysis work.

Power line is not a standard communication medium. As a result of the primary function of the power lines, they are not designed for communication in the first place and their corrupted communication characteristics complicates the design of detailed model for PLC as compared to the explicitly identified models for other communication media like coax or optical cables.

Moreover, the power line channel impedance fluctuates with the frequency in a range of a few Ohm to few kOhm. Also, the load conditions change rapidly. The discontinuities in branch cables cause reflections and echoes. The impedance characteristic of the power line conveys some peaks at some frequencies. This effects lead to a multipath environment propagation and leads to deep narrowband notches in the frequency response.

Considering the PLC applications in HV and LV side of the transmission and distribution system, the noise in power line should be studies both on the HV side and the LV side.

6.2 NOISE IN HIGH VOLTAGE PLC SYSTEMS

In case of HV PLC applications, the Signal to Noise ratio (SNR) of a power line significantly suffers from the unsteady conditions of weather and rippled frequency characteristics. Noise in HV PLC channel can be divided into two main categories:

1. Noise at normal (stationary) operation: Major sources of this type of noise are the thermal agitation of conductors, static discharges and corona, and noise due to interference with other PLC communication systems and radio stations.

2. Noise at transient and emergency operation: Most important causes of this type of noise are power line faults, circuit breaker and isolator operation and lightning discharge. During normal operation the most dominant noise source is corona. Burcascano, Cristina, D'Amore studied the corona noise in HV power lines by identifying the power spectral density and Gaussian noise voltage with variable root mean square value in the time domain [127]. As a result, it can be stated that a HV power line is itself a noise source due to corona discharges. In other literature transient noise and emergency operation (circuit breaker and relay operations) and strong asynchronous impulses in HV power lines are also revised [128].
In summary, the fundamental noise types in HV power lines comprise corona discharge, static discharges, lightning, power factor correction banks and circuit breaker operation. The major parts of these noises are eliminated by medium-to-low voltage transformers on the low voltage side, so the most common interference in low voltage domestic networks can be attributed to the various household devices and office equipment connected to the network. In rest of this chapter of the thesis work, the noise models, characteristics and measurements of noise on the low voltage side of the power line will be studied.

6.3 NOISE IN LOW VOLTAGE PLC SYSTEMS

For many years low voltage power lines have been a communication medium in low bit-rate applications such as automation of power distribution and automatic meter reading. Nowadays also some other benefits such as internet access, home networking and local area networks have captured attention to the power line communication [3].

The major advantage of power lines is that they are easy to access through pre-installed and abundant infrastructures of wires and wall outlets in existing buildings [129].

Moreover the recent developments in telecommunications and digital signal processing enable the producers to solve the existing problems of PLC applications with limited amount of new investment [3], [130].

Clearly determining the characteristics of a communication channel is important for data transmission over any communication medium. Noise characteristics, attenuation and frequency response are the most important characteristics. Another important problem is the matching the input impedance of the power line as seen by a PLC transmitter in order to couple the transmitter power to the power line [131].

Moreover, there are various ambiguities that originate from the unstable and unpredictable aspects of PLC applications such as location (industrial zone or urban area, indoor or outdoor), time, frequency, user access, load characteristics, voltage level (low or medium) and cable layout (overhead or underground) [132]

6.3.1. Operating Environment of Low Voltage Power Lines

Operating environment of any communication technology determines the evaluation process of it. This fact, that is valid for power line communication, is usually ignored by most textbooks and literature. There are some common practices and assumption for communication systems, which should somehow be modified to be applied to power line analysis [133].

In most of the communication system models, the superposition principle is benefited to obtain a result. These systems, for which superposition principle applied, are modeled as the addition of stationary and impulse noises. Noise at the receiver side is regarded as the addition of the background noise and the appliance noises.

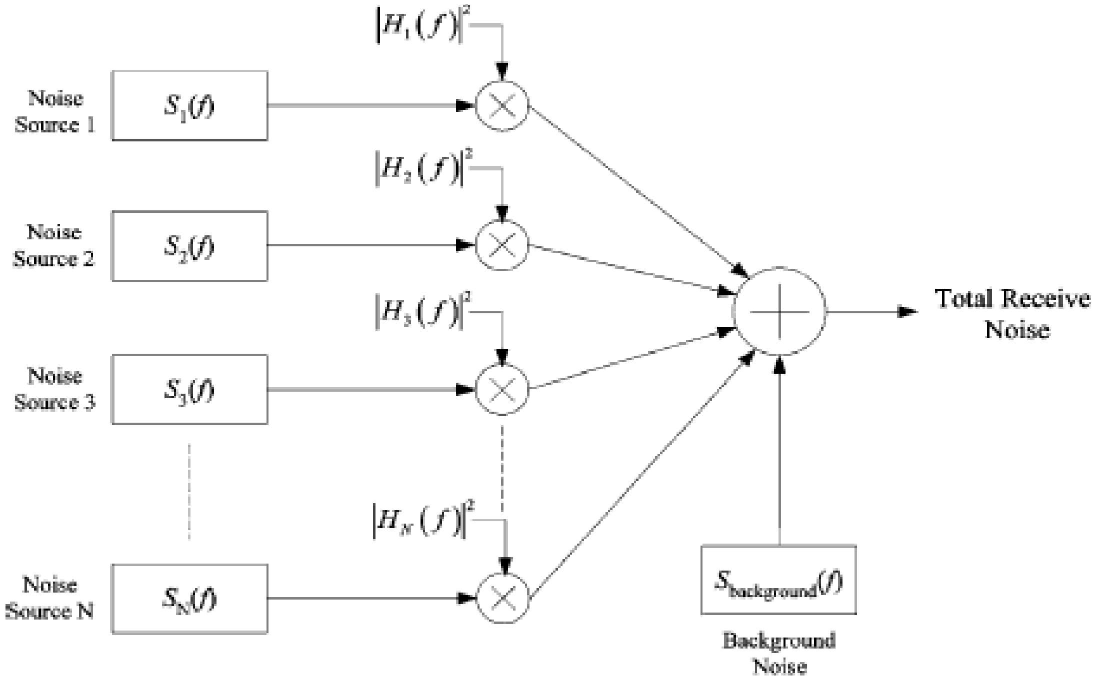


Figure 6.1: Illustration of modeling for total receiver noise for a system that superposition principle applies to [134]

For a system designer, the important point is the amount of noise reaching the receiver or the receiver's signal to noise ratio (SNR). S_i is the noise power spectrum for the i^{th} noise source and $H_i(f)$ is receiver noise spectrum for the i^{th} source, in other words: the transfer function between the i^{th} noise source and the receiver. As the appliances operate independently and the resulting noise signals of the corresponding noise sources are not correlated, the superposition principle is used. The aggregate noise spectrum in the receiver side can be expressed as [134]

$$S_{rx\_appliance}(f) = \sum_{i=1}^{N} \left[S_i(f) * \left| H_i(f) \right|^2 \right] \tag{6.1}$$

Consequently, the total noise in the receiver side is the summation of the corresponding appliance noises and the background noise [135].

$$
\begin{aligned}
S_{rx}(f) &= S_{background}(f) + S_{rx\_appliance}(f) \\
&= S_{background}(f) + \sum_{i=1}^{N}\left[S_i(f).\left|H_i(f)\right|^2 \right] \qquad (6.2)
\end{aligned}
$$

However the main two conditions of this principle, which are linearity and time invariance, are not applicable for the power line networks. An example for nonlinearity comes into scene when a packet's signal voltage adds up to the AC mains voltage and causes power supply diodes to turn on and off at the packet carrier frequency. Similarly, the time dependent impedance variation at a point of a power line network, resulting from the appliances alternately drawing and not drawing power from the network at twice the AC line frequency, is an example for time variance of the power line system.

One other ambiguity is the assumption that wiring capacitance dominates signal propagation effects. For the case of the termination or load impedance is greater than the characteristic impedance of the wire, it can be assumed that wire capacitance is dominant. However, power lines are often loaded with impedances considerably below the characteristic impedance of the wire and this violates the validity of the assumption above. Capacitors used in TV sets and computers to meet the electromagnetic emission regulations, resistive heating elements such as space heaters and cooking ovens are examples of loads with low network impedance at the communication frequencies. Comparing the entries of Table 6.1, one can observe that the impedance of the mentioned devices is approximately an order of magnitude below the characteristic impedance of power wiring.

Table 6.1: Power wire characteristics [14]

Wire Type	c/ft (pF)	L/ft (mH)	r/ft ohm @130 kHz	Z_0 ohms	v ft/nsec
12-2 BX metai clad	22.7	.125	.0132	74.2	.594
12-2G Romex NM-B	10.4	.214	.0136	143	.670
18-2 Lamp cord	13.2	.203	.0235	124	.610
18-3 IEC power cord	30.8	.195	.0315	79.6	.408

Table 6.2: Low impedance power line loads [14]

Low Impedance load	Impedance at 100kHz
0.1uF EMC capacitor	16 Ohms
2kW 240VAC space heater	30 Ohms

In order to model the attenuation with a full transmission model, the high frequency models of the specified loads are needed. However, there is a first order approximation that can be used to simplify the impedance characteristics. For a single line communication if the wire runs less than 1/8 of wavelength, then the wire inductance dominates the low impedance loads. For this case, the actual attenuation can be modeled by a lumped model conveying solely a wire inductance and low impedance loads.

In addition to all these facts, noise in power line communication is not Gaussian, nor stationary, nor white. As a result the PLC channels do not match any usual noise modeling techniques [136].

6.3.2 Classification of Noise in Low Voltage Power Lines

As stated before, the low voltage power lines (LVL) are the transmission lines that contain all the devices and equipment connected to the secondary part of a distribution transformer. There are various definitions in different sources about noise classifications of low voltage power lines. Taking Hooijen's classification as a basis for the frequency range below 200 kHz, the additive noise in power line communication channels can be abstracted under five categories [136]. Brief descriptions of them are given below. They will be detailed further in the following topics of this chapter.

1. Colored Background noise: Background noise has a relatively low power spectral density. The spectral power density of the noise decays for higher frequencies. This type of noise, that is primarily a summation of several noise sources with low power,

fluctuate with time. Colored background noise is sometimes referred as Additive Colored Gaussian Noise (ACGN) [137]

2. Periodic impulsive noise synchronous to the mains frequency (harmonic noise): This type of noise will be referred as harmonic noise during this chapter. When the system is switched on and off at 50 Hz, harmonic noise is created at the higher harmonics of 50 Hz. Obviously, harmonic noise is created by devices switching periodically to the system frequency, resulting in a train of impulses in the time domain or noise at the higher harmonics of the system frequency [138]

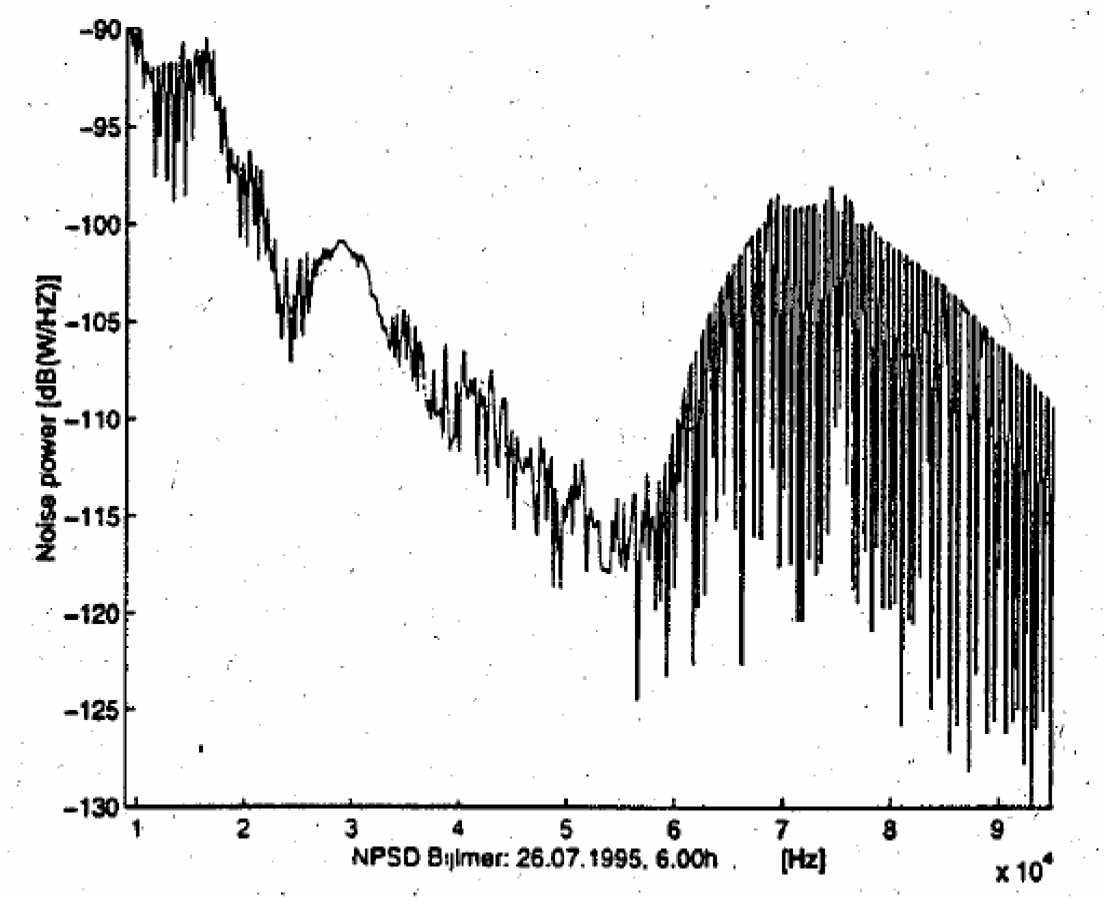


Figure 6.2 Strong noise synchronous to power frequency measured at the suburban location [139]

Figure 6.2 above is the example for harmonic noise in a suburban location. The harmonic noise is concentrated between 60 to 95 kHz. In addition to the harmonic noise occurring in every 0.02s, which is the primary harmonic cycle for a system frequency of 50 Hz, noise pulse are recorded in every 0.015s, corresponding to a frequency of 66.7 Hz. This second noise type that occur at a noninteger multiple of the system frequency is referred as interharmonic noise.

The duration and interarrival time of harmonic noise are worth investigating. They mainly have a short duration of several microseconds and a PSD decreasing with frequency. Many appliances generate noise synchronously to the instantaneous value of the mains voltage. The primary source of this kind of noise is switching actions of rectifier diodes, found in many electrical appliances and energy-saving devices, operating synchronously with the mains frequency [130]. Therefore, there is still a lot to benefit from a model which identifies the statistics of the instantaneous value of the noise [134]

3. Asynchronous impulsive noise: This type of impulse noise is totally asynchronous and random with amplitude much higher than the magnitude of the background noise. One must distinguish between the repeating impulses caused by devices switching synchronously with the mains frequency and the asynchronous impulsive noise which is a stand-alone event. Principally, any device interrupting electrical current at the mains frequency might cause asynchronuous impulsive noise with comparatively high amplitude and short duration [115]

The main sources are the switching transients, electric motors and silicon controlled rectifiers (SCR's) [140]. The most disrupting devices are those that operate for a long duration of time such as SCR's in light dimmers. Another example are the commutators such as electric drill motors that make and break contact throughout the operating period of the device and cause high amplitude broadband impulse noise components. Figure 6.3 shows the asynchronous impulsive noise examples for an electric drill and a silicon controlled rectifier (SCR) in a light dimmer.

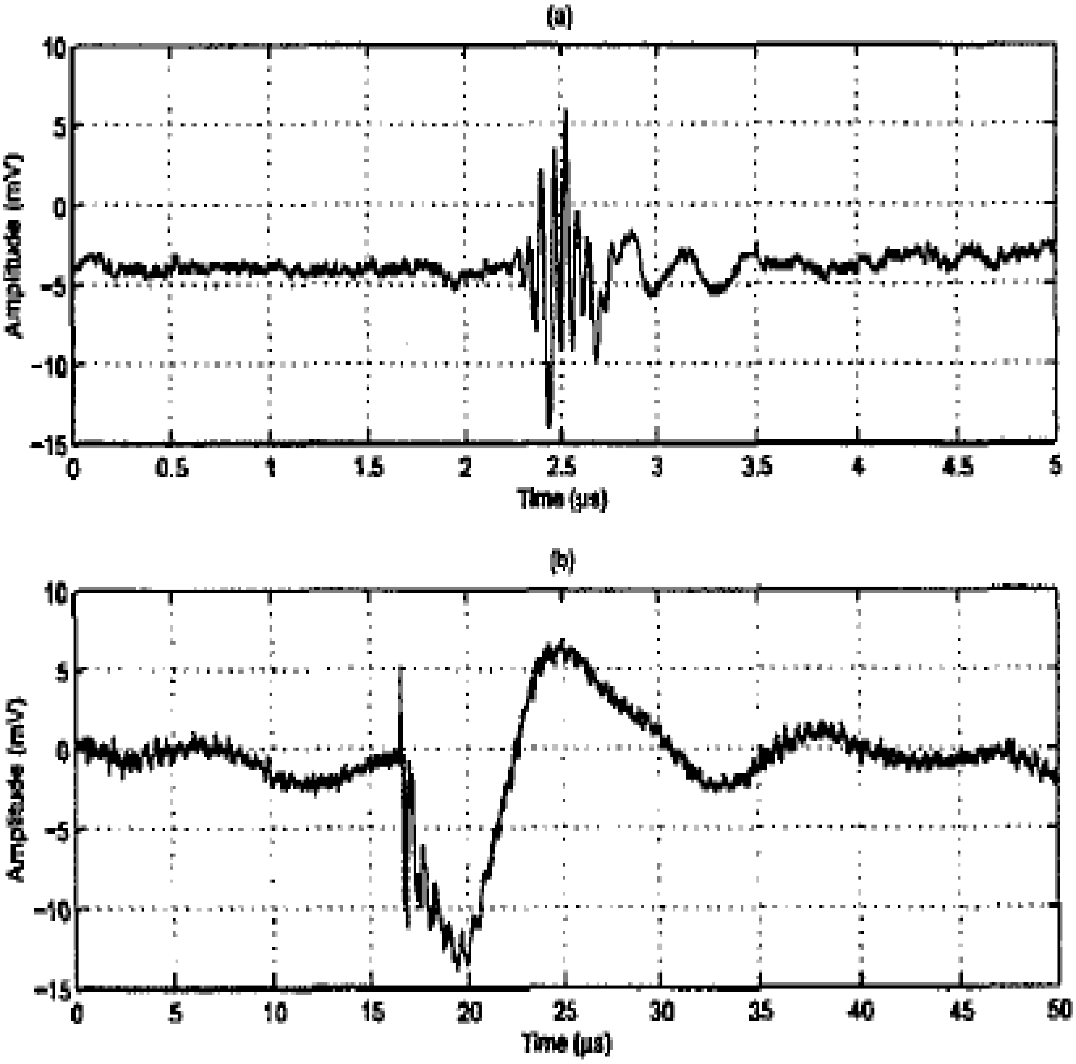


Figure 6.3: The asynchronous impulsive noise examples caused by an electric drill and a silicon controlled rectifier (SCR) respectively [113]

The disconnections of elements of the mains line can also cause asynchronous impulses. Their duration is some microseconds up to a few milliseconds (typically but not necessarily less than 100 μs). The PSD of this type of noise can rise 50 dB above the background noise and the interarrival time is random.

4. Periodic impulsive noise asynchronous to frequency: This is a rarely observed kind of noise and in some literature it is classified under asynchronous impulsive noise as it does not synchronize with the mains frequency and its source _ usually

switching power supplies (switch-mode power supplies)_ is not clearly identified in most of the observations. The repetition range changes between 50 Hz to 200 kHz which leads to a spectrum of discrete lines with a frequency range depending on the repetition rate.

5. Narrow band noise: Narrow band noise, as implied from the name, is the type of noise that occurs in a narrow section of the frequency band. This type of interferences can rise up to 30 MHz. The source is generally ingress of broadcast stations in the medium and shortwave broadcast bands i.e. sinusoidal signals with modulated amplitudes caused by ingress of radio broadcasting. Some examples are broadcast, commercial, military, citizens band and amateur radio stations. This type of noise is frequency specific and may possess differential and/ or common mode. Their perturbation is comparatively stationary. They are not easy to identify and they vary during the day time. Due to the extension of the mains, narrow band noise can have noteworthy effects.

The propagation of radio signals operating between 1 and 30 MHz is a problem for all communication media. Paul A. Brown explains this problem with an example of UK medium wave broadcast stations operating in the 0.5 to 1.5 MHz range [140]. He explains that these broadcast stations can be received with relatively stable levels of quality during the day time. On the other hand, during the night and twilight, the more distant broadcast stations that share the same spectrum begin to dominate as the ionosphere alters the skip distance and the quality diminishes. Nevertheless, ingress originating from the military (aeronautical and maritime fixed and mobile) and commercial sources is less problematic due to their relatively low power levels and limited bandwidth. Moreover, citizens band and amateur radio stations do not create considerable disturbances as they are frequency specific and are localized despite their comparatively high signal levels.

Sodium street lights are another source of narrowband noise especially during the warm up period which may last for 2-3 minutes. Nowadays, also some energy efficient lighting devices that have recently entered the market create narrowband disturbance at some specific portions of high frequency spectrum. Commonly, the propagation mode of the devices that cause narrowband noise is the differential mode between the line and neutral conductors.

6.3.3. THE DETAILED ANALYSIS OF NOISE TYPES

6.3.3.1 Background noise

Background noise can basically be defined as the portion of the noise that remains after subtracting all other types of noise measurement at a certain location. Background noise which exists permanently on the power line has a frequency dependent power spectrum density [135].

The Hooijen's measurements and model in his paper "A Channel Model for the Low-Voltage Power Line Channel; Measurement and Simulation Results" are the most detailed and commonly accepted studies about background noise. In this paper Hooijen makes experiments about the background noise characteristics of the power line in different locations and different times of the day.

Hooijen performs his measurements depending on the residential power circuit illustrated in Figure 6.4 below.

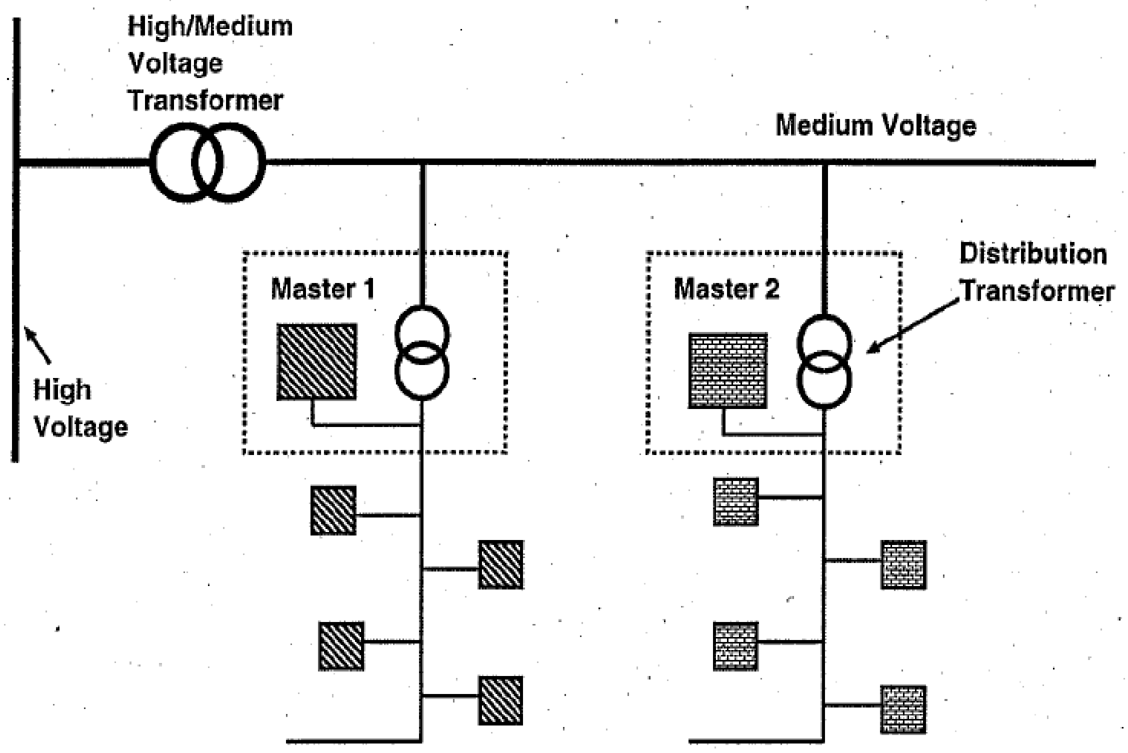


Figure 6.4: Residential power circuit that Hooijen uses in his measurements [139], [141]

Firstly, he states that the coherence time of spectra significantly differs between locations and as a function of the time of the day. During night time when the human activity is relatively low, noise levels are around 90 dB(W/Hz) at 9 kHz and -125 dB(W/Hz) at 95 kHz. At the night time the background noise levels are observed to be almost stationary in time. On the other hand, during the day the noise levels are more unpredictable and fluctuating, varying up to 15 or 20 dB above or below the average value over the frequency of interest. Another interesting observation was that the more the noise curve deviates from the average value the less it takes to go back to average. This fluctuation also depends on location. In rural areas, the fluctuation took place within minutes, whereas in urban areas the fluctuations lasted for several hours.

The distribution of the noise spectra measured at the urban location is as follows;

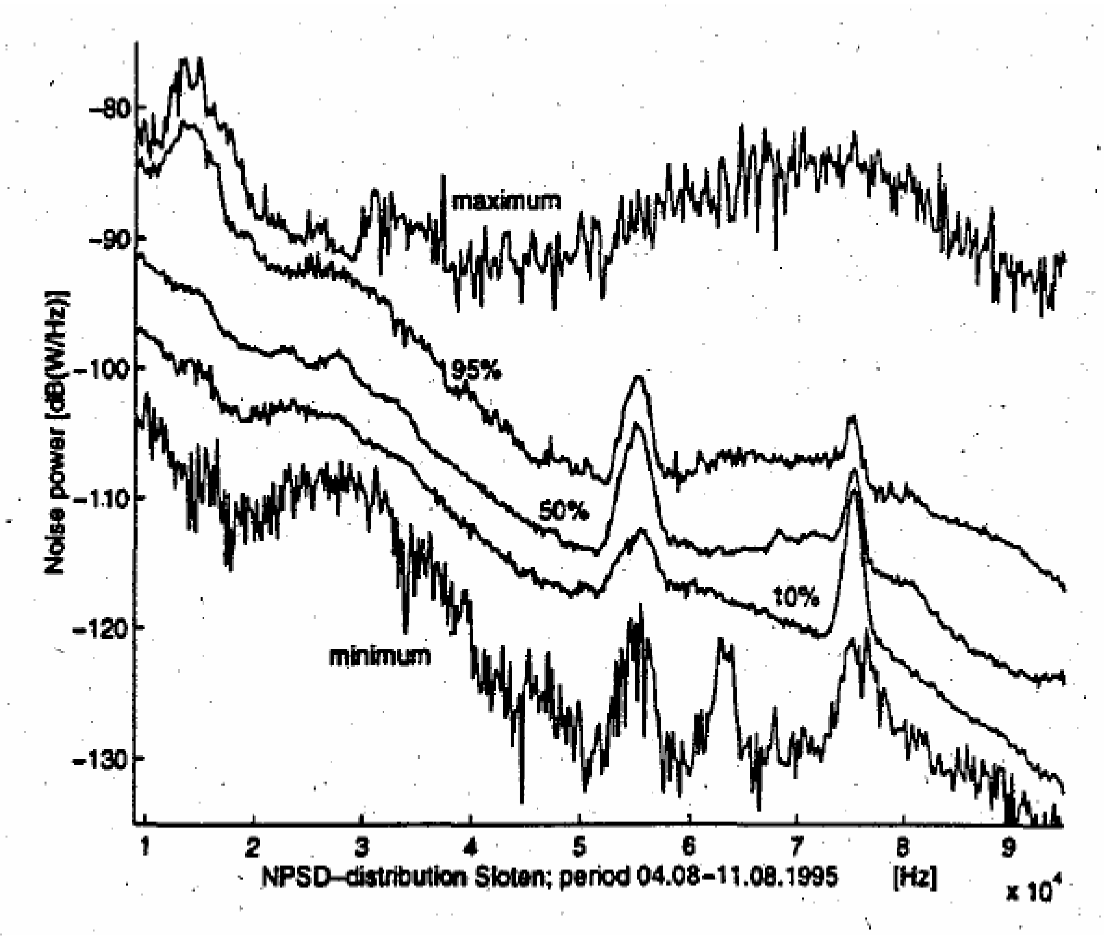


Figure 6.5: Distribution of all noise spectra measured at the urban location of measurement [139]

Studying 700 different spectra measured at different times, Hooijen approximates the background noise at a certain location at an arbitrary time for a frequency between the frequency range of 9 to 95 kHz as [138], [142]

$$N(f) = 10^{(K - 3{,}95 * 10^{-5} f)} \left[W / Hz \right] \tag{6.3}$$

Hooijen points out that K is a slowly varying Gaussian random variable with mean, μ= -8.64, and standard deviation, σ=0.5. The best case is calculated for K=μ-2σ, when only background noise is present. For the worst case, K= μ+2σ and apart from the background noise, the contributions of the other noise types are also considered.

However, for the following analysis, the contributions from other noise types are neglected as they occupy only a narrow portion of the frequency band and time period compared to the always existing, ever present and wide band background noise. Also, for most of the cases, these noise types are much weaker compared to the worst case background noise.

Then, using $K = \mu \pm 2\sigma$, (6.4)

$$N_{best}(f) = N_{background,best}(f) = 10^{(-9,64-3,95*10^{-5} f)} \quad (6.5)$$

$$N_{worst}(f) = N_{background,worst}(f) = 10^{(-7,64-3,95*10^{-5} f)} \quad (6.6)$$

For an PLC based RPC modem that transmit 25 W, the received signal power at a distance d from the transmitter is

$$S_{re,best}(d) = 25*10^{-0,004*d} \, [W] \quad (6.7)$$

$$S_{re,worst}(d) = 25*10^{-0,010*d} \, [W] \quad (6.8)$$

Similarly, the background noise RMS voltage in a low voltage power line for phase-to-neutral coupling, can be modeled by two envelope equations a function of frequency [6].

Worst Case: $V_n = 0,001 f_{kHz}{}^2 - 0,25 f_{kHz} - 40(dBV)$ (6.9)

Best Case: $V_n = 0,001 f_{kHz}{}^2 - 0,25 f_{kHz} - 52(dBV)$ (6.10)

For f_{kHz} denoting the frequency in kHz in the range of 0-250 kHz and the measurement bandwidth chosen as 500 Hz, the frequency bands represented are plotted in Figure 6.6 [138], [142].

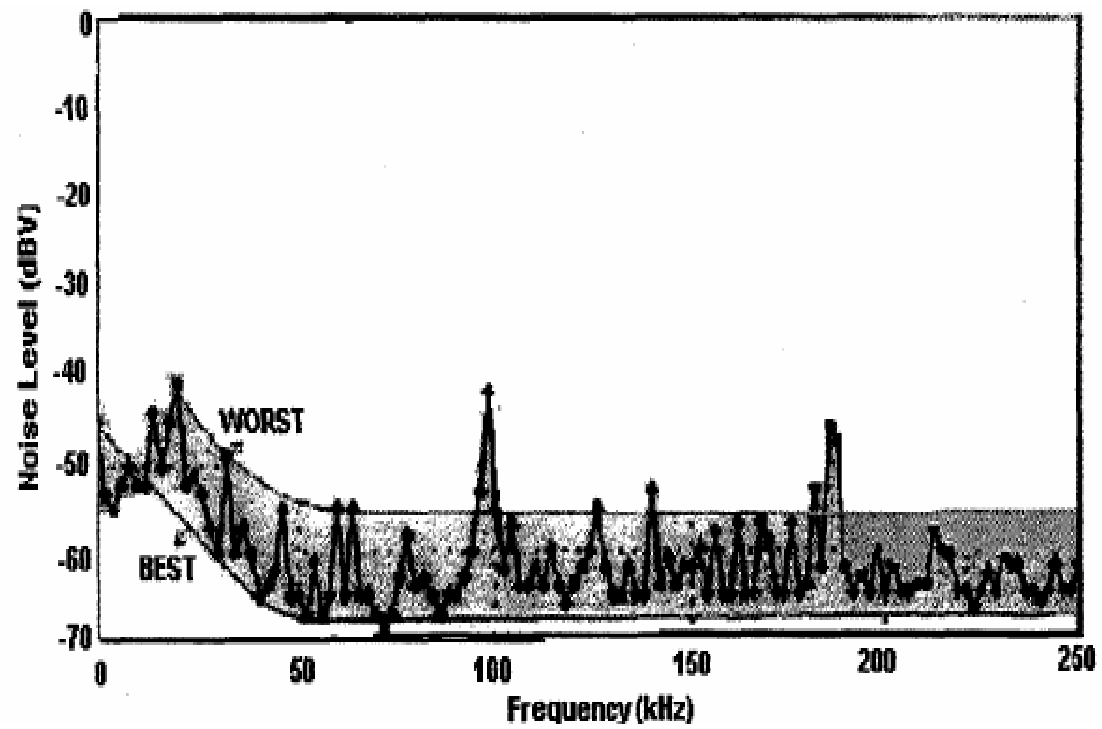
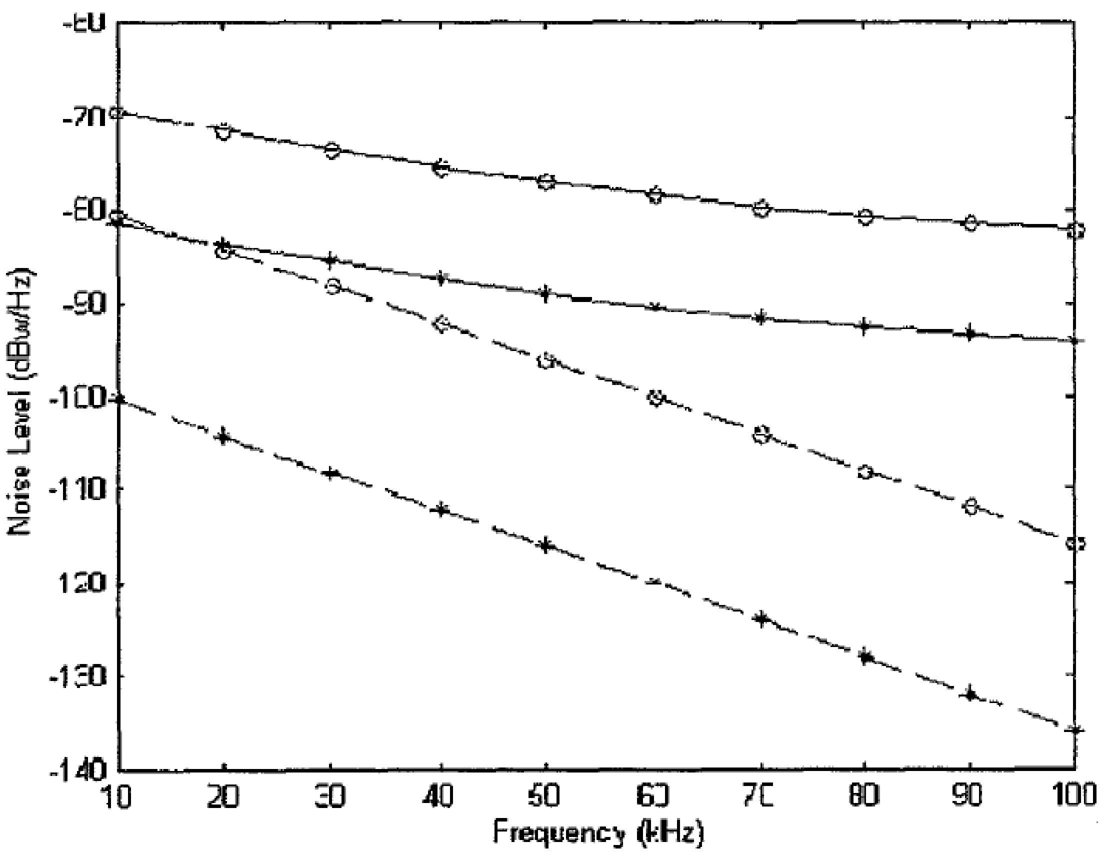


Figure 6.6: Background noise level of a low voltage power line [3]

The prediction by (6.3) and the worst and best case approximations in (6.9), (6.10) are compared in Figure 6.7. It is interesting to see that the 20 dB difference persists between the best and worst case approximations, throughout the frequency range specified.



_________o worst case according to (6.9)

_________* best case according to (6.10)

-------------o worst case according to (6.3) ($K=\mu+2\sigma$)

-------------* best case according to (6.3) ($K=\mu-2\sigma$)

Figure 6.7: Comparison of noise PSD versus frequency [3]

6.3.3.2 Impulsive noise

Impulse noise is defined as eventual short time perturbations. Impulsive noise duration is usually observed to be lower than 100µs [3], [143]. There is no conventional model for impulse noise characteristics. In most of the literature the noise models for telephone networks are used to model impulsive noise characteristics [144] – [147].

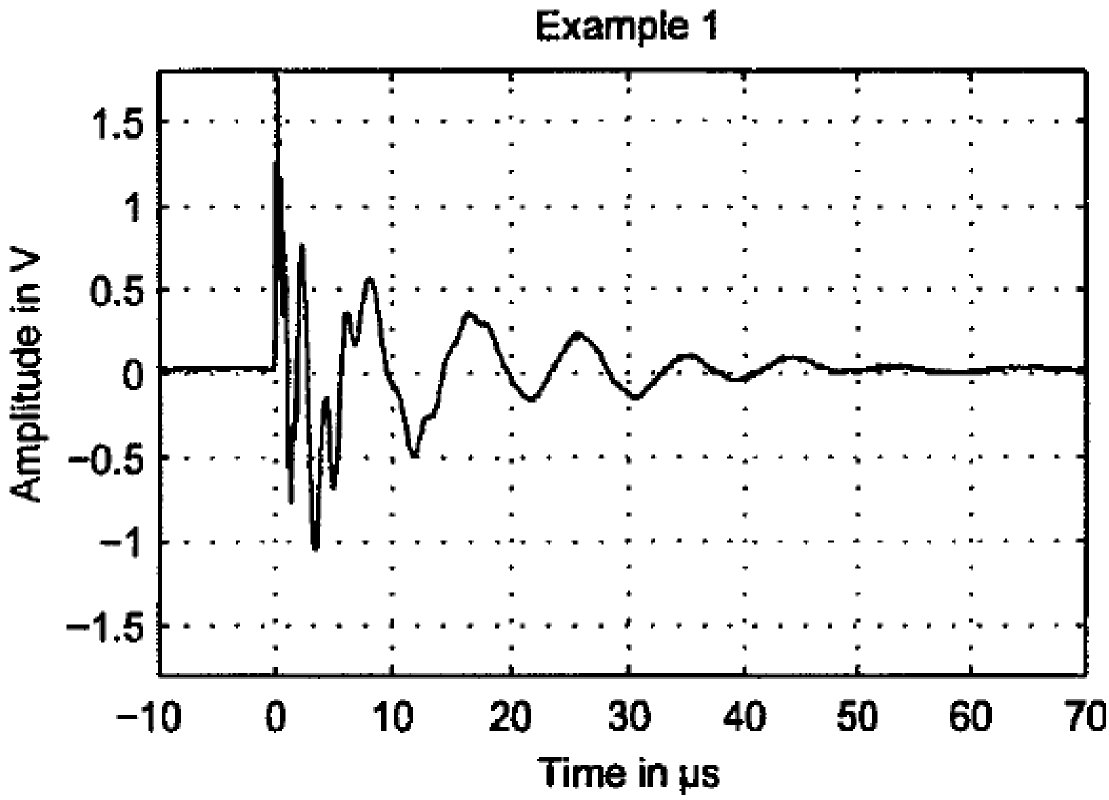
In these works, usually Laplace probability density function (PDF) is employed to estimate the impulse magnitude and as a result of laboratory measurements, impulse magnitudes are observed to be approximately 10 dB to 40 dB above the average background noise level. These levels of noise have strong destructive effects on bit transmission, causing potential failures in communication [145].

Hooijen approximates the time duration of impulse by a double lognormal PDF, which originates for the corresponding noise models for telephony networks [139]. The mean value was reported to be 100 µs, still the time and location dependency was mentioned as a parameter that should be considered. Although the impulses originate from various and uncorrelated sources, interarrival time which is inversely related to the frequency of occurrence can be modeled by the Poisson distribution as $f_1(t) \approx \lambda e\text{-}\lambda t$ for λ being the mean frequency of occurrence of the impulse noise for $0 \leq \lambda \leq 0,5$ impulses per second [142].

The impulsive noise will be investigated under three sections: asynchronous impulsive noise, periodic impulsive noise synchronous to the system frequency (harmonic noise) and the periodic impulsive noise asynchronous to the system frequency.

6.3.3.2.1 Asynchronous impulsive noise

Contrary to background noise asynchronous impulsive time is unstationary over time and introduces the short time variance in the power line environment originating usually from switching transients anywhere in the power line network. The usual shape of the noise is similar to damped sinusoids or overlaid damped sinusoids. In Figure 6.8, there are two time domain examples of impulse noise waveforms. The sharp rising edge followed by a damped oscillation is clearly identified in the first impulse waveform. The impulse duration is around 50 ps. For the second example, it is hard to come up with a specific waveform. However the clear-cut ending is easily observed. The impulse magnitude is around 0.1 V and the impulse duration is 90 ps. Finally it can be observed that the interarrival time is inversely related to the frequency of occurrence and can generally be identified by an exponential PDF [137].



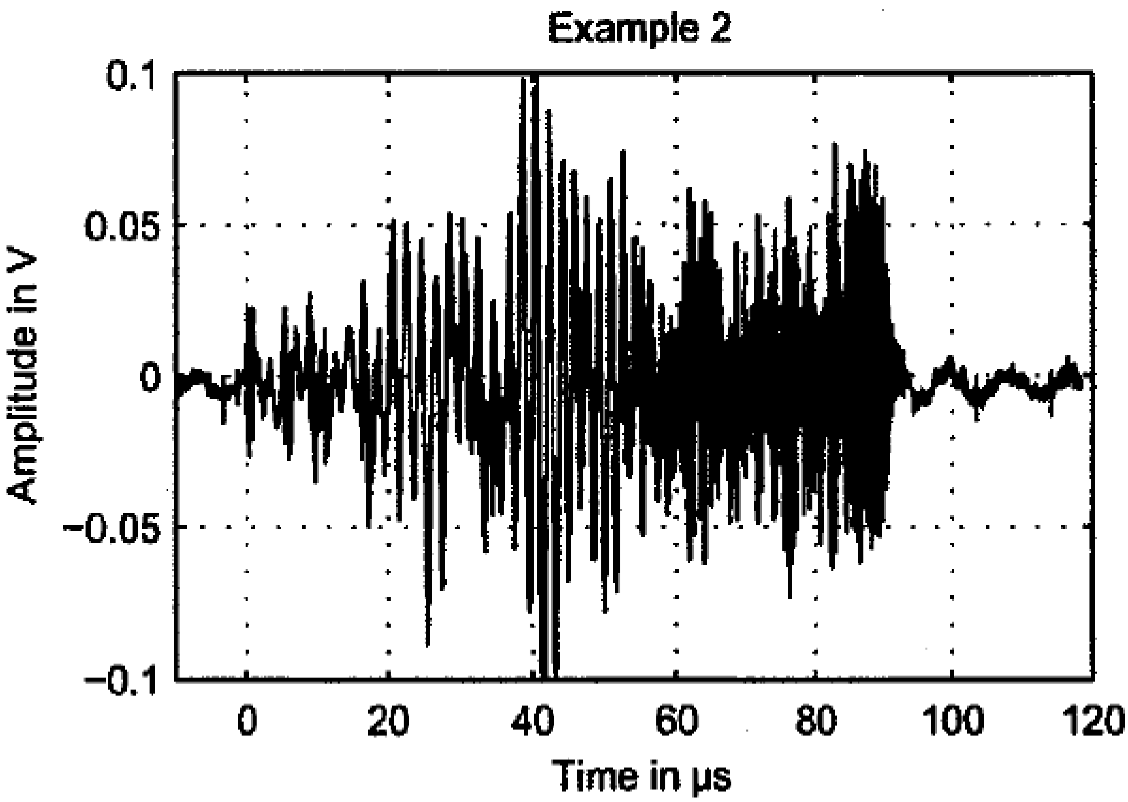


Figure 6.8: Time domain signal of two impulse events REF an analysis of the broadband noise scenario in powerline networks [137]

Some other considerable aspects of types of impulse noise are the impulse energy and the impulse power. Taking interarrival time t_{arr} and the impulse width t_w, and using the time domain signal waveform n_{Imp} (t), the impulse energy is calculated as E_{imp} [137]

$$E_{imp} = \int_{t_{arr}}^{t_{arr}+t_w} n_{imp}(t)^2 dt \tag{6.11}$$

As seen above, the impulse energy is affected by impulse width as well as the signal waveform and course. That is why in order to compare the impact of an impulse noise with that of a background noise, the mean power of the noise is more appropriate. The impulse power can similarly be calculated as; [137]

$$P_{imp} = \frac{1}{t_w} \int_{t_{arr}}^{t_{arr}+t_w} n_{imp}(t)^2 dt \tag{6.12}$$

The mean power of a sample of a background noise signal n(t) over an observation time T_B is;

$$P_N = \frac{1}{T_B} \int_0^{T_B} n(t)^2 dt \tag{6.13}$$

The impulse energy and impulse power are the two explanatory measures of the asynchronous impulsive noise effects on a channel. The mean power distributions of background and impulse waveforms draw a picture of the dynamic change of the noise scenario during an impulse event.

Moreover, it is interesting to observe that the instantaneous noise amplitude of asynchronous impulsive noise is positively related with the absolute instantaneous voltage of the power line. Switching devices in some appliances such as thyristors, emit asynchronous impulsive noise when they turn on. This type of noise occurs at different timings for different appliances. However the noise amplitude is larger when the thyristors commutate under higher instantaneous voltage as seen in Figure 6.9.

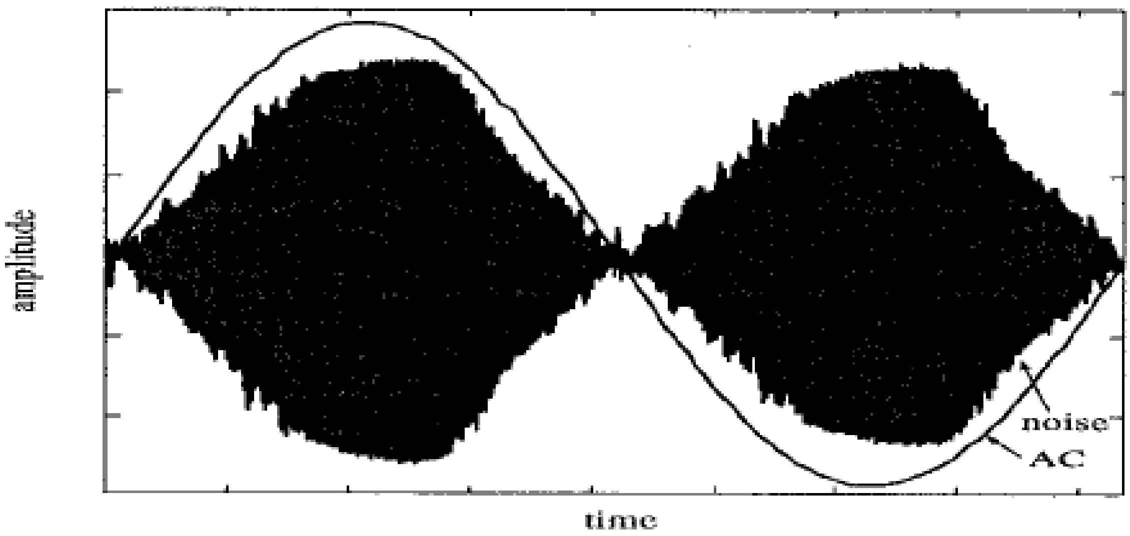


Figure 6.9: The amplitude of the instantaneous asynchronous impulsive noise increases with the absolute instantaneous value of the power line voltage [148]

6.3.3.2.2 Periodic impulsive noise synchronous to the mains frequency (harmonic noise)

The major sources of this type of noise are the switching power supplies, power converters, and silicon controlled rectifiers that switch on and off at system frequency, generating noise waveforms at the higher harmonics of the system frequency [137].

The odd harmonics are usually monitored to be more dominant. Depending on the energy of the individual impulses, periodic impulsive noise usually causes destruction of one or several coincident bits during transmission. Besides, for phase angle control devices such as light dimmers, impulsive noise synchronous at twice the power line frequency can usually be observed. When this type of noise occurs, the bit error rate increases drastically. The solution may be choice of a more appropriate coding technique [105], [138], [142].

Another important point is that, some relatively old studies indicated that this type of noise attenuates very fast as frequency increases, becoming harmless at the frequencies of interest. However practical experiments prove the opposite. The dimmers generate both odd and even harmonics of 50 Hz that can severely disturb the PLC network [105], [149], [150].

In order to get a more detailed understanding of the periodic impulsive noise in power line conductors, the following experiment was carried out in Telecommunication Research Laboratories (TR Labs) of University of Saskatchewan [151].

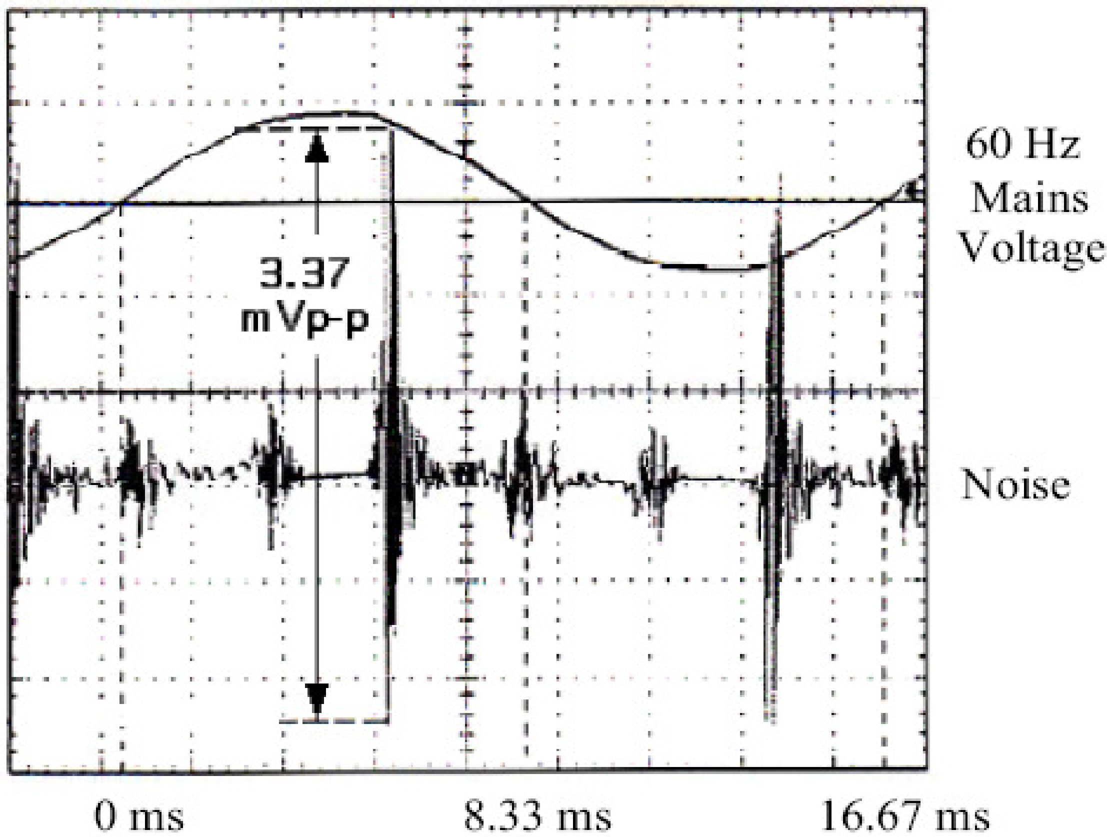


Figure 6.10: Noise in the 50 – 500 KHz range [152]

The noise bursts are observed during each half cycle of the system frequency (60 Hz in this case). The first burst is at the zero crossing when the fluorescent lights are extinguished are reignited. The second and third bursts occur when the power supply rectifiers begin and stop conducting. What makes this noise synchronous is the fact that the noise burst stay in fixed positions relative to the 60 Hz zero crossings in each cycle. In other words, noise synchronous to power system frequency can be considered as a train of noise impulses in the time domain, arriving in every $1/k*f_{system}$ seconds, with k an integer, usually k=1 or k=2. The spectrum of this type of noise is composed of a series of harmonics of the $k*f_{system}$ fundamental component.

6.3.3.2.2.1 Byte Errors Originating From the Impulsive Noise Synchronous to the System Frequency

Depending on the energy of the individual impulses, periodic impulsive noise synchronous to the system frequency usually causes destruction of one or several coincident bits during transmission. Furthermore, the synchronous impulsive noise that occurs at twice the system frequency can increase bit error rate drastically.

A measurement system composed of half duplex 60 kb/s FSK modems with mark and stop frequencies at 150 and 250 kHz respectively was established to investigate the time slot quality and the transmission errors originating from the noise in power line channels [152], [153]. Asynchronous transmission was used so that the clock recovery of receivers is not an issue to be considered. The transmitter and receiver microcontroller was utilized for 10-bit universal asynchronous receive transmit (UART) serial data communication. The data block of the UART was composed of a start bit, an 8-bit information byte and a stop bit.

Firstly, the transmitted data was kept constant and the same data was sent several times from receiver to transmitter in order to study the quality of transmission. As the sent data packet is constant and known by the receiver, the correctness of the data was checked easily. The microcontroller in the receiver was programmed to set an output pin to high (+5V), if an error in any byte is received. If the data is correctly received, the output of the microcontroller remained low. The output of the microcontroller was connected to an oscilloscope set and the sensitivity was set to 1 V/div.

Clearly, the received signal & noise and the byte errors traces (second and third traces) indicate that the byte errors occur simultaneously with the noise bursts.

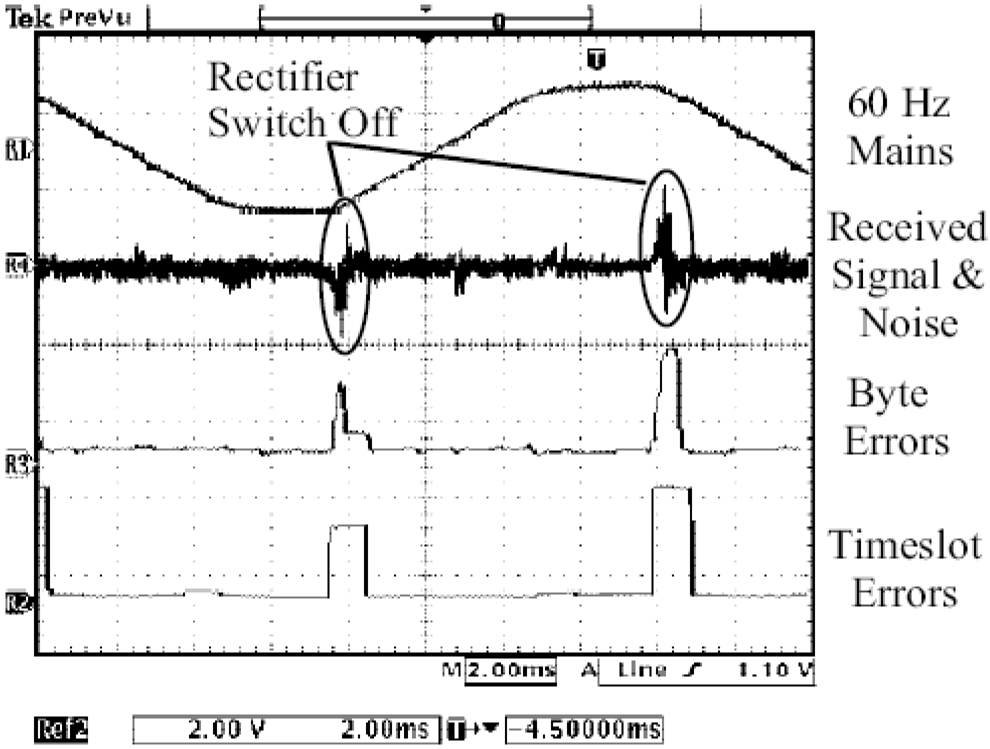


Figure 6.11: Synchronous noise and errored timeslots [152]

In order to investigate the transmission characteristics of the line and apply the time transmission protocol, the power line cycle which has a period of 16.67 ms (for a system frequency of 60 Hz) was divided into 16 intervals. Each time interval corresponds to approximately 1 ms. The microcontrollers were synchronized with the 60 Hz power line zero crossings. The errors were recorded in each cycle and the bit for the byte errors was set to high in case of an error in that timeslot in the previous cycle. The trace corresponding to the timeslot errors uses the averaging function of the oscilloscope to calculate the average number of timeslot errors.

6.3.3.2.2.2 Timed Transmission Protocol and the Resulting Time Slot Quality

6.3.3.2.2.2.1 Master-Slave and Channel Identification

The timed transmission protocol aims to calculate the predictable error characteristics and increase the efficiency of the power line channel. The proposed model uses a protocol with one master and up to 15 slaves. The master controls all the data transfer and slaves do not transmit without the permission of the master. The carrier sensing and collision detection algorithms are unnecessary in this case as the master controls all the data traffic. The purpose of this protocol is to able to determine, control and communicate the timeslot quality information and increase the system efficiency. This is achieved by the centralized communication architecture composed of the master and slaves. A threshold is determined for the number of errors in a timeslot. Each slave monitors the data number of errors in the data they receive and they store this information in their timeslot tables. If the number of errors exceeds a predefined limit, the slaves identify this time slot as BAD. The timeslot information refreshed every 10 seconds by the polling operation of the master. During this polling operation, slaves respond to the master with a request to send (RTS) and/or information on BAD timeslots. When the slave completes the polling operation for all the slaves, it finds the intersection of the GOOD timeslots which is the candidate timeslot for a lossless communication. Note that, if a timeslot is identified to be BAD by at least one slave, this timeslot is marked as BAD in the master timeslot table which is later broadcast to all the slaves. Following that, the master begins to give clear to send (CTS) command to slaves that requested channel access with the RTS. The CTS specifies a number of power cycles the slaves are given permission to communicate and the slaves can only have channel access in the GOOD timeslots in these power line cycles. On the other hand, the master broadcast special “check” packets in the BAD power cycles and continues to refresh the information to detect the GOOD and BAD timeslots [154]. Figure 6.12 below exemplifies the algorithm with the master and two slaves.

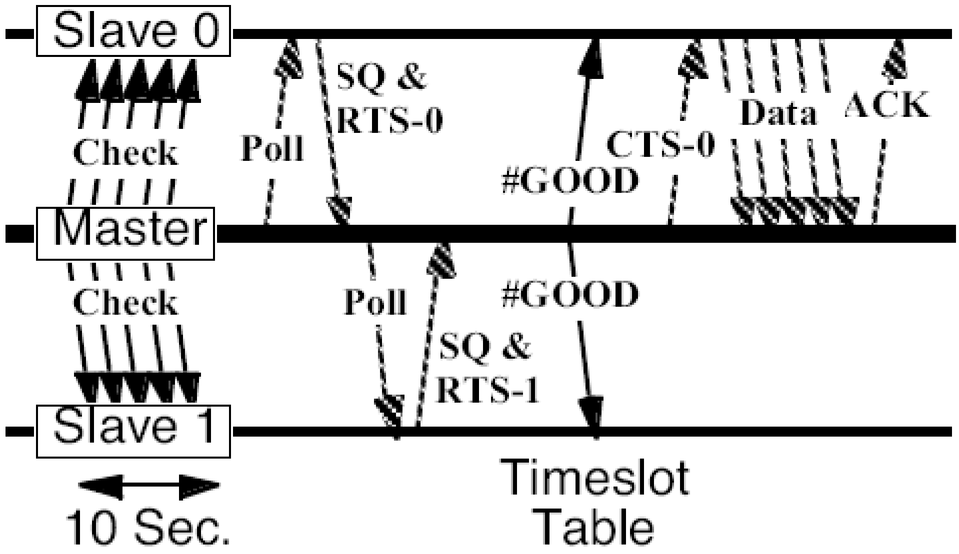


Figure 6.12: The master and slave polling algorithm [152]

As expected, there is no master table and no information about the channel in the beginning. So the master broadcasts “check” packets to all the slaves for 10 seconds and slaves screen the quality of reception. Then the master polls each slaves and collect the slot quality (SQ) and/or request to send (RTS) from the slaves. As the polling command is critical to decide the quality of communication for the following cycles, the master sends polling commands during all 16 timeslots of one full cycle. Furthermore, the master demands to receive at least two successful transmissions to make certain of the GOOD and BAD timeslots. The algorithm is completed when the master composes the master timeslot, broadcasts it to all the slaves and begins to send out CTS. After 10 seconds, the master begins to poll each slave again.

6.3.3.2.2.2.2 Packet Data Transmission

In the case that the message length exceeds one timeslot, acknowledge (ACK) strategy is employed. If the message is to be sent over a series of timeslots, the timeslot following the data transmission is used for sending an ACK message. A similar protocol called stop and wait protocol is studied by Zheng and Akhtar [155]. In this protocol, after sending the message, the sender stops and waits for an acknowledgement from the receiver. If acknowledgement is not received in the next timeslot, the packet is retransmitted. However, duplicate retransmission can occupy the channel unnecessarily. To prevent this problem, a sequence bit is used in the packet against duplicate transmissions. If the packet sent is a retransmitted one, the sequence bit is kept constant. If the packet is a new one, the sequence bit is toggled. The receiver detects the sequence bit and if the sequence bit is the same for the two packets received, the receiver ignores the retransmission. This is possible if an ACK packet is lost.

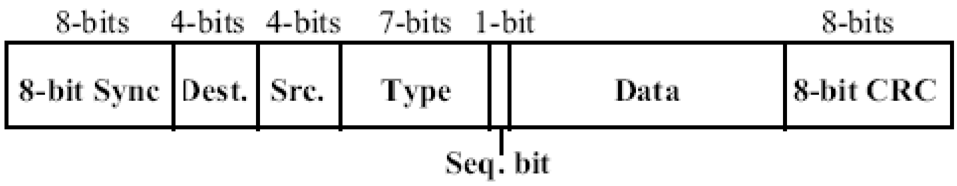


Figure 6.13: The packet format [152]

The packet format is demonstrated. The first 8 bits are error checking bits (an 8-bit CRC). Then the bits for destination, source and type information follows respectively. For the transmission protocol, the packets cover one millisecond timeslots. As a result the data rate determines the number of bits transmitted per packet. For the design explained above, the data rate is 60 kb/s, consequently 60 bits (32 overhead and 28 data bits) are transmitted per packet. 28/32 is not a good data to overhead ratio however data rates can be increased via a more efficient modulation.

6.3.3.2.2.3 Protocol Performance

Ackerman, Dodds and Mc Crosky performed a test to relate the transmission efficiency with the number of slots used. For the case, all the 16 timeslots are used and no data error occurs, then the efficiency is 1.0. If only the half of the channel is used and again no data error occurs, then the efficiency is 0.5. In practice, when the noisy time slots are employed, the data errors lead to lower efficiency. The test was initially performed without a timed transmission protocol. The two cases studies were for message lengths of 5 and 15. An additional byte was allocated for ACK. The principle is that in the beginning only the low error ratio timeslots were used and the high error ratio timeslots were employed only after all timeslots were spent.

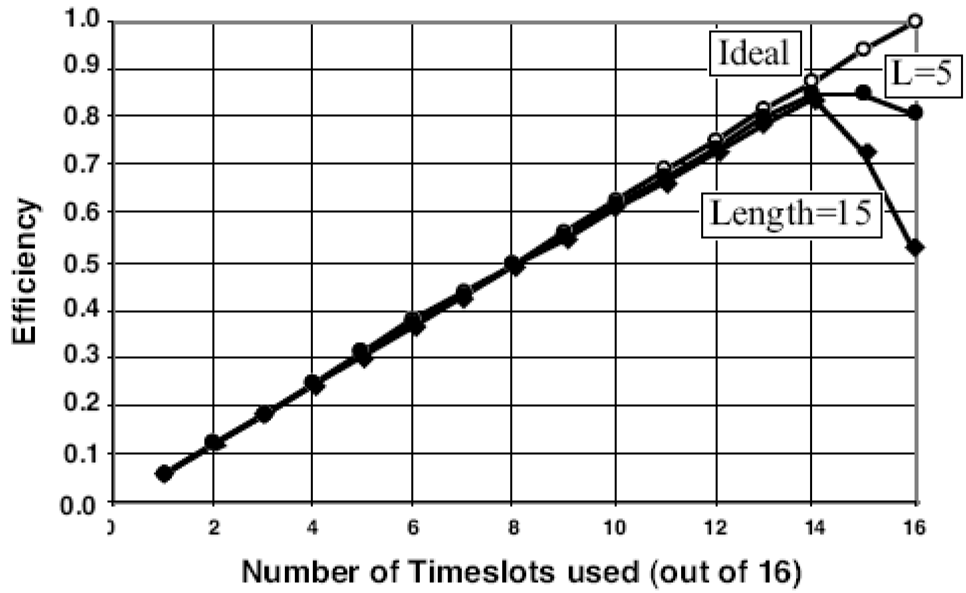


Figure 6.14: Efficiency vs. timeslots used [152]

The Figure 6.14 demonstrates the efficiency vs number of time slots used for message lengths of 5 and 15. Note that there is a minor deviation from the ideal case until the high error ratio timeslots are benefited. When the high error ratio timeslots are employed, the probability of corruption increases. Moreover, the corruption is more dominant for the longer message as the probability of employing the bad timeslots is higher. In conclusion, when the number of timeslot (the probability of bad timeslots occupied) increases, the efficiency decreases.

6.3.3.2.2.3.1 Identification of Bad Time Slots

In order to investigate the accuracy of detection of the noisy (BAD) timeslots, a test was performed under the effect of noises originating from power supply rectifiers and a lamp dimmer.

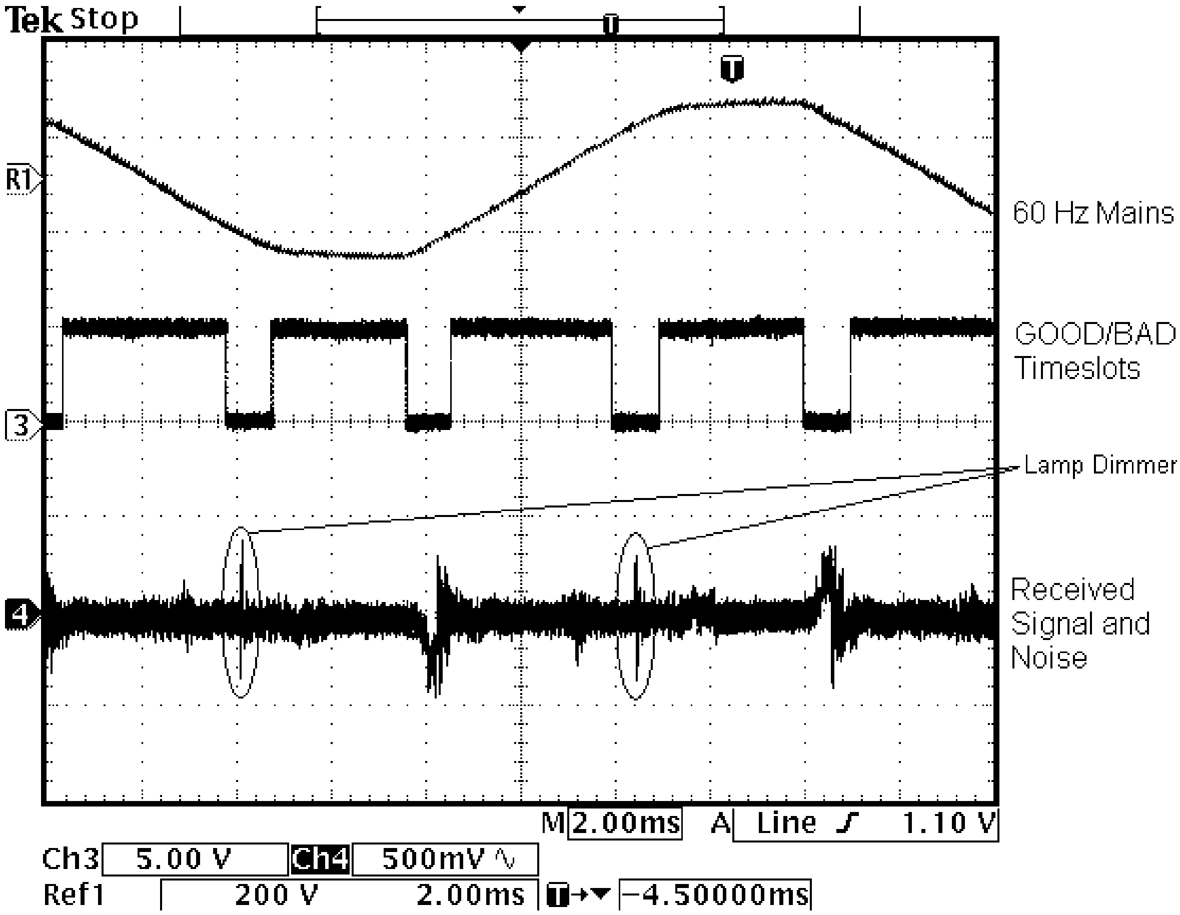


Figure 6.15: Lamp dimmer in the dim position [156]

The first trace is the 60 Hz mains signal. The one below is the GOOD/BAD timeslots identified according to the third trace which is the received signal including the noise. These traces were taken after the master and slave were given sufficient time to detect BAD timeslots and develop a timeslot table. Two BAD time slots corresponding to the noise caused by the lamp dimmers were detected [144]

6.3.3.2.2.3.2 Performance with two bad time slots

Data throughput is commonly used to determine the efficiency of a communication protocol. The throughput is the ratio of the data received to the transmission capacity of the channel. In this case, the ACK packet that the receiver responds back is also considered for the messages of all lengths. ACK packet apparently limits the throughput by occupying a packet for data packet transmitted. Thus, a message of length one timeslot has a throughput of 0.5 if no errors occur. If the message length increases the throughput gradually approaches 1.0. For each data error, the receiver asks for a retransmission and the throughput decreases.

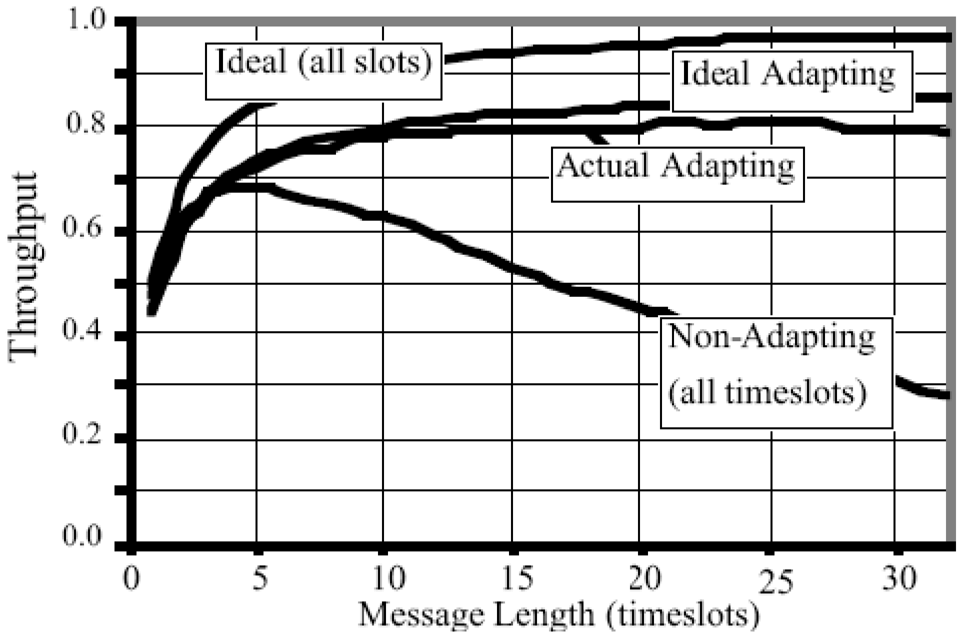


Figure 6.16 Throughput vs. message length (2 BAD slots) [156]

The Figure 6.16 above illustrates the throughput vs. message lengths for 4 different cases. For an ideal channel, there are no data errors and all timeslots are used. For the case that, two timeslot are noisy and the remaining ones are GOOD, the throughput is 14/16=87.5 %. The channel for two bad timeslots in a cycle is called ideal adapting channel. However, in a practical channel, GOOD timeslots, that are eligible to be used for transmission, will have some noise and data retransmission will be required which reduces the throughput. Without adapting, the throughput peaks at 0.65 for message length of 5 and as the message length is increased, the throughput decreases steeply. For the actual adapting case, the throughput maintains a rather stable pattern even for longer message lengths.

The adaptation to changing noise conditions is also important for the performance at the timed transmission algorithm. A lamp dimmer is used to exhibit the adaptation capability of the protocol to changing noise conditions. In the Figure 6.17, it was expressed that the two of the four disturbances were due to a lamp dimmer placed in the low position. In the Figure 6.18, the noise characteristics of the channel were transformed as the lamp dimmer was adjusted to high position. The algorithm successfully detected the new condition as the master and slave reassessed the timeslot quality and reorganized the master timeslot table. As a result, the two of the BAD timeslots are placed in different positions.

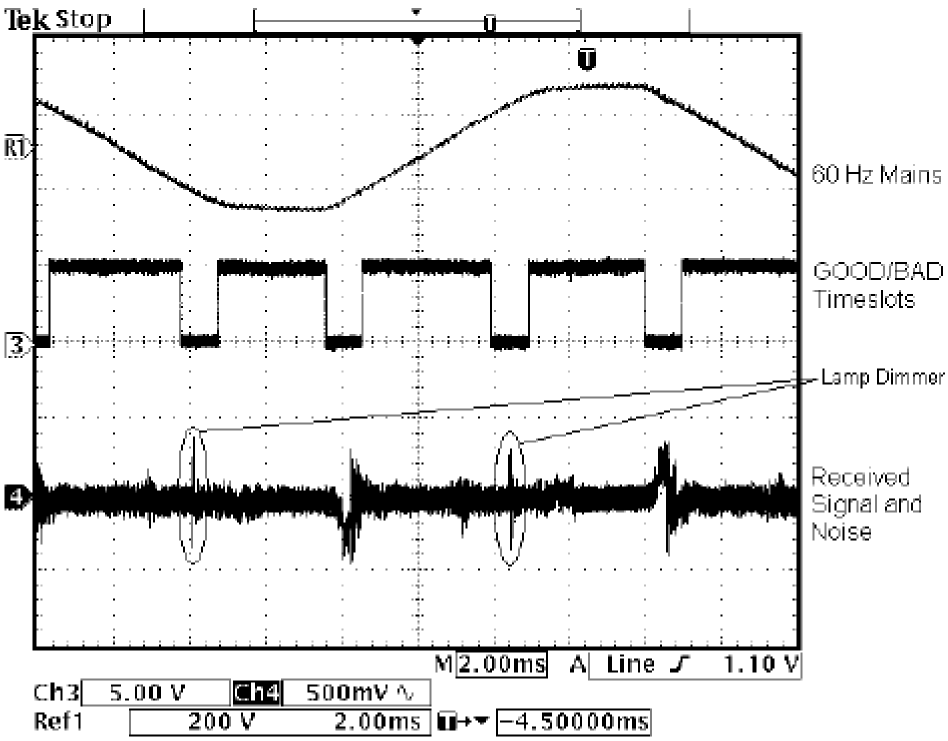


Figure 6.17: Lamp dimmer in the dim position [156]

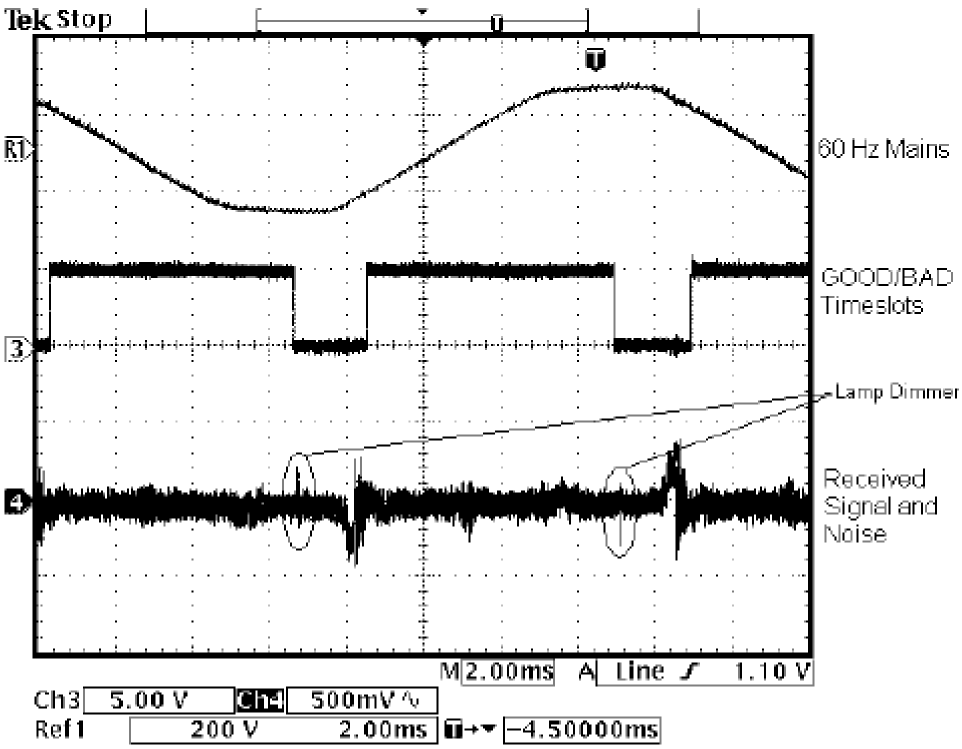


Figure 6.18: Lamp dimmer in the bright position [156]

6.3.3.2.2.3.3 Performance with Four Bad Timeslots

The performance for four bad time slots was studied with a similar test hardware implemented with the lamp dimmer. The ideal, adapting and non adapting throughput characteristics are demonstrated in Figure 6.19. For the non-adapting case, the throughput characteristic reaches a peak of 0.5 at a message length of 3 and declines sharply afterwards. The adapting algorithm improves the throughput characteristic with a peak of 0.7 and maintains a consistent throughput through the range of message lengths. For the case of four timeslots, the difference between the ideal channel curve and the adapting channel curve is higher than the case for the two timeslots. This is a result of the fact that for the case with four time slots, only 12/16 of the channel capacity is utilizable.

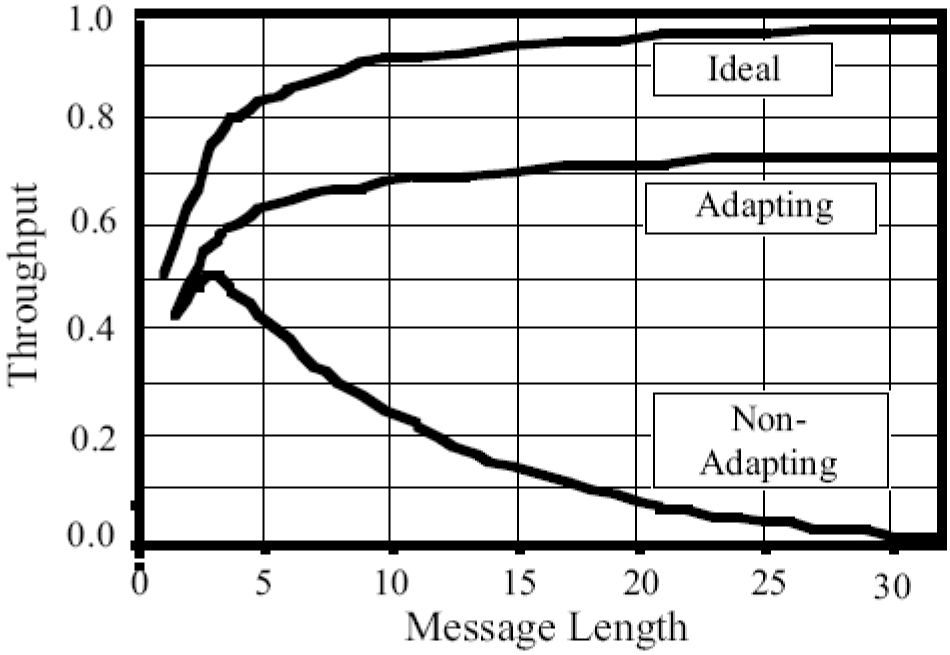


Figure 6.19: Throughput vs. Message Length [156]

6.3.3.2.2.4 Optimum Error Threshold

Optimum error threshold is defined as the limit for the percentage of errors to determine whether a timeslot is GOOD or BAD. Considering only one timeslot is causing all the errors, the rest of the channel (15/16) is employable. For short messages that each timeslot only once in every transmission, a BAD timeslot is expected to have a success rate higher than 15/16 in order to be considered as GOOD. Then the threshold for this case is 1 – 0.9375 = 6.25%. Likewise, for two BAD timeslots, threshold is 6.7%. If the message is longer and uses each timeslot twice, then the one BAD timeslot error threshold is 1 – (0.9375)*(0.9375) = 3.2%.

Consequently, for the case that all the errors are caused by a single timeslot and all other timeslot being error free, the equation of error threshold to determine a timeslot bad is as follows; [152]

$$Th_{opt} = 1 - \left(\frac{\#GOOD - 1}{\#GOOD}\right)^{\left(\frac{\#GOOD}{messagelenght + 1}\right)} \qquad (6.13)$$

For error rate above this, the timeslot is marked as BAD; for an error rate below this, the timeslot is determined to be GOOD.

6.3.3.2.3 Periodic impulsive noise asynchronous to mains frequency

As stated before, periodic impulsive noise asynchronous to frequency is not a very common kind of noise and most literature classify this type of noise under asynchronous impulsive noise as it does not synchronize with the mains frequency and its source _ usually switching power supplies (switch-mode power supplies)_ is not clearly identified for most of the cases.

Switching power supplies are used in various electronic devices such as PCs and electronic fluorescent ballasts and they inject a noise rich in the harmonics of the switching frequency to mains line. As the switching frequency of power supplies is different from the system frequency, the resulting harmonics of the switching power supply frequency is asynchronous to the mains frequency. The repetition range changes between 50 Hz to 200 kHz which leads to a spectrum of discrete lines with a frequency range depending on the repetition rate [157].

Figure 6.20 is a common example of periodic impulsive noise that occurs due to the switching power supplies. Those semi-deterministic periodic pulses, that are periodic during a certain interval of time with a frequency around several hundreds of kHz, can be identified in certain phases of the cycle.

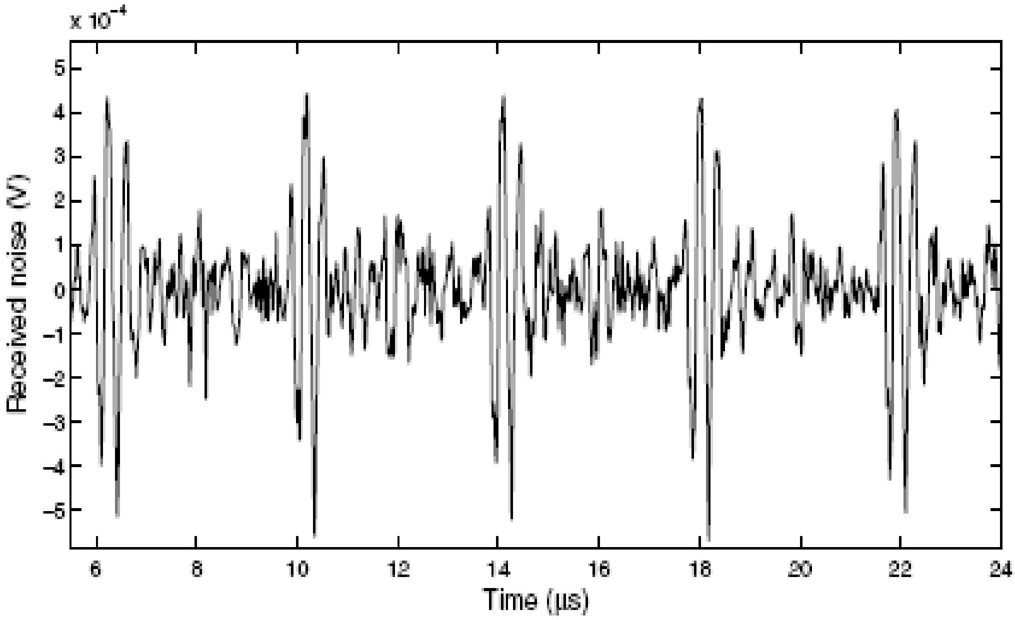


Figure 6.20: Impulsive noise with a period of approximately 250 kHz [14]

Besides, Figure 6.21 demonstrates the voltage waveform for the charging stand of an electronic toothbrush. It is observed that the voltage waveform for the switching supply noise is very similar to an ideal sawtooth waveform.

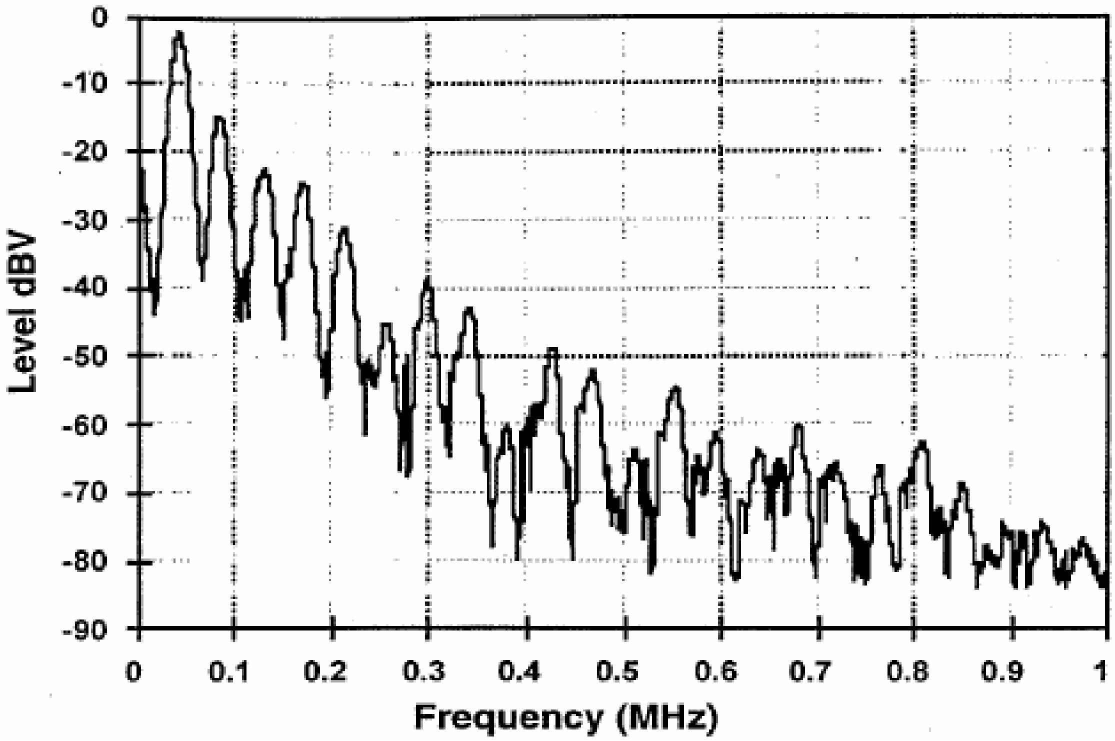


Figure 6.21: Noise from electric toothbrush charging stand [14]

Other examples for periodic impulsive noise asynchronous to frequency are power line intercoms and baby monitors. These devices operate between 150 kHz to 400 kHz and they inject signals of several volts peak to peak on the power line. Figure 6.22 shows the voltage spectrum of a power line intercom.

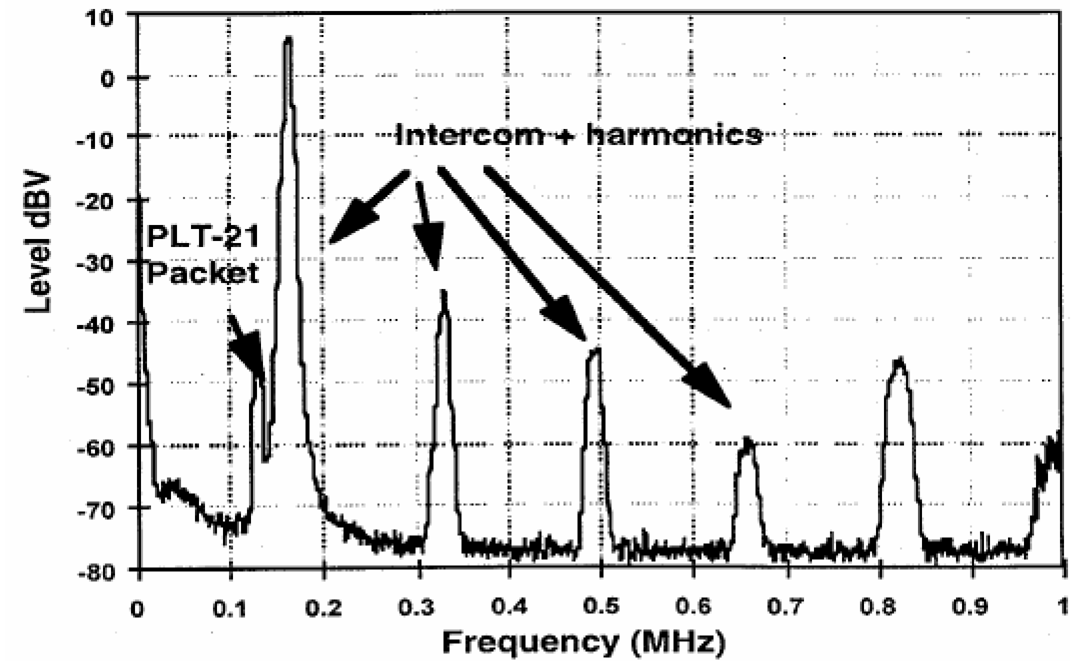


Figure 6.22: Power line intercom spectrum [14]

One final example for this type of noise is the noise caused by pickup of radio broadcasts. Power lines act as antennas and they pick up signals from the multi-thousand watt radio transmitters that cause interference with a magnitude of approximately 1 volt peak to peak observed around 200 kHz

6.3.3.3 Narrow band noise

Narrow band noise that resides in a relatively limited and narrow frequency band is mainly caused by time coded transmissions that couple to the power lines [137].

In addition the harmonics of horizontal retrace frequency of television receivers (15.6 kHz for European standards) and computer monitors are common sources reported in various literatures. That is normally called as jitter [2]. The jitter is generally referred as the unwanted variation of one or more characteristics of a periodic signal in telecommunications [158]. Jitter characteristics may be observed as the interval between the successive pulses or the amplitude or frequency or successive cycles. Moreover the jitter period is defined as the interval between two instants of maximum disturbance amplitude. Consequently the transmission frequencies that are multiples of these frequencies should be avoided at the design of a PLC network.

As stated above the main source of narrow band noise is the horizontal retrace frequency of television and time coded transmissions that couple with the power lines. Various narrow band disturbances are observed in the harmonics of 15.6 kHz which is the PAL standard used in most European countries. Figure 6.23 shows an easily noticeable narrow band disturbance around 78 kHz which is the 5th harmonic of the horizontal retrace frequency of television receivers for European standards. In some other articles, narrow band disturbances around 25, 30, 46, 49, 55, 62, 75, 78, 94 kHz were measured however the source of these noises were not clearly identified [101], [142].

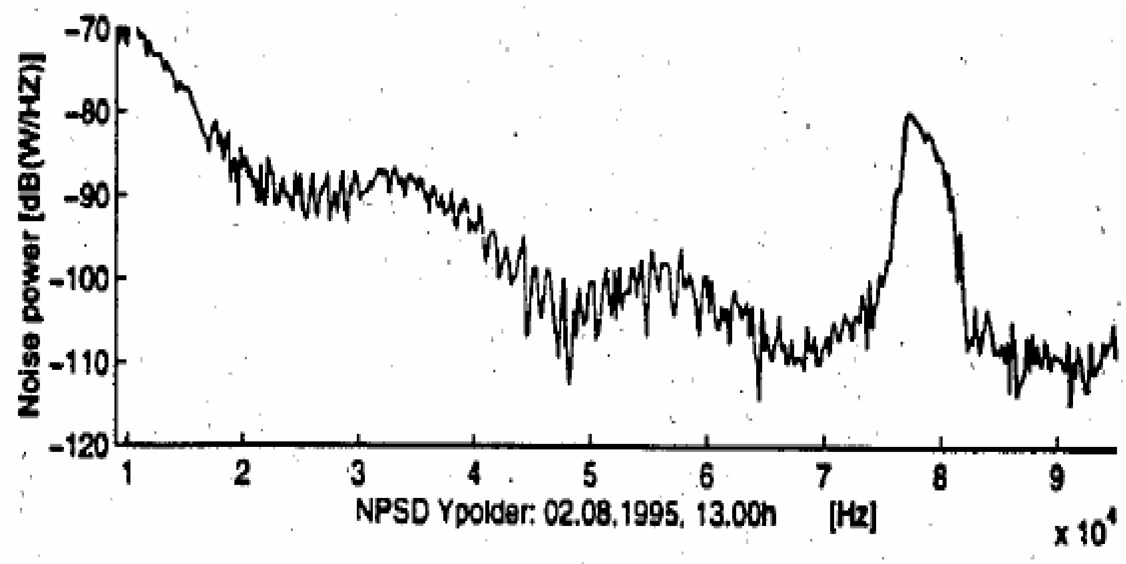


Figure 6.23: Strong narrow band noise measured at an industrial location [139]

6.3.4 Other Observed Noise Types that are not classified

In addition to the classified noise types, there are some other disturbances in power line channels. The most common ones are momentary low voltage, momentary high voltages, interharmonics, ringing waves, three phase imbalance, poor power factor, and notches. All of these disturbances may cause some power quality problems in the system [159].

Momentary low voltage may have two major effects on the power line channel. If the voltage goes too low for some period of time, the metering nodes may reset and lose communications with the host. In this case, either retransmission is initiated or if the cut off is more than the tolerable duration, the actual data in the process of transmission could be lost. As a result, the metering units should be resistant to long periods of low or no voltage without losing its memory and should be able to initiate self-restarting and retransmission procedures when necessary. The momentary high voltages have similar effects to the system and may also be harmful to the components of the device. Therefore, the device components should be able to withstand possible surges on the distribution system. Furthermore, interharmonics, which are the frequencies corresponding to the non-integer multiples of the power frequency, should be taken into consideration. If the magnitudes of the harmonics and the interharmonics are high enough in the transmission frequency band of the system, data could be lost or sent incorrectly. Consequently, the PLC based AMR devices and host computers should be able to discern the waveform signatures of their devices and the system devices that produce harmonics and interharmonics.

In addition to the sources of harmonic noise, the following are some major sources of harmonics and interharmonics: [160]

- Rotating AC Machines
- Fluorescent Lighting
- Glow Discharge Lighting
- Static VAR Compensators
- Static Watt Compensators
- Overexcited Transformers
- Transformer Magnetizing Current
- Adjustable Frequency Controls, Drives
- Adjustable Speed Controls/Drives

- Controlled Rectifier Applications (Light Dimmers)
- Electric Heating Controllers
- Switching Power Supplies

Additionally, the ringing waves that decay oscillatory can have similar effects for power line channels as harmonics and interharmonics. Besides the ringing waves may be caused from components faults in the PLC system originating from inrush currents. Furthermore, the three phase imbalance and the resulting excessive neutral currents can have disturbing effects of the power line channel transmission methods that depend largely on the neutral line as a transport medium.

Power factor may have negative effects for the PLC modulation techniques that depended on the zero crossings of voltage and current waveforms. On the other hand, power factor in a system is rarely unity and the participating PLC based devices should be designed accordingly.

Finally, the notches in the sinusoidal waveform may have similar effects on the PLC based systems if the notches are deep enough to trigger a crossing where there really is not a crossing for the ideal transmission. PLC devices should be able to distinguish and ignore these kinds of voltage notching to provide faultless communication. Table 6.3 summarizes these additional types of interferences and disturbances for a PLC based communication system.

Table 6.3: The most common disturbances and power quality issues that are not classified conventional noise types in low voltage PLC systems [160]

Selected Characteristics of Power Quality Issues				
Issue	**Duration**	**Frequency Characteristics**	**Occurrence**	**Typical Causes**
Momentary Low Voltage (Sags)	Transient	Low Frequency Components	In Networked Systems or in Radial Systems Fed by Networked Systems	Remote Faults
Momentary High Voltage (Spikes, Swells)	Transient	High Frequency Components	Due to Lightning, and Inductive Circuit Switching	Lightning, Switching, Improper Grounding
Harmonics	Steady state	Generally Confined to Odd Integer Multiples of the Power Frequency, Usually Third, Fifth, Seventh, Eleventh, and Thirteenth Harmonics	In Load Currents for Solid State Switched Loads (For Example, Adjustable Speed Drives, Compact Fluorescent Lamps)	Solid State Switched Loads, Nonlinear loads, Adjustable speed drives, Rectifiers, Inverters, Fluorescent lamps
Interharmonics	Steady state	Non-integer Multiples of the Power Frequency	In Load Currents for Devices as a	Solid State Switched Loads with

			Result of Asynchronous Switching, Non-Linear Effects and Aperiodicity	Problems, Adjustable Frequency or other Control Malfunction
Ringing Waves (Decaying Oscillatory)	Transient	A Transient High Frequency (For Example, - 17" Harmonic)	Capacitor Switching, Transformer Energization	Inrush Current, Shunt Capacitors
Three Phase Unbalance, Neutral Current	Steady state	Power Frequency	Three-phase Systems	Unbalanced Load, Improper Grounding, Unbalanced Voltage Supply
Poor Power Factor	Steady state	Power Frequency	Power System Where Reactive Power is Either Too Far Leading or Lagging	Either Too Much Reactive Power from Correction Devices or Too Little Reactive Power from Customer Equipment
Notches in Sinusoidal Wave	Steady state	High Frequencies	Due to Switching of Inductive Circuits Using	Adjustable Speed Drives

			Solid State Switches	
Radio frequency	Steady state	High-frequency (e.g., f > 500 kHz) sinusoidal signals of typically low amplitude impressed on the power frequency		Radio transmitters

6.3.5 Power Line Coupling

In order to avoid impedance mismatch and obtain galvanic isolation and voltage scaling, power line coupling methods should be employed for the connections between the power line and the measurement device. The benefits of line coupling will be analyzed in detail in Chapter 7 where the experimental results are described.

In general, there are two different types of signal coupling for power lines: differential or line to neutral mode [14], [102], [161].

Obviously, the line to neutral method can be used if the neutral line is available, which is not always the case for residential applications. Line to neutral coupling, or common mode in some literature, makes use of the ground wire as the second terminal. This method is favorable in the sense that the neutral line, which is the return path for the entire noise component in the power line, has less attenuation and less noise. Still, this method has some potential dangers and may suffer from some safety regulations. Consequently, most producers use the first method, differential coupling [162].

Additionally, the signal transfer between the two phases should be investigated. Considering the fact that, the interwiring capacitance is negligible and that the distribution transformer is not designed for the high frequencies used for power line communication, other methods of signal transfer should be put into practice. The first solution is a sizable load connected between the terminals L1 and L2 to increase the signal transfer rate. However, the reliability of the system can not depend on the presence of such loads as they may not be always connected to the system. Thus, a different solution should be employed. A capacitor selected according to the used frequency would be an appropriate solution. However, this method is not favorable if there are communication nodes operating between the two lines because the capacitor will shunt the voltage signal to be sent or received by this node. The typical solution to this situation is illustrated in Figure 6.24. This coupling circuit has a fairly low attenuation path of approximately 3 dB for the signal transmitted between the phases.

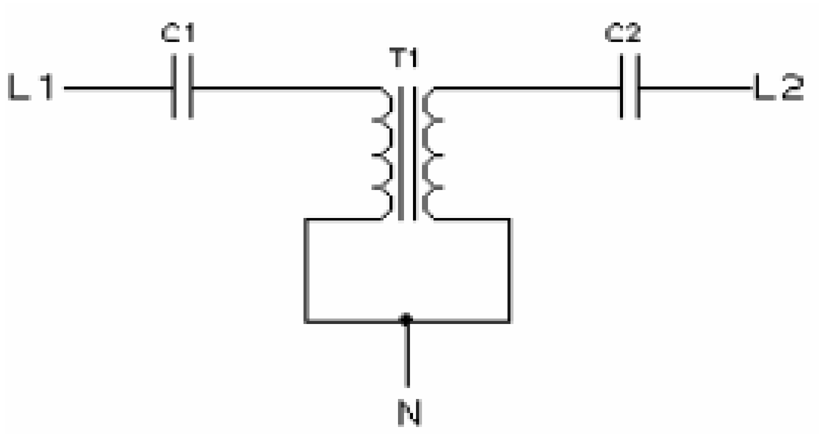


Figure 6.24: Recommended Phase Coupling Circuit [2]

Usually the method for injecting the signal at the desired frequency is to capacitively couple the transceiver's output to the power line. The transformer is utilized for safety reasons. In addition, some manufacturers use nonisolated circuits to decrease the transfer loss. Considering that the transformers inductance and the related capacitance for an LC circuit, the transformer's inductance should be calculated in such a way that the resulting LC circuit behaves as a high pass filter for the transmitted signal. An additional isolation is required to minimize the attenuation due to the different loads connected to the power line (especially the switching power supplies that has EMI filtering). For this purpose, at the frequency of interest, the inductance of the power line is usually sufficient as the line impedance is about 10 Ω per 100 feet. Thus, moving the node a few meters away from the load is enough to solve the problem.

The Figure 6.25 below is a generic topology that is employed to couple the communication circuit to the power line. The different protocols of different manufacturers use the variations of this topology.

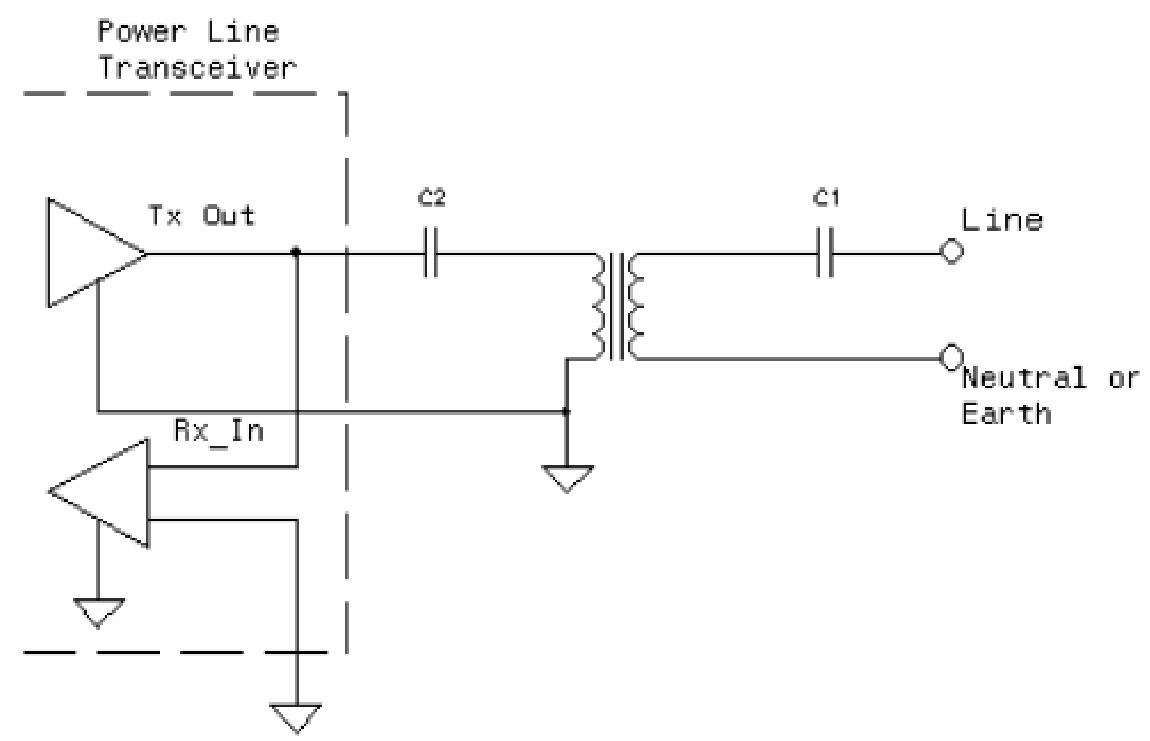


Figure 6.25: Transformer Isolated Coupling Circuit for Power Line Communications [2]

As the X-10 protocol uses the zero crossing detection, additional circuitry is used to perform the task. Figure 6.26 is the proposed coupling circuit for the X-10 protocol [163].

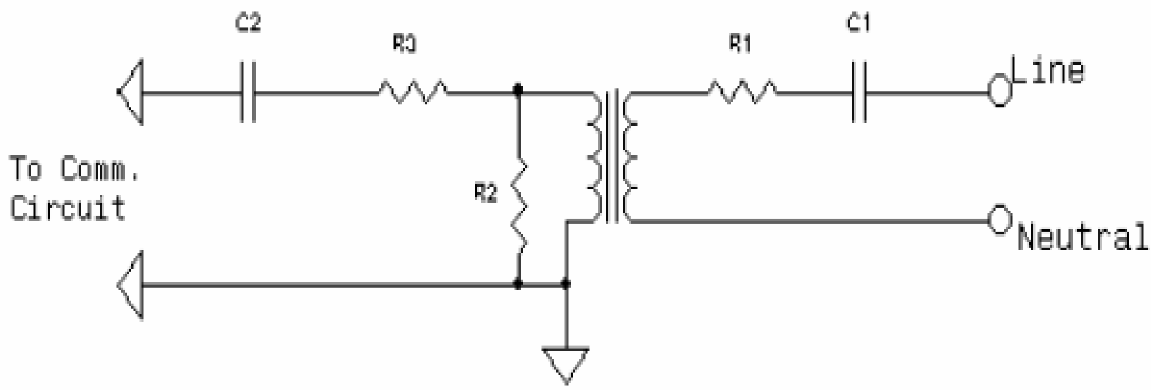


Figure 6.26: Power Line Coupling Circuit found in X-10 Devices [2]

On the other, Intellon that uses CEBus protocol proposes a power amplifier to boost the spread spectrum signal before coupling it to the power line [164]. Amplifier produces a 6Vp-p into a 10Ω load and in this way increases the performance under low line impedance conditions. The CEBus protocol uses the frequency spectrum from 100 to 400 kHz. Thus, a bandpass filter must be added to the coupling circuit. On the other hand, a wide frequency window makes the system more vulnerable to noise interference and the filter design specifications become more demanding. However, as the spread spectrum technology uses only a portion of the signal for detection, the receiver becomes more resistive to these kinds of impairments. Figure 6.27 shows the coupling circuit for a CEBus device designed by Intellon.

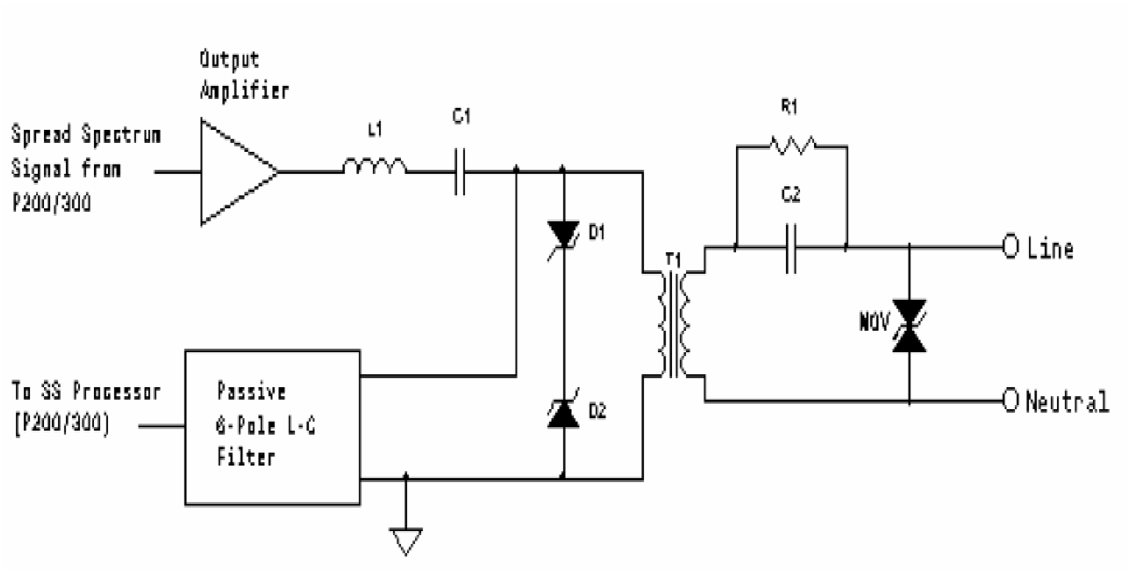


Figure 6.27: Power Line Coupling for CEBus Devices suggested by Intellon Corp [2]

The power line transceivers of the LonWorks network function on a narrower frequency band compared to the CEBus devices. Figure 6.28 is the demonstration of the power line coupling circuit of the Echelon's PLT-21 transceiver [164].

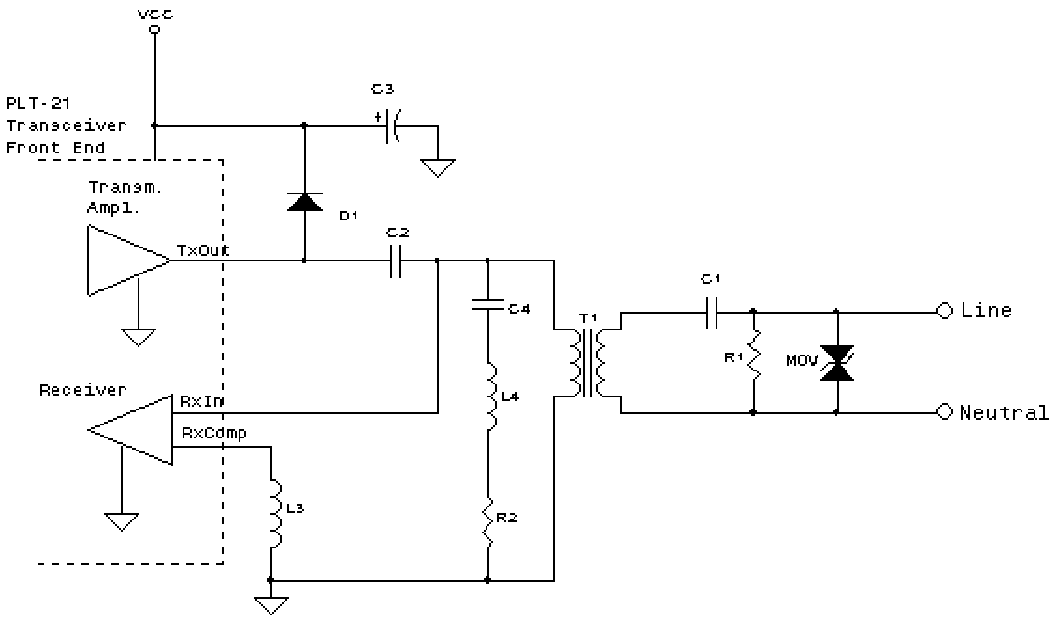


Figure 6.28: Coupling Circuit for LonWorks PLT-21 Transceiver

Capacitors C1 and C2 are supposed to have low impedance values for the transmission frequency band of 125 – 140 kHz. As the output impedance of the transceiver is around 1 Ω, the capacitors are selected to have impedance of the same order at the frequency of interest to minimize the overall output impedance of the circuit. However this condition entails a large capacitance value and the C1 that is connected to the power line might need to be expensive for volume protection. Again the transformer's inductance and the capacitor form a LC circuit with C1. This series resonant circuit should be tuned accordingly to the frequency of the transceiver. On the other hand, the RLC circuit formed by R2, L2 and C4 is necessary when the power line node includes triacs and SCR's or operates below 12 V_{dc}. Moreover, the capacitor C3 regulates the overvoltages that may result from system transients.

6.4 CONCLUSION

In this chapter, the noise types for power line communication channels are investigated. The conventional classification is presented, accompanied by other types of disturbance and interferences that are commonly observed.

The conventional classification includes (colored) background noise, asynchronous impulsive noise, periodic impulsive noise synchronous to the system frequency (harmonic noise), periodic impulsive noise asynchronous to the system frequency and the narrow band noise. The (colored) background noise, narrowband noise and the periodic impulsive noise asynchronous to system frequency are usually summarized as background noise in most literature. The root mean square (rms) of these three types of noises usually varies slowly over time. These three types of noise are mostly stationary over periods of seconds, minutes or even hours. The other two types of noise, asynchronous impulsive noise and periodic impulsive noise synchronous to mains frequency (harmonic noise) are time variant. Their PSDs are considerably higher and they cause bit errors in transmission. To sum up, in most cases the power-line noise can be considered as a superposition of the background noise and the impulsive noises from all nearby appliances. Further detail will be given about these noise types and the theoretical studies will be verified with experiments in the following chapter.

CHAPTER 7

EXPERIMENTAL RESULTS OF THE CLASSIFIED NOISE TYPES FOR POWER LINE CHANNEL

7.1 EXPERIMENTAL SETUP

For the purpose of conducting the laboratory experiments and verifying the theoretical studies in the preceding chapters, two separate experiments were carried out in METU, Electrical and Electronics Engineering Department, Electrical Machines and Drives Laboratory and R&D Laboratories of MAKEL facilities in Hadımköy.

In both of the experimental setups, single phase voltage of the mains line was observed and logged. Measurements were made between the phase and neutral using the nearest socket to the incoming mains cable to the laboratory. All sources of locally generated interference were either suppressed or switched off during the measurement period. The interference measured was either generated in laboratory building and adjacent buildings and then transmitted by the network, or in the case of broadcast signals, picked up by the network and the wiring of all the buildings connected to it. The mains voltage was initially measured without any devices connected in order to identify the background noise. Then various noise sources were connected one by one and related waveforms were logged both using a spectrum analyzer and two different data acquisition devices. The experimental system diagram is illustrated in Figure 7.1.

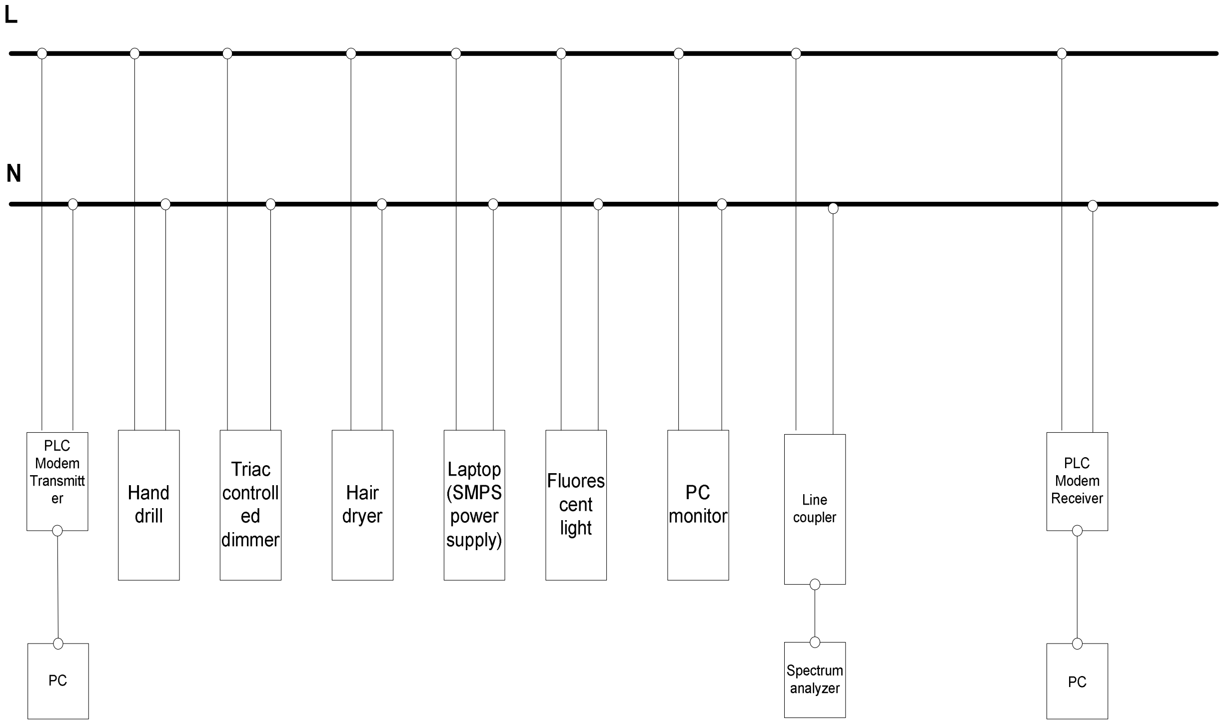


Figure 7.1: Schematic representation of the measurement setup used for the noise measurement.

The schematic in Figure 7.1 is applicable for field testing. In the laboratory experiments, slight changes are made on the design. In the experiments conducted in METU laboratories, the time domain data of voltage was logged by using a digital oscilloscope, Lecroy 6050A. Logged data was both processed in the time domain to observe the instantaneous changes and transferred to PC to be converted to frequency domain for further analysis.

During the experiments in MAKEL laboratories, first online characteristics in frequency domain were observed by using a spectrum analyzer, Agilent N9320A. Following that mains voltage data was logged to a digital data acquisition device Wavebook with a resolution of 16 bits, via a high impedance voltage probe. Digital data was transferred to PC and converted to frequency domain to be analyzed accordingly. Below are the technical specifications of data acquisition devices used throughout the experiments; Wavebook 516E and Lecroy 6050A.

Table 7.1: The technical specifications for data acquisition devices Wavebook 516 E and Lecroy 6050A 500 Mhz oscilloscope quad 5 GS/s.

	Wavebook 516E	Lecroy 6050A
Bandwidth	1 MHz	500 MHz
Resolution	16 bit	8 bit
Analog input channel	8 differential, expendable to 72 differential	4
Memory per channel	1 MB	1 MB
Input Signal Range	-10 to + 10 V	-5 to + 5 V
PC Communication	10/100 Base T Ethernet (300 ft. max)	10/100 Base T Ethernet (RJ 45 connector)
Input Bandwidth	DC to 500 kHz	DC to 500 kHz
Input Impedance	Single ended: 5 MΩ in parallel with 30 pF Differential: 10 MΩ in parallel with 30 pF	1 MΩ in parallel with 20 pF
Accuracy	For ± 2 to ± 10 V: $\pm 0,012\%$ of reading, 0,006% of range For ± 1 V: $\pm 0,018\%$ of reading, 0,008% of range	50 Ω: 2mV/div – 1V/div fully variable 1 MΩ: 2mV/div – 10V/div fully variable
System includes	WaveView,PostView, comprehensive dirves for DASYLab, LabVIEW, MATLAB, Visual C++, Visual C#, Visual Basic	10:1 10 MΩ, 500 MHz BW positive probes Standard ports: 10/100 Base T Ethernet, USB, Parallel, RS-232, SVGA Video Out, Audio in/out

Table 7.2: The technical specifications for Agilent N9320A Spectrum Analyzer

	Agilent N9320A Spectrum Analyzer
Frequency Range	9 kHz to 3 GHz AC coupled 100 kHz to 3 GHz Preamp on
Set-up resolution	1 Hz
Frequency span resolution	1 Hz
Resolution bandwidth (RBW) Accuracy:	± 20 % 1 kHz to 1 MHz RBW ± 5 % 10 Hz to 900 Hz RBW
Sweep Time Range: Sweep mode:	 9,2 ms to 4000s span>0 Hz 20 μs to 4000s span= 0 Hz (zero span) Continuous, single

In the experiments in MAKEL facilities, the spectrum analyzer was connected to the line through a line coupler. The coupler is composed of two MKP plastic capacitances (470 nF, 250V AC rated voltage) and a Vacuumschmeize transformer, model no T60403-D4097-X051. See Figure 7.2 below.

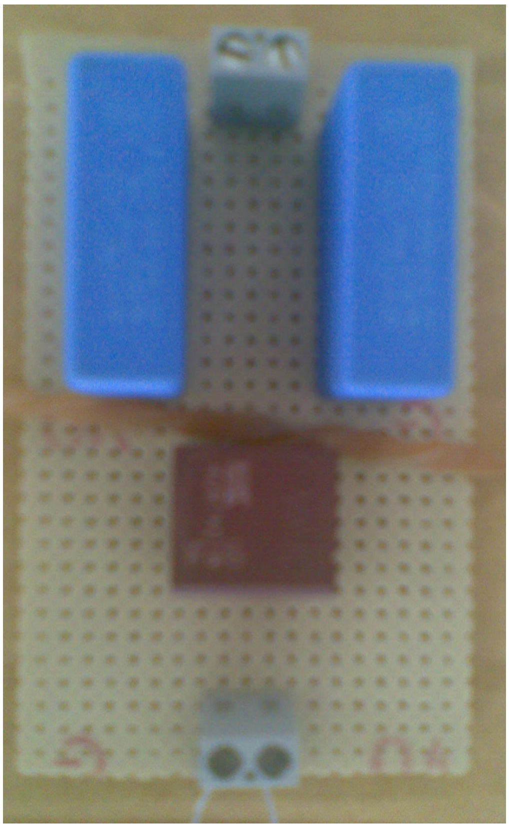


Figure 7.2: The photograph of the line coupler used for the experiments in MAKEL's R&D Laboratories.

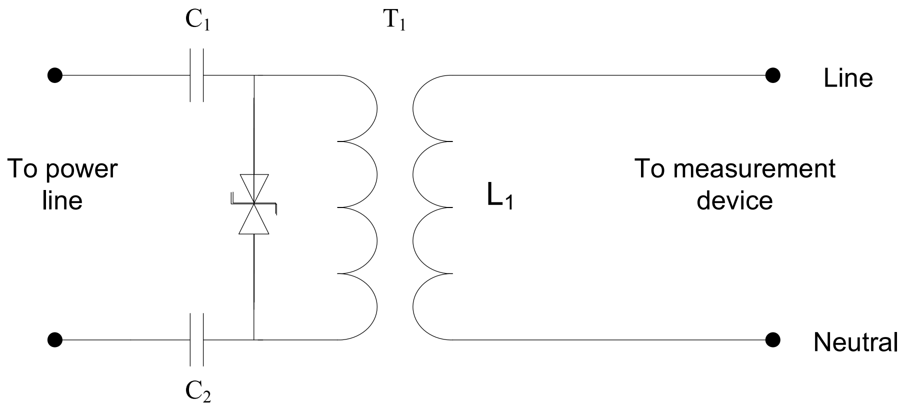


Figure 7.3: The schematical representation of the coupling circuit used [113].

The coupling circuit shown in Figure 7.3 is used as an interface between the power line and the spectrum analyzer. This is a transformer isolated, differential mode, coupling circuit, and isolates the connected device from the power-line. The line coupler is used to inject the carrier signal to the power line. It is composed of the isolation transformer, capacitors and diodes. The combination acts as a high pass filter circuit. Coupler simply blocks the nominal 50 Hz power signal component and fulfills the over-voltage protection and impedance matching function in addition to its regular voltage scaling mission. The high pass filter design effectively removes the 50 Hz signal and its harmonics, but also other spectral components with low frequencies [159], [165], [166], [167].

Furthermore, the coupling unit, which was connected directly between the phase to neutral and the measurement device, provides high-pass type galvanic isolation between mains and measurement devices. Galvanic isolation is the principle of isolating functional sections of electric systems so that charge-carrying particles cannot move from one section to another, i.e. there is no electric current flowing directly from one section to the next. Energy and/or information can still be exchanged between the sections by other means, however, such as by capacitance, induction, electromagnetic waves, optical, acoustic, or mechanical means. The coupling circuit allows transmitting and receiving high frequency signals and also blocks and isolates the analyzer input from the 50 Hz components on the mains wiring. The coupling circuit is composed of a broadband transformer and capacitors with device models and specifications stated before. This design behaves as a high-pass (LC) filter, avoiding the triggering on low frequency impulse response and passing only the higher frequency signals of interest to the spectrum analyzer. Additionally, on the primary side of the transformer, two Zener diodes are placed in opposite directions for the overvoltage protection in both directions.

Two different filters are used for CENELEC A and CENELEC B frequencies.

Filter 1

For C_1=C_2=470 nF and L_1= 3,9mH the cut off frequency is 3 kHz. The cutoff frequency is the frequency for which the transfer function magnitude is -3dB. The squared magnitude of the frequency response of Filter 1 is shown in Figure 7.4

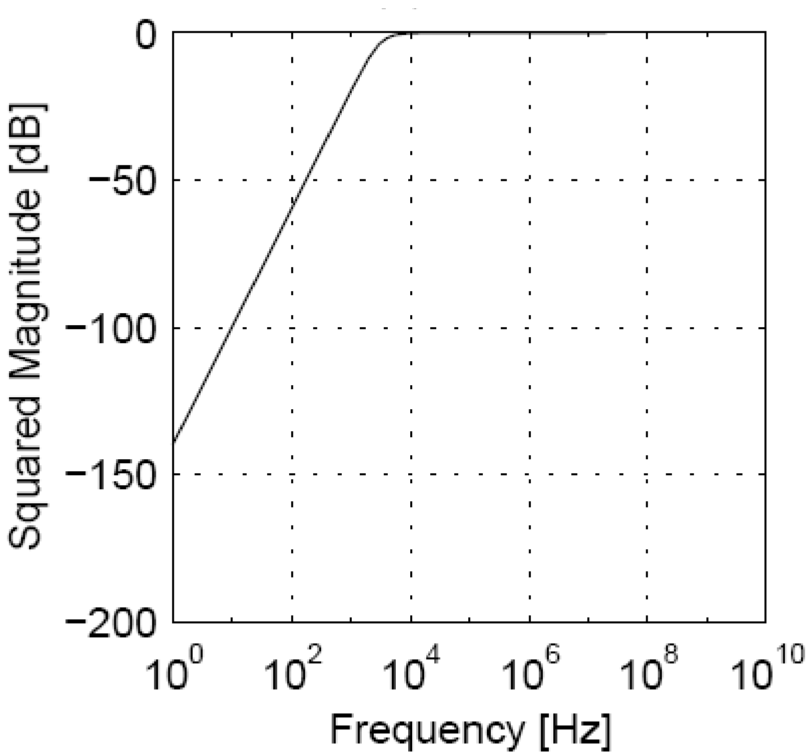


Figure 7.4: The squared magnitude of the frequency response of the Filter 1.

Filter 1 has a flat frequency response above 10 kHz and is suitable for the measurements in CENELEC A band which is limited to the frequency band between 9 to 95 kHz.

Filter 2

For C_1=C_2=220 nF and L_1= 1mH the cut off frequency is 25 kHz. The squared magnitude of the frequency response of Filter 2 is shown in Figure 7.5

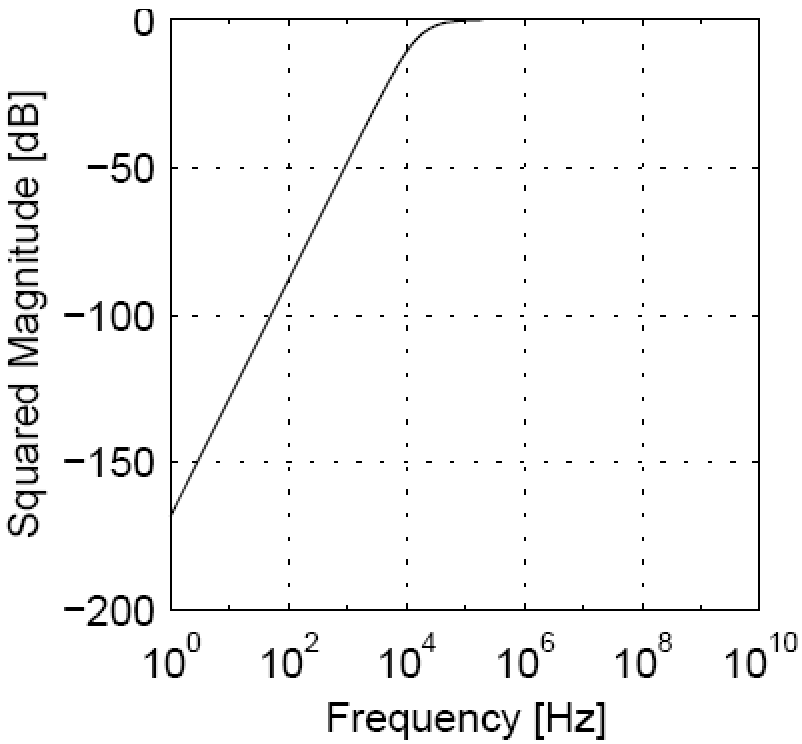


Figure 7.5: The squared magnitude of the frequency response of the Filter 2

Filter 2 attenuates low frequencies more than the Filter 1 does and increases the dynamic range of the receiver. Filter 2 is suitable for the frequencies above 100 kHz and can be used for the measurements for CENELEC B and C bands. As the filter has a non-flat frequency response below 100 kHz, the absolute value of the input impedance of the filter increases. According to the test measurements, the reduction in power of the noise and the signal on the power line is small above 25 kHz. Below 25 kHz, the noise and the signal is scaled by a factor which is the combination of the attenuation of the filter and the impedance mismatch between the filter and the power line [165], [166], [167].

As the Figures 7.4 and 7.5 exhibit, the filters attenuate low frequencies, thus the 50 Hz signal and its harmonics are effectively removed to a certain degree. Still, as the aimed frequency band during the experiments is CENELEC A band, for all the noise measurements Filter 1 was used.

The analyzer's settings were carefully chosen to obtain data that provided sufficient details to enable the wanted signals to be identified from the background noise and other interference. This was achieved by first choosing the bandwidth and the frequency span. The frequency span and the resolution bandwidth were considered together as they were both dependent on the signals under investigation, broadcast radio carriers that were the most frequent and highest level of interference observed. A resolution bandwidth of 1 kHz was selected, as this matched the sample spacing chosen to suit the 150 kHz span and contained the required detail.

For all the experiments, firstly, no device was connected to the line to measure the background noise. The power source of the measurement devices were connected to a phase different from the observed phase. Then the noise sources were connected separately and individually at different times to measure the related noise characteristics. The measurement was made about the voltage and the power spectrum densities of the noise emitted by individual electrical appliances.

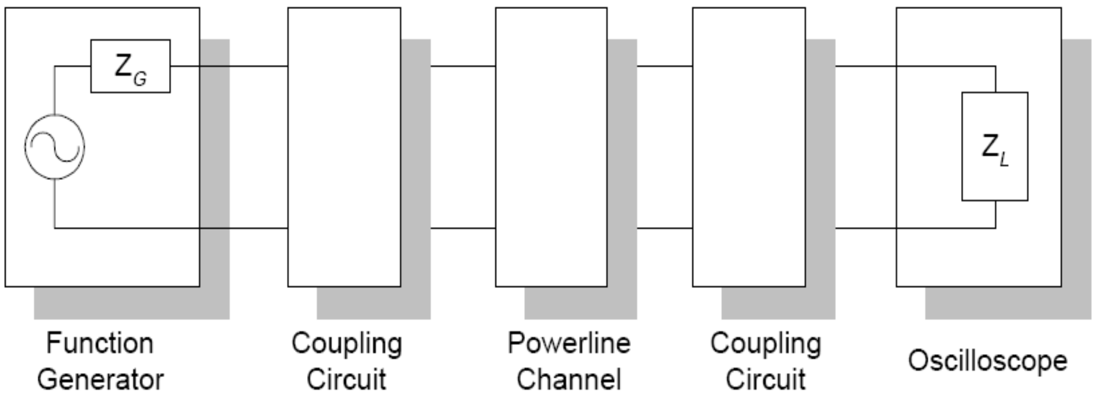


Figure 7.6: A schematic of the measurement setup for Agilent N9320A spectrum analyzer.

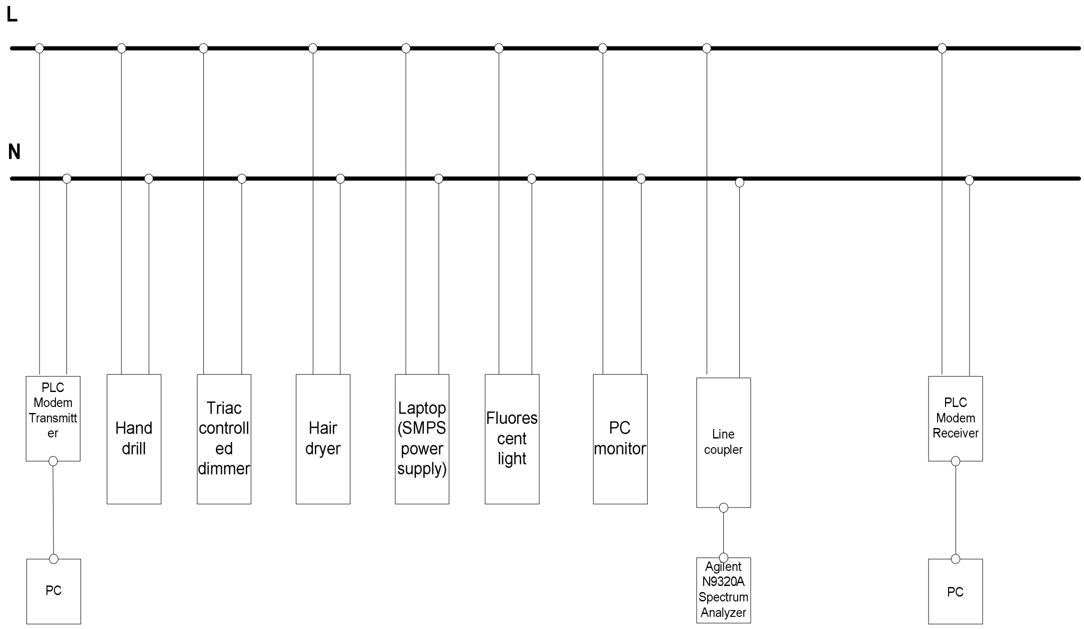


Figure 7.7: The test schematics for the Agilent N9320A Spectrum Analyzer

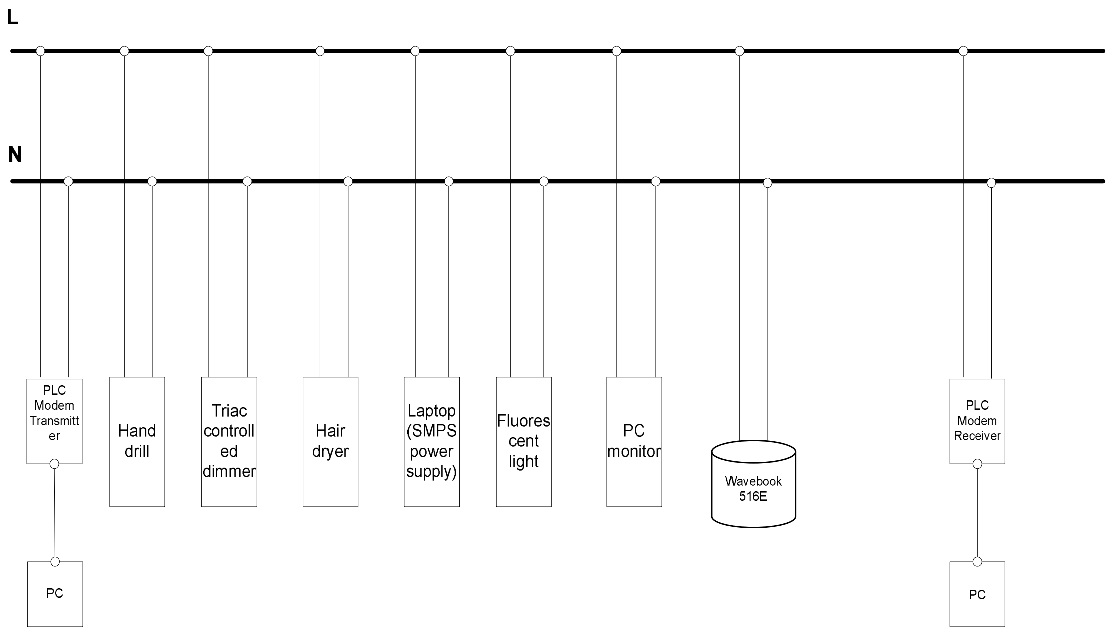


Figure 7.8: The test schematics for the Wavebook 516E Digital Data Acquisition Device

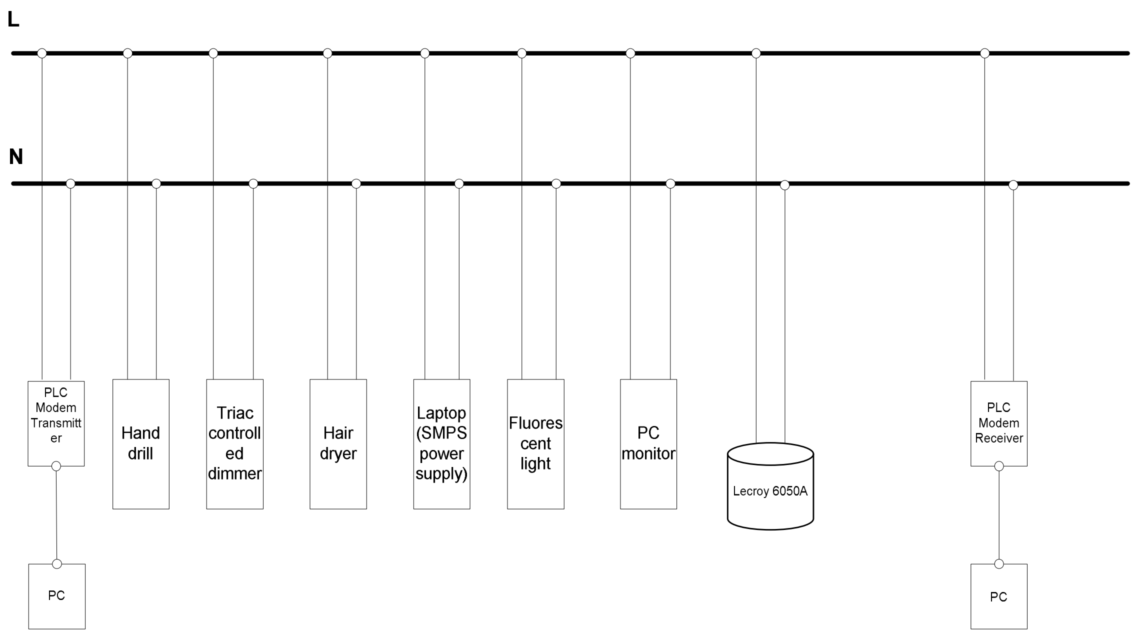


Figure 7.9: The test schematics for the Lecroy 6050A Digital Data Acquisition Device

For the experiments that voltage data is logged with digital data acquisition devices Lecroy and Wavebook, line coupler is not used. Line coupler is only used to connect the signal generator to the line. The logged data was transferred to the PC and the Fast Fourier Transform of the data was obtained using the mathematical analysis tools of MATLAB. The used algorithm is given in Appendix B.

According to Nyquist theorem, for the discrete data there is an upper limit on the frequency at which you can get meaningful information. The Nyquist theorem states that a signal with the bandwidth B can be completely reconstructed if a sampling rate of 2B samples per second is used. Consequently, the highest frequency that can be uniquely fit to the data, called the Nyquist frequency, equals half of the sampling frequency. In the experiments the sampling frequency of the signal delivered was chosen to be 1 MHZ which allows an acquisition of channel frequency response up to 500 kHz.(Note that Nyquist frequency is 500 kHz which is simply the half of 1 MHz). However in practice accurate frequency characteristics are observed for lower frequencies than the Nyquist frequency. Hence frequency response with required accuracy can be observed properly between 9 kHz and 148.5 kHz.

As a measure of the noise level indicated in frequency domain, the power spectrum is analyzed as it describes how the power of a signal is distributed in the frequency domain. To estimate the power spectrum of a signal, N samples are taken in the time domain at a sample rate of F_s samples per second during N/F_s seconds.

Thus, resolution of the frequency response (FR) is determined via the number of samples in the data as given in

$$FR = 1/\text{ total sampling time} \quad (7.1)$$

For the measurements with the digital data acquisition devices, time domain data is logged with 1M sample/second for 5 seconds which corresponds to 5M samples leading to a resolution of 0.2 Hz in the frequency response.

Noise can be studied both in the frequency domain and time domain. In order to calculate the duration and interarrival time of impulses, the measured data is observed in time domain. On the other hand the frequency domain gives a clear picture of the PSD of the data which is meaningful for the observation of background noise. As discussed in Chapter 6, all the electronic and electrical equipment connected to the power line should be taken into account in noise measurements. Some of these devices generate background noise while others such as light dimmers inject impulse noise. Switching devices are main cause of harmonic noise. Also there are deterministic noises that are induced from the environment onto the power lines because power lines act as antennas due to their length. One example of that kind of noise is radio stations transmitting at medium and short wave bands.

Noise sources can be associated to every load whose power spectral densities (PSD) have been measured. During the experiments, 5 different appliances have been analyzed. The noise characteristics of a dimmer, laptop, monitor, drill, florescent lamp and hair drier were observed. All the devices are located to an equal distance from the source and the observation point, as their influence on the received noise depends considerably on how close to the signal path they are [168].

7.2 NOISE MEASUREMENT TECHNIQUES

The noise accessible models stated in the literature usually depend on empirical measurements as it is very difficult to come up with noise models through solely analytical derivation. There are mainly two approaches for noise measurements; frequency-domain approach or time-domain approach.

The frequency-domain approach is based on the measurement of noise frequency spectrum in the frequency domain either using a spectrum analyzer or using conversion techniques such as fast Fourier transform or discrete time Fourier transform [169]. On the other hand, time-domain approach depends on real-valued noise waveforms in the time domain.

Considering the existing literature, the background noise is mostly modeled in the frequency domain, while the impulsive noise is characterized in both the frequency domain and time domain.

The background noise can be modeled by using two models in the frequency domain. The most widely-recognized one is spectrum fitting. In this model the voltage spectrum density or the measured noise PSD is explicitly expressed as function of frequency. This model usually yields a good approximation for the average noise spectrum but still lacks any information on the random behavior of the noise at each individual frequency. To cover this defect, statistical analysis methods are promoted. In this model's context, the background noise variation at each frequency is fitted into certain probability density functions. The aim of statistical analysis methods is to identify the statistical characteristics of the noise at a specific frequency by using the PDFs of the waveforms and the corresponding statistical parameters of mean and standard deviation.

For impulse noise modeling, the noise spectrums produced by noise sources are observed initially in frequency domain. This approach provides ample information about the magnitude of the impulse noise over the specified frequency range but is not detailed enough to model the statistical variation of the impulse noise. On the other hand, time domain models focus on statistical characteristics of three major parameters of impulsive noise; pulse amplitude, pulse width and interarrival time. The method depends on deriving the probability distribution curves from the measurements. The probability distribution curves for pulse width and the interarrival time are obtained by the superposition of some proposed exponential distributions. Compared to the method depending on direct measurements, this method describes not only the probability density functions of impulse magnitude and interarrival time but also the time transition properties of the distributions. In other literature, Middleton’s class A noise model is used to model the amplitude distribution of the impulsive noise. It is still vague if this approach can be applied to impulsive noise modeling as the model is initially developed for man-made impulse interference. Moreover, a cyclo-stationary noise model is introduced to describe the characteristics of background noise and impulsive noise. This model suggests that a significant amount of power line noise changes in synchronism with half cycles of the supplying voltage. The noise is modeled as the superposition of the sinusoidal waves of corresponding amplitudes and frequencies.

In this thesis work, the time domain and frequency domain approaches are used to study the impulsive noise and the frequency domain approach is used to model the background noise. Statistical models are not employed in the measurements as these methods need continuous studies and measurements that can last for several weeks according to the existing literature.

Analyzing the observations below, it should always be considered that power line channel is a time variant communication channel since the noise, attenuation and the phase shift of the channel varies continuously depending on the geographical location, operating frequency and the time of the day. The aim is not to build a general model but to investigate the experimental observations of theoretical calculations, models and assumptions that are mentioned in Chapter 6

7.3 EXPERIMENTAL RESULTS FOR THE BACKGROUND NOISE

As stated in the theoretical analysis, background noise can basically be defined as the portion of the noise that remains after subtracting other types of noise measured at a certain location. Background noise exists permanently on the line. In the frequency band of interest, the most remarkable characteristic of background noise is its non-whiteness, i.e., its power spectral density (PSD) is frequency dependent and decreases with increasing frequency.

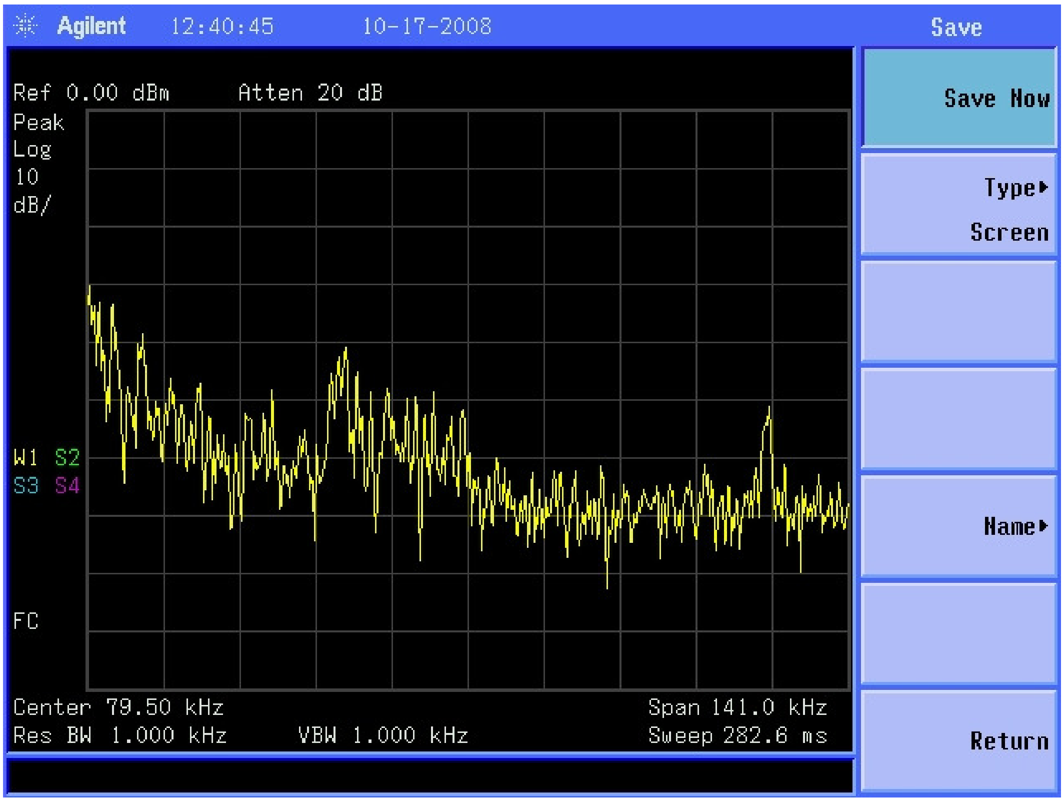


Figure 7.10: The background noise spectrum in the frequency domain.

Hundreds of measurements are taken in the laboratory in different times of day. As seen from the background noise waveform in Figure 7.10, the noise spectrum has relatively large values at low frequencies and smaller values at high frequencies. However the instantaneous noise spectrums are observed not to change significantly over time. The noise amplitude spectrum defines the general characteristic of the noise with respect to time. The maximum amplitude of the background noise is observed to reach 70 dB(μV) and the average levels of decrease was around 40 dB/(decade), between 14 kHz and 140 kHz. The average absolute noise levels were around 70 dB(μV) at 9 kHz and 40 dB(μV) at 95 kHz. The average absolute noise level was observed to decrease to 30 dB(μV) around 150 kHz.

For the measurements in MAKEL facilities, each record has a length of 5 sn in the frequency range between 9 - 150 kHz. It was observed that the typical run starts at low frequencies up to 20 kHz and above 20 kHz, the power density was decaying steadily as the frequency increases. Finally, around 150 kHz, a decay of almost 30 dB was monitored when compared to 20 kHz.

Note that for the Hooijen's studies, it was stated that the PSD of the background noise decayed with increasing frequency with a slope of 20-25 dB/decade for indoor environment, and 35 dB/decade for outdoor environment.

7.4 EXPERIMENTAL RESULTS FOR THE APPLIANCE NOISE

In order to measure the remaining four types of noise, electrical appliances are connected to the power line and the noise spectrums induced by these appliances are measured and recorded. The measurement procedure is summarized in two steps. First the background noise of the mains line is measured without any appliances connected. Secondly, an appliance is connected between the phase and the neutral to measure the combined effect of background and appliance noise. It should be kept in mind that noise spectrum calculated in this measurement is the power spectrum and the different sources combine in terms of their power and not amplitude as the noises are noncoherent.

In the Figure 7.11, the rms magnitudes of noise voltage values of various electric appliances are listed. It can be observed that the power line noise effect decreases with the increasing frequency. The cleaner, the air conditioner and the rice cooker are the equipments with the highest average noise values. The cleaner's average noise value is very large as the noise is generated through all the frequency band of interest. Note that, the equipment which involves a motor such as cleaner, drier, washing machine and the built-in equipment with the inverter circuit such as air conditioner and fluorescent light have relatively lower average noise levels.

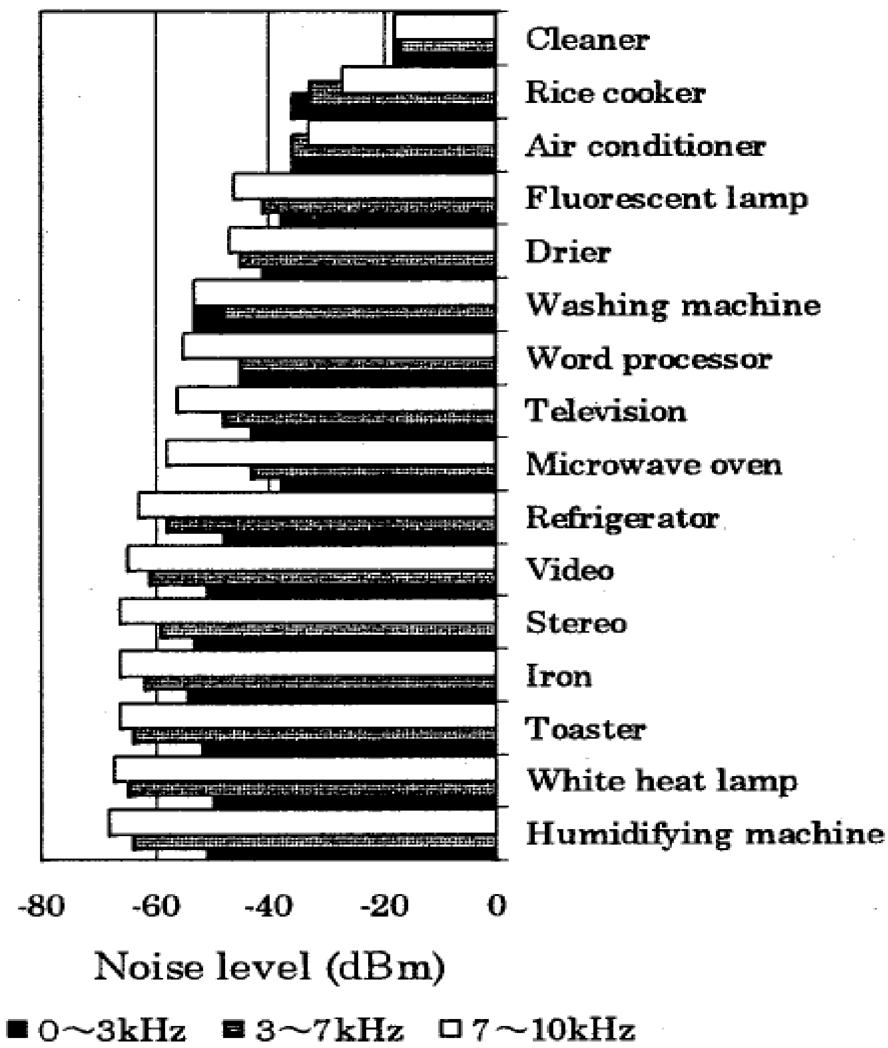


Figure 7.11: The rms magnitudes of noise voltage values of various electric appliances

Below are the average noise measurements for some common household appliances.

Table 7.3: Measured amplitude and duration characteristics of noise from common household appliances [170].

Electric Apparatus	Amplitude (mV)		Duration (us)	
	Average Value	Standard Deviation	Average Value	Standard Deviation
(Single Pulse)				
Electric Oven	329.2	431.2	1015.8	505.2
Iron	369.3	585.8	760.2	347.9
(Periodic Pulses)				
Television Monitor	197.2	311.3	722.4	34.3
Light Dimmer	670.8	1199.3	140	7.5
(Continuous Pulses)				
Vacuum Cleaner	1457.5	2155.5	Always	---
Dryer	87.9	119.7	105.3	56

7.4.1 Impulsive noise

As stated in the Chapter 6, the core parameters of the impulse noise in power lines are the impulse duration, interarrival time and amplitude.

The most common and noticeable impulse noise source is triac-controlled light dimmer. An ordinary light with a bulb filled with inert gas produces strong noise due to the impulsive current induced by electron emissions in the bulb. When we set the lamp to medium brightness, the inrush current is maximized and several tens of volts are injected to the line as impulse noise. The period of these impulses produced when the lamp is connected to the line is half of the

AC cycle. Using a high pass filter to eliminate the system frequency, the typical stand alone impulse noise shape that is observed in the experiments is represented in Figure 7.12.

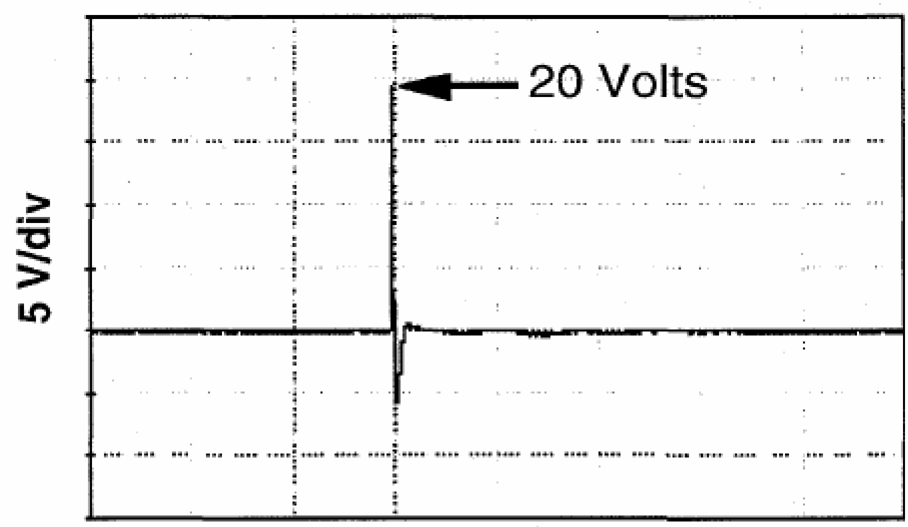


Figure 7.12: Impulsive noise for triac-controlled light dimmer

In the experiments performed in MAKEL facilities, an analog spectrum analyzer is used rather than a FFT based device. By choosing a proper analyzer bandwidth and sweep-time, it was possible to distinguish between the impulse noise and narrow band interference. The estimation for the recordings performed was made with periods of 20ms, according to the 50 Hz European AC cycle). A second data acquisition to be analyzed was performed about 500 ms after the previous one to check the stability of the channel frequency response after the impulsive noise. The acquisition time was kept long enough to avoid the disturbing effect of a long impulsive noise.

7.4.1.1 Asynchronous impulsive noise and periodic impulsive noise asynchronous to system frequency

The asynchronous impulsive noise and the periodic impulsive noise asynchronous to system frequency are investigated over the same experiment.

Figure 7.13 below is the voltage spectrum for the start up of the triac controlled dimmer. An asynchronous impulsive noise is clearly observed around 93.5 kHz.

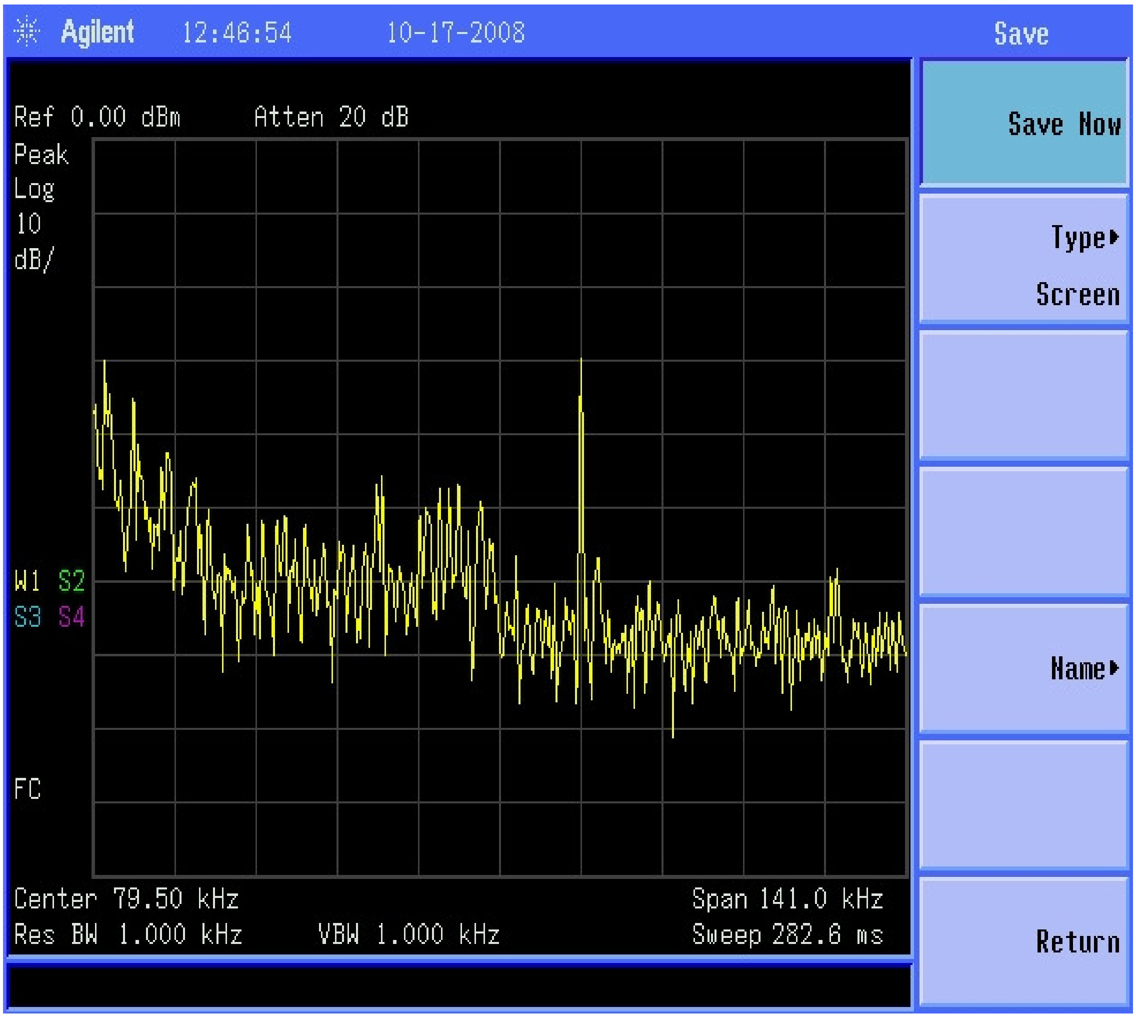


Figure 7.13: The transient asynchronous impulsive noise for the triac controlled dimmer.

After the start up, when the dimmer voltage spectrum reaches the steady state, the Figure 7.14 below is the representation of the periodic impulsive noise caused by the triac controlled dimmer. In steady state, the dimmer produces a periodic impulsive noise. The dimmer was observed to produce approximately a mean noise of 25-30dB(μV) over the background noise throughout the frequency band of interest.

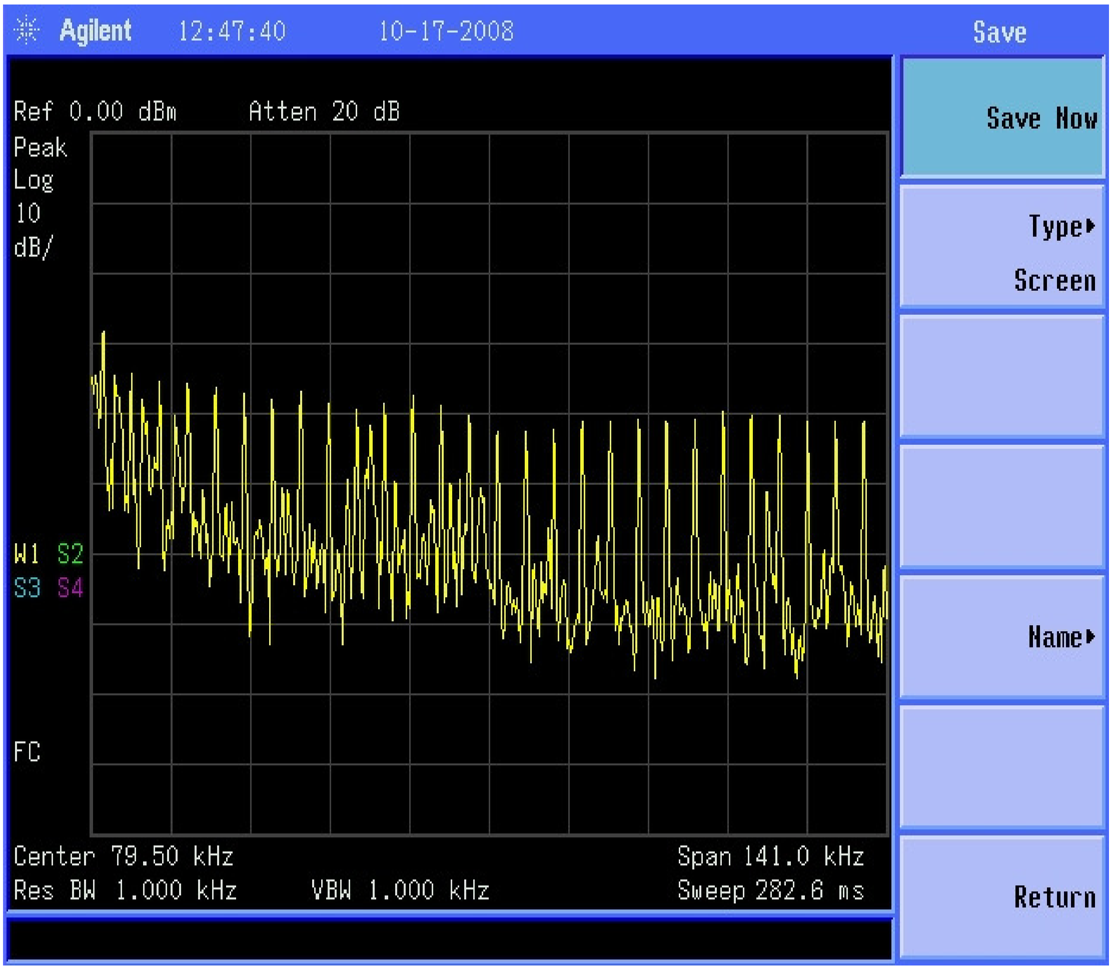


Figure 7.14: The steady state voltage spectrum of the asynchronous periodic impulsive noise for the triac controlled dimmer.

Then the defining parameters of impulse noise are used to analyze the measurements.

- Impulse width: The impulses were observed to last for much less than 12.5 ms which is the approximate impulse width for Hooijen's measurements. Among the 120 worst case, the mean time between occurrence was calculated to be 2.6 ms.

- Impulse interarrival time: Interarrival time was observed only in one location in METU laboratories. Studied literature indicates that the number of impulses that occur per unit of time is highly frequency dependent. As the measurements are performed only in one location, the observed characteristics are not detailed enough to enlighten the reader about the location dependency of impulse interarrival time. Besides, the measurements were performed during day time in the weekend. As a result, the time dependency of the impulse interarrival time was not clearly identified either. However, the obtained spectrums were detailed and explanatory enough to state the fact that the probability of occurrence of a noise impulse is independent from the occurrence of another impulse. The worst case for the interarrival time was measured as 2.7 ms and the mean time for the impulse interarrival time was measured as 17s. Moreover the impulsive noise characteristics that are observed during the experiments had strong peaks

- Impulse duration: As a result of hundreds of measurements, the duration for the impulse noise sample ranged between several microseconds up to a few milliseconds. On average the spectral density of the impulsive noise was in the order of 30 dB above the background noise. Figures 7.15 and 7.16 are the examples of asynchronous impulsive noise in the ms and μs respectively.

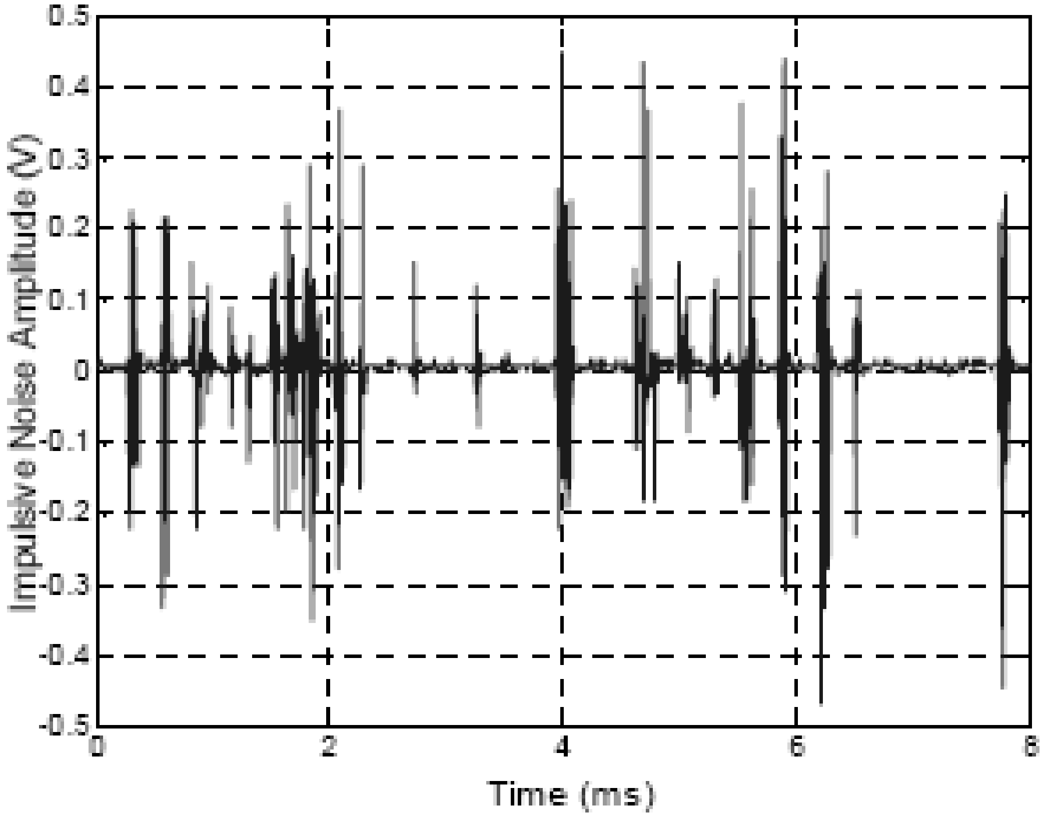


Figure 7.15: Asynchronous impulsive noise in ms scale

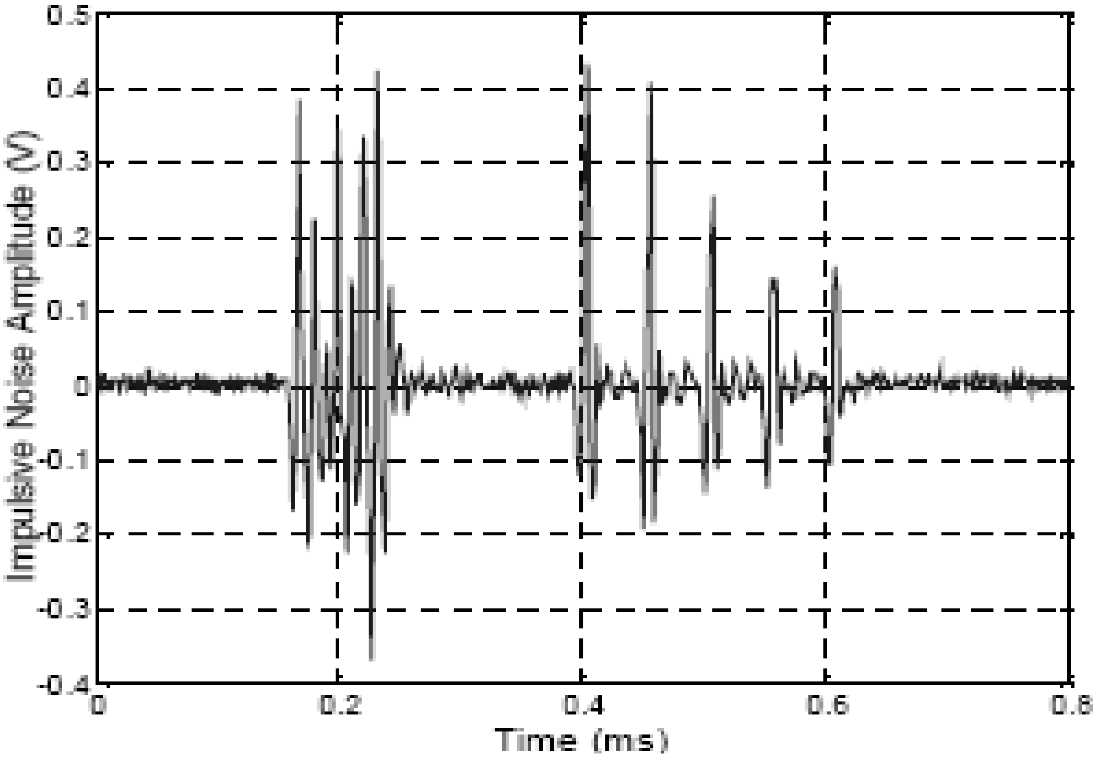


Figure 7.16: Asynchronous impulsive noise in μs scale

Moreover, at the startup, a 1800W industrial dryer machine was observed to cause asynchronous impulsive noise as seen in Figure 7.17.

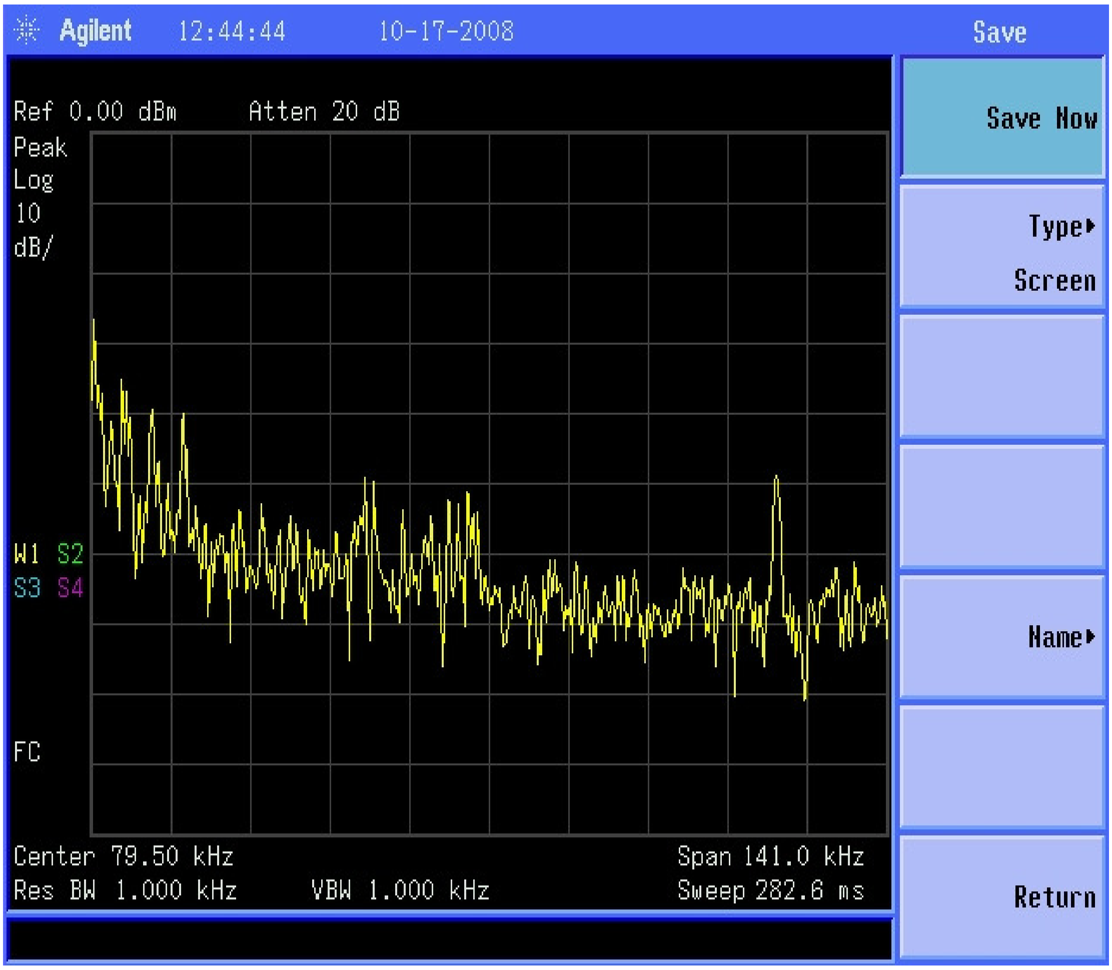


Figure 7.17: The transient impulsive noise for the startup of the industrial dryer.

The industrial dryer did not have significant effect on the voltage spectrum of the power line in the steady state.

7.4.1.2 Impulsive noise synchronous to the system frequency (Harmonic noise)

As stated in previous chapter, the major sources of this type of noise are the switching power supplies, power converters, and silicon controlled rectifiers that switch on and off at system frequency.

The experiments performed were able to verify that the odd harmonics are usually monitored to be more dominant. The Figure 7.18 is obtained by using the Fast Fourier Transform (FFT) function of the data obtained in the METU Machinery Laboratories for the power line voltage spectrum of a specific phase under the conditions of fluorescent light disturbance. The MATLAB algorithm designed for the FFT is given in Appendix A. For this experiment set up, the sampling frequency is 500 kHz. The fundamental component is observed in 50 Hz. Besides, the 3rd, 5th, 7th, 9th, 11th, 13th harmonics are clearly observed as expected.

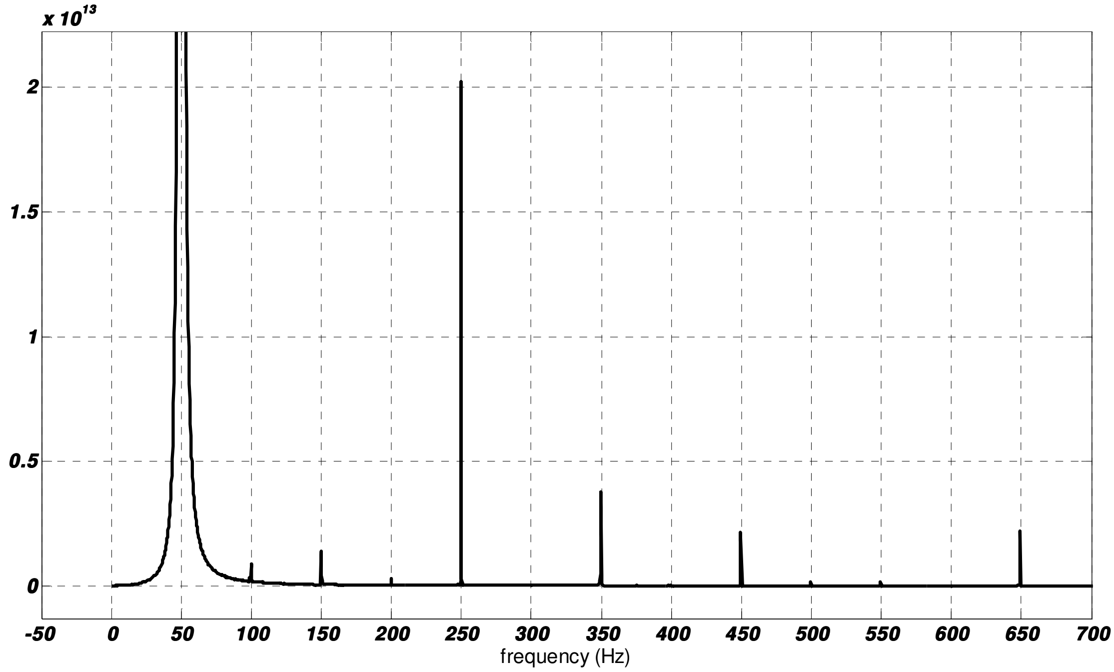


Figure 7.18: The fundamental and the odd harmonics observed by taking the Fast Fourier Transform of the system voltage.

On the other hand the laptop with the switched mode power supply (SMPS) was observed to cause harmonic noise over the entire frequency band. The peak noise level was observed to reach to 95 dBμV.

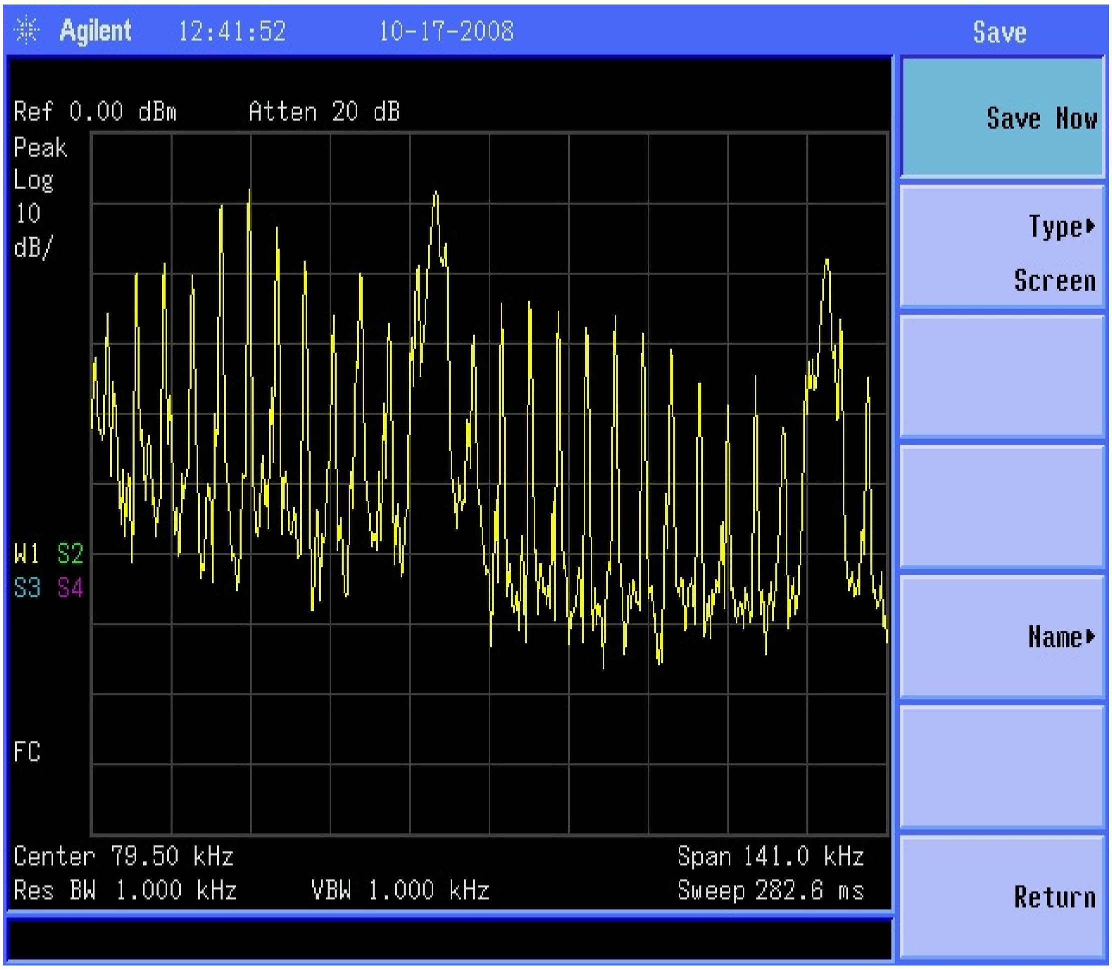


Figure 7.19: The voltage spectrum for the laptop with the switched mode power supply

7.4.2 Narrow band noise

One of the main sources of this noise was reported to be the horizontal retrace frequency of television. This frequency is 15.6 kHz for the PAL standard used in the most European countries and some narrow band disturbances are observed at harmonics of this frequency. Time coded transmissions can also cause narrow-band noise by coupling to the power lines. Narrow band disturbances were observed at 25 kHz, 32 kHz, 46 kHz, 49 kHz, 55 kHz, 62 kHz, 75 kHz, 78 kHz and 94 kHz.

Figure 7.19 below is the voltage spectrum for a PC monitor connected to the mains line. There are some minor varieties from the background noise waveform which is always present in the line. The narrow band disturbances are observed around 25, 46, 55, 69, 75 and 78 kHz.

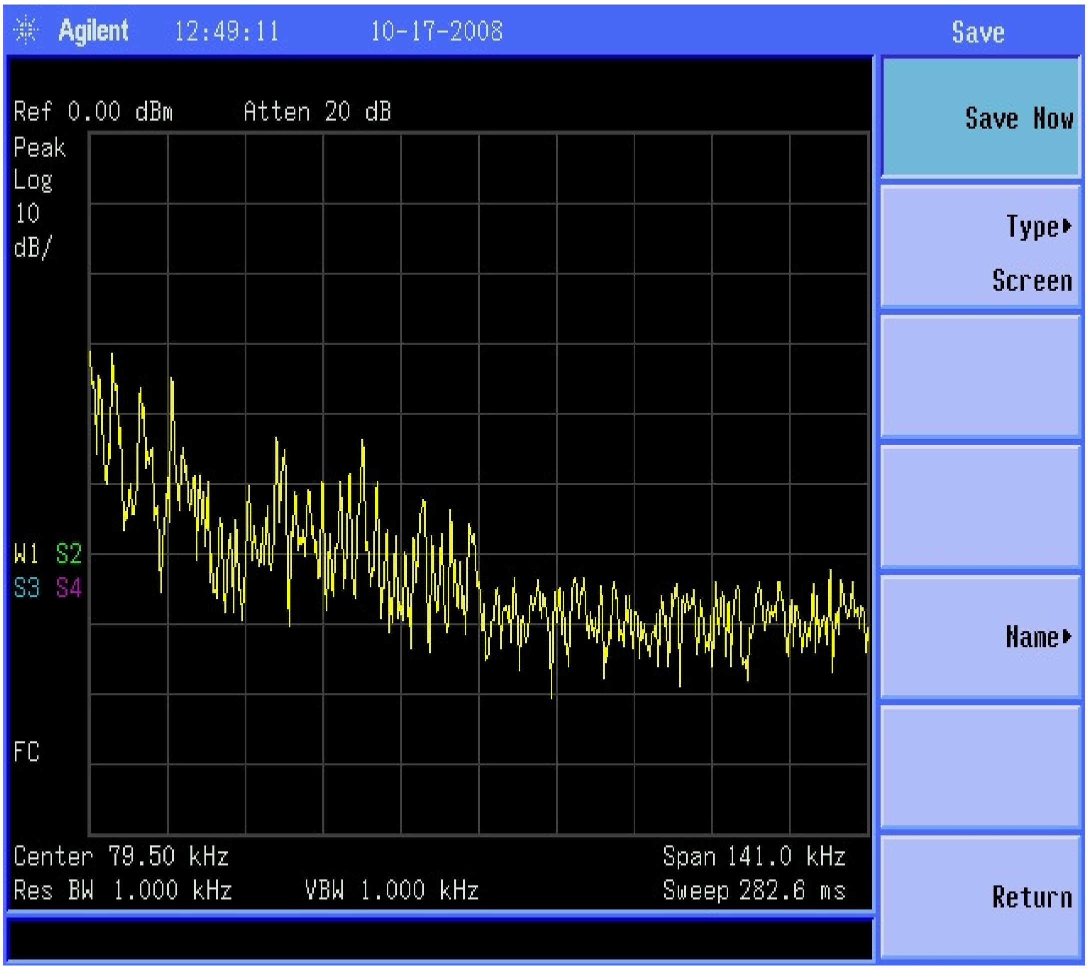


Figure 7.20: The voltage spectrum for the PC monitor indicating a narrow band noise between 9 to 79.5 kHz.

Moreover, for the experiments performed in MAKEL laboratories, the drill was observed to generate a narrow band noise in the frequency band between 9 to 37 kHz. The voltage spectrum for this type of noise decayed significantly in the larger frequencies.

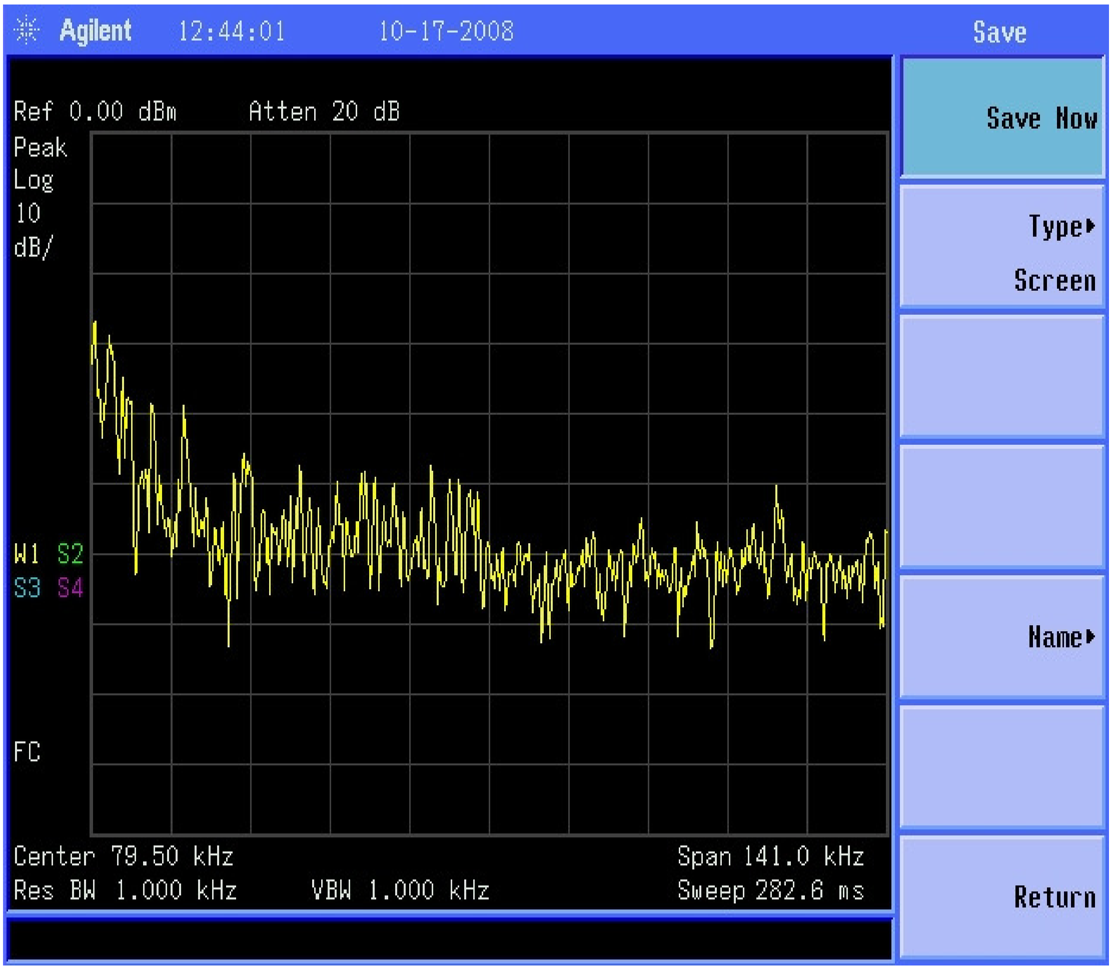


Figure 7.21: The voltage spectrum for the hand drill indicating a narrow band noise

7.5 Conclusion

As stated before, despite the fact that power line channel is corrupted by high background noise, almost unpredictable impulse noise and high attenuation, PLC has been gaining a great interest for the applications such as AMR (automatic meter reading) and SCADA (supervisory control and data acquisition), home automation and internet access. However, presently there are some technical and regulatory aspects that limit the data rate transmitted. Currently, by the use of CENELEC norm EN 50065, the frequency band between 3 kHz and 148.5 kHz is allocated for various access protocols for different categories of users. Limits for the terminal output voltage in the operating band and for limits for conducted and radiated disturbance are identified. Likewise, the noise and attenuation characteristics in low and medium voltage power lines are defined by an IEC standard. The experimental studies that are made in this thesis work are restricted to the frequency bands allowed by these standards. On the other hand there, due to great pressure from the producers in the market and in the light of the promising studies for power line transmission in high frequencies, there are ongoing efforts for modeling the power line channel up to 30 MHz for high data rate communications. In addition, to the regulatory problems, due to some technical obstacles such as varying line impedances, significant noise and high attenuation, currently the data transmission is limited to low data rates in the range of a few kbits.

During the experiments, a coupling circuit was used to isolate the 50 Hz signals from the communication signals. Primarily, the coupling circuit was used to couple the communication signals to and to extract them from the power line. The coupling circuit has a nearly flat frequency response with negligibly small insertion loss in the frequency band of interest. The sampled data was analyzed by using PostView and the Wavebook's special software in the time and frequency domain. Also the time domain data obtained over the data acquisition devices (Lecroy and Wavebook) was converted to frequency domain by using FFT functions of MATLAB. The output of the Agilent spectrum analyzer was logged in the laptop in the JPEG format.

The last two chapters of this thesis work presents a review of common noise types for the low-voltage power lines and aims to verify the results of these theoretical studies and parameters with the indoor noise measurements

To increase the reliability of digital communications on power lines, more research is needed on modeling of the power line channel. The ultimate purpose of similar studies should be to obtain a more refined and realistic power line channel model by using theoretical and experimental results and to cover frequency ranges up to 450 kHz to communicate at higher data rates.

CHAPTER 8

CONCLUSION

8.1 Experimental results and Conclusion

PLC that is studied in this thesis work as a method for sending the data through existing electric cables alongside electrical current enables the conversion of the electricity distribution grid, which is the widest existing cable network in the world, into a data transmission network. The power line channel communication has recently become a flexible way to implement reasonable cost, reliable, and widely accessible networks in the domestic environment. The technology opens up new opportunities for the mass provision of last-mile local access. It can furthermore provide new information services in both the energy and telecom sectors. Being a bidirectional communication system, PLC provides opportunities for tariff management and remote load control as well as automatic meter reading. So as to say, PLC offers cost effective and dependable solutions for industrial control and home automation applications such as control of intelligent household appliances, remote monitoring of alarms and air conditioning systems etc. More importantly, PLC offers all these added value services without significant additional infrastructure investments.

The PLC offers a permanent connection as well as symmetric and bidirectional communication. It has good performance and excellent geographical coverage. It is also relatively economical because of its available infrastructure. This technology is highly attractive compared to other local access technologies in terms of capital expenditure and implementation requirements.

The main characteristics of the PLC that are emphasized through this thesis work can be summarized as follows:

- The CENELEC standard EN-50065-1 defines the frequency bands, signaling levels, power limits and other procedure for power line communication in Europe. Briefly, 3 – 95 kHz is allocated for the use of electricity suppliers and 95 – 148,5 kHz is reserved for consumer use.

- For the frequency band between 95 and 148,5 kHz, the signal level is restricted to 116 dBV (class 116 equipment) for general use and the signal level is limited to 134 dBV (class 134 equipment) for industrial applications.

- The modulation types are not studied in details during this thesis work. The candidate modulation types are briefly mentioned. They are FSK, ASK and spread spectrum.

- Load variability, impedance variations and attenuation are some other important problems of PLC that complicate the data transmission.

- Interoperability and standardization are also urgent requirements for the healthy research and development activities of PLC. The internationally common standards are necessary to enable the component manufactures and system developers to contribute to communication and control applications of PLC similar to those of Global System for Mobile Communications (GSM), Universal Mobile Telecommunications Systems (UMTS), Internet etc. The collection of data from all around the world in a standardized manner is also beneficial for common standard system design and equipment standardization. Obviously, different countries have different standards of power grid network. Voltage level, line frequency and power distribution architecture can be considerably different. Still, the standardization and interoperability guarantee the international viability.

So as to say, power lines and their associated networks are not originally designed for communication purposes, making the accurate transfer of communication signals difficult. Noise levels in the networks are often excessive; cable attenuation in the systems at the frequencies of interest is often very large; important channel parameters such as impedance and attenuation are hard to predict due to their unpredictable nature. Still, the development of the technology has gone through a long path to reach today’s state. The power line carrier channel (PLCC) technology now applies much higher frequencies and substantially reduces the noise levels.

In the scope of the thesis, the first 5 chapters are allocated to a comprehensive investigation about the methodology used for the power line communication based automatic meter reading applications, the power line channel communication applications in European and Turkish markets, the advantages and disadvantages of power line communication compared to its rival technologies and the characterization and modeling of power line communication methods.

In the last two chapters of the thesis work, the noise types classified in the literature are investigated in details. The power line channel, in a way similar to other communication media such as RF, operates in a noisy environment with various noise sources appearing concurrently. Motors, switch-mode power supplies, fluorescent ballasts are examples of sources that generate impulse and background noises. Moreover, these sources contribute to a time varying environment in means of both impedance and attenuation.

In Chapter 6, the noise types are studied in detail. The identified noise types are background noise, impulsive noise, harmonic noise and narrowband noise. In Chapter 7, the measurements and observations for the theoretically defined noise types are verified via experiments in METU EE Machinery and Drives Laboratories and R&D laboratories of MAKEL in Hadımköy.

During these experiments, the background noise was permanently and extensively monitored for all instances of measurement. The background noise was illustrated in frequency domain by using the digital output of the Agilent spectrum analyzer in a predefined frequency range. The background noise was observed to decay slightly more rapidly compared to the rate of decay for the indoor low voltage power cables, represented in the theoretical studies. The average rate of decrease was measured to be around 40 dB/decade in the frequency band of interest (9 - 150 kHz) whereas for the theoretical studies the rate of decay was on the order of 25 dB/decade for indoor low voltage power cables. Besides, the average magnitude of the background noise measured in the experiments was higher than the theoretical studies.

The remaining 4 noise types were classified under appliance noise as their presence during the experiments was attributed to and verified through the existence of an appliance connected parallel to the power line. The impulsive noise was classified under three titles; asynchronous impulsive noise, periodic impulsive noise synchronous to the system frequency (harmonic noise), periodic impulsive noise asynchronous to system frequency.

The asynchronous impulsive noise was clearly determined at the start up of a triac controlled light dimmer connected parallel to the power line. In the steady state of the triac controlled dimmer, periodic impulsive noise asynchronous to the system frequency was observed with a mean magnitude of 25 – 30 dBμV. Impulse strength is typically 10 dB above the background noise level and can exceed 40 dB. Impulse strength depends on which noise sources are present as well as on the proximity of these noise sources to the receiver. Furthermore, the three defining parameters of impulsive noise were measured during the experiments; impulsive width, impulse interarrival time and impulse duration. The observed impulse width was usually in tolerable proximity of the theoretical values. Finally, the impulse interarrival time exhibited a wide variability with an average impulse magnitude of 30 dB above the background noise. Again, this result for the interarrival time was in line with the theoretical provisions.

The harmonic noise was the most clearly observed noise type during the experiments as the waveform for the harmonic noise was very close to the theoretically foreseen waveform. Converting the data logged to the digital data acquisition device (Lecroy 6050A) into the frequency domain by using the Fast Fourier Transform (FFT) function of the MATLAB, the fundamental component and the odd (3rd, 5th, 7th, 9th, 11th, 13th) harmonics of the signal were explicitly monitored. Unfortunately, the experimental results obtained were inadequate in means of differentiating the narrow band noise evidently from the background noise. Particularly, the hand drill showed a narrow band disturbance over a limited frequency band. Because noise, as well as wanted signals, was subjected to attenuation, noise sources close to the receiver were observed to have the greatest effect on the received noise structure, mainly when the network attenuation is large. Additional studies over a wider frequency band are needed to identify narrowband noise more evidently. Finally, some noise sources were observed to increase the background noise power, others to increase the impulse noise power, and some others to increase the power of both noise types.

Note that, all of the measurements were carried out in a laboratory environment for indoor power cables over the frequency range 9-150 kHz. Since intensive measurements are needed to be able to reach conclusive results, the results presented here should be taken as preliminary.

The last two chapters of this thesis work presents a review of the conventional noise types for the low voltage power lines and aims to verify the results of these theoretical studies and parameters with the indoor noise measurements. In order to increase, the reliability of digital communications on power lines, more research is needed on modeling of the power line channel. The ultimate purpose of the similar studies should be to obtain a more refined and realistic power line channel model by using theoretical and experimental results and to cover frequency ranges up to 450 kHz to enable the reliable communication at higher data rates.

Despite the fact that PLC still has considerably disadvantageous characteristics such as continuously fluctuating and unpredictable impedance that jeopardize proper line coupler design, high attenuation and highly destructive noise along the frequency of interest, there are some methods to avoid the observed disturbances in the power line communication network as a result of the experimental studies performed. Finally, the following methods can be proposed to facilitate improved power line channel performance and reliability.

8.2 Recommendations

A) Using PLC line to transfer meter consumption and power simultaneously, the signal collision is probable. Therefore it is recommended to use powerful filters at system line to ignore 50 Hz harmonics. A high pass filter similar to the filter used in the experiments performed helps a lot. The production of a range of filters for different applications on the power network to provide robust connectivity for devices will be essential as these systems advance. In addition, filters function to overcome the variable impedance of the low voltage mains line. Besides, the DC and AC signals should be coupled by using capacitor and inductor respectively.

B) Noisy resources should be eliminated to transmit data correctly. Power supplies used in the system are major sources of noise, so a power supply with lower noise seems to be necessary. A switching power supply with powerful 50 Hz harmonics elimination is an appropriate choice. In addition to the noise sources investigated in Chapter 7, universal motors operating into a 50 Hz power circuit generate a flat noise spectrum that can be up to 30 dB above the background noise for a large motor. Similarly, incandescent light dimmers produce 50 Hz harmonic noise. The level of phase to neutral noise produced can be up to 40 dB above normal background noise at 10 kHz for 400 W of lighting. Besides, appliances with dc motors can generate noise similar to that generated by universal motors. On the other hand, the residential background noise consists of random, spectrally smooth noise combined with 50 Hz harmonic noise and narrowband noise from TV receivers or video.

C) It is possible to increase transmitting signal amplitude to increase transmission distance range by varying elements of the PLC modem driver circuit but note that this should not harm the receiving modem in short distances. Actually, signal distance range and transmission distance should be compromised. PLC signal distance range depends on consuming load and line quality.

D) Impedance matching and appropriate coupling are very important. Usually impedance of power cables is resistive in 10-60 Ω range; as a result, coupler input impedance should be resistive and equal to the line impedance at carrier frequency.
There are various methods to couple system units. The choice of capacitor and inductor is crucial. The design must be based on the followings:

- Appropriate choice of C_{eq} value for the coupling circuit to block power line frequency, considering high impedance at mains frequency (50 Hz for the experiments performed)
- Coupling capacitor and inductor resonance at desired carrier frequency to prepare resistive impedance, powerful filtering and elimination of power signal harmonics.

Besides, a distribution transformer present in the transmission path will cause heavy losses because of its low impedance. When transmitting from a distribution transformer, heavy coupling losses should be taken into account.

E) In high interfering places, power level repeaters can be used to transmit at low level power. However, using redundant repeaters can cause a reduction in transmitting power.

F) Considering the major application area of PLC to be AMR, there are some brief implications about AMR. Compromising should be considered to make an AMR system. Obviously, a modern one is more expensive than the conventional reading system, but the new AMR system can increase reliability as well as speed. In addition, calculation of different issues such as demand, tariff and load profile is possible to optimize power consumption. Finally, consumption optimization, accurate
calculation of power consumption charge by applying tariff in day long and semi - yearly, demand calculation in a period and energy storage by informing the consumers are fundamental reasons to use AMR system in spite of the high construction cost.

8.3 Future Work

The trend of the future in PLC is expected to witness improvements in the areas of equipment design, transmission efficiency, and applications. It is anticipated that these improvements will be of an evolutionary nature rather than of a revolutionary one.

A) For electronic equipment, the equipment designs should be improved with sophisticated integrated circuits. By this way, smaller, less costly, more reliable and versatile equipment can be developed

B) For the transmission equipment, the transmitter and amplifiers with higher power outputs should be developed in order to be used for applications requiring greater signal strength. This can further be supported with improvements in transmitter frequency and reliability.

C) For the receiving equipment, obviously, the transmitted signal should be more effectively separated from the incoming noise and extensive noise monitoring should be employed. Moreover, the circuits available in integrated form should contribute to new types of signal discriminators and demodulators. Lastly, large scale digitally integrated circuits should be used, increasing the use of logic in the receivers to improve their overall security and dependability as well as to reduce the cost of receiver and transmitter designs.

D) In the case of system improvements, the limitations in the range of PLC channels are due to insufficient SNRs (signal to noise ratio) at the carrier receivers. The signal levels that couple to the line should be raised to increase the range. However, the improvements in the signal levels are considerably limited because of the high cost of increasing the power significantly above the 100 W level. In order to accomplish the increase in signal levels, the coupling efficiency can be improved with intrabundle channels which utilize insulated wires in one line phase for the transmission of carrier signals. Besides, a separately suspended coaxial cable can be employed for the exclusive use of carrier communications. Finally, some other possible actions are the usage of more efficient shielded signal cables such as improved coaxial cable, triaxal cable, and video cable pairs.

E) In the case of PLC applications, the present applications are expected to be improved to function above 300 kHz. On the HV side of utility services, more complicated protective relaying systems can be integrated with PLC applications for the digital transmission of digitally encoded information for data and control purposes. On the LV side, automatic meter reading, revenue billing, selective load shedding and control of distribution system operations are the promising application areas for PLC.

F) The noise types observed in the low voltage power line network should be modeled separately and more realistically. A possible way to implement this is to develop a laboratory model that can be used to represent the LV section of the power distribution network. Noise and cable attenuation measurements can be performed using this laboratory set up to obtain realistic data for modeling. This should take into the account that different cables in the LV distribution network have different attenuation factors due to their difference in diameter and the materials for their dielectrics.

G) A significant barrier to automatic meter reading using power line carrier technology is regulation standards. In order to implement the system successfully it is important to understand and revise the current standards and regulations that are related to power systems, frequency spectrum allocation, and telecommunication. Closer studies should be carried out on those aspects.

H) The impedance conditions of the network, the protocols for different services, the vulnerability to communication interference, the production of equipment with impedance in a specified range and investigation for the disturbance of signal transmission with other systems of communication are some other critical areas of development for the lossless transmission of data.

I) The standardization of the meter ID is important for electrical utilities that provide AMR services. When the meter ID is standardized, this network parameters can be made more relative with the power distribution grid information, such as indicating the phase a meter belongs, LV section and branch the meter is located. This will bring a greater convenience for the utilities since they can easily and quickly locate any meter installed in the AMR network.

J) The high degree of automation, the concept of electronic power markets, the necessity of detailed observation platforms for the management and control demands a reliable and secure communication system. This system must allow for communication to and between large numbers of nodes in broadcast applications. Making use of the grid as communication means gives automatically the access to a highly distributed communication channel. Power line communication technology is a major candidate for these control and automation applications. For this purpose, issues such as dependability, security, protection against intrusion and similar issues must be examined.

K) In addition, in future work it might be interesting to investigate the influence of narrowband noise and synchronous noise on the system performance. Adaptive loading is able to mitigate these types of noise sources just by switching off the affected tones. However the poor bandpass filtering properties of the FFT may cause problems when the interfering frequency doesn't fall on the FFT's grid. The use of windowing techniques in the time domain to improve the frequency behavior of the FFT is one option. On the other hand, the destructive influence of impulse noise cannot be overcome with simple improved bit loading strategies. Some kind of forward error correction should be combined with multicarrier modulation in order to provide frequency and time diversity.

L) Moreover, the statistical behaviors of different types of noise such as amplitude characteristics of background noise and short wave radio disturbances and also number, frequency and amplitude of narrowband disturbances can be studied by software and hardware simulations. Moreover, the measurements presented in this thesis work for the interarrival time and impulse width should be improved by the detailed analysis of sophisticated coding schemes and frequency of bit and burst errors. Moreover, the measurement and parameter determination of noise waveforms at many locations, the construction of a database of power line noise, and the establishment of a standard set of parameters are important areas of investigation for Turkish low voltage power line network.

Last but not the least important possible solution to avoid the disturbances and noises described might be to increase the operating frequency of the PLC system. Because of the wide geographical coverage of reticulation networks, coordinating bodies have formulated specifications to restrict the bandwidth and power levels of communications signals, in order to limit interference with other users of low frequency radio communications. Considering all the disturbances described a higher utilization of the radio frequency spectrum or selection of a higher frequency band in the order of 10 MHz to 100 MHz can help to avoid the major disturbances described throughout this thesis work. The noise elimination provided by the selection of higher frequencies can be supported by usage of advance modulation techniques, such as orthogonal frequency division multiplexing (OFDM) to improve the data transmission performance. However, another problem arises in this case. At these frequencies the power lines will act as antennas, causing additional interferences with the radio waves and other communication media. The additional problems with operating in higher frequencies are due to the power requirements, considerable variation in the impedance of the power line and disturbance to other transmission carriers. Moreover, around these frequencies, signal attenuation on the channel was shown to be a summation of coupling losses and line losses, both of which can be very high, making it very difficult to transmit over distances of more than 500 m. [136]

Power line carrier communication is a recent and rapidly evolving technology, targeting at the utilization of the electricity power lines for the transmission of data. The power line carrier communication offers a multitude of new information services, both in the energy and telecom sectors. As stated throughout the thesis, PLC technology has a number of important strengths and several main weaknesses. However, the upgrade path for the PLC technology makes it highly attractive compared to other local access technologies in terms of capital expenditure and implementation requirements. Since the PLC technology has not reached to the point of maturity and does not have a strong customer base, the technology requires further expansion. Also, the economy of certain low data rate applications such as automatic meter reading, encourage the development of simple signaling schemes with lower complexity and better performance than current low end solutions. However, it is still an open question whether wide band signaling schemes can be developed for power channel.

To sum up, in the last seven decades there have seen considerable developments in utilizing the low voltage network for the dual purpose of supplying power and data communication services for utilities, third parties and customers. Still, it should be noted that PLC is an evolving technology in its early stages of development and other communication media such as GSM, GPRS, Ethernet protocol 802.11b, and direct fiber are more dependable and sustainable despite their disadvantages in means of cost and ubiquity. The power line is limited in frequency range until megahertz transmission is commonly implemented; therefore interfacing into hybrid network with radio, telephone, wireless, GSM, GPRS and fiber systems must be considered to provide a fully integrated communications system for a wider range of services. Finally, it is important to note that although general rules apply, each power ine communication application needs special attention, individual design and testing to ensure optimal performance.

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