Investigation into the impedance and communication requirements for the low voltage distribution line in the high frequency spectrum

Thesis

Investigation into the Impedance and Communication Requirements for the Low Voltage Distribution Line in the High Frequency Spectrum.

Tanzirul Haq

MSc

A thesis submitted to the Open University Faculty of Mathematics, Computing and Technology for the degree of Doctor of Philosophy.

February 2012

DATE OF SUBMISSION: 29 FEBRUARY 2012

DATE OF AWARD: 6 JANUARY 2013

BEST COPY

AVAILABLE

Variable print quality

Abstract

Power Line Communications is long established for low data rate applications over high-voltage power lines. It is now charting new territory in high speed data transmission to the high frequency band of 1MHz and upwards over the low-voltage segment below the distribution transformers. Since the power line is designed for transmission of power instead of signal transmitting originally; it has many shortages when used as a signal communication channel. The heterogeneous structure of the power line network with numerous branches and impedance mismatches causing reflections and attenuations during signal transmission, and thus communication signal cannot be sent out or received completely. From this point of view, the power line impedance is a very important parameter in the design of power line communication (PLC) modem architecture, which is subject to legislations that limit the signals in the line. Variations on the impedance of the power line affect the communications channel performance. For the optimum modem design, power line impedance must be known. Power line impedance changes with time, carrier frequency, load variations, architectures and locations of the lines in city, urban, rural & industrial environment.

The objective of this study is to determine the impedance of power distribution network in a frequency range from 1MHz to 30MHz. This is in line with international standard bodies including CENELEC, IEC, ITU and ETSI, which stipulates that for propagation characteristics of power line and EMC regulations, data transmission rate are evolving and are being extended all the time to data rate up to 100Mbps.

This thesis covers impedance measurements carried out in college buildings in Somerset, UK together with some residential houses in Somerset and London. The college buildings have both three-phase and single-phase architectures with various laboratories where loads are randomly switched on and off. An impedance analyser is used to carry out the measurements which performs a scan through a programmable frequency limits and acquires impedance parameters in the frequency domain. Measurements were monitored using Microsoft Remote Desk Top client application. Series of experimental measurements were carried out in the Bridgwater College and residential houses in Bridgwater and also in London.

The first part of the thesis offers detailed introduction to the topics of electricity supply networks, power line communications, modulation techniques and electromagnetic compatibility, noise and transmission line characteristics.

From the experimental results, presented in graphical format, a number of conclusions can be drawn. A wide range of impedances are observed for single phase measurements, within the range of 3 – 584 Ω for large buildings and residential houses. For three phase measurements impedances varied from 21 – 340 Ω.

The thesis concludes with a suggestion of how these measurements may be used in PLC modem design. Dynamic output-impedance PLC modems may be designed using a real-time impedance detector of the power line and the adjustable output impedance-power amplifier. Therefore, modem output impedance may be matched to the real time line impedance.

Declaration

All work and ideas recorded in this thesis are original unless otherwise acknowledged in the text or by reference. The measurements were designed and undertaken by myself.

The contents of this thesis have not been submitted in support of an application for another degree in this university, nor for any degree or diploma at any other institution.

Acknowledgments

This work would not have been completed without the help and support of many others but I would like to specifically mention the following:

First of all my gratitude to Dr John Newbury and Dr Kerry John Morris of the Open University for supervising this research.

Research colleagues Dr Ray Brannon (late), Dr Iain Summers and Frazer Robertson of the Power Systems Communication Research Group (PSCRG) at the Open University for sharing information and experiences.

My gratitude also goes to my friends Clive Pembury and Peter Holt of Bridgwater College for their support and motivation.

I am also thankful to my colleagues Dr Jonathan Gill, Paul Miles and Daniel Basra for their support and help during this research project.

This thesis is dedicated to my father, Zahirul Haq, who has given unfailing support and encouragement throughout. I will also be indebted to my wife Mahfuza and my children for their tolerance, encouragement and patience during the research program.

Contents

Figures

Tables

List of Abbreviations and Acronyms

Access System	A PLT system used to provide access from a subscriber to the internet or other centralized content provision, and owned by the utility company.
a.c.	Alternating Current
ADC	Analogue to Digital Coverter
ADSL	Asymmetric Digital Subscriber Line
ARQ	Automatic Repeat Request
Backhaul network	The wide area network linking PLT nodes to the head end or Point of Presence.
BPL	Broadband over Power Line – US name for PLT
bps	Bits Per Second
BPSK	Binary Phase Shift Keying.
Bandwidth	A measure of the rate at which digital bits can be transported from one place to another, also frequency span over which useful signals can be transmitted.
BER	Bit Error Rate
BNC	BNC connector (Bayonet Neill–Concelman) is a common type of RF connector used for coaxial cable.
dBm	Logarithmic power measurement relative to one milliwatt (1mW = 0 dBm)
CATV	Community Antenna TeleVision – aka cable TV
CENELEC	Comite Europeene de Normalisation Electrotecnique – European Committee for Electrotechnical Standardization.
CISPR	Comite International Special des Perterbations Radioelectriques – International Special Committee on Radio Interference.
CPU	Central Processing Unit
CSV	Coma Separated Values
dBμV	Logarithmic voltage measurement relative to one microvolt (1μV = 0 dBμV)

DDS	Direct Digital Synthesizer
DSP	Digital Signal Processing
DSL	Digital Subscriber Line – all variants
DSSS	Direct Sequence Spread Spectrum
EMC	Electromagnetic Compatibility
ETSI	European Telecommunications Standard Institute
FCC	Federal Communications Commission (USA)
FDM	Frequency Division multiplexing – a method of accommodating multiple users on a communications medium by allocating separate frequencies to different users or services.
FEC	Forward Error Correction
FM	Frequency Modulation
FSK	Frequency Shift Keying
HF	High frequency (3MHz – 30 MHz)
HV	High Voltage (33 kV-400 kV)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
Kbps	Kilobits per second
LAN	Local Area Network
LCL	Longitudinal Conversion Loss
LV	Low Voltage (240-415 V)
MAC	Medium Access Control
Mbps	Mega bits per seconds
MV	Medium Voltage (11 kV-33 kV)

OFDM	Orthogonal Frequency Division Multiplexing
PLC	Power Line Communications
PLT	Power Line Telecommunications
POTS	Plain Old Telephone Service
PSD	Power Spectral Density
PSK	Phase Shift Keying
PVC	Polyvinyl Chloride
RCS	Ripple Carrier Signalling
SNR	Signal-to-Noise Ratio
USB	Universal Serial Bus
VLSI	Very Large Scale Integration Circuits
VNA	Vector Network Analyser
WAN	Wide Area Network
VSWR	Voltage Standing Wave Ration

Chapter 1: Introduction

Power line communication or power line carrier (PLC), also known as Power line telecommunications (PLT), or Broadband over power lines (BPL) are systems for carrying data on a conductor also used for electric power transmission.

While the idea of sending communication signals on the same pair of wires as are used for power distribution is as old as the telegraph itself, the number of communication devices installed on dedicated wiring far exceeds the number installed on A.C. mains wiring. The reason for this is not, as one might think, the result of having overlooked the possibility of A.C. mains communication until recent decades. In the 1920's at least two patents were issued to the American Telephone and Telegraph Company in the field of "Carrier Transmission over Power Circuits".

The communication flow of today is very high. Many applications at high speed and a fixed connection are often preferred. If the power utilities could supply communications over the power-line to the customers it could make a tremendous breakthrough in communications. Every household would be connected at any time and services being provided in real time. Using the power-line as a communication channel could also be a cost-effective way compared to other systems because it uses an existing infrastructure.

The deregulated market has forced the power utilities to explore new markets to find new business opportunities, which have increased research activities in Power-Line Communications (PLC) over the last decade. The research has initially been focused on providing services related to power distribution such as load control, meter reading, tariff control, remote control and smart homes. These value-added services would open up new markets for the power utilities and hence increase profit. The moderate demands of these applications make it easier to obtain reliable communication. Firstly, the information bit rate is low; secondly, they do not require real-time performance.

With the inevitable arrival of broadband access, the demand for sending digital voice, video and internet data within the home increases continuously. If it would be possible to supply this kind of network communication over the power-line, the utilities could also become communication providers, a rapidly growing market. On the contrary to power related applications, network communications require very high bit rates and in some cases real-time responses are needed (e.g. TV and video). This complicates the design of a communication system but has been the focus of many researchers during the last years.

The power-line was initially designed to distribute power in the range of 230 V/50 Hz and 110 V/60 Hz in an efficient way, hence it is not adapted for communication and advanced communication techniques are needed.

This thesis explores the theoretical and practical aspects of Power Line Communications techniques. To this end, a number of specific goals were proposed at the start of the project:

- To gain detailed knowledge in to the history and development of PLC and the challenges faced by PLC techniques.

- An investigation into the impedance of the low-voltage power line system and how line impedance affects the signal attenuation and propagation characteristics and consequently the communication conditions of the power line. Much of the experimental work was carried out in Bridgwater College and some residential houses in Somerset, England. The location could be classified as semi-rural.

1.1 Overview of Power Line Communication Systems

Power Line Communications (PLC) is the use of existing electrical power line system to transport data. The main idea behind PLC is the reduction in operational costs and expenditure for realization of new telecommunications networks as shown in figure 1. Power utility companies have been using this technology for many years to send or receive data on the power grid using existing electrical infrastructure.

Historically, also, a primary motivation for power line communication has been to do load management in future. A second important motivation had been to facilitate meter reading from a distance. A UK study has shown that a meter reader achieves an average information rate of only about 1 bps (bits per second) [21].

In 1838 the first remote electricity supply metering and in 1897 the first patent on power line signalling were proposed in the UK [19]. In the 1920's applications were patented in the US, and during the same period the first commercial production of electromechanical meter repeaters took place. The electrical power utility in London used PLC to remotely control some of its equipment on the grid such as high-voltage switches in the 1920s. This technique is still employed by several utilities that use analogue or digital devices to transfer data over many miles of electrical cables.

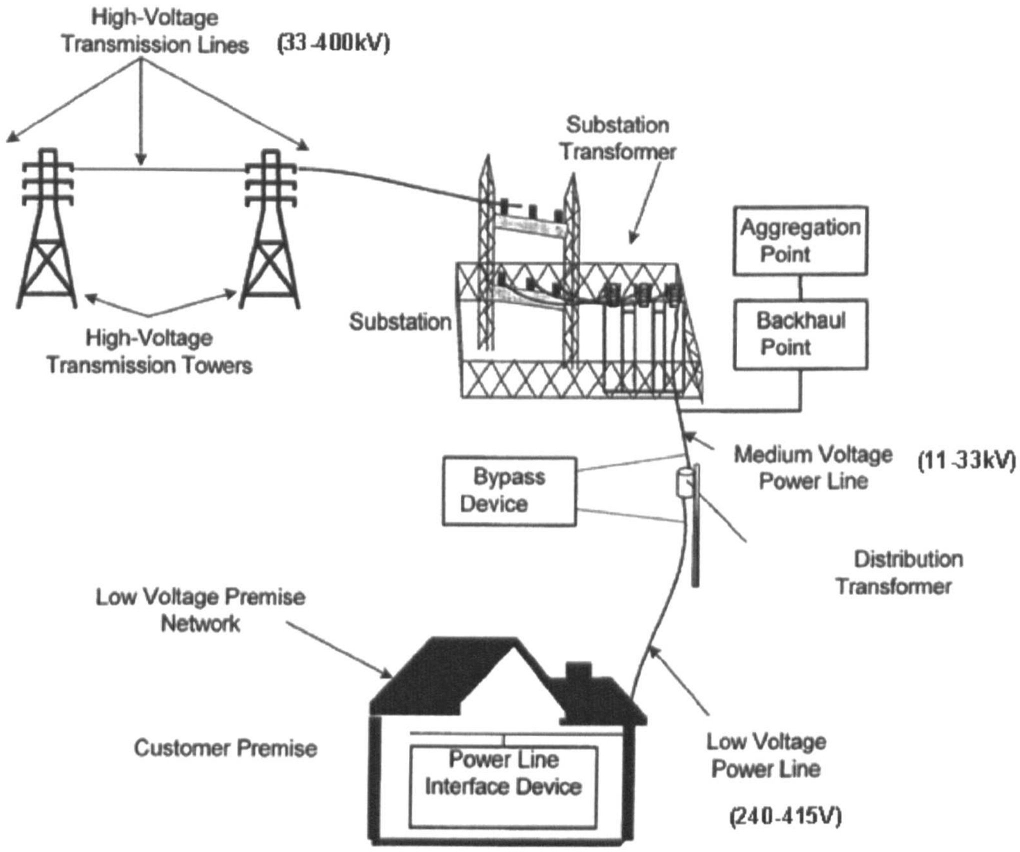


Figure 1. Power Line Communications Systems

Data transmission over power lines has been around for quite some time, one might wonder why it is receiving such renewed interest recently especially considering the data rate for protection and telemetering purposes is at most a few kbps (kilobits per second) and is not comparable to the Mbps (Mega bits per seconds) data that needs to be supported for multimedia applications. The answer is a combinations of effects that took place during the mid-thru late 1990s, namely, the explosive growth of the internet and the gigantic leaps in Very Large Scale Integration Circuits (VLSI), Digital Signal Processing (DSP) and growth of sophisticated communications technology. Engineers have suggested that what was required for PLC to move into the main stream was a commercialised version of various military communications technology (e.g. spread spectrum, OFDM, discussed in chapter 3)

Events like Electricity Power Act of December 1989 have made power line communications a viable technology for high speed home networking as well as being a possible solution for *last mile* problem. The market for power line communications (PLC) is two-fold: to the home, or *last mile*[1] access; and in the home or *last inch* access.

PLC standards have evolved constantly over the years, especially the last 20, and resulted after 1994 in the digital power line boost promising new revenues for energy utilities and cheap Internet access for consumers.

Thus high-, medium- and low-voltage supply networks have been used for internal communications of electrical utilities and for the remote measuring and control tasks. PLC is also used for internal electrical installations within buildings and homes for various communications applications.

[1] The "last mile" or "last kilometer" is the final leg of delivering connectivity from a communications provider to a customer. The phrase is therefore often used by the telecommunications and cable television industries. The actual distance of this leg may be considerably more than a mile, especially in rural area.

Generally, PLC systems may be divided into two groups:

- Narrowband PLC system (3 kHz - 148.5 kHz) (as per standard EN 50065 low-voltage communications standard of CENELEC) allowing communications services with relatively low data rates (up to 100 kbps) and ensuring realization of various automation and control applications as well as a few voice channels.

- Broadband PLC systems (1.6 MHz - 30 MHz) (Access Band 1.6 MHz – 10 MHz and in house band 10 MHz - 30 MHz) allowing data rates beyond 2 Mbps and, accordingly, realization of a number of typical telecommunications services in parallel, such as telephony and internet access.

Broadband PLC in low-voltage supply networks seems to be cost-effective solution for *last mile* communications networks, the so-called PLC access networks. Access networks implement the inter-connection of the customers/subscribers to wide-area communication networks. They allow a large number of subscribers to use various telecommunications services. However, the cost of realization, installation, and maintenance of access networks are very high. In most cases, access networks are still the property of incumbent network providers (the former monopolistic telephone companies). Because of that, new network providers try to find solutions to realize their own access networks. A promising possibility for the realization of access networks is offered by the PLC technology. Nowadays, there are many activities concerned with the development and application of PLC technology in the access area. Thus, we find a number of manufacturers offering PLC products that ensure data rates between 2 and 4 Mbps and announcing new PLC systems with data rates up to 45 Mbps or more. There are also numerous PLC field trials worldwide, as well as several PLC access networks in commercial use. The number of PLC subscribers is still growing. A similar development in medium-voltage and in-home PLC networks is in progress as well. In particular, the problem of electromagnetic compatibility of PLC system with reference to their coexistence with other telecommunications services, such as various radio services, has not yet been completely solved. Therefore, PLC technology is now in a very important development phase that will determine its future, its application areas, and its penetration into telecommunications world in competition with other broadband technologies. During the last decades, the usage of telecommunication systems has increased rapidly. Because of a permanent necessity for new telecommunication services and additional transmission capacities, there is also a need for the development of new telecommunication networks and transmission technologies. From the economic point of view, telecommunications promise big revenues, motivating large investments in this area. Therefore, there are a large number of communications enterprises that are building up high-speed networks, ensuring the realization of various telecommunication services that can be used worldwide.

After the privatisation of the UK Electricity Supply Industry in 1990, distribution network operators became free to participate in activities beyond the supply of electricity and many have looked at the provision of telecommunication services for additional revenue. This is also true outside the UK in those countries where electricity supply has been liberalised.

In a large number of countries, the access networks are still the property of incumbent network providers. Because of this, the new network providers try to find a solution. An alternative solution for the realization of the access network is offered by the PLC technology using the power supply grid for communications. Thus, for the realization of the PLC networks, there is no need for the laying of new communication cables. Therefore, application of PLC in low-voltage supply networks seems to be a cost-effective solution for so-called *last mile* communication networks. Nowadays, network Subscribers use various telecommunications services with higher data rates and QoS (Quality of Service) [2]requirements.

To make communications in a power supply network possible, it is necessary to install so-called PLC modems, which ensure transmission of data signals over the grids as shown in figure 2.

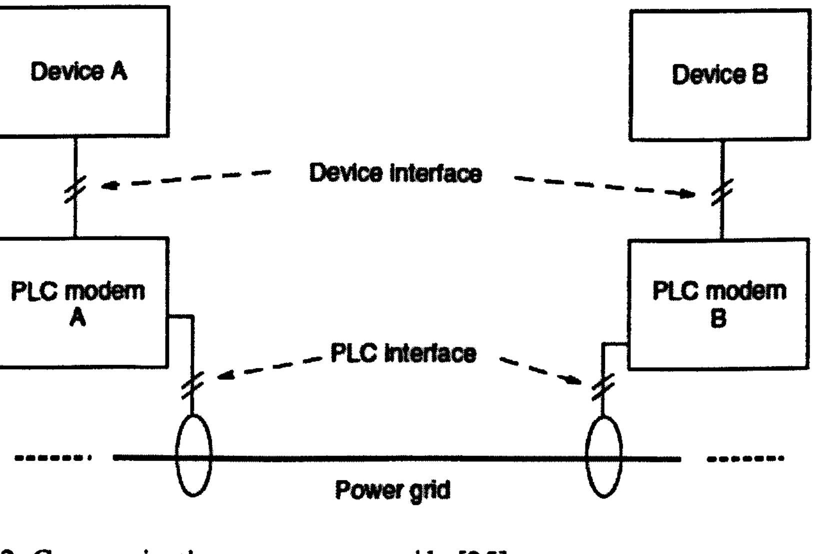


Figure 2. Communication over power grid. [25]

[2] Quality of Service - refers to a broad collection of networking technologies and techniques. The goal of QoS is to provide guarantees on the ability of a network to deliver predictable results. Elements of network performance within the scope of QoS often include availability (uptime), bandwidth (throughput), latency (delay), and error rate.

A PLC modem converts a data signal received from conventional communication devices, such as computers, telephones, and so on, in a form that is suitable for transmission over power lines. In the other transmission direction, the modem receives a data signal from the power grids and after conversion delivers it to the communications devices. Thus, the PLC modems, representing PLC-specific communication equipment, provide a necessary interface for the interconnection of various communications devices over power supply networks. The PLC-specific communications devices, such as PLC modems, have to be designed to ensure an efficient network operation under transmission conditions, typical for power supply networks and their environments.

However, power supply networks are not designed for communications and they do not present a favourable transmission medium. PLC transmission channel is characterized by a large and frequency-dependent attenuation, changing impedance and fading as well as unfavourable noise conditions. Various noise sources, acting from the supply network, due to different electric devices connected to the network, and from the network environment, can negatively influence a PLC system, causing disturbances in an error-free data transmission. On the other hand, to provide higher data rates, PLC networks have to operate in a frequency spectrum of up to 30 MHz, which is also used by various radio services. Unfortunately, a PLC network acts as an antenna producing electromagnetic radiation in its environment and disturbs other services operating in the same frequency range. Therefore, regulatory bodies specify very strong limits regarding the electromagnetic emission from the PLC networks, with a consequence that PLC networks have to operate with a limited signal power.

This causes a reduction of network distances and data rates and increases sensitivity to disturbances.

The reduction of the data rates is particularly disadvantageous because of the fact that PLC access networks operate in a shared transmission medium, in which a number of subscribers compete to use the transmission resources as shown in Figure 3.

In the case of PLC access network, the transmission medium provided a low-voltage supply network used for communication between the subscribers and the PLC base station, which connects the access network to a wide area network (WAN) realized by conventional communication technology.

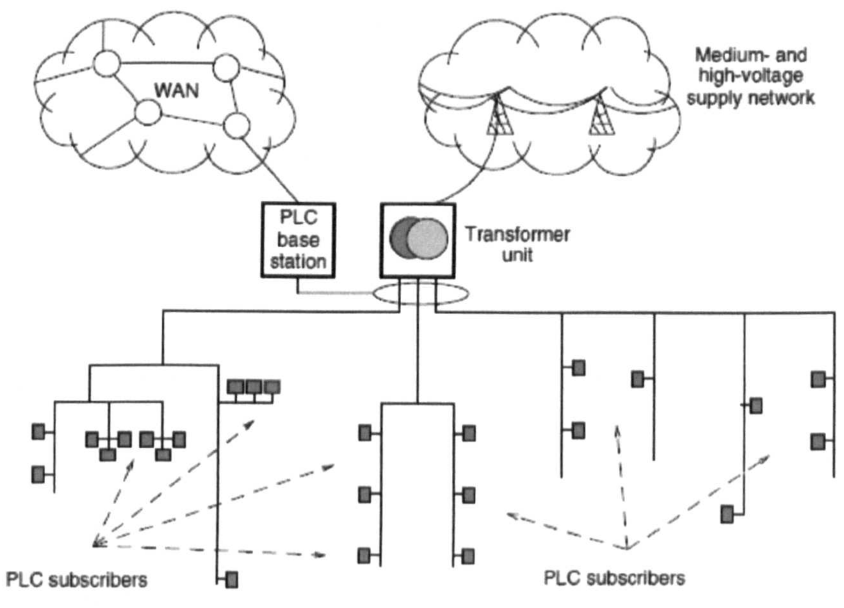


Figure 3. PLC access network. [25]

To reduce the negative impact of power line transmission medium, PLC systems have to apply efficient modulation, such as spread spectrum and Orthogonal Frequency

Division Multiplexing (OFDM). The problem of disturbances can also be solved by well known error-handling mechanisms (e.g. forward error correction (FEC), Automatic Repeat reQuest (ARQ). However, their application consumes a certain portion of the PLC network capacity because of overhead and retransmission. On the other hand, a PLC access network has to be economically efficient, serving possibly a large number of subscribers. This can be ensured only by a good utilization of limited network capacity. Simultaneously, PLC systems have to compete with other access technology (e.g. digital subscriber line (DSL), cable television (CATV) and to offer different telecommunication services with a satisfactory QoS. Both good network utilization and provision of QoS guarantees can be achieved by an efficient Medium Access Control (MAC)[3] layer.

Currently in 2011, there are no existing standards or specification considering physical and MAC layers for PLC access networks. The manufacturers of the PLC equipment developed proprietary solutions for the MAC layer that are incompatible with each other.

The new PLC promises *super-connectivity* that may connect just about anything that plugs in to a wall socket to each other and to the web. It also promises enablement of infrastructure to provide the backbone for widespread provisioning of broadband access to homes.

---

[3] The Media Access Control Layer is one of two sub-layers that make up the Data Link Layer of the OSI model. The MAC layer is responsible for moving data packets to and from one Network Interface Card (NIC) to another across a shared channel.

But a lot of this still remains a promise. Though, the potential of PLC is doubtless, issues like technical, regulatory and market structure are inhibiting achievement of what is at an arm's length to us.

PLC could bring the following benefits to our lives at home:

- High-speed, always on internet access
- High-quality streaming video/audio
- Voice-over-IP and low-cost telephony services
- Real-time security monitoring/reporting
- Networked energy management
- Online communication between smart appliances
- The ability to control appliances remotely by email/phone/PDAs.
- A variety of content services such as weather and other promotional information

PLC can also provide benefit to the Utility companies:

- Real-time automated meter reading
- Fault detection and location/outage reporting
- Load switching/balancing
- Power quality monitoring
- Protection against tampering
- Substation-to-substation communications
- TV audience monitoring system (BARB – Broadcaster's Audience Research Board)

Continuous research and experimentation with higher bandwidth data transfer across electric grids is now leading to unprecedented market opportunities for home automation with PLC technology allowing for high speed, broadband communications over medium and low voltage channels.

- PLC promises the *last mile* connectivity with high-speed data communication to homes plus the ability to carry voice/data traffic for internal communication between computers, printers, and other appliances within the home, expanding possible applications for data based services.
- PLC guarantees a much denser penetration inside homes as compared to competing mediums. There is an average of 2 phone sockets per home in the UK compared to 30 to 40 power sockets. In Brazil 93 percent of households have electricity while only 25 percent enjoy basic telephone service [20].
- In Europe, a single transformer serves 100 to 250 households operating at 230 volts of power [20].
- In 2001, German regulators approved laws regulating the *efficient and disturbance-free* use of frequencies in and along power cables. This clears the way for the introduction of technologies like telecommunications via power lines.
- Sweden has passed legislation that mandates the extension of broadband service to every home. This is promoting active investigation in to finding lower-cost alternatives than fibre-optic cable.

Power Line Communications has already started to create a buzz. PLC providers are hoping to go head-to-head with DSL (Digital Subscriber Line), fixed wireless, and cable modem companies and are expecting to be able to offer superior service at competitive costs.

However, where there is a lot of promises, there are some concerns too, specifically electricity utilities' cables are hostile environments with electrical noise spiked by other electrical loads. This may not be a major concern anymore with advanced modulation techniques to overcome this technical obstacle. Also, equally important are the safety and reliability issues of electrical services provided to the customers in light of the ageing power grids the world over.

1.2 Summary

From the physical perspective, there is no fundamental difference between the transmission of high-frequency signals over the power transmission lines and the transmission of power energy of 50 Hz. Although energy transmission and the transmission of high-frequency signals on lines are similar physical processes, there is a considerable difference in the properties of the lines at the different frequencies. In particular, the loss along the lines increases considerably with higher frequency. For any communication channel, impedance, noise and signal attenuation are basic parameters that determine communication performance. The main objective of this research programme is to:

- Establishing a consistent measurement method for measuring impedance characteristics on the Low Voltage Distribution network. (Initial sites include the laboratories and classrooms at Bridgwater College, followed by some residential houses in Somerset and London, UK)

1.3 Thesis Structure

The thesis comprises of six chapters that lead from basic power transmission line system, through a detailed discussion of different aspects of Power Line Communications.

Chapter 2:	Power Line Communication System Architecture.
Chapter 3:	Power Line Communications Propagation Characteristics.
Chapter 4:	Experimental work.
Chapter 5:	Experimental Results
Chapter 6:	Conclusions and further work

Chapter 2: Power Line Communication System Architecture

This chapter describes the architecture of the power network system and overview of the broadband PLC system.

1.2 The United Kingdom Power Distribution Network

Introduction:

Until the early 1930s the supply of electrical power throughout the UK was in the hands of local electrical generating and distribution companies. There was no national standardization of voltage and both d.c. and a.c. systems co-existed. National Grid system was established to provide a better system for all consumers. It consists of over 7000 km of overhead power lines.

Some milestones leading to the growth of the national grid:

- 1831 Michael Faraday demonstrates the generation of electricity by electromagnetic induction
- 1890-1900 many small power stations around UK start to supply electricity to local customers
- Early 1900s in the US, George Westinghouse and Nicola Tesla develop new generators which enable power stations to work together
- 1926 Central Electricity Board established in the UK with the purpose of interconnecting power stations
- 1933 Construction of first national grid finished

- 1937 national grid switched on
- 1950s New national grid – the super-grid constructed with more carrying power
- 1990 Privatisation of UK's electricity industry leads to creation of National Grid Company which is responsible for electricity transmission

Economics demanded that the power stations which supplied the grid distribution network should be built either near to a convenient fuel supply or near to a major user of electricity. The electrical power had to be carried over large distances and the cheapest system was, and still is an overhead power line suspended from pylons.

Some of the immediate advantages of having a common national electrical system are:

- All electrical appliances can be standardised
- Power stations can be switched in or out quite quickly to match generating capacity and consumer demand
- Overloaded power stations can be assisted by those under a light load
- A multi-path grid distribution system will help to ensure continuity of supply in the event of a single line failure

The starting point for the following studies is an analysis of typical power network structures on the various voltage levels of the UK electric energy supply system as shown in figure 4.

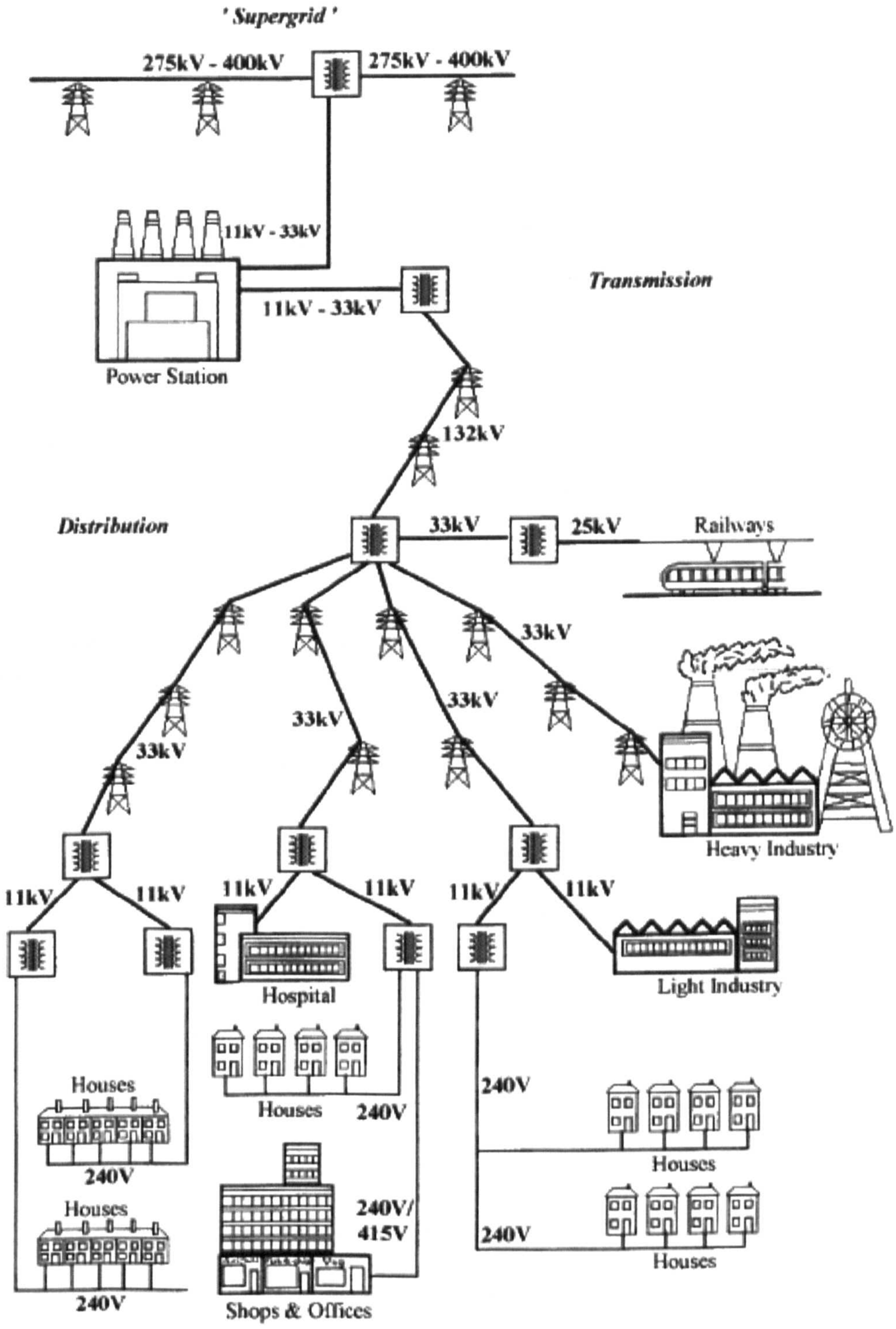


Figure 4. UK electrical system from power station to customer (K Morris 2001)

Three voltage levels are:

- High-voltage (33kV-400 kV) networks connect the power stations with large supply regions or big customers. They usually span very long distances, allowing power exchange within a continent. High-voltage networks are usually realized with overhead supply cables

- Medium-Voltage (11kV-33 kV) networks supply larger areas, cities and big industrial or commercial customers. Spanned distances are significantly shorter than in the high-voltage networks. The medium-voltage networks are realized with overhead and underground networks.

- Low-voltage (240V-415 V, in the USA 110 V) networks supply the end users either as individual customers or as a single user of a bigger customer. Their length is usually up to a few hundred meters. In urban areas, low-voltage networks are realized with underground cables, where in rural areas they exist usually as overhead network.

Each of these voltage levels are adapted to the bridging of certain distances. The voltage levels are interconnected by transformers, designed in such a way that the energy loss is as low as possible at the power frequency (50 Hz). Since the initial 132 kV network was completed in 1936, the Grid has been extended until it now covers the whole of the UK. The Grid System consists of an extensive interconnected transmission networks supplying the whole country and is controlled by the National Grid. When the supply industry was nationalized in 1948, generation also became part of the system. The Grid network is now supplied from a small numbers of very large and highly efficient power stations (coal, gas and nuclear) strategically placed where fuel and water are easily available. The basic networks are still 132 kV but increasing demands and the necessity to supply bulk power over long distances has brought about the introduction to the Super Grid. This consists of transmission lines with voltages of 275 kV and 400 kV forming the main 'arteries' of the supply system.

1.3 The United States Power Supply Network

On the distribution level, typically 80% of the power lines are overhead in the U.S. In urban areas most of the cables run underground. MV ranges from 4kV to 34kV and the line length varies between 5 km to 50 km approximately. A MV distribution circuit consists of a three phase main trunk. Depending on the load, a two phase tap or a one phase tap extends into load areas. In less densely populated areas, MV circuits are fed by a single sub-station with standby backup from an alternate sub-station. In large cities, however, an underground meshed network is fed from multiple sources. Therefore MV lines basically run along every street of a town or city. In direct neighbourhood to buildings single-phase transformers provide the LV (access), which is immediately passed to the building's panel boards. Transformers are often mounted on poles or located in special boxes, next to a building. On the primary side, the transformers are fed with one phase and neutral, while the secondary provides 240V with a grounded centre tap as shown in Figure 5.

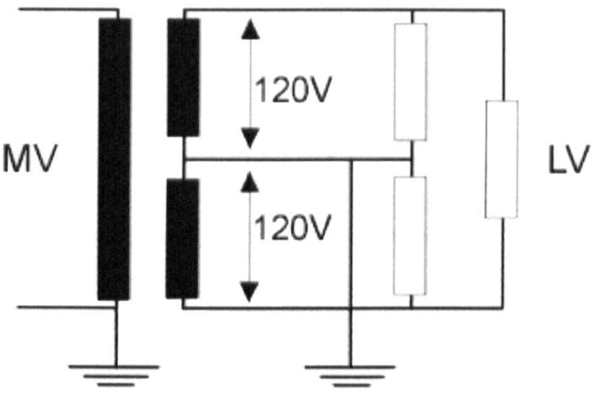


Figure 5. USA Split-Phase System with MV/LV Transformer and Loads

The length of a secondary circuit (LV level) is usually less than 300m, with one to about ten customers for a transformer. Typically, in residential areas a customer receives power over three wires, providing 2x120V or 240V. Standard loads are connected to the 120V feeds, while large loads, e.g. heaters use the 240V level.

An access domain PLC system might be installed in the sub-station, feeding signals into the MV wires of the distribution circuit. However, as most residences receive single phase service only, the PLC signal must be injected between phase and neutral. Due to significant attenuation for HF-signals, transformer bridging will be necessary. Another possible scenario would be a hybrid approach, connecting all transformers with the sub-station via optical fibres, and feeding the PLC signals into the secondary circuits of the transformers. This way of course much higher data rates can be ensured, as only a few customers have to share the medium. Indoor PLC applications in the U.S. look very similar to European ones, i.e. signals are injected between one phase and neutral on the 120V level, as most devices are connected to such feeds.

1.4 The Japanese Power Supply Network

The structure of the Japanese power supply grid is very similar to the U.S. network. The HV level uses more than 22 kV, and on the MV level, i.e. from sub-station to transformer, 6.6kV is the usual level. Similar to the U.S., transformers are mounted close to the tops of poles feeding two-phase secondary circuits with a neutral line, which is connected to a ground rod. Thus the customer receives power over 2 or 3 wires at 100V or 200V. Over 90% of the Japanese power supply network is realized in the form of overhead wiring, generally cables. Mid to large scale flats have their own MV/LV transformers inside the building. The typical length of a LV circuit is about 50 to 200 meters. Typically up to 30 households are supplied by one transformer.

Due to the high density of population in most Japanese cities, the number of households fed by one MV transformer sub-station is considerable. Thus, if PLC would be deployed on the MV level, numerous customers would have to share the capacity, so that unacceptably low data rates might result. Thus, in Japan, PLC would be most efficient on the LV distribution grid. As optical fibers are deployed along most Japanese MV lines, a powerful backbone network is already available there. Similar to the U.S., most indoor loads are supplied from 100 V feeds, so that the PLC signal must be injected between phase and neutral.

1.5 The United Kingdom Local Distribution System

The main substation feeding a particular area is usually placed as close to the loads centre as possible. The substation will be supplied from the grid transmission line, usually by means of a 33 kV secondary transmission line or underground cable. From the main substation there will be high-voltage distribution cables radiating outwards to feed the local distribution substations. This will be at 11 kV. The local substations will also be interconnected by means of further 11 kV cables, so that a ring system of feeders is formed. By employing this ring system it is possible to isolate any of the cables without interrupting the supply to any substation. Transformers at each substation feed into a network of low-voltage distributors which radiate from the substation and to which the consumers' supplies are connected. These low voltage cables may also be interconnected by means of link pillars or underground boxes. Figure 6 shows a typical arrangement for such a distribution system.

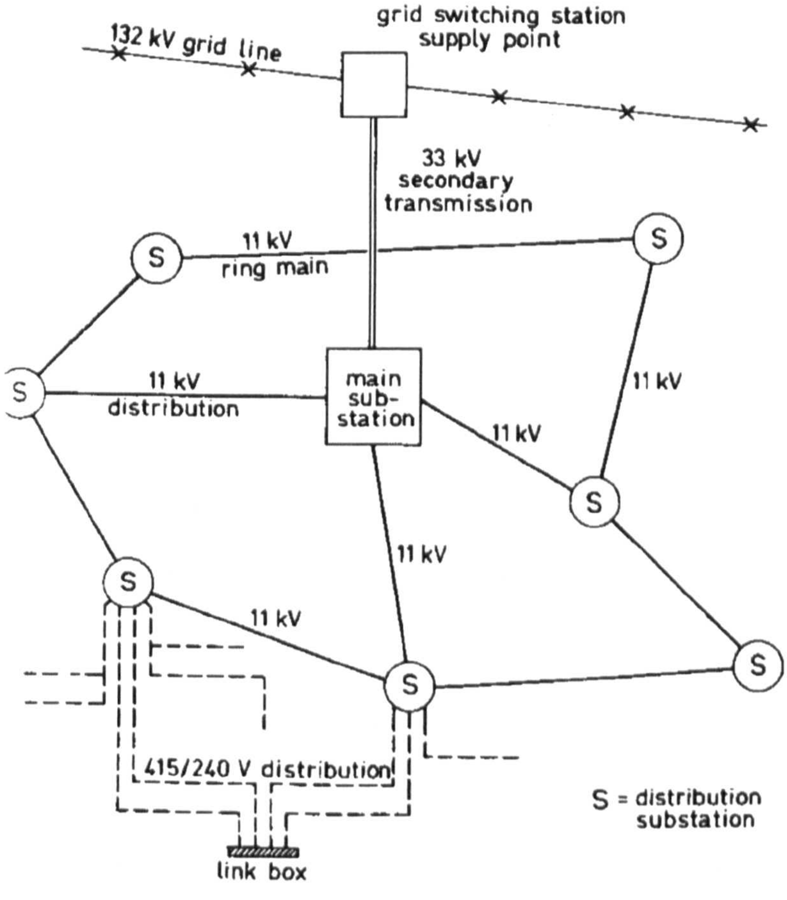


Figure 6. Layout of electrical distribution system [64]

1.6 Operating Voltages

On long transmission lines, the losses can be high. By raising the operating voltage, thereby reducing the current for a given power being delivered, the losses can be reduced and the efficiency of transmission increased. For any given line there is also a definite voltage which will give the minimum cost. This is 'economic voltage' for the line. To find this voltage, a number of factors have to be taken into account, including local conditions, but a rough guide is 1000 V per mile of line. However, in order to standardize in the manufacture of equipment, certain standard voltages are used. These are: 400 kV and 275 kV for the Super Grid; 132 kV for the original Grid; and 33 kV for secondary transmission; 11kV, 6.6 kV and 3.3 kV for primary distribution. The standard distribution voltages for consumer's supplies are 415 V three-phase 50 Hz a.c. for power, and 240 V single-phase 50 Hz a.c. for lighting and heating supplies.

1.7 Consumer's Supplies

For power purposes, a higher voltage leads to greater efficiency. The three-wire and three-phase systems are provided for high power circuits while the lower voltages are provided for low power circuits. Two systems are mainly used. Single-phase and Three-phase system.

- A.C. Single-Phase Two-wire System: The supply is normally from the secondary of a transformer at the distribution substation. One side of the secondary is always earthed, and the conductor connected to this side is the neutral. The conductor connected to the other end of the secondary winding is the live conductor (figure 7).

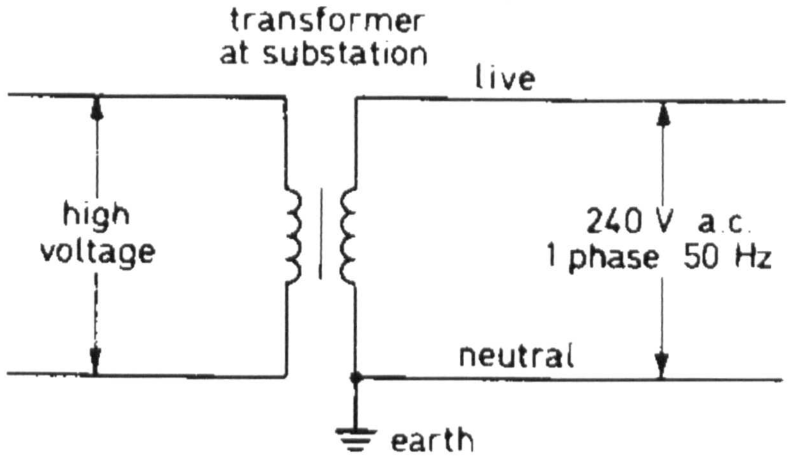


Figure 7. A.C. single-phase two-wire system [64]

- A.C. Single-phase Three-wire system: The supply is from the secondary of a distribution transformer. The transformer is centre-tapped and is earthed at this point. The third conductor is connected to the centre tapping, and this becomes the neutral. The two outer conductors are live conductors (figure 8). Power circuits are connected to the two live conductors and lighting loads to one of the live conductors and the neutral. This type of supply is quite common in rural areas where power is required for farming purposes and the high voltage system is single phase.

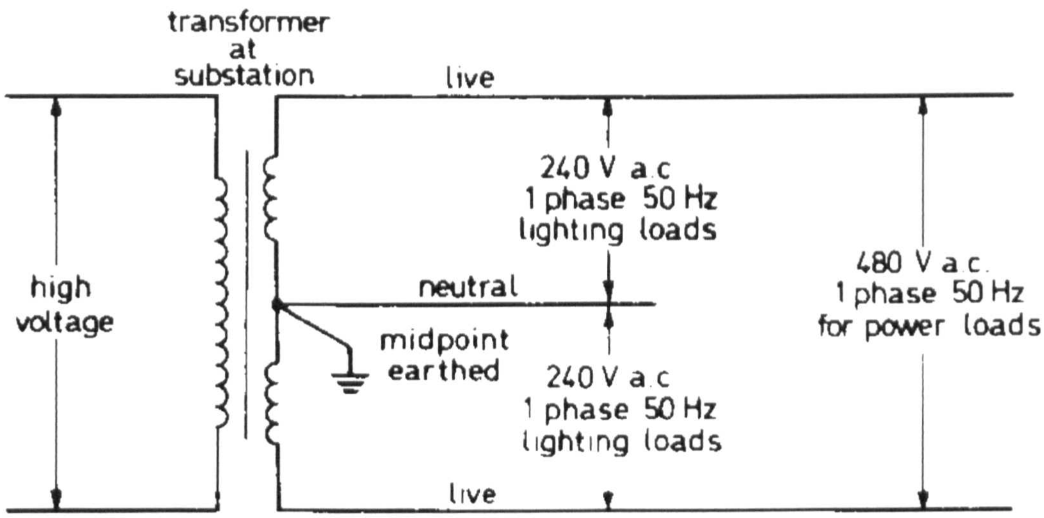


Figure 8. A.C. Single-phase three-wire system [64]

- A.C. Three-phase Four-wire system: This is the system used for general distribution purposes wherever three-phase supplies are available. Essentially, this consists of three single-phase circuits with a common earthed conductor called the neutral. The transformer windings are connected in star formation, the star point being earthed and also connected to the neutral conductor. Since there is a phase difference between the voltages of each phase, the total voltage across two phases will be 1.73 times the phase voltage. The conductors connected to the outer terminal of each phase are known as live conductors. To distinguish one phase from another it is usual to give the phases a colour coding of red, yellow and blue. The cores of the cables are marked or numbered accordingly. Three phase power supplies are connected to the three live or line conductors, and lighting and single-phase supplies are connected to one of the lines and the neutral. By connecting the single-phase supplies to each phase in rotation, a fair balance of load over the three phases is usually obtained.

Figure 9 shows the system from the distribution transformers, with connections made for both single-phase and three-phase supplies.

- A.C. Three-phase three-wire system: This system is not usual for general supplies, but it may be found for certain circuits within a factory. If a three-phase power load is balanced on all phases, then there will be no current in the neutral and it can be omitted. In such a case, a three-wire system can be used. Single-phase supplies, however, cannot normally be taken from this system (figure 10).

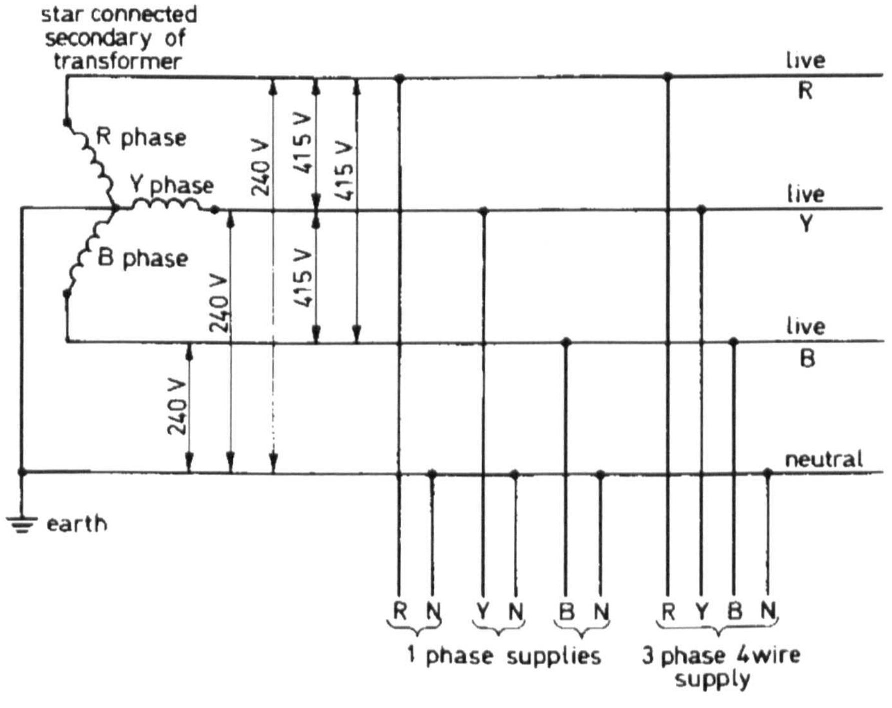


Figure 9. Three-phase four-wire system [64]

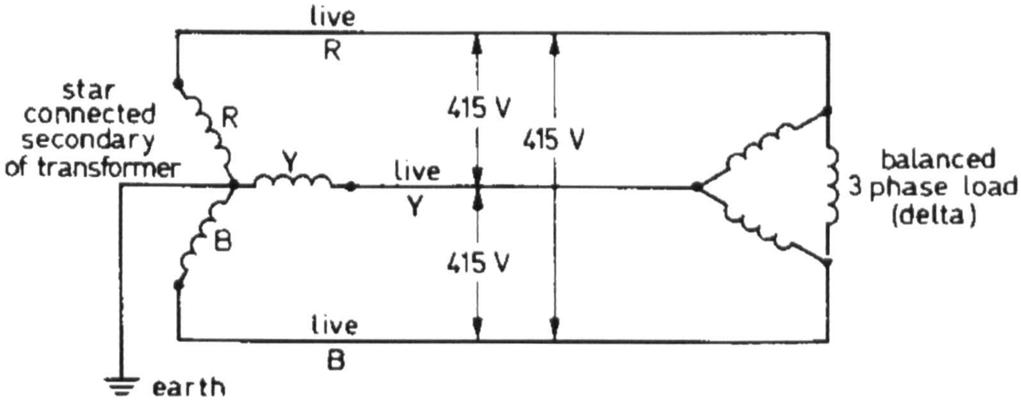


Figure 10. Three-phase three-wire system [64]

The type of supply offered to a consumer depends upon the nature of the consumer's load and the type of process being carried out. Figure 11 shows the layout for a small consumer (typical UK houses). At the incoming supply point the supply authority have a means of isolating consumer's circuits from the supply by the installation of fuses or a circuit breaker. The metering equipment is also connected at this point. The meters may be connected direct, but for supplies of about 50 kVA and over it is usual to supply the meter from a current transformer. The small consumer will be supplied direct from the three-phase, four-wire distributor.

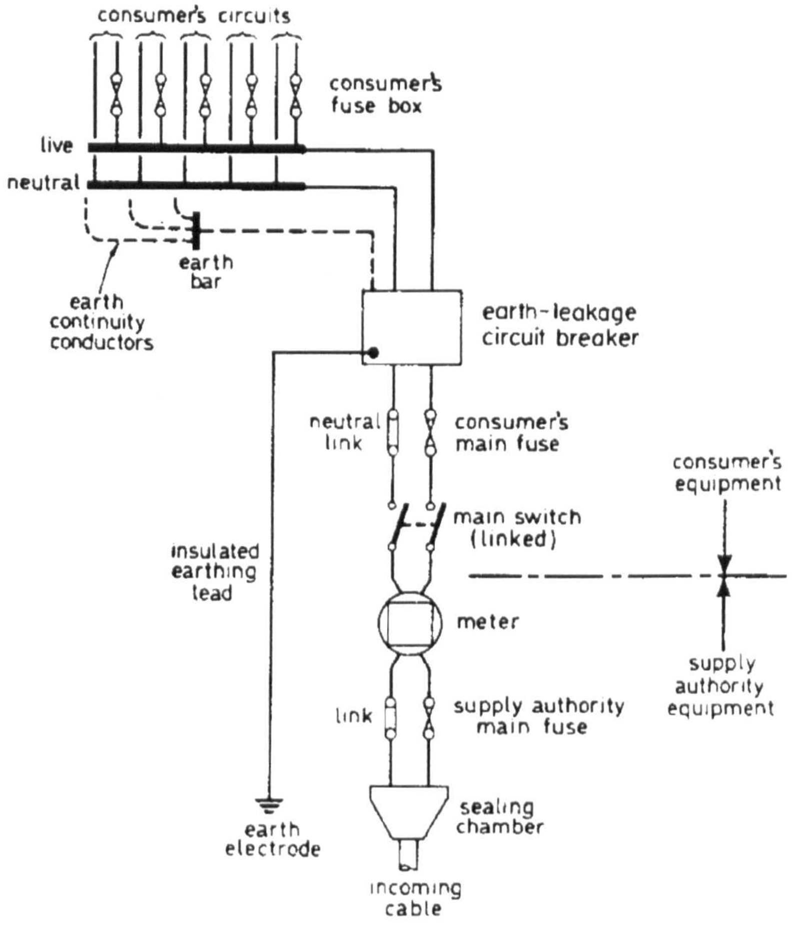


Figure 11. Small consumer's single-phase supply [64]

Larger consumers with loads of up to 300-500 kVA may require a supply direct from a local substation, as shown in Figure 12. In this case no other consumer will be connected to the supply cable, even when it is laid for some distance along a street.

A consumer with a load of up to 1000 kVA will receive supply from a separate substation situated on his own land or in part of his factory premises. This substation will supply only the one consumer. Figure 13 shows this arrangement.

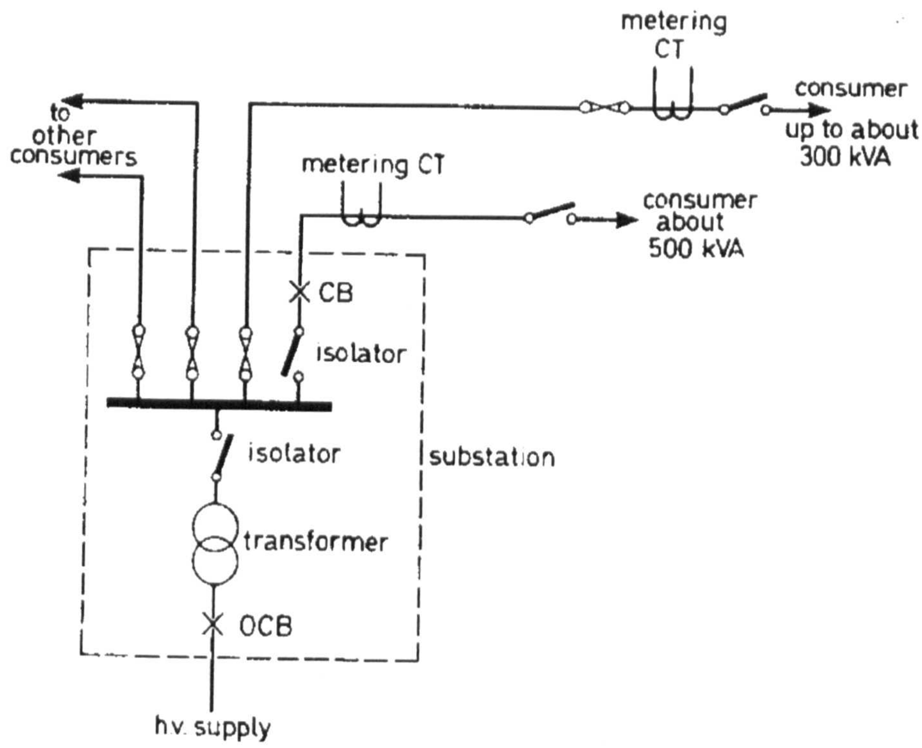


Figure 12. Supply to consumers with loads up to 500 kVA [64]

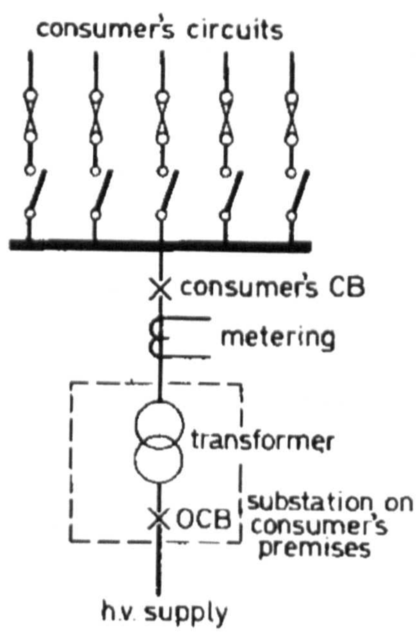


Figure 13. Supply to consumers with load up to 1000 kVA [64]

1.8 Consumer Layout

The layout of consumer's circuits depend upon the size of the installation. For a very small installation, the consumer's distribution board from which the final power, heating and lighting circuits are fed will be supplied direct from the equipment at the supply intake. Even small industrial consumers, however, usually require a supply that justifies the installation of a small bus bar system situated in a special switch room. The supply intake and metering equipment will be placed in this room. The bus bar will be fed through an isolator and the consumer's main fuses, or through a circuit breaker. A typical layout is shown in figure 14. A larger consumer may have its supplies connected to a ring main system, as shown in Figure 15.

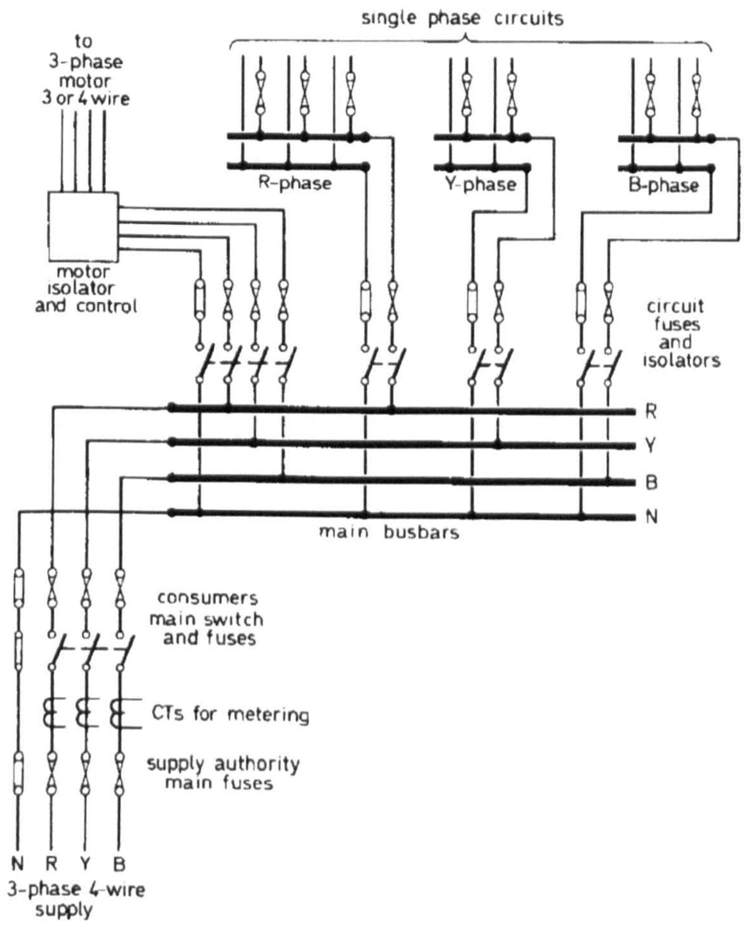


Figure 14. Typical supply for a small factory [64]

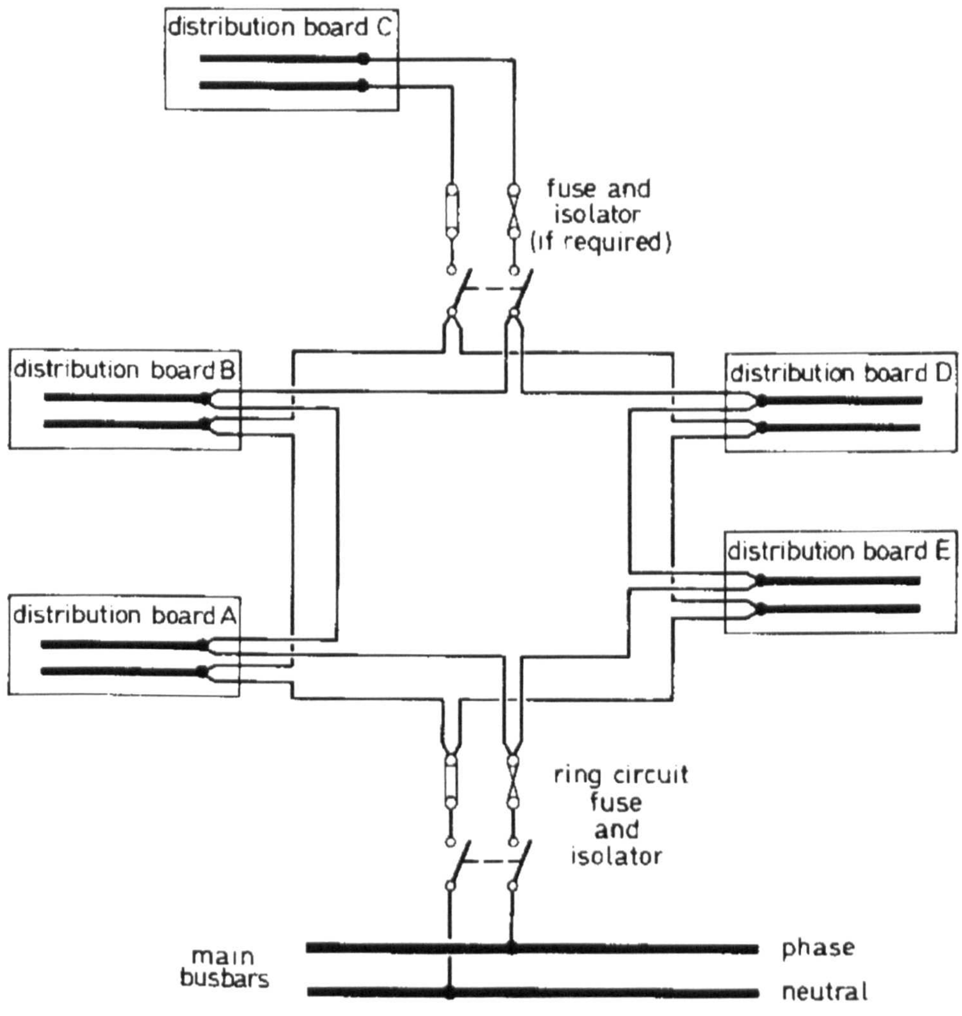


Figure 15. Ring main system (normally three-phase and neutral-one phase and neutral only shown for simplicity) [64]

The ring will be a three-phase and neutral system, but for simplicity only one phase and the neutral are shown in the diagram. Each distribution board will supply different sections, and the fact that they are on a main system gives greater security. Fuses and/or isolators are used to protect or isolate any of the boards as shown for board C in the diagram. Figure 16 is a single-line diagram of a section of a typical three-phase four-wire distribution system. Circuit breakers control the output from the main substation. These feed into main distribution boards in each section of the consumer's premises. Other sub-distribution boards are supplied from the main board, and from these are fed the circuits for small power, lighting, and heating loads.

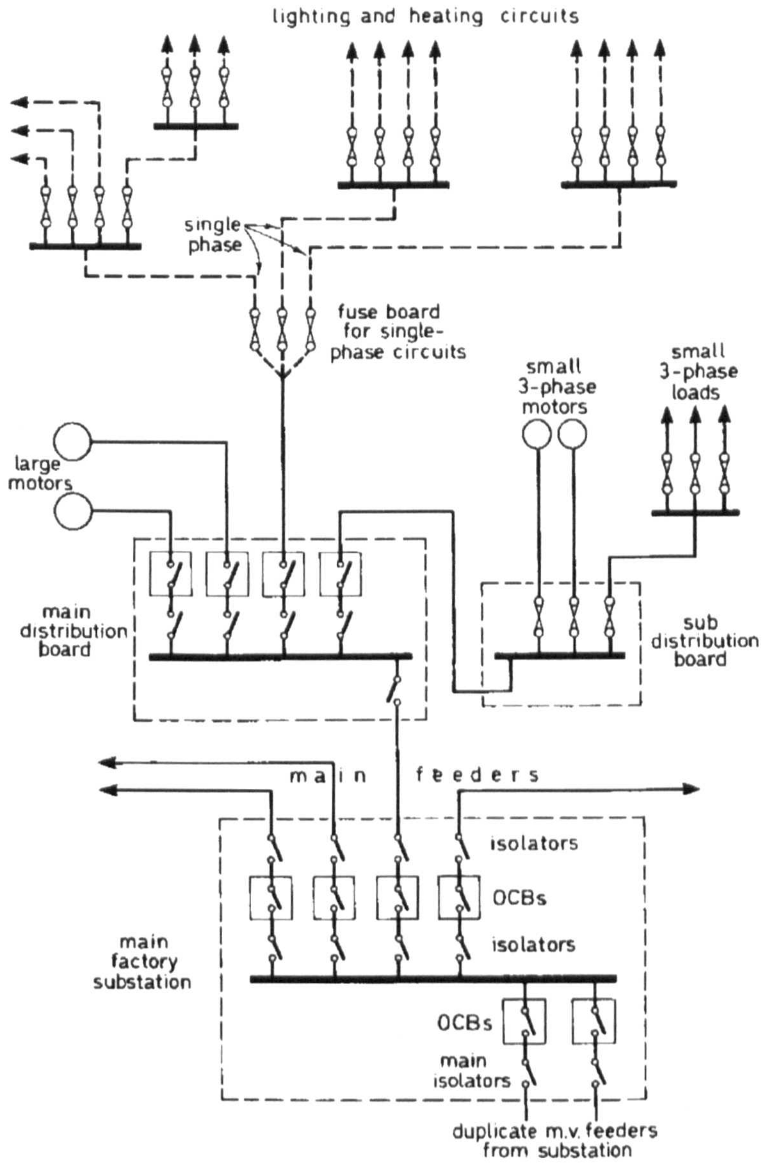


Figure 16. Typical three-phase, four-wire distribution – single line diagram [64]

1.9 Low-Voltage System Operation

As Low-voltage networks are the most likely to have PLT deployed on them, it is important to understand the operational constraints imposed upon the PLT system by the power system operations necessary to meet regulatory commitments of providing a continuous power supply to customers. This section describes those constraints by reference to the typical LV network configuration shown in Figure 17.

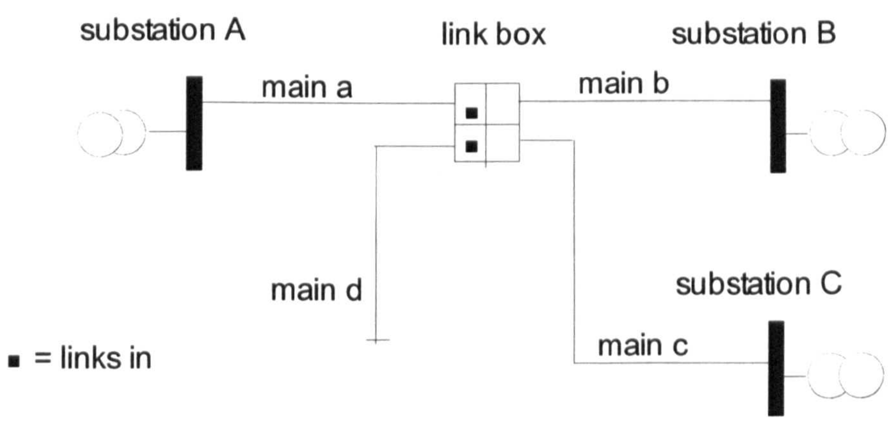


Figure 17. LV network configuration

Figure 17 shows the basic arrangement of a residential network with three secondary substations A, B and C. Each substation has a number of feeders supplying the houses around it, but only those feeders associated with interconnections to other substations are shown. Mains a, b and c are interconnections that meet in a link box; they are also used to feed the houses that are distributed along their routes. Because of the geographic layout, it is convenient for main d to be fed from the link box, rather than directly from a substation.

The link box is an underground connection box into which the cables are jointed. It has lugs connected to each cable conductor, allowing the same phases on different cables to be interconnected using removable links that are inserted with an insulated tool. The normal running condition for the network is shown; the box acts as an 'open point' between the substations and the links to mains b and c are normally left out. The links are in between cables a and d so that cable d receives its normal feed from substation A. If a fault occurs that shuts down one of the substations supplies can be restored by inserting links. For example, if the HV supply to substation B fails it is possible to restore supplies to customers on main b by removing fuses at substation B to isolate the main, then fitting links into the box to connect main b to substation A or substation C. A further option is to leave the feeder fuses in at the failed substation and open the transformer links to isolate the transformer from the bus bars. It is then possible to feed further customers from substations A or C via the bus bars of substation B. However, that type of back feed is often impractical because of excessive voltage drop or other load related problems. This type of network rearrangement is used as a short-term solution while repairs are carried out.

It is clear that the type of change of running conditions described above must take precedence over any communications requirements and must be carried out promptly to avoid or minimize the penalties associated with guaranteed supply standards, which require suppliers to compensate customers for supply interruptions that exceed the time limits specified by the regulator. This means that any PLT system must be able to cope with unexpected changes to the topology of its physical layer, which is a challenge in terms of both transmission standards and network management.

The majority of underground LV networks in the UK are operated as described above. However, the old London Electricity Board did operate 'solid' networks, in which substations ran in parallel. It is understood that this practice may have been abandoned due to safety problems associated with excessive fault level; such operation also requires the use of directional over current protection at the substations to avoid back feeding HV faults from the LV network, which makes the substations excessively complicated.

Similar configurations are applied to urban overhead networks where the substations are closely spaced. In that case, the underground link box is replaced by a 'section pole' on which the conductors on either side terminate on separate insulators, so that they are not connected through. To restore supplies under fault conditions a linesman visits and fits 'jumpers[4]' between the wires on each side of the pole. This feature is less likely to be available in rural areas because of the greater distances between substations, many of which are pole mounted and may only feed a single house or a small group of houses.

[4] Temporary connections

1.10 Historical Overview of PLT

Power Line Communications is the usage of electrical power supply networks for communication purposes. In this case, electrical distribution grids are additionally used as a transmission medium for the transfer of various telecommunications services. The main idea behind PLC is the reduction of cost and expenditure in the realization of new telecommunications networks.

High- or medium-voltage power supply networks could be used to bridge a longer distance to avoid building an extra communications network. Low-voltage supply networks are available worldwide in a very large number of households and can be used for the realization of PLC networks to overcome the so-called telecommunications *last mile.* Power line communications can also be applied within buildings or houses, where an internal electrical installation is used for the realization of in-home PLC networks.

Power line communications has been around since the early half of the 20^{th} century when utility companies started monitoring and controlling devices on the power grid using low frequencies. This one-way communications technology was also used in the management of street lights. In the mid1980s experiments on higher frequencies were carried out and a bidirectional communication technology was developed by the end of the decade. It is around the same time that X-10[5] protocol established that power line infrastructure can be effectively and inexpensively used for carrying data.

[5] X-10 is an international and open industry standard for communication among electronic devices used for home automation. It primarily uses power line wiring for signaling and control, where the signals involve brief radio frequency bursts representing digital information.

This technology was unidirectional and sent signals to simple receivers to control lights and other equipment. Although these newer technologies demonstrated great improvement in performance, yet it was soon evident these were not adequate for high data rate applications especially at high speeds and noisy environments. Thus came along OFDM (Orthogonal Frequency Division Multiplexing) (discussed in chapter 3) and the birth of the higher data rate PLCs with high-speed transmissions.

The first Carrier Frequency Systems (CFS) had been operated in high voltage electrical networks that were able to span distance over 500 km using 10W signal transmission power [1]. Also, the communication over medium- and low-voltage electrical networks has been realized. Ripple Carrier Signalling[6] (RCS) systems have been applied to medium- and low-voltage networks for the realization of load management[7] in electrical supply systems.

The early transmission systems from the 1900's used extremely low date rates and consequently low transmission frequencies of the order of kHz. However, as more applications demanded higher data rates the frequency of transmission increased. Therefore, according to the data services available to customers on the network determines the frequencies and bandwidth of the transmission system. The frequency

---

[6] Ripple control is a communication method for Load management task. It is based on broadcast information where the power supply network is utilized as the transmission medium. The low frequency signal is fed into the network via a coupling filter. This signal can be fed in series or parallel to the supply network at high, medium or low-voltage level and is superimposed in the network.

[7] Load management is the process of balancing the supply of electricity on the network with the electrical load by adjusting or controlling the load rather than the power station output. This can be achieved by direct intervention of the utility in real time, by the use of frequency sensitive relays triggering circuit breakers, or by time clocks, or by using special tariffs to influence consumer behavior.

used is directly related to the application and local environment. Table1 provides the typical power line communication technique and representative frequency band for the particular system.

PLT Technique	Frequency range
Ultra Narrow Band(UNB)	10Hz
Power Frequency	50/60Hz
Ripple control	100Hz to 1000Hz
Distribution PLT	3kHz to 40kHz
Transmission PLT	30kHz to 500kHz
Local PLT	40kHz to 30MHz

Table 1. Early Power Line Techniques and Frequencies

The early techniques of Ultra Narrow band operating at extremely low frequency of 10Hz though to ripple control operating in the frequency band 100Hz to 1000Hz are used for basic switching of equipment in the electricity distribution network.

In the late 1990's there was a considerable development in providing high data rate transmission systems for internet services to residential and industrial customers. These new services introduced data and voice over the internet protocol "VoIP" provided a common communication service to all residential and industrial customers. These services demand the higher data rates and hence bandwidth. The characteristics of such services ranging from security of service through to signal error are shown in Table 2.

Parameter	Ultra Narrow Band	Distribution PLT	Broadband PLT
Range	Excellent	Very good	Very good
Data Rate	Low	High	Excellent
Security	Good	Good	Good
Line Conditioning	Minimal	Excellent	Excellent
Latency(time delay)	Good	Medium	Low
Error rate	Low	Excellent	Good

Table 2. Parameters of Power Line Carrier Systems

Table 2 demonstrates that there is no ideal PLT communication system. Good quality parameters include the range the system will operate over, however, for the Broadband PLT system the data rate is excellent and current systems operate at 250 Mbyte and higher speeds are becoming available. In comparison for the low data rate system a longer range is achievable. Therefore, it is important to determine the exact services that will be transmitted over the power line network.

Table 1 details the early power line carrier frequencies, many of which are still operational today. However, manufacturers and utility companies have combined to develop power line systems for greater range and higher speed and consequently services such as video on demand. Also the national and international standards bodies have become involved to provide neutrality to the vast range of services being developed throughout the world and potentially coexistence between the operations of such systems.

Today the operational frequency bands used throughout the world have specific frequency ranges for data signals being transmitted between the backbone network and the home or building, known as the "Access Network" and the data network inside the home or building known as the "In-house network." Further, the networks are classified as low frequency and high frequency systems.

Internal electrical networks have been mostly used for realization of various automation services. Application of in-home PLC systems makes possible the management of numerous electrical devices within a building or a private house from a central control position without the installation of an extra communication network. Typical PLC-based building automation systems are used for security observance, supervision of heating devices and light control.

Current PLC networks are designed as two independent systems, the outdoor infrastructure or the medium-voltage (MV) grid and the customer premise network, which is low voltage (LV) distribution network. The MV network can serve several buildings for access to the backbone data network and therefore, must guarantee higher-level of reliability than the internal networks. The MV grid is utilized for backhaul applications for the PLC network while the low voltage is utilized for customer premise applications. Separating the infrastructure allows greater bandwidth utilization on the medium grid for enhanced services.

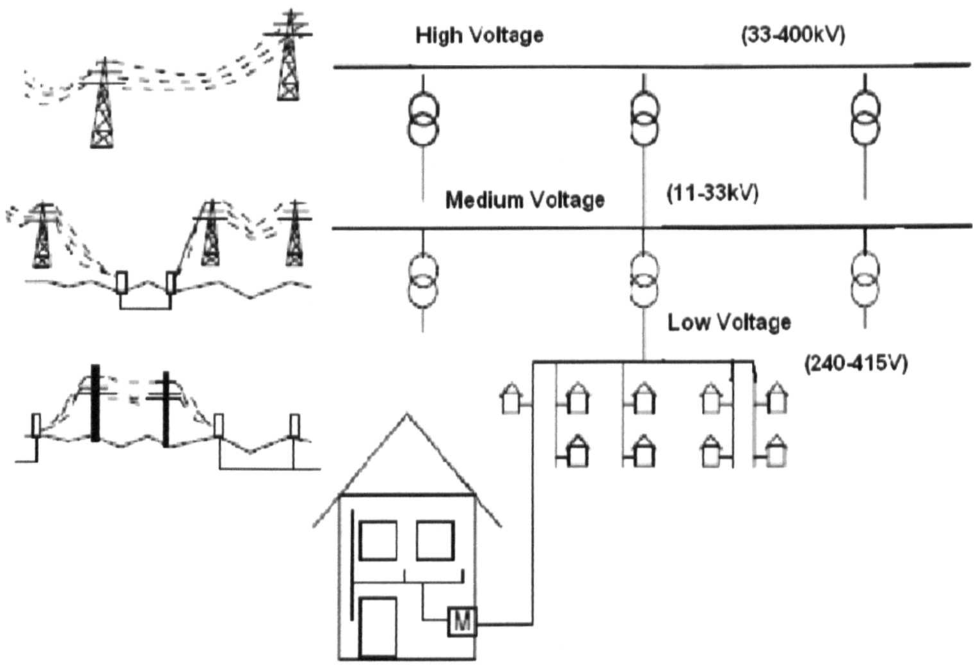


Figure 18. Power Supply Networks [25]

In-home electrical installations belong to the low-voltage network level. However, internal installations are usually owned by the users. They are connected to the supply network over a meter unit (M) as shown in figure 18. On the other hand, the rest of the low-voltage network (outdoor) belongs to the electrical supply utilities.

Low-voltage supply networks directly connect the end customers in a large number of households worldwide. Therefore, the application of PLC technology in low-voltage networks seems to have a perspective regarding the number of connected customers. Low-voltage networks cover the last few hundred of meters between the customers and the transformer unit and offer an alternative solution using PLC technology for the realization of the so-called *last mile* in the telecommunications access area.

1.11 Regulatory Standards for PLC

One of the major issues currently under debate is the radiated emission of power lines. Sources of information from power line networks can be the upstream signals at customer premises, the upstream signals at adjacent customer premises and downstream signals at the substation.

For mains-borne communications, there is a European standard, CENELEC (Comité Européen de Normalization Electrotechnique), EN50065-1:1991 [48]. The standardization process for PLT equipment is shown in Figure 19 [Newbury 2005].

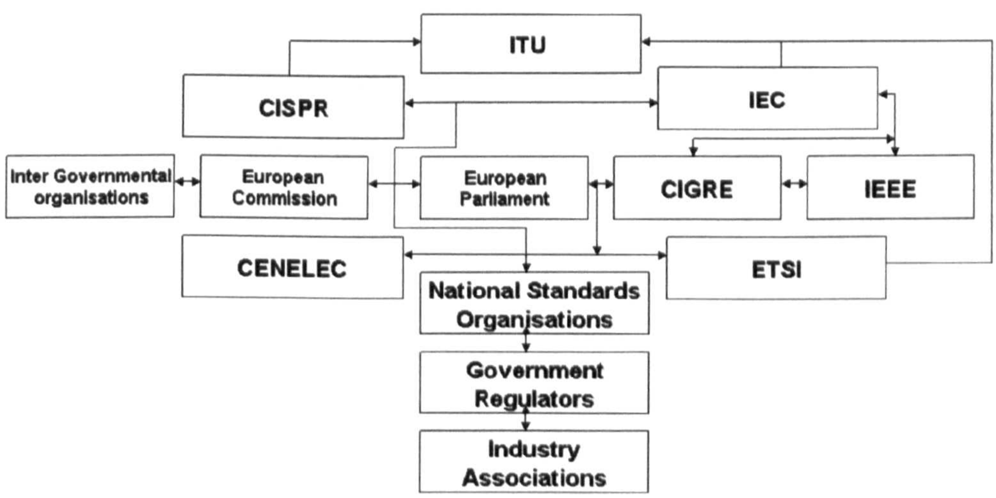


Figure 19. PLT Regulatory and Standardization framework [Newbury 2005]

There are standards being developed for Broadband PLT system – CISPRE 22 PLT, also CELELEC – SC205A and the IEEE PLT.

The bodies referred to by the acronym in figure 19 and their functions are identified and listed in table 3. The European and international standardization bodies produce standards that are used by the national standardization bodies (e.g. the British

Standards Institute in the UK) to produce national standards, as well as being used in their own rights. In addition, because PLT has the potential to interfere with radio services, the national radio regulators (e.g. OFCOM, formerly the Radiocommunications Agency, in the UK) are also involved in producing regulatory standards, which are used to determine whether or not the apparatus is at fault if an interference complaint is received.

Acronym	English name of body	Aim/Function
CENELEC	European committee for Electrotechnical Standardization.	European electrical standards.
CIGRE	International Council on Large Electrical System.	"Worldwide exchange of engineering and knowledge and information". [CIGRE 2005]
CISPR	International Special Committee on Radio Interference. They develop standards for Broadband PLT.	Sub committee of IEC for the "protection of radio services in the frequency range 9kHz to 400 GHz" [CISPR 2005].
IEC	International Electrotechnical Commission.	"Leading global organization for international standard in...electrical technologies" [IEC 2005]
IEEE	Institute of Electrical and Electronic Engineers. They develop Broadband PLT standards – P1775.	Worldwide electrical standards.
ETSI	European Telecommunications Standards. Institution	European ICT standards.
ITU	International Telecommunications Union	"...coordination of global telecommunications and networks and services". [ITU 2005]

Table 3. Bodies involved in PLT Standardization and Regulation

The regulations on key parameters such as frequency range and signal power is specified in CENELEC EN50065 "Low voltage mains signalling".

The standards applicable to PLT fall into two categories:

- Conducted emission standards - Conducted emission standards define the amount of power that a device (in this case a PLT modem) is allowed to inject into the network to which it is connected. These tend to be associated with certification of the device for CE marking and are product standards.

- Radiated emission standards - Radiated emission standards are more complicated because they must take account of the characteristics of the network to which the device is connected. Regulatory standards are used for enforcement of the radio regulations.

There is a general consensus that standards should be devised that treat all types of wired media carrying communications signals alike, so that the standards under development is required to apply to all the following systems:

- POTS (Plain Old Telephone Service)
- DSL (Digital Subscriber Line – all variants)
- CATV (Community Antenna TeleVision – aka cable TV)
- PLT (Power Line Telecommunications)
- BPL (Broadband Power Line – US name for PLT)

The standard EN50065 allows for PLC communication systems to operate in the frequency band 3-148.5 kHz, avoiding interference with ripple control systems at the lower boundary, and interference with Long Wave (LW) and Medium Wave (MW) radio broadcasts by posting the upper boundary. CENELEC then divide this band in to further categories as shown in figure 20.

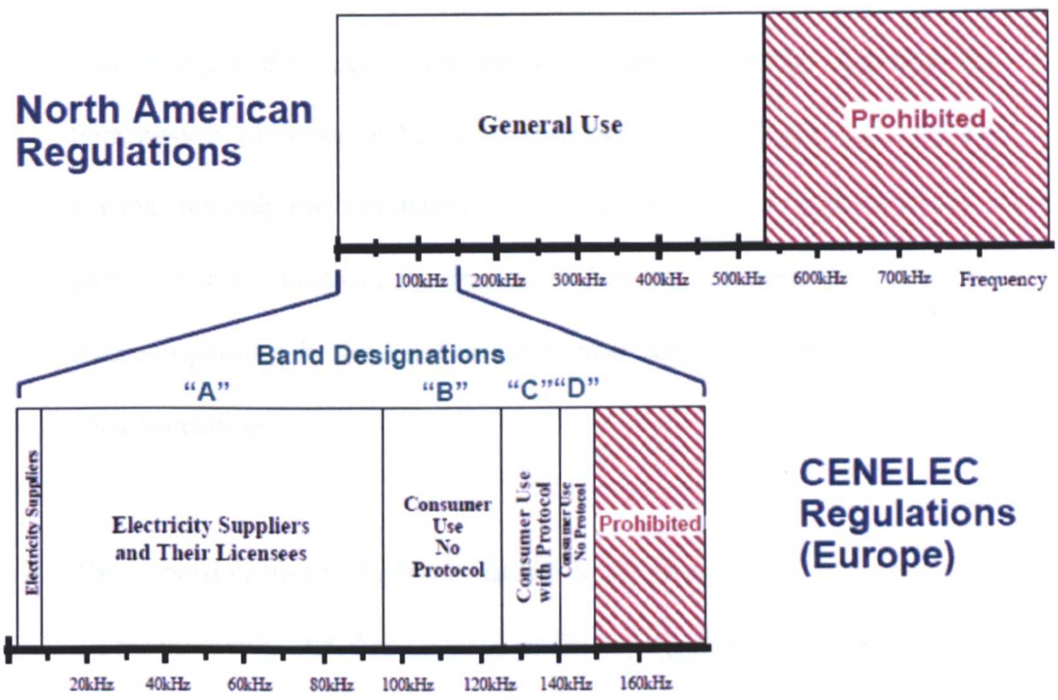


Figure 20. CENELEC (Europe) and FCC (US) Frequency Band Allocation [56]

- A - Band (3-95 kHz) is allowed for electrical utility use, for such things as automated meter reading and customer load control. This band is known as the Access Band.

- The range (95-148.5 kHz), comprising the B, C and D bands is reserved for end-user applications. These three bands are primarily differentiated by regulations in protocols for each band, B band, from 95-125 kHz requires no use of access protocol for establishing communications. Thus, it is possible for two systems to transmit simultaneously on the B band and therefore messages to collide. This band is designed for use in applications such as baby-monitors and intercoms. This band is known as the In-house Band.

- The C-band (125-140 kHz) requires an access protocol to be used by devices transmitting at this range. This protocol is aimed at making simultaneous transmission of messages highly improbable. Thus, different systems may cohabit, but only one transmitter can operate at any time. Specifications are given for access protocol frequencies, and so on. Applications for these devices operating in this band would be intra-building computer communications.

- The D-band (140-148.5 kHz) is similar to the A band in that it requires no access protocols, and thus message collision is possible. This band is no longer in use.

Another important specification in the standard is the maximum transmitted power from a PLC device should not exceed 500 mW. This correlates with the 134 dBμV (equivalent to 5V) maximum signal voltage level specified at 9 kHz, and the 120 dBμV (equivalent to 1V) capped as the maximum signal voltage level at 95 kHz. Generally, for indoor applications the transmission signal amplitude is restricted to 630 mV within a bandwidth of 50 kHz. For outdoors communications such as AMR, transmission signal strength of up to 5 V are granted within the specified 95 kHz frequency threshold [48].

The EN50065 Standard also specifies interference immunity requirements for PLC systems, including both for immunity to interference from other power line communication systems and for interference generated by the system. Again, the standard is split up into utility and end-user categories. Testing methods for determining such immunity are also given. Lastly, EN50065 specifies such things as communication protocols, equipment impedance (for avoiding excessive signal attenuation due to multiple PLC devices of low impedance on one network), and filter specifications for carrier removal [60].

In America and Japan, only MW or AM broadcasts need to be considered. These start at 535 kHz, with intermediate frequencies of typically 455 kHz as shown in figure 20.

Thus, American PLC systems often operate in the band 100-450 kHz. American FCC's (Federal Communications Commission) Rules and Regulations list PLC systems as "Restricted Radiation Devices", and as such there are very few applicable regulations on them, nor do they require licensing or registration. IEEE PES committee have a low-voltage standard for narrowband frequencies and P1775 is the broadband standard. CENELEC standard significantly differs from American and Japanese standard, which specify a frequency range up to 500 kHz for the application of PLC services.

CENELEC standard makes possible data rates up to several thousand bits per second, which are sufficient only for some metering functions (load management for an electrical network, remote meter reading), data transmission with very low bit rates and the realization of few numbers of transmission channels for voice connections. However, for application in modern telecommunications networks, PLC systems have to provide much higher data rates (beyond 2 Mbps). Only in this case, PLC networks are able to compete with other communications technologies, especially in the access area.

For the realization of the higher data rates, PLC transmission systems have to operate in a wider frequency spectrum (up to 30 MHz). However, there are no PLC standards that specify the operation of PLC systems out of the frequency bands defined by the CENELEC. Currently, there are several bodies that try to lead the way for standardization of broadband PLC networks including the following:

- PLCforum is an international organization with the aim to unify and represent the interest of players engaged in PLC from all over the world. There are more than 50 members in the PLCforum; manufacturing companies, electrical supply utilities, network providers and research organisations. PLCforum is organised into four working groups: Technology, Regulatory, Marketing and In-house working group.

- The HomePlug Powerline Alliance [HomePlug] is a not-for-profit corporation formed to provide a forum for the creation of open specifications for high-speed home power line networking products and services. HomePlug is concentrated on in-home PLC solutions and it works close to PLCforum as well.

- Standardization activities for broadband PLC technology are also included in the work of European Telecommunications Standard Institute (ETSI) and CENELEC.

1.12 Narrowband PLC

The narrowband PLC networks operate within the frequency range specified by the CENELEC EN50065 standard. The utilities use narrowband PLC for the realization of the so-called energy-related services. Frequency bands B and C are mainly used for the realization of building and home automation. Nowadays, the narrowband PLC systems provide data rates up to a few thousand bits per seconds (bps) [2]. The maximum distance between two PLC modems can be up to 1 km. To overcome longer distances, it is necessary to apply a repeater technique.

First narrowband PLC networks have been realized by the usage of Amplitude Shift Keying (ASK) [2]. The ASK is not robust against disturbances and, therefore, is not suitable for application in PLC networks. On the other hand, Binary Phase Shift Keying (BPSK) is a robust scheme and, therefore, is more suitable for application in PLC. However, phase detection, which is necessary for the realization of BPSK, seems to be complex and BPSK-based systems are not commonly used. Most recent narrowband PLC systems apply Frequency Shift Keying (FSK), and it is expected that BPSK will be used in future communication systems [2].

Broadband modulation scheme are also used in narrowband PLC systems. The advantages of broadband modulation, such as various variants of spread spectrum, are its robustness against narrowband noise and the selective attenuation effect that exists in the PLC networks [2]. A further transmission scheme also used in narrowband PLC system is Orthogonal Frequency Division Multiplexing (OFDM) [3].

A comprehensive description of various narrowband PLC systems, including their realization and development, can be found in [2].

A very important area for the application of narrowband PLC is building/home automation. PLC-based automation systems are realized without the installation of additional communication networks (figure 21).

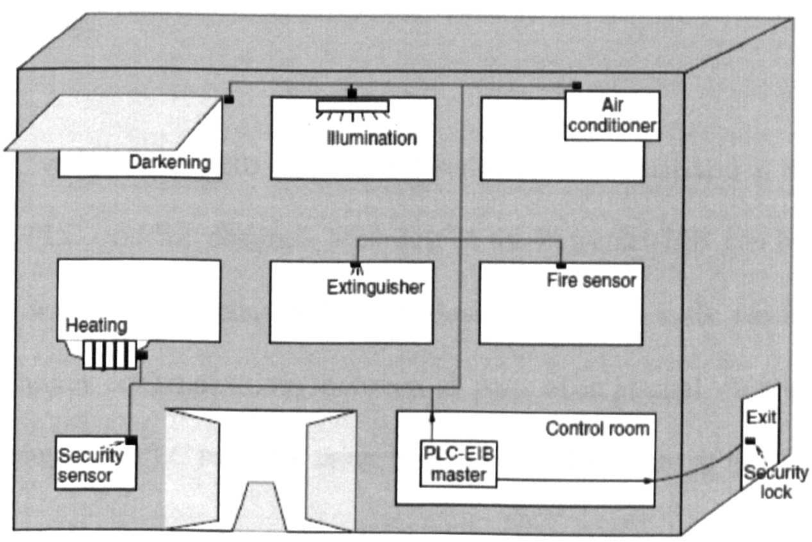


Figure 21. Structure of an automation system using narrowband PLC [25]

Thus, the high costs that are necessary for the installation of new networks within existing buildings can be significantly decreased by the usage of PLC technology.

Automation systems realized by PLC can be applied to different tasks to be carried out within buildings, including:

- Control of various devices that are connected to the internal electrical installation, such as illumination, heating, air-conditioning and elevators.

- Centralized control of various building systems, such as window technique (darkening) and door control.

- Security tasks, observance and sensor interconnection.

PLC-based automation systems are not only used in large buildings but they are also very often present in households for the realization of similar automation tasks (home automation).

A PLC variant of the EIB (European Installation BUS) standard is named 'Powernet-EIB'. PLC modems designed according to the Powernet-EIB can be easily connected to any wall socket or integrated in any device connected to the electrical installation. This ensures communications between all parts of an internal electrical network. Nowadays, the PLC modems using FSK achieve data rates up to 1200 bps [2].

As it is specified in CENELEC EN50065-7 standard, power supply utilities can use band A for the realization of so-called *energy related services*. In this way, a power utility can use PLC to realize internal communications between its control centre and different devices, ensuring remote control functions, without building extra telecommunications network or buying network resources at a network provider as shown in figure 22. Simultaneously, PLC can be used for remote reading of a customer's meter units, which additionally saves cost on the personnel needed for manual meter reading. PLC can also be used by the utilities for dynamic pricing depending on the day of time, total energy offer as well as for observation and control of energy consumption and production.

Building automation is a typical indoor application of the narrowband PLC systems, whereas the energy-related services are mainly indoor applications. An interesting example of an application of a PLC-based automation system in the outdoor area [4]. In this case, a PLC-based airfield ground-lighting automation system is used for individual switching and monitoring of airfield lighting. The length of the airfields and accordingly the necessary communications networks in a large airport is very long (several km). So, the narrowband PLC can be applied to save costs on building a separate communications network. This is also an example of PLC usage for the realization of so called critical automation services with very high security requirements, such as the light control of ground aircraft movement in the airports.

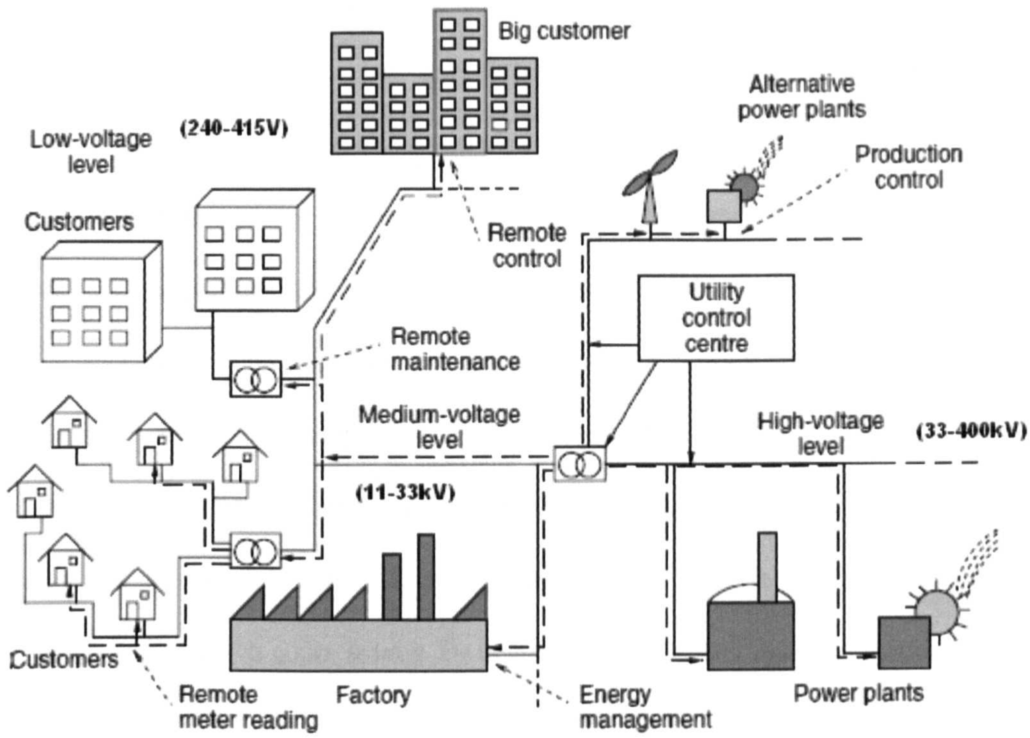


Figure 22. General structure of a PLC system used for energy-related services [25]

1.13 Broadband PLC

Broadband PLC systems provide significantly higher data rates (more than 2 Mbps) than narrowband PLC systems. Where the narrowband networks can realize only a small number of voice channels and data transmission with very low bit rates, broadband PLC offer the realization of more sophisticated telecommunications services, multiple voice connection, high speed data transmission, transfer of video signals, and narrowband services as well. Therefore, PLC broadband systems are also considered a capable telecommunications technology.

The realization of broadband communications services over power line grids offers a great opportunity for cost-effective telecommunications networks without the laying of new cables. However, power line systems are not designed for information transfer and there are some limiting factors in the application of broadband PLC technology. Therefore, the distances that can be covered, as well as the data rates that can be realized by PLC systems, are limited. A further very important aspect for application of broadband is its Electromagnetic Compatibility (EMC). For the realization of broadband PLC, a significantly wider frequency spectrum is needed (up to 30 MHz) than is provided within CENELEC bands. On the other hand, a PLC network acts as an antenna becoming a noise source for other communication systems working in the same frequency range (e.g. various radio services). Because of this, broadband PLC systems have to operate with a limited signal power, which decrease their performances, data rates and distance.

Current broadband PLC systems provide data rates beyond 2 Mbps in the outdoor arena, which includes medium- and low-voltage supply networks, and up to 12 Mbps in the in-home area. Some manufacturers have already developed product prototypes providing much higher data rates of the order of 40 Mbps. Medium-voltage PLC technology is usually used for realization of point-to-point connections bridging distances up to several hundred metres. Typical application area of such systems is the connection of local area network (LAN) between buildings or within a campus and the connection of antennas and base stations of cellular communication systems to their backbone networks. Low-voltage PLC technology is used for the realization of the so called *last mile* of telecommunication access networks. Because of the importance of telecommunication access, current development of broadband PLC technology is mostly directed toward applications in access networks including the in-home area.

1.14 Structure of PLC Networks

The low voltage supply networks consist of a transformer unit and a number of power supply cables linking the end users, which are connected to the network over meter units. A Power line transmission system applied to a low-voltage network uses it as a medium for the realization of PLC access networks. In this way, the low-voltage networks can be used for the realization of so-called *last mile* communication networks.

The low-voltage supply networks are connected to the medium- and high-voltage networks via a transformer unit as shown in figure 23.

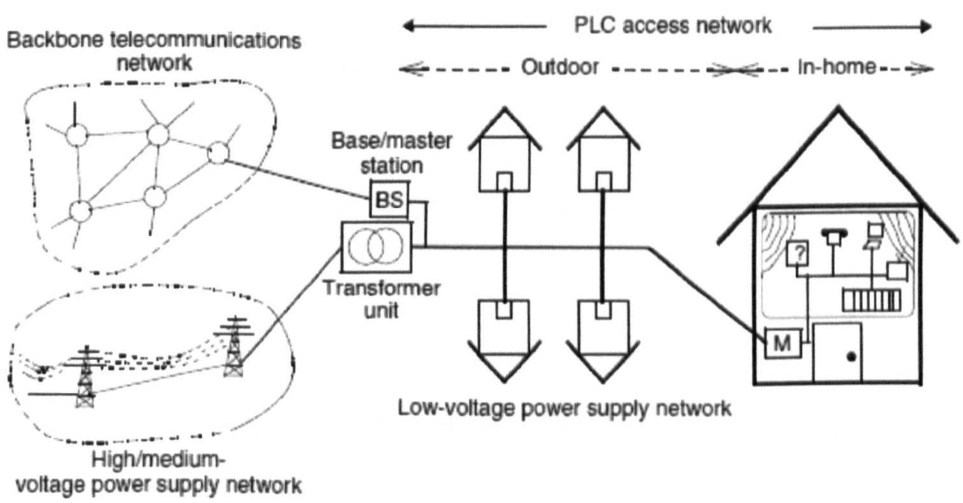


Figure 23. Structure of a PLC access network [25]

The PLC access networks are connected to the backbone communications network (WAN) via a base/master station (BS) usually placed within the transformer unit. Many utilities supplying electrical power have their own telecommunications networks linking their transformer units and they can be used as a backbone network.

The connection to the backbone network can also be realized via a subscriber or a power street cabinet, especially if there is a convenient possibility for its installation. In any case, the communications signal from the backbone has to be converted in to a form that makes possible its transmission over the low-voltage power supply network. The conversion takes place in a main/base station of the PLC system.

The PLC subscribers are connected to the network via a PLC modem placed in the electrical power meter unit (M in Figure 23) or connected to any socket in the internal electrical network. In the first case, the subscribers within a house or building are connected to the PLC modem using another communications technology (e.g. DSL, WAN). In the second case, the internal electrical installation is used as a transmission medium that leads to the so-called *in-home PLC solution*.

The modem converts the signal received from the PLC network into a standard form that can be processed. On the user side, standard communications interfaces are usually offered. Within a house, the transmission can be realized via separated communications network or via an internal electrical installation. In this way, a number of communications devices within a house can also be connected to a PLC access network.

1.15 In-home PLC Networks

In-home PLC systems use internal electrical infrastructure as the transmission medium. It makes possible the realization of PLC local networks within houses, which connect some typical devices existing in private homes; telephones, computers, printers, video devices and other devices. In the same way, small offices can be provided with PLC LAN systems. In both cases, the laying of new communications cables at high cost is avoided.

Nowadays, automation services are becoming more and more popular not only for their applications in the industrial and business sectors and within large building, but also for their applications in private households. Systems providing automation services like security observation, heating control and light control have to connect a big number of end devices such as sensors, cameras, motors and lights. Therefore, in-home PLC technology seems to be a reasonable solution for the realization of such networks with a large numbers of end devices, especially within older houses and buildings that do not have an appropriate internal communication infrastructure.

Basically, the structure of an in-home PLC network is not much different from the PLC access systems using low-voltage supply networks. There can also be a base station that controls an in-home PLC network, and connects it to the outdoor area as shown in figure 24.

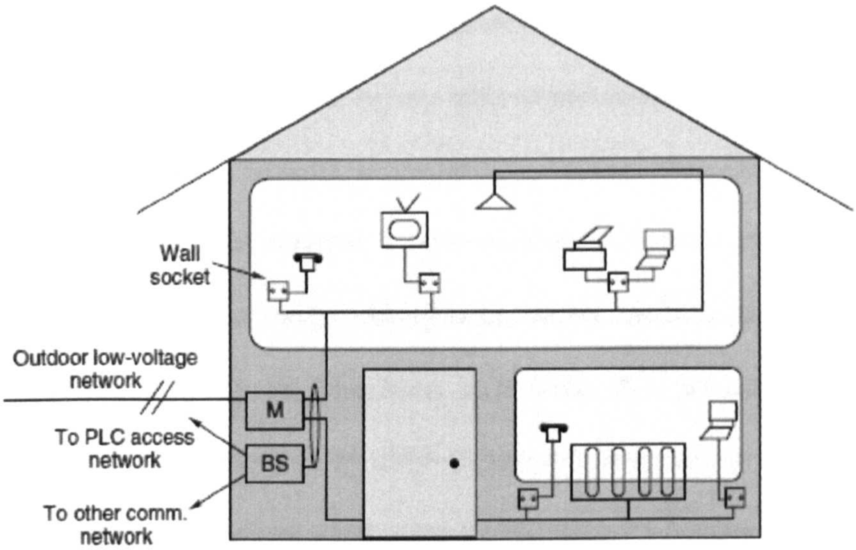


Figure 24. Structure of a PLC in-home network [25]

The base station can be placed with the meter unit, or in any other suitable place in the in-home PLC network. All devices of an in-home PLC network are connected via PLC modems, such as the subscribers of a PLC access network. The modems are connected directly to the wall power supply sockets, which are available in the whole house. Thus different communications devices can be connected to the in-home PLC network wherever wall sockets are available.

An in-home PLC network can exist as an independent network covering only a house or building. However, it excludes usage and control of in-home PLC services from a distance. On the other hand, a remote controlled in-home PLC system is very comfortable for the realization of various automation functions (e.g. security, energy management). Also connection of an in-home PLC network to a WAN communication system allows the usage of numerous telecommunications services from each electrical socket within a house.

In-home PLC networks can be connected not only to a PLC access system but also to an access network realized by any other communications technology. In the first case, if the access network is operated by a power utility, additional metering services can be realized; for example, remote reading of electrical meter saves the cost of manual reading, or energy management, which can be combined with an attractive tariff structure. On the other hand, an in-home PLC network can be connected to an access network provided by different network operators as well. The users of the in-home network can also profit from the liberalized telecommunications market.

There are also other cost effective communications systems for the realization of the broadband in-home networks. Wireless LAN (WLAN) systems are providing data rates beyond 20 Mbps. So, in contrast to the in-home PLC WLAN allows mobile usage of telecommunication services, such as cordless telephony, and other various portable communication devices.

1.16 PLC Network Elements

PLC networks use the electrical supply grids as a medium for the transmission of different kinds of information and the realization of various communications and automations services. However, the communications signal has to be converted in to a form that allows the transmission via electrical networks. For this purpose, PLC networks include some specific network elements ensuring signal conversion and its transmission along the power lines.

The main tasks of the basic elements are signal preparation and conversion for its transmission over power lines as well as signal reception. The following two devices exist in every PLC access network:

- PLC modem
- PLC base/master station

A PLC modem connects standard communications equipment, used by the subscribers, to a power line transmission medium. The user-side interface can provide various standard interfaces for different communications devices (e.g. Ethernet, Universal Serial Bus (USB) interfaces for realization of data transmission). On the other side, the PLC modem is connected to a power grid using specific coupling methods that allows the feeding of communications signals to the power line medium and its reception as shown in figure 25 [25].

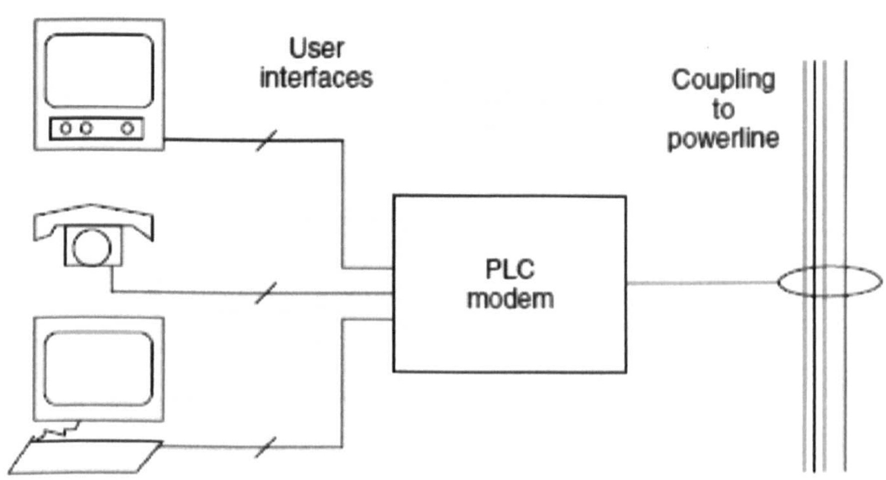


Figure 25. Connections of PLC modem [25]

The coupling has to ensure a safe separation and act as a high pass filter dividing the communications signal (above 9 kHz) from the electrical power (50 or 60 Hz). To reduce electromagnetic emissions from the power line, the coupling is realized between two places in the access between a phase and neutral conductor in the indoor area [2]. The PLC modem implements all the functions of the physical layer including modulation and coding. The second communications layer (data link layer) is also implemented within the modem including its MAC (Medium Access Control) and LLC (Logocal Link Control) sub-layers (according to the OSI reference model).

A PLC base station (master station) connects a PLC access system to its backbone network (Figure 23). It realizes the connection between the backbone communications network and the power line transmission medium. However, the base station does not connect individual subscriber devices, but it may provide multiple network communications interfaces, such as xDSL for connection with a high speed network (figure 26). In this way, a PLC base station can be used to realize connection with backbone networks using various communication technologies.

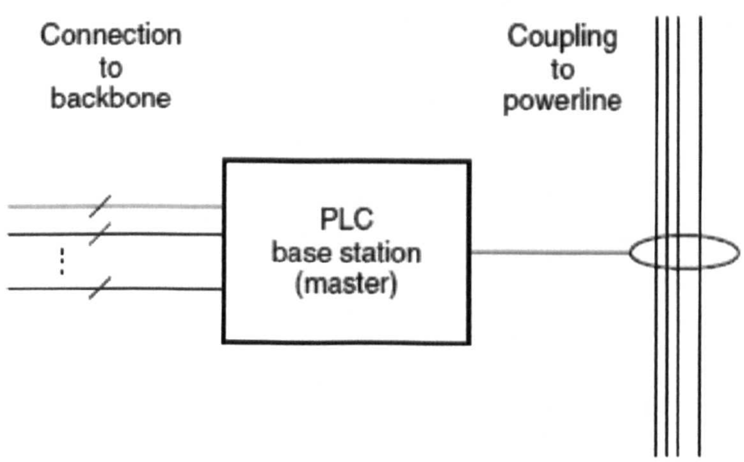


Figure 26. Connection of PLC base station [25]

Usually, the base station controls the operation of a PLC access network. However, the realization of network control or its particular functions can be realized in a distributed manner. In a special case, each PLC modem can take over the control of the network operation and the realization of the connection with the backbone network.

1.17 PLC Smart Grid Systems

A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users.

Essentially, all modern societies and economies build on the reliable supply of electricity, provided through complex electricity networks. However, the fundamental architecture of these networks has hardly changed over the past decades. We mainly find centralized energy generation in large, predominantly carbon-based power plants, which are often remote from the distributed consumption centres, and limited interconnection capabilities between the different areas.

Only today, we are experiencing a change in paradigm towards interactive and more customer-centred electricity networks, which will entail many changes in network design and control. These networks are collectively referred to as Smart Grids. Different entities worldwide are currently involved in giving a new perspective to the evolution of electricity networks into Smart Grids. These include, for example, the InteliGid initiative of the Electric Power Research Institute (EPRI) in the USA and the

Smart Grids Technology platform in Europe. They share the vision of new products, processes and services which will improve the efficiency of electricity networks, allow for integration of new and small energy resources and ensure the reliable operation of the existing and new infrastructure. Figure 27 demonstrates the evolutionary character of smart grids.

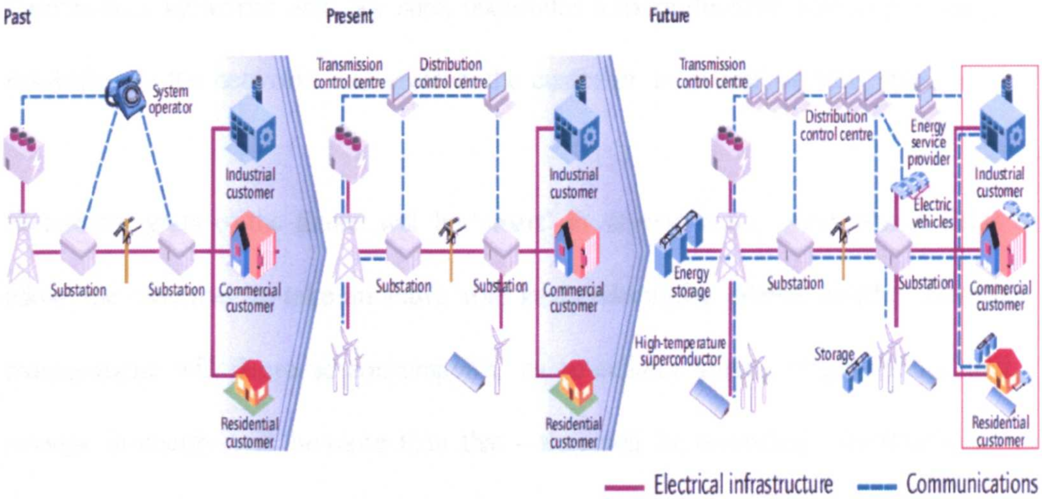


Figure 27. Smarter electricity systems.

Benefits of Smart Grid will include increase in power transfers and reduction in power losses, enhanced power electronic technologies, increase in the degree of automation, system-wide remote control, new simulation tools to assist the adaptation of innovative technologies for practical application, and communication, metering and business systems. While technology for smarter grids has been available for some time, there was insufficient impetus and pressure to apply them. This is different today, and Smart Grids will incorporate the latest technologies to ensure network flexibility, accessibility, reliability and economy.

The grid today is still one that carries the electricity flow in one direction, from the power stations to the consumers. Dispatching of power and network control is the responsibility of central facilities, without consumer participation, and consequently without end-to-end cooperation. In future, distribution grids will be active and will accommodate bidirectional power flows. Market forces will affect these grids deeply, and the grid control centre will progressively acquire an overall supervisory role. Distribution networks will, for sure, undertake a more decisive role in providing reliability to the network, and involve the customer in overall service efficiency.

Electricity grids of the future will be 'smart' in several ways. First, Smart Grids will allow the customer to take an active role in the electricity power supply. Demand management will decrease consumption, as an indirect source of generation, and savings in energy will be more than that – they will be rewarded. Distributed generation will become a reality and the grid will prepare for better interconnection. Second, the new system will offer greater efficiency. Operation and maintenance of the network will gain efficiency, and the quality factors of the services will improve as a consequence. Electricity links will improve their performance, go supranational and take environmental concerns into consideration. Third, digital technology will make the grid smarter. These include intelligent devices to monitor and measure, bidirectional communications to allow devices to communicate among each other and with control centres, and advanced control systems to let computers take automatic decisions, while releasing human operators from repetitive tasks to focus and control the global picture.

1.18 Modulation and Coding Systems for PLC

Having reviewed the characteristics of power line and PLC system, it is now possible to compare various communication technology used for PLC. We will begin by examining technologies in order of historical significance. Many early power line communication devices used narrow band transmission combined with a phase-locked-loop type receiver. These are now discussed in details.

Modulation is a process of mapping of the information on changes in the carrier phase, frequency or amplitude or combination. The choice of the modulation technique for a given communications system strongly depends on the nature and the characteristics of the medium on which it has to operate.

The power line channel presents hostile properties for communications signal transmission, such as noise, multipath propagation, and strong channel selectivity. Besides the low realization costs, the modulation to be applied for a PLC system must also overcome these channel impairments. For example, the modulation, to be a candidate for implementation in PLC system, must be able to overcome the nonlinear channel characteristics. This channel nonlinearity would make the demodulator very complex and very expensive, if not impossible, for data rates above 10 Mbps with single-carrier modulation. Therefore, the PLC modulation must overcome this problem without the need for a highly complicated equalization. Impedance mismatch on power lines results in echo signal causing delay spread, consisting in another challenge for the modulation technique, which must overcome this multipath. The chosen modulation must offer a high flexibility in using and/or avoiding some given frequencies if these are strongly disturbed or are allocated to another service and therefore forbidden to be used for PLC signals.

There are many means of digitally modulating a carrier frequency. Different modulation schemes such as Frequency Shift Keying (FSK), Code-Division Multiple Access (CDMA), Binary Phase Shift Keying (BPSK), and Orthogonal Frequency Division Multiplexing (OFDM) are discussed as an appropriate choice for PLC [46]. Depending on the target application, each modulation technique has certain advantages and disadvantages.

Most digital modulation schemes operate with an analogue carrier, which is varied in some way to represent the digital information to be transmitted[8].

1.18.1 Frequency Shift Keying (FSK)

One of the simplest types of digital modulation is two-frequency Frequency Shift Keying (FSK), the digital form of analogue Frequency Modulation (FM). Here, one frequency is used to represent a binary 1 and another to represent a binary 0 (figure 28). One or other of the frequencies is always present on the line while communication is in progress.

[8] One exception is Ultra Wide Band (UWB), which uses narrow pulses

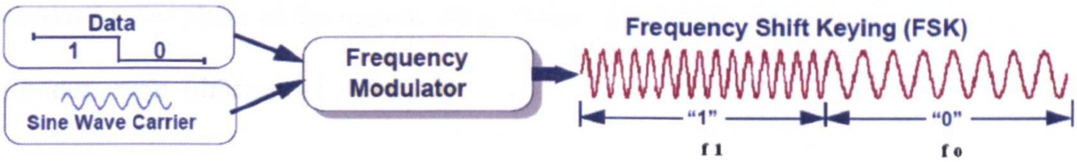


Figure 28. Frequency Shift Keying (FSK) Waveform [50]

The modulated signal can be written very simply as consisting of two different carriers.

$v_0(t) = V_c \cos(2\pi f_0 t)$ (Eqn. 1)

$v_1(t) = V_c \cos(2\pi f_1 t)$ (Eqn. 2)

$v_0(t)$ in response to a 0 and $v_1(t)$ in response to a 1.

For lowest-cost and low data rate power line system FSK seems to be a good solution. For FSK a significant part of the spectrum is attenuated more than 40 dB (3 – 6 MHz). There are also parts that are not flat for FSK transmission.

1.18.2 Binary Phase Shift Keying (BPSK)

Another simple method is to use a single carrier frequency and to shift the phase of the carrier in one direction to represent a binary 1 in the input data stream and to shift it back to represent a binary 0. This is known as Binary Phase Shift Keying (BPSK) (figure 29). At the receiver, detection is achieved either by comparing the phase of the received carrier with a locally generated carrier (coherent detection) or by comparing the phase of the current cycle of the received waveform with that of the previous cycle (differential detection).

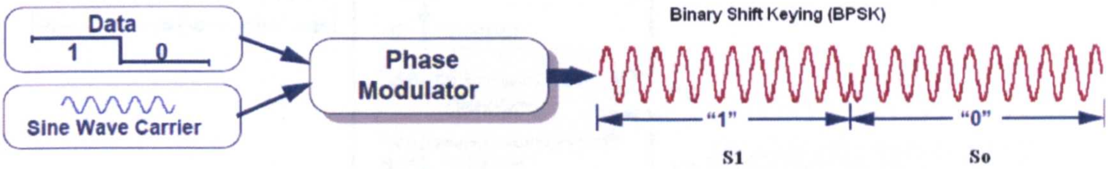


Figure 29. Binary Phase Shift Keying (BPSK) Waveform [50]

Mathematically, BPSK is represented as below:

Where,

$s_0 = - V_c \cos 2\pi f_c t$ (Eqn. 3)

$s_1 = Vc \cos 2\pi f_c t$ (Eqn. 4)

1.18.2.1 Phase Locked Loop Receiver

A phase-locked-loop receiver which can be used to receive any of these two transmissions (FSK and BPSK) is illustrated in figure 30. With this technology the PLL typically adjusts the phase of the receiver's local oscillator until the down converted and filtered signal in the quadrature (Q) channel is nulled out. The filtered "I" channel is then used as recovered representation of the transmitted data.

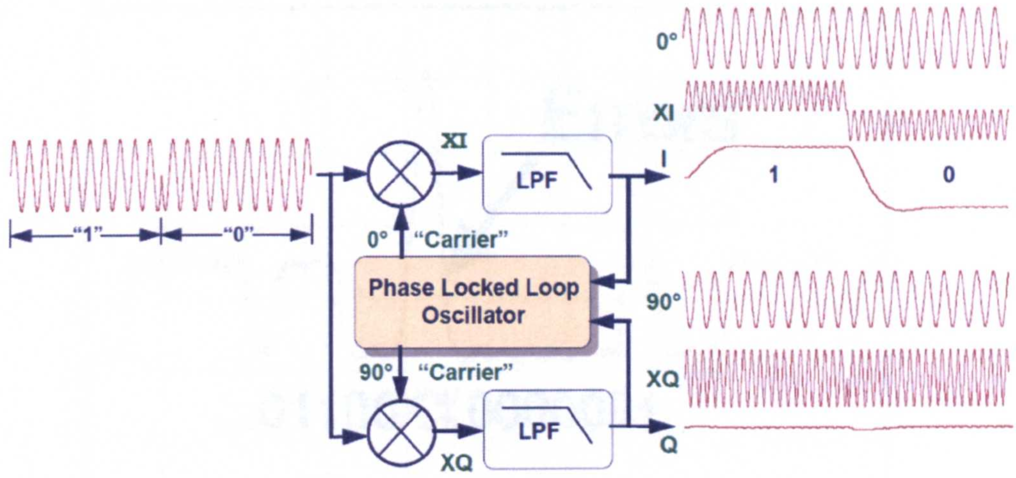


Figure 30. A phase locked loop receiver [50]

A serious limitation with this approach emerges when it is evaluated in light of typical power line noise. Impulse noise from light dimmers is spread over several bit times by the required narrow receive filter. Figure 31 is an oscilloscope plot of the output from one of these receivers with a 66 dB attenuated input signal, disturbed by an impulse from a light dimmer located next to the receiver. As the graph shows, two of the received bits are in error. This and other limitations have caused many companies to abandon this technology for use in power line communication.

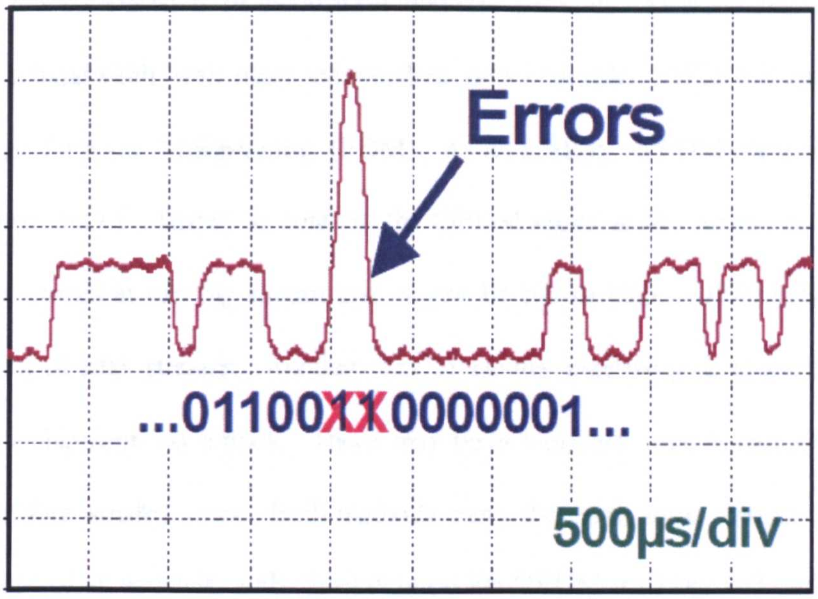


Figure 31. Errors in PLL recovered signal due to impulse noise [50]

1.18.3 Orthogonal Frequency Division Multiplexing (OFDM)

Recent investigations have focused on modulation techniques that have shown good performances in other difficult environment and were therefore adopted for different systems with wide deployment. Transmission rates up to 10 Mb/s can be achieved with more band-efficient modulation techniques such as OFDM. The Orthogonal Frequency Division Multiplexing (OFDM), which has been adopted for the European Digital Audio Broadcasting (DAB), the Digital Subscriber Line (DSL) technology.

In this section, the principles of OFDM techniques are discussed. Then, some practical realizations of the modulator (or transmitter) and its corresponding demodulator (or receiver) are proposed for each modulation.

OFDM is a combination of modulation and multiplexing. Multiplexing is a method of sharing a bandwidth with other independent data channels. OFDM is special case of frequency Division Multiplexing (FDM). As an analogy, a FDM channel is like a water flow out of a faucet, in contrast the OFDM signal is like a shower. In a faucet all water comes in one big stream and cannot be sub-divided. OFDM shower is made up of a lot of little streams. Another way to see this intuitively is to use the analogy of making a shipment via a truck. There may be two options, one to hire a big truck or a bunch of four smaller ones. Both methods carry the exact same amount of data. But in the case of an accident, only ¼ of data on the OFDM trucking will suffer. These four smaller trucks when seen as signals called the sub-carriers in an OFDM system and they must be orthogonal for this idea to work. The independent sub-channels can be multiplexed by frequency division multiplexing (FDM), called Multi-Carrier Transmission or Multi-Carrier Modulation (MCM). MCM is the principle of transmitting data by dividing the data stream into several parallel bit streams, each of which has a much lower bit rate, and by using several carriers, called subcarriers, to modulate these sub-streams.

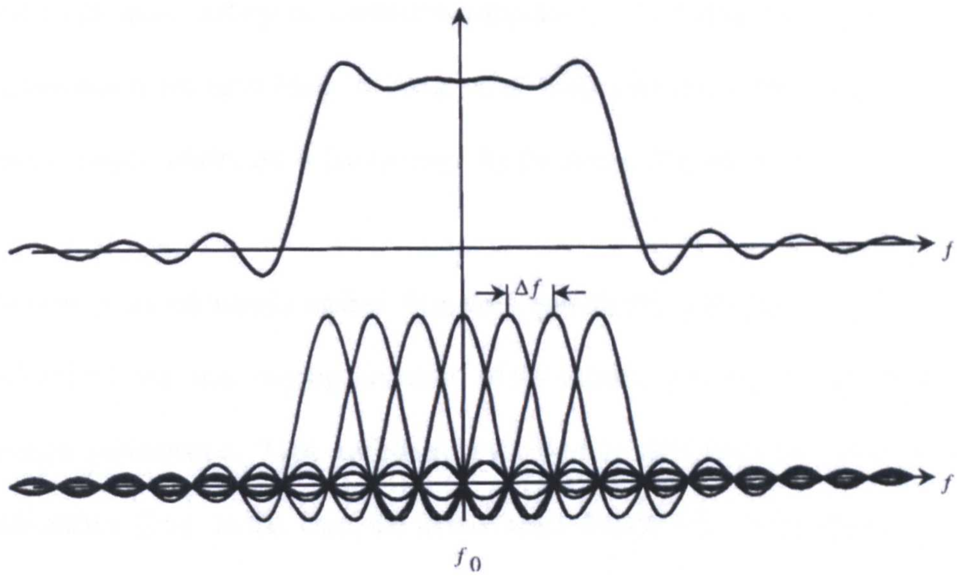


Figure 32. Seven OFDM symbol presentation in the frequency domain [2]

The first systems using MCM were military HF radio links in the 1960s. Orthogonal Frequency Division Multiplexing is a special form of MCM with densely spaced subcarriers and overlapping spectra, as shown by the OFDM symbol representation in the frequency domain in figure 32. To allow an error-free reception of OFDM signals, the subcarriers' waveforms are chosen to be orthogonal to each other. Compared to modulation methods such as Binary Phase Shift Keying (BPSK), OFDM transmits symbols that have relatively long time duration, but a narrow bandwidth. In the case of a symbol duration which is less than or equal to the maximum delay spread, as is the case with the other modulations, the received signal consists of overlapping versions of these transmitted symbols or Inter-Symbol Interference (ISI). Usually, OFDM systems are designed so that each subcarrier is narrow enough to experience frequency-flat fading. This also allows the subcarriers to remain orthogonal when the signal is transmitted over a frequency-selective but time invariant channel. If an OFDM modulated signal is transmitted over such a channel, each subcarrier undergoes a different attenuation. By coding the data sub-streams, errors which are most likely to occur on severely attenuated subcarriers are detected and normally corrected in the receiver by the mean of forward error correcting codes.

In spite of its robustness against frequency selectivity, which is seen as an advantage of OFDM, any time-varying character of the channel is known to pose limits to the system performance. Time variations are known to deteriorate the orthogonality of the subcarriers [26]. In this case, the Inter-Carrier Interference (ICI) appears because the signal components of a subcarrier interfere with those of the neighbouring subcarriers.

By transmitting information on N subcarriers, the symbol duration of an OFDM signal is N times longer than the symbol duration of an equivalent single-carrier signal. Accordingly, ISI effects introduced by linear time dispersive channels are minimized. However, to eliminate the ISI completely, a guard time is inserted with a duration longer than the duration of the impulse response of the channel. Moreover, to eliminate ICI, the guard time is cyclically extended. It is to be noted that, in the presence of linear time dispersive channels, an appropriate guard time avoids ISI but not ICI, unless it is cyclically extended [28]. For this reason a guard time with Tcp duration is added to the OFDM symbol, and in order to build a kind of periodicity around this OFDM symbol the content of this guard time is duplicated from the first part of the symbol, as represented in figure 33.

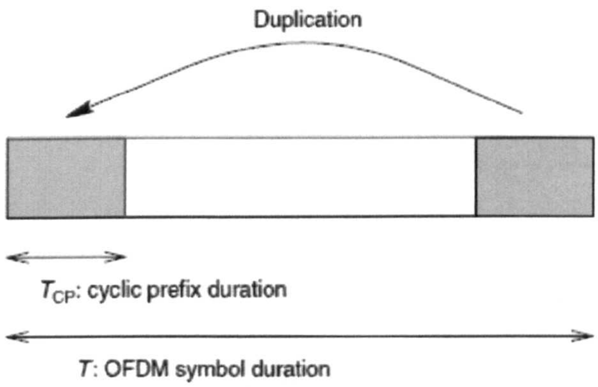


Figure 33. Adding the cyclic prefix by duplicating the first part of the original symbol

In this case, the guard time becomes the cyclic prefix (CP). The insertion of the appropriate cyclically extended guard time eliminates ISI and ICI in a linear dispersive channel; however, this introduces also a loss in the signal-to-noise ratio (SNR) and an increase of needed bandwidth [25].

The SNR loss is given by:

$$SNR_{loss}(dB) = 10\log\frac{T}{T - T_{cp}} \qquad \text{(Eqn. 5)}$$

and the bandwidth expansion factor is given by:

$$\varepsilon_B = \frac{T}{T - T_{cp}} \qquad \text{(Eqn. 6)}$$

1.18.3.1 Generation of OFDM Signals

The generation of the OFDM symbols is based on two principles. First, the data stream is subdivided into a given number of sub-streams, where each one has to be modulated over a separate carrier signal, called subcarrier. A simplified example of OFDM using 4 sub-carriers is shown in figure 34 and figure 35.

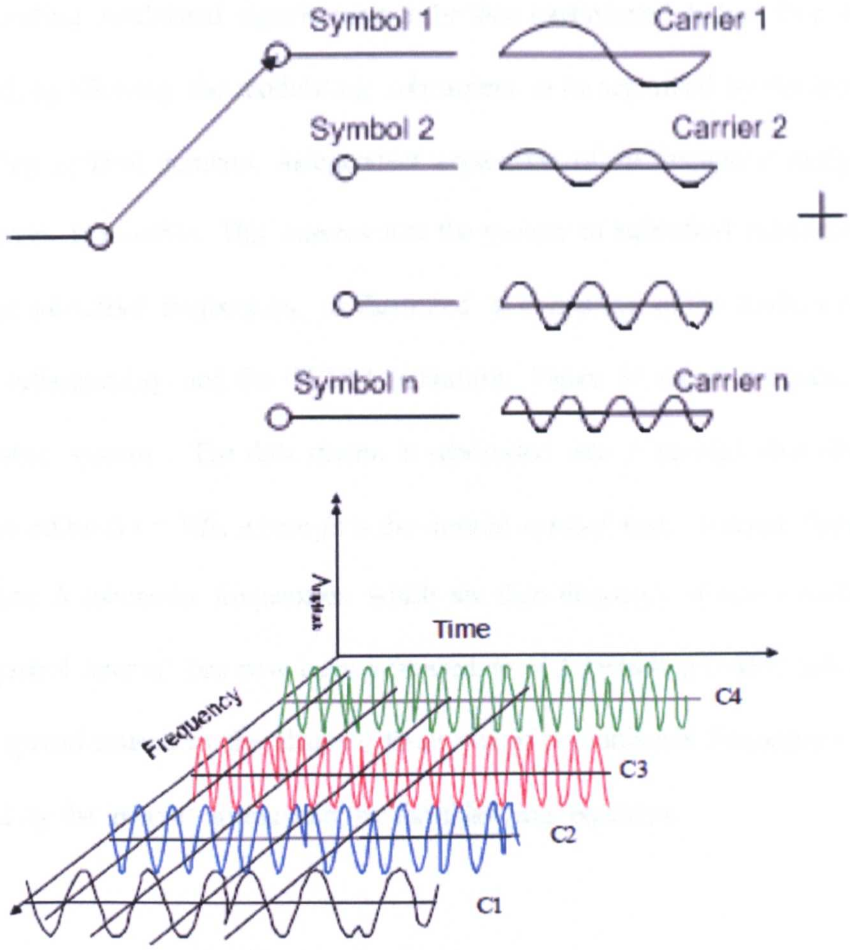


Figure 34. OFDM signal in time and frequency domain. [30]

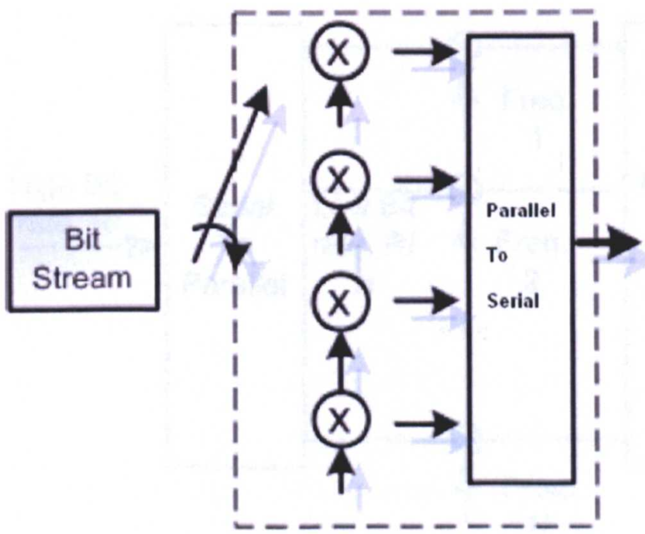


Figure 35. Simplified functional diagram of an OFDM signal creation.[30]

The resulting modulated signals have to be then multiplexed before their transmission. Second, by allowing the modulating subcarriers to be separated by the inverse of the signalling symbol duration, independent separation of the frequency multiplexed subcarriers is possible. This ensures that the spectra of individual subcarriers are zero at other subcarrier frequencies, as illustrated in consisting of the fundamental concept of the orthogonality and the OFDM realization. Figure 36 shows the basic OFDM transmitter system . The data stream is subdivided into N parallel data elements and are spaced by $\Delta t = 1/fs$, where fs is the desired symbol rate. N serial elements modulate N subcarrier frequencies which are then frequency division multiplexed. The symbol interval has now been increased to $N\Delta t$ which provides robustness to the delay spread caused by the channel. Each one of two adjacent frequencies is then spaced by the interval formulated by the following equation:

$$\Delta f = \frac{1}{N.\Delta t} \qquad \text{(Eqn. 7)}$$

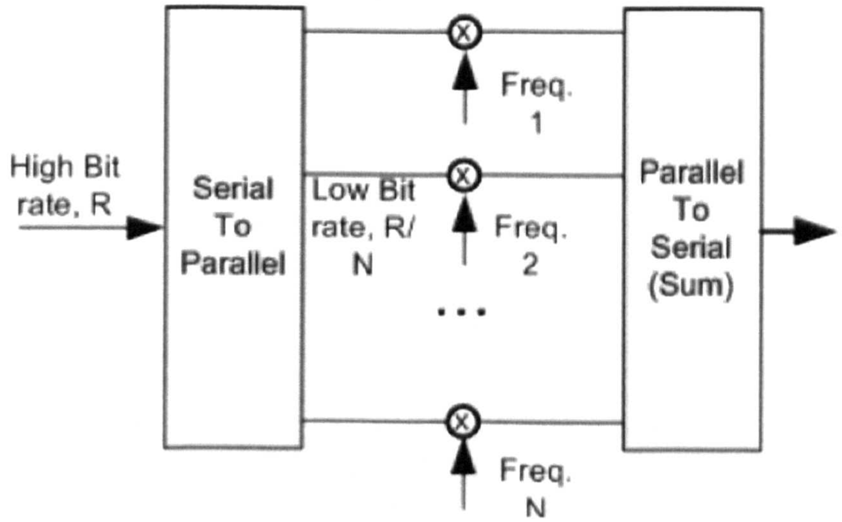


Figure 36. Basic multi-carrier OFDM transmitter.[30]

1.18.4 OFDM Simulation using MATLAB

Studies of OFDM signals and their performance under varying channel conditions often utilize highly specialised mathematical tools such as MATLAB Simulink. This software package provides a rich set of built-in libraries and standard building blocks for use in rapid development. Channel characteristics, modulation and demodulation techniques are modelled, simulated, and studied under these parameterizations. The OFDM simulator contains a large number of variable parameters that leads to a myriad of channel conditions and BER rates. The relevant variable parameters for the purpose of this study include:

- Modulation type – OFDM
- Multipath
- Number of effective subcarriers
- Number of symbols in cyclic prefix and cyclic postfix
- Transmitter gain, receiver gain
- Mean transmit power, receiver noise figure
- SNR
- Frequency offset

These variable parameters are fed into MATLAB. A dynamic channel is then generated based on the input parameters. The OFDM model in Simulink, upon the start of simulation, generates a stream of bits and modulates them to the specified modulation scheme. Modulation is the process of translating an outgoing data stream into symbols for transmission by the sender. The symbols are then brought to the transmitter RF front end and simulated across the generated channel. On the receiver side, the OFDM receiver locks on the incoming signal and the receiver baseband demodulates the signal back to the stream of bits. The transmit and receive bits are compared and BER is calculated based on the number of error bits and the total number of bits sent. Furthermore, the receiver calculates the effective SNR per OFDM subcarrier seen at the receiver baseband. The average received effective SNR is calculated at the end of simulation. A picture of the OFDM simulator is shown in figure 37.

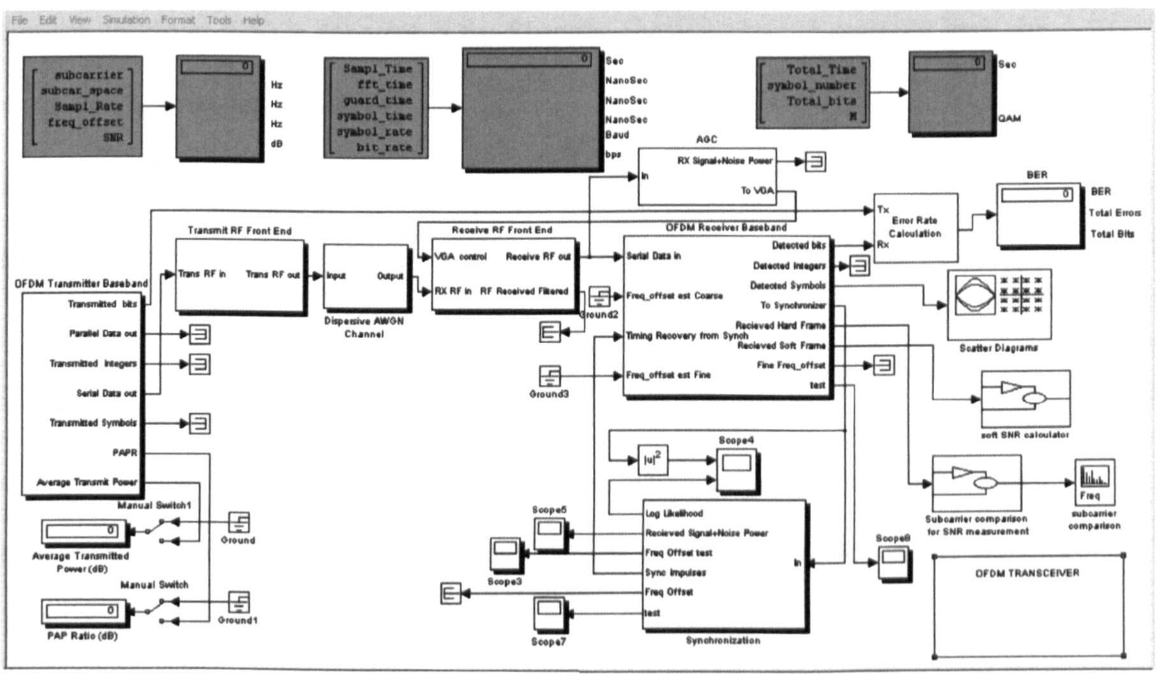


Figure 37. The MATLAB Simulink OFDM Simulator. [67]

1.18.5 Spread-Spectrum Modulation (SS)

Spread-spectrum (SS) communications technology was first described on paper by an actress and a musician! In 1941, Hollywood actress Hedy Lamarr and pianist George Antheil described a secure radio link to control torpedos and received a U.S. patent. It was not taken seriously at that time by the US Army and was forgotten until the 1980s. It has now become increasingly popular for applications that involve radio links in hostile environments.

Spread-spectrum (SS) is apparent in the Shannon-Hartley channel capacity limit for error-free communication theory:

$$\textit{Channel Capacity, } C = B \log_2\left(\frac{S}{N}+1\right) \text{ bits/second} \qquad \text{(Eqn. 8)}$$

Where,

C is the channel capacity in bits per second (bps), which is the maximum data rate for a theoretical bit-error rate (BER). B is the required channel bandwidth in Hz, and S/N is the signal-to-noise power ratio.

The Shannon-Hartley theorem tells us if the required information transfer is less than the capacity limit (C), then error-free communication is possible. If information transfers at a rate greater than C is attempted, then errors in transmission will always occur no matter how well the equipment is designed.

To be more explicit, one assumes that C, which represents the amount of information allowed by the communication channel, also represents the desired performance. Bandwidth (B) is the price to be paid, because frequency is a limited resource. S/N ratio expresses the Spread spectrum is a type of modulation that spreads data to be transmitted across the entire available frequency band, in excess of the minimum bandwidth required to send the information. The first spread-spectrum systems were designed for wireless digital communications, specifically in order to overcome the jamming situation, that is, when an adversary intends to disrupt the communication. To disrupt the communication, the adversary needs to do two things; first to detect that a transmission is taking place and second to transmit a jamming signal that is designed to confuse the receiver. Therefore, a spread-spectrum system must be able to make these tasks as difficult as possible. Firstly, the transmitted signal should be difficult to detect by the adversary, and for this reason the transmitted spread-spectrum signal is mostly called noise-like signal. Secondly, the signal should be difficult to disturb with a jamming signal.

Spread spectrum originates from military needs and finds most applications in hostile communications environments; such is the case in the PLC environments. Its typical applications are the cordless telephones, wireless LANs, PLC systems and cable replacement systems such as Bluetooth. In some cases, there is no central control over the radio resources, and the systems have to operate even in the presence of strong interferences from other communication systems and other electrical and electronic devices. In this case, the jamming is not intentional, but the electromagnetic interferences may be strong enough to disturb the communication of the non-spread spectrum systems operating in the same spectrum.

1.18.6 Direct Sequence Spread Spectrum (DSSS)

This is probably the most widely recognized form of spread spectrum. The DSSS process is performed by effectively multiplying an RF carrier and a pseudo-noise (PN) digital signal as shown in figure 38. First the PN code is modulated onto the information signal using one of several modulation techniques (e.g. BPSK). Then, a doubly balanced mixer is used to multiply the RF carrier and PN modulated information signal. This process causes the RF signal to be replaced with a very wide bandwidth signal with the spectral equivalent of a noise signal. The demodulation process (for the BPSK case) is then simply the mixing/multiplying of the same PN modulated carrier with the incoming RF signal. The output is a signal that is a maximum when the two signals exactly equal one another or are "correlated". The correlated signal is then filtered and sent to a BPSK demodulator.

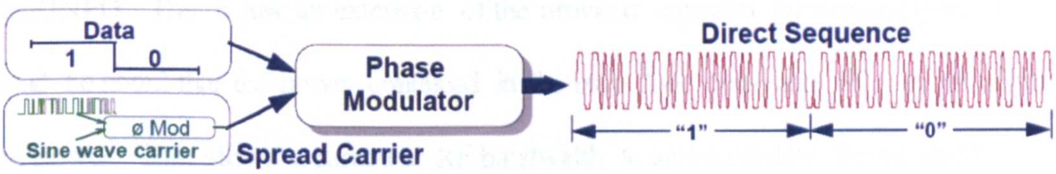


Figure 38. Direct Sequence Spread Spectrum [50]

The signals generated with this technique appear as noise in the frequency domain. The wide bandwidth provided by the PN code allows the signal power to drop below the noise threshold without loss of information. The spectral content of an SS signal is shown in figure 38. This is just the spectrum of a BPSK signal with a (sin x / x)2 form.

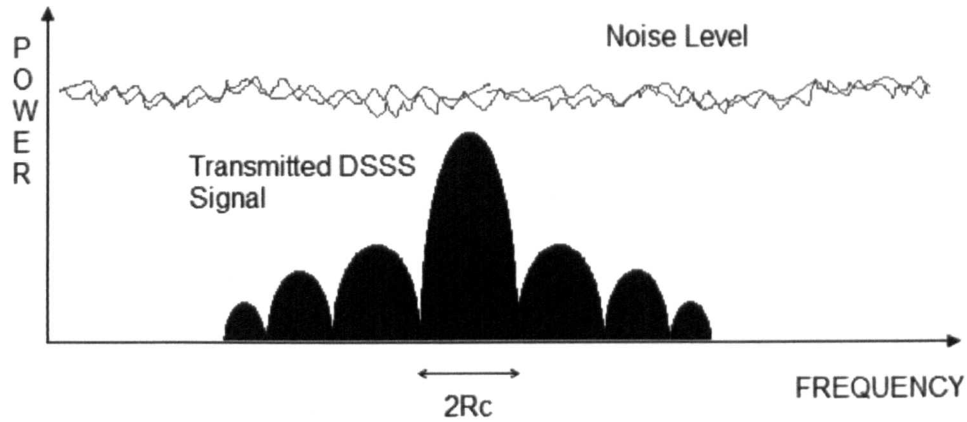


Figure 39. BPSK DSSS Spectrum

The bandwidth in DSSS systems is often taken as the null-to-null bandwidth of the main lobe of the power spectral density plot (indicated as 2Rc in figure 39). The half power bandwidth of this lobe is 1.2 Rc, where Rc is the chip rate. Therefore, the bandwidth of a DSSS system is a direct function of the chip rate; specifically 2Rc/RINFO. This is just an extension of the previous equation for process gain. It should be noted that the power contained in the main lobe comprises 90 percent of the total power. This allows a narrower RF bandwidth to accommodate the received signal with the effect of rounding the received pulses in the time domain.

One feature of DSSS is that QPSK may be used to increase the data rate. This increase of a factor of two bits per symbol of transmitted information over BPSK causes an equivalent reduction in the available process gain. The process gain is reduced because for a given chip rate, the bandwidth (which sets the process gain) is halved due to the two-fold increase in information transfer. The result is that systems in a spectrally quiet environment benefit from the possible increase in data transfer rate.

Direct Sequence Spread Spectrum (DSSS) is the most applied form of the spread spectrum in several communications systems. To spread the spectrum of the transmitted information signal, the DSSS modulates the data signal by a high rate pseudorandom sequence of phase modulated pulses before mixing the signal up to the carrier frequency of the transmission system. Typical applications for the resulting short-range data transceivers include satellite-positioning systems (GPS), 3G mobile telecommunications, W-LAN (IEEE802.11a, IEEE802.11b, IEE802.11g), and Bluetooth. SS techniques also aid in the endless race between communication needs and radio-frequency availability (the radio spectrum is limited, and is therefore an expensive resource).

1.18.7 Frequency Hopping Spread Spectrum

Frequency Hopping Spread Spectrum technology is derived from military radio technology where it was designed to be inherently secure and reliable under adverse battle conditions. Frequency Hopping is a very robust and reliable Spread Spectrum technology and ideal for applications where data reliability is critical.

Here, the carrier frequency (or frequencies) deliberately changes, either at set time intervals, or in response to other conditions as shown in figure 40.

Figure 40. Frequency Hopping Spread Spectrum [50]

Frequency changes in the time domain, may occur in a controlled, pseudo-random fashion in order to provide security from interception. Alternatively, the frequencies may change in response to conditions on the transmission medium (i.e. power line noise within a certain frequency band causes the carrier to change to a frequency outside of that band). This type of transmitter is typically no more complicated than its narrowband counterpart. In practice the extra modulation step is simply performed prior to storing a "pre-spread" carrier fed into read only memory (ROM).

Spread spectrum reception is then performed by correlating the received spread spectrum signal with a replica of the expected waveform. The process is shown in figure 41.

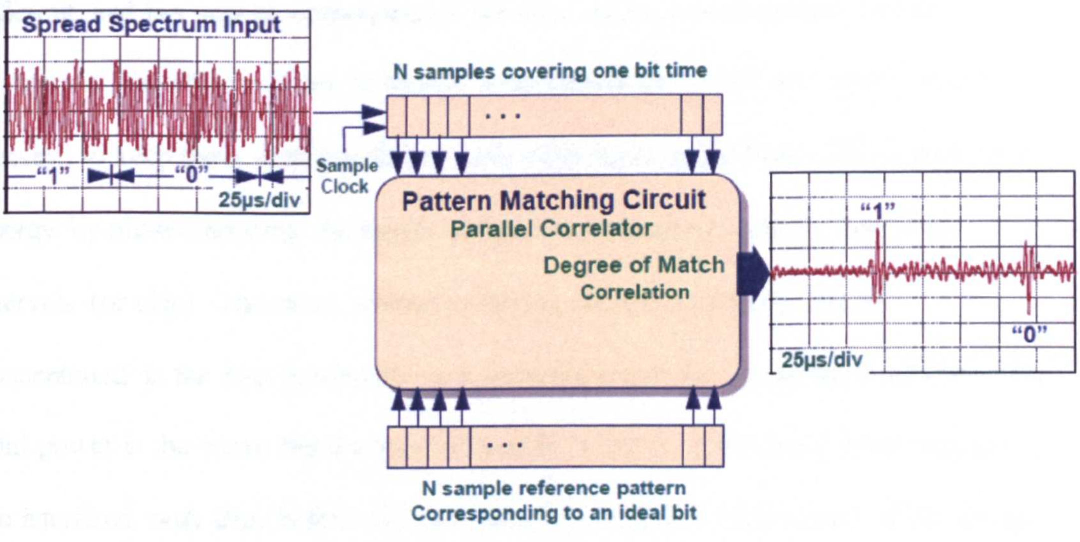


Figure 41. A spread spectrum receiver [50]

Another characteristic of spread spectrum technology which must be considered relates to the bandwidth consumed by a spread signal. CENELEC regulations (EN-50065-1) prohibit power line signalling above 150 kHz due to potential interference with low frequency licensed radio services. Furthermore, the European community has viewed power line bandwidth as a resource to be shared between all interested parties. The result of these regulations is that the consumer use bands are too narrow for the effective use of spread spectrum technology.

1.18.8 Comparison of DSSS and FHSS

The comparison can be achieved according to different evaluation parameters, such as the spectral density reduction, interference susceptibility and capacity. Furthermore, the choice of suitable scheme according to the system needs is based on parameters that are linear or inversely dependent on each other. Both DSSS and FHSS reduce the average power spectral density of a signal. The way they do it is fundamentally different and has serious consequences for other users. For an optimal system realization, the objectives are to reduce both transmitted power and power spectral density, to keep them from interfering with other users in the band. DSSS spreads its energy by phase-chopping the signal so that it is continuous only for brief time intervals (or chip). Therefore, instead of having all the transmitted energy concentrated in the data bandwidth, it is spread out over the spreading bandwidth. The total power is the same, but the spectral density is lower. Of course, more channels are interfered with than before, but at a much lower level. Furthermore, if the spread signal comes in under the noise level of most other users, it will not be noticed. Traditional FHSS signals lower only their "average" power spectral density hopping over many channels. But during one hop, a FHSS signal appears to be a narrow band signal, with a higher power spectral density. The interference susceptibility is another important parameter which allows the system to operate properly. In DSSS receivers, the de-spreading operation consists in multiplying the received signal by a local replica of the spreading code. This correlates with the desired signal to push it back to the data bandwidth, while spreading all other non-correlating signals. After the de-spread signal is filtered to the data bandwidth, most of the noise is outside this new narrower bandwidth and is rejected. This helps only with all types of narrowband and uncorrelated interference, and it has no advantage for wideband interference since spread noise is still noise and the percentage that falls within the data bandwidth is unchanged. The FHSS signal is agile and does not spend much time on any one frequency. When it hits a frequency that has too much interference, the desired signal is lost. In a packet switched system, this results in a retransmission, usually over a clearer channel. In a fast enough FHSS system, the portion of lost signal may be recovered by using a FEC. DSSS have more advantages than the FHSS systems [32].

1.18.9 Choice of Modulation Scheme for PLC Systems

Several investigations have been carried out to find suitable OFDM implementations for PLC networks. In order to avoid hard degradation of OFDM signals over the transmission channel, which is caused by the frequency-selective fading, a method for subcarriers power control is proposed in [33]. This solution consists of controlling the transmission power of each subcarrier of OFDM signal in order to maximize the average SNR of each subcarrier of the received signal. This controlling is so flexible that the total transmitted power is not increased. Further improvement of such controlling is possible by spreading the parallel sub-streams at the output of the serial-to-parallel converter output [34, 35]. An OFDM system which subdivides the original information into three parallel data groups, where each group is mapped according to BPSK and coded according to Reed–Solomon code or convolution code, is also investigated in [36]. Performances of OFDM system were also investigated under different noise scenarios, especially under the impulsive noise, which is considered the dominating noise in a PLC environment [37, 38]. OFDM has proven its ability to deal with multipath propagation in wireless broadband transmission system as well as radio interference in asymmetrical DSL.

Spread-spectrum modulation techniques, with direct sequence or frequency hopping, were investigated to be implemented in a PLC physical layer. For example, in [39], a so-called "low complexity all-digital DSSS transceiver" is proposed, which is based on a delay-locked loop for clock recovery and on a phase recovery that is implicit in the timing synchronization. An "iterative detection algorithm" for M-ary spread-spectrum system over a noisy channel is investigated and this shows a remarkable improvement of the detection performance for M-ary systems [40]. Spread Spectrum, due to its robustness against interference and its ability for multiple access operation, has been considered as a solution for PLC. Around 1985 several Japanese Post Office Ministry worked enthusiastically toward planning a power line home bus system. The first proposal using SS was put forward by NEC in 1993. NEC Home Electronics Co., developed a SS power line home communications system for a 10-450 KHz frequency band and a bit rate of 9.6 kb/s, with a processing gain of 31 [47].

However, the main drawback of the spread-spectrum technique is the relative lower realizable bit rate, in comparison with OFDM systems. This makes any decision about the modulation to be adopted for a PLC system more difficult. By deciding for a given modulation, the system designer must know which performance has the higher priority for him and which ones have less importance. Besides the high realizable bit rates, the OFDM systems also show a high robustness against the channel distortions, a flexibility in avoiding the strongly affected channels and an optimal bandwidth utilization by the usage of the slightly disturbed channels through the bit-loading procedure. The main advantage of the spread spectrum is its electromagnetic compatibility, by the radiation of weak electromagnetic fields in the environment [2].

1.18.10 Error Detection and Correction Techniques

PLC networks operate with a signal power that has to be below a limit defined by the regulatory bodies . On the other hand, the signal level has to keep data transmission over PLC medium possible. This means, there should be a certain SNR (*Signal- to-Noise Ratio*) level in the network making communications possible. As long as the SNR is sufficient to avoid the disturbances in the network, the error handling mechanisms do not have to act; for example, if the SNR is sufficient to avoid an influence of the background noise in a PLC network.

More difficulties in PLC transmission systems are caused by impulsive noise, which has much higher power than the background noise. In this case, the SNR is not enough to overcome the disturbances and the resulting in transmission errors. On the other hand, if the noise impulses are longer, additional mechanisms for error handling have to be applied: mechanisms for error correction and retransmission mechanisms for short-term disturbances and capacity reallocation mechanisms for long-term disturbances.

Transmission errors in a digital communication system can be reduced by the use of two main techniques:

- Forward error Correction (FEC)
- Automatic Repeat request (ARQ)

In many transmission systems, forward error correction and interleaving mechanisms are applied to cope with the disturbances. In this case, the transmission systems are able to manage a situation when a number of bits are damaged and, in spite of that, to correct the data contents. The usage of the FEC mechanism gives rise to an overhead, which takes a portion of the network transmission capacity; for example, about 50% overhead is used for the FEC in the GSM system, which improves BER (*Bit Error Rate*) values from 10^{-3} (pure wireless transmission channel) to 10^{-6} [41]. Particular methods for FEC to be applied in PLC networks are the point of current and future research works [42].

In spite of the applied FEC mechanisms and the ability of communication systems to avoid different kinds of disturbances, it is still possible that the transmitted data may be damaged. In the case of errors, the damaged data has to be retransmitted by an ARQ (Automatic Repeat reQuest) mechanism. The application of ARQ can reduce error probability to a very low value and it is only limited by the remaining error probability of CRC (*Cyclic Redundancy Check*) code used for error recognition, or error tolerance specified by a particular application. To deal with disturbances, various communication systems apply a so-called hybrid ARQ/FEC solution, a combination of ARQ and FEC mechanisms [43, 44], which is also expected to be used in PLC networks. The application of ARQ is suitable for data transmission without delay requirements. However, for time-critical services, such as telephony, ARQ adds additional delays that may be not acceptable.

The ARQ mechanisms deal with a relatively short duration of the disturbances (some milliseconds) that occur on one or several data units. On the other hand, so-called long-term disturbances (e.g. caused by narrowband noise produced by short-wave radio stations) make one or more transmission channels unavailable for a longer time. In this case, the ARQ mechanism would constantly repeat the data, making the transmission inefficient. Because of that, long-time disturbed transmission channels should not be used for any transmission until the disturbance disappears. If a disturbed channel is currently used for the transmission, channel reallocation has to be carried out to allow the continuation of affected connections using other error-free channels. The possibility for implementation of reallocation mechanisms has to be also included in the features of the PLC MAC layer.

1.18.11 Forward Error Correction

Forward Error Correction (FEC) is a widely used method to improve the connection quality in digital communications and storage systems. The word "forward" in conjunction with error correction means the correction of transmission errors at the receiver side without needing any additional information from the transmitter. The main concept of FEC is to add a certain amount of redundancy to the information to be transmitted, which can be exploited by the receiver to correct transmission errors due to channel distortion and noise. Therefore, in the literature, the FEC coding is mostly described as channel coding. Shannon presented in his mathematical theory of communication that every transmission channel has a theoretical maximum capacity, which depends on the bandwidth and the signal-to-noise-ratio (SNR), as formulated by Eqn.8 [45]. The capacity of implemented systems is mostly much smaller than the maximum possible value calculated by the theory. For this reason, the use of suitable codes has to allow further improvement in bandwidth efficiency.

1.18.12 Bit Error Rate in PLC System

The performance of any digital transmission system is expressed in terms of its bit error rate (BER), which quantifies the reliability of the entire system from "bits in" to "bits out". The BER is equivalent to the output signal-to-noise ratio of an analogue system and is the probability that a transmitted bit will be incorrectly received.

The BER of a digital system is a simple concept; its definition is simply:

$$BER = \frac{Number\ of\ bits\ in\ error}{Number\ of\ bits\ received} \qquad (Eqn.9)$$

With a strong signal and an unperturbed signal path, this number is so small as to be insignificant. It becomes significant when we wish to maintain a sufficient signal-to-noise ratio in the presence of imperfect transmission through electronic circuitry (amplifiers, filters, mixers, and digital/analogue converters) and the transmission channel.

Noise is the main enemy of BER performance. Noise is a random process, defined in term of statistics. The BER is quoted as a number; for example, 1 x 10^{-5} means that, on average, one bit in every 100 000 will be in error. An error in the correct reception of a bit may occur because noise picked up by the system has corrupted the signal waveform to such an extent that that the decision circuitry in the receiver cannot accurately determine whether a bit is a one or zero.

The efficiency η of a digital system is:

$$\eta = \frac{\textit{Received information bit energy}}{\textit{noise density}} = \frac{E_b}{N_0} \qquad (Eqn. 10)$$

The noise density N_o is the noise level in a 1 Hz bandwidth and is equal to -204 dBW +F dB, where F is the noise figure of the receiving system.

Efficiency η and BER can be defined in terms of the probability of error (POE),

$$POE = \frac{1}{2}(1 - erf)\sqrt{\frac{E_b}{N_o}} \qquad \text{(Eqn. 11)}$$

Where,

erf is the error function.

The error function is different for the each of the various modulation methods. POE is proportional to $\frac{E_b}{N_o}$, which is a form of signal-to-noise ratio. The energy per bit, E_b

can be determined by dividing the carrier power by the bit rate. As an energy measure, E_b has the unit of Joules. N_o is in power (Joules/seconds) per Hz (seconds), so $\frac{E_b}{N_o}$ is in dimensionless term, or simply, a numerical ratio.

One way to lower the spectral noise density is to reduce the bandwidth, but we are limited by the bandwidth required to transmit the desired bit rate (Nyquist criteria)[9]. We can also increase the energy per bit by using higher power transmission, but interference with other systems can limit that option. A lower bit rate increases the energy/bit, but we lose capacity. Ultimately, optimizing $\frac{E_b}{N_o}$ is a balancing act among these factors.

1.19 Summary

This chapter has discussed the UK power distribution network and given an overview of PLT system. Different digital modulation systems for PLT are discussed and compared. The low-voltage networks have complex topologies that can differ from one network to another. This difference comes from the fact that they have parameters whose values can be varied, such as user density, the user activity and the connected appliances. Generally it can be concluded that low-voltage power supply networks, also including in-home part of the network, have a physical tree topology. However on the logical level, a PLC access network can be considered a bus network, representing a shared transmission medium.

[9] Nyquist criteria states that a band limited analogue signal that has been sampled can be perfectly reconstructed from an infinite sequence of samples if the sampling rate exceeds $2B$ samples per second, where B is the highest frequency in the original signal.

Low voltage networks were designed only for energy distribution to households and a wide range of devices and appliances are either switched on or off at any locations and at any time. This variation in the network leads to strong fluctuation of the medium impedance. These impedance fluctuations and discontinuity lead to multipath behaviour of the PLC channel, making its utilization for the information transmission more delicate. Besides these channel impairments, the noise present in the PLC environment makes the reception of error-free communication signal more difficult.

Two main modulation schemes, namely the OFDM and the Spread Spectrum, with its two forms of Direct Sequence and Frequency Hopping have already shown very good performance. These modulation techniques are robust against narrowband disturbances, which are also expected in the PLC networks and therefore they are considered as suitable scheme for PLC. The modulation technique to be applied to PLC has to overcome the strong PLC channel impairments in order to realize acceptable BER with a SNR as low as possible, to be able to coexist with other systems already deployed in its environment and to guarantee a satisfactory quality of service.

The next chapter present the theory of transmission lines and will explain in more detail the issues of EMC in PLC and work on impedance that has been presented to date by other authors.

Chapter 3: Power Line Communications Propagation Characteristics

3.1 Transmission Channel Characteristics

Power Line Communication is based on transmission and reception using power line wires. Similarly, DSL and cable systems use transmission wires but of different quality. This classes them generally as wire line systems. However, DSL and cable systems are well established throughout the world and have been in use before the introduction of high-frequency PLC systems. They have a well established set of parameters such as characteristic impedance. The PLC system is designed for power transmission at either 240V/50Hz or 110V/60Hz. Further, DSL and cable systems are subject to the IEC CISPR 22 product standards and have a set of emission levels and frequency bands. PLC systems do not have these well defined parameters and therefore are subject to potential interference to other established communication systems.

Standard Communication Characteristics - Deterministic

- Unique frequency specification
- Characteristic impedance
- Minimum noise
- Constant bandwidth
- Standard architecture
- No common mode current
- No radiated emission to cause interference

For PLC systems the characteristics or the lack of them is shown below:

PLC System Communication -Non-Deterministic

- Unique frequency specification
- Impedance
- Minimum noise
- Constant bandwidth
- Standard architecture
- Common mode current
- Radiated emission

Therefore, PLC systems are subject to variable parameters, which are virtually constant for DSL and cable systems. In order to establish the lack of constant characteristics in PLC systems it is necessary to understand the wiring of the PLC network and the propagation of signals along the power distribution lines. This involves understanding the mode of propagation as the signal travels along the transmission line as a differential signal and why there is a common mode signal generated because of the variable line impedance.

The power line was not specifically designed for data transmission and provides a harsh environment for the transmission and receiving of data. There are a number of particular conditions that affect PLC. The impedance of the power distribution network varies considerably according to the type of power cable and network topology, according to the configuration being a single-phase, ring main or a three-phase tree and branch network. Also the frequency of transmission will determine the impedance values of the circuit. This leads to the cable attenuation which may be very high according to the frequency of operation. This can also lead to standing waves on long cables and lead to frequency nulls in the frequency response. In addition, the interfacing of the equipment to the power line will introduce attenuation and noise to the circuit which is affected to by the impedance of the line.

A channel is a physical path between a transmitter and a receiver. Low-voltage power lines consists of many channels each with its own characteristics and quality. Figure 41 shows a communication system using the power line as a channel.

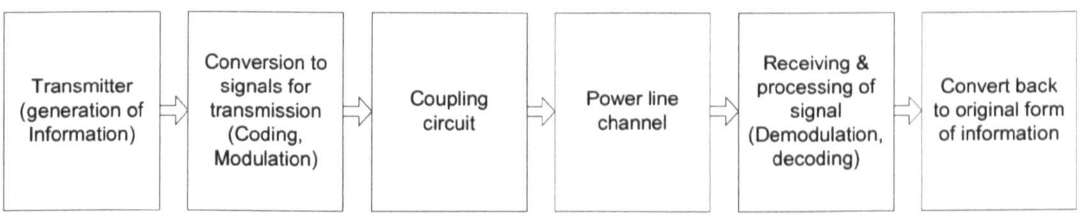


Figure 42. Communication system for the power line channel

A coupling circuit is used to connect the system to the power-line. The purpose of the coupling circuits is two-fold. Firstly, it prevents the damaging 50 Hz signal, used for power distribution, to enter the equipment. Secondly, it certifies that the major part of the received/transmitted signal is within the frequency band used for communication.

PLC technology presents a cost-effective alternative for the realization of the access networks. Electrical supply networks are not designed for communications and therefore, they do not represent a favourable transmission medium. In this chapter, some specific performance problems limiting the application of PLC technology will be discussed.

The power line cables are divided in an asymmetric way (Figure 43), having many irregular connections between network sections and customers and transitions between overhead and underground cables (Figure 44).

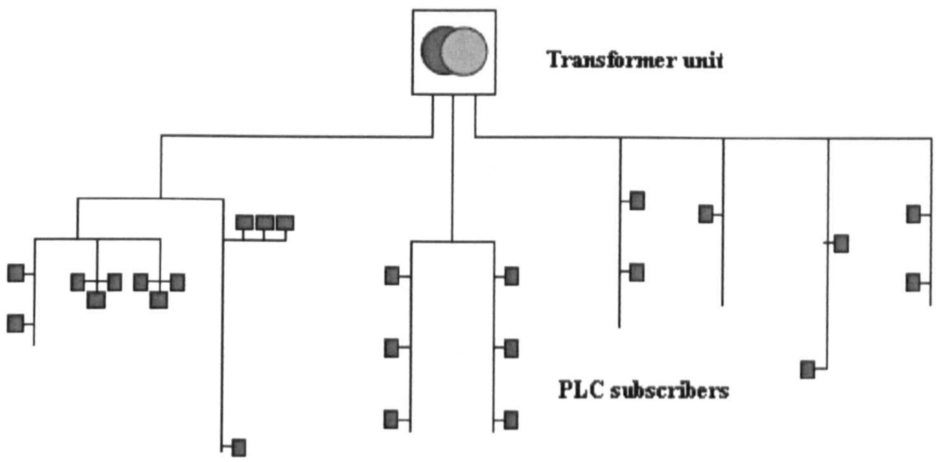


Figure 43. Structure of low-voltage supply network [25]

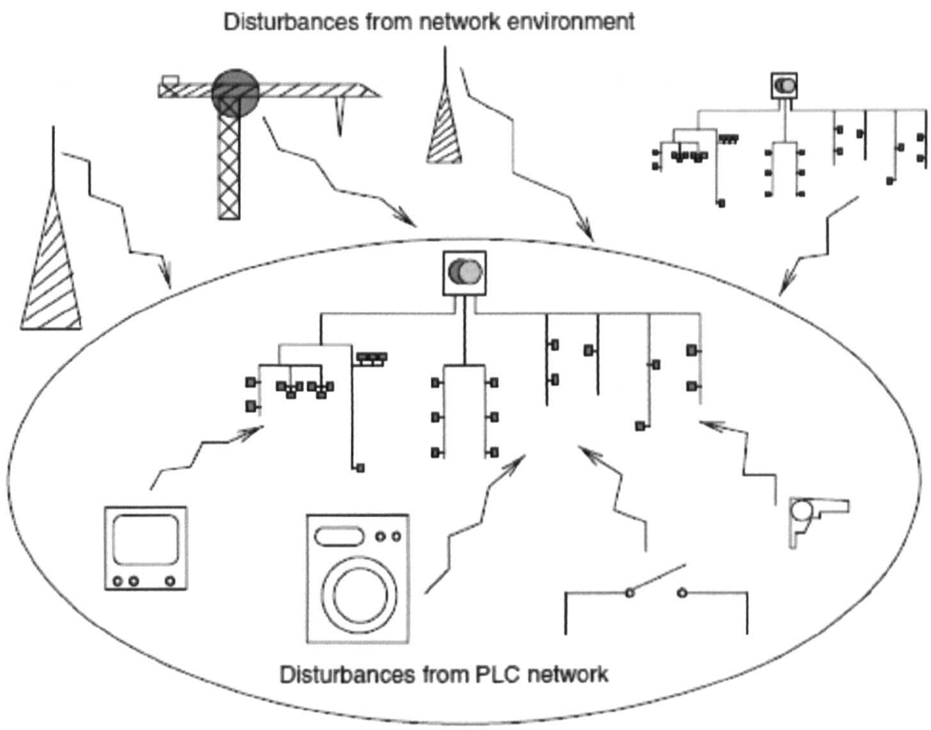


Figure 44. The influence of various disturbance sources [25]

Common causes of noise on high- and medium voltage electrical power networks include corona discharge, lightning, power factor correction banks and circuit breaker operation. On the low-voltage network, much of this noise is filtered by medium/low voltage transformers.

3.2 Electromagnetic Compatibility (EMC) of Narrowband and Broadband PLC Systems

Electromagnetic Compatibility (EMC) is an important consideration for the development and operation of Power Line Communications systems. From the electromagnetic point of view, the injection of the PLC signal in to the power cables results in the radiation of an electromagnetic field in the environment, where the power cables begins acting like an antenna. This field is seen as a disturbance for the environment and for this reason its level must not exceed a certain limit, in order to realize the so-called *electromagnetic compatibility*. Electromagnetic compatibility means that the PLC system has to operate in an environment without disturbing the functionality of the other system existing in this environment.

In this section, after giving a definition of EMC, different aspects and terms are defined. Then, two ways for the classification of electromagnetic disturbances are discussed. To be able to describe the real electromagnetic influence of the PLC systems on its environment, several measurements have been achieved. The measurements were a starting point of the standardization efforts for PLC systems for fixing the limits of the allowed electric (and also the magnetic in some cases) radiated field in their environments. Different standards, standard proposals and standardization bodies are also considered in this section.

3.2.1 EMC Terms

Electromagnetic compatibility is the ability of a device or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances in the form of interferences to any other system in that environment, even to itself. EMC means living in harmony with others and that has to be viewed from two aspects:

- *To function satisfactorily* - meaning that the equipment is tolerant of others. The equipment is not susceptible to electromagnetic (EM) signals that other equipment puts into the environment. This aspect of EMC is referred to as *electromagnetic susceptibility* (EMS).

- *Without producing intolerable disturbances* - meaning that the equipment does not interfere with other equipment. The emission of EM signals by the equipment does not cause electromagnetic interference problems in other equipment that is present. This EMC behaviour is also pointed out as *electromagnetic emission* (EME).

The two main aspects, EME and EMS, and their different variants are presented in figure 44. The concept of susceptibility is complementary to another EMC concept, which is immunity, causing, most of the time, a kind of confusion between both terms. The two terms have quite different meanings. Susceptibility is a fundamental characteristic of a piece of equipment and one can find an EM environment that will adversely affect that equipment. Immunity, on the other hand, when measured in a certain way, indicates to what extent the environment may be EM polluted before the equipment is adversely affected [56].

The electromagnetic noise propagates by conduction and by radiation and therefore, the emission can have consequences both inside and outside of the system, containing the source of the disturbances. An obvious example is when a hairdryer operates and the picture on a traditional cathode ray tube TV screen deteriorates. This is caused both by radiated electromagnetic energy through space and also conducted energy along the mains cable. At the same time the TV is said to be susceptible to both radiation and conduction.

In case of EME realization by conducted emissions, we can talk about the intrasystem compatibility; and in the case of EMC by radiated emission, the achieved compatibility is the intersystem compatibility. A similar distinction can be made for the susceptibility, where intersystem compatibility is achieved by the conducted susceptibility (CS) and the intrasystem tolerance is realized through the radiated susceptibility (RS), as presented in figure 45.

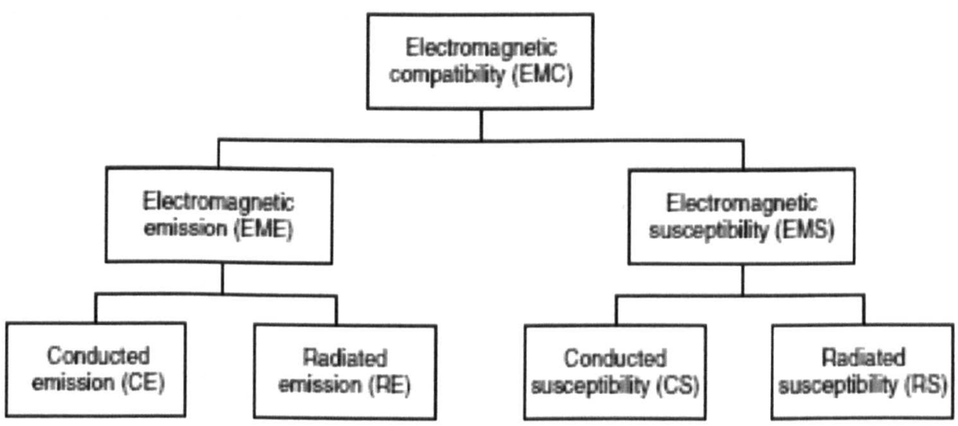


Figure 45. Different areas of EMC

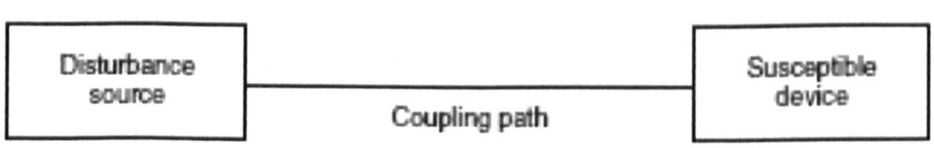


Figure 46. Basic model of an EMC problem

Because *electromagnetic interference* (EMI) first emerged as a serious problem in telecommunications (or, in particular, in broadcasting), EMC tends to be discussed, even to the present day, within the scope of telecommunications technology. Therefore, during the design of a telecommunications device or a system, the EMC aspect of the product must be carefully investigated before it enters the phase of wide range production. The standardization organization International Electrotechnical Commission (IEC) and CISPR 22 PLT defined the EMI as 'degradation of the performance of a device or system by an electromagnetic disturbance'; [IEC89]. This means that the EMC problem can basically be modelled in three parts; as illustrated in figure 46:

- a source of an EM phenomenon, emitting EM energy;

- a victim susceptible to that EM energy that cannot function properly owing to the EM phenomenon; and

- a path between the source and the victim, called *coupling path*, which allows the source to interfere with the victim.

In practice, one source may simultaneously disturb several parts of equipment and several sources may also disturb a single part of equipment. However, the basic model for the investigation of EMC problems remains that in Figure 46. This model allows the conclusion that if one of these three elements is absent, the interference problem is solved. For this reason, if a source of disturbance is causing many problems, it may make sense to suppress that source, that is, block the coupling path as close as possible to the source. However, not every source can be blocked, as for example, the broadcast transmitters. A single part of an equipment that suffers interference can often be screened off, which means that the coupling path is blocked as close as possible to the affected equipment [56].

3.2.2 EMC Classification

The electromagnetic disturbances from an electrical device are not easy to precisely describe, specify and analyse, but there are some general methods to classify them on the basis of some of the characteristics of the offending signals. Generally, the character, frequency content and transmission mode provide the basis for classifying electromagnetic disturbances. A first method of classifying the EM disturbances is based on the methods of coupling the electromagnetic energy from a source to a receptor. The coupling can be in one of four categories:

- conducted (electric current),
- inductively coupled (magnetic field),
- capacitive coupled (electric field), and
- radiated (electromagnetic field).

Coupling paths often use a very complex combination of these categories making the path difficult to identify even if the source and the receptor are well known. The interference may also be radiated from the equipment via a number of different paths, depending on the frequency of that interference. For example, at high frequencies, assemblies and cables on the Printed Circuit Boards (PCBs) may strongly radiate.

At lower frequencies, interference may be coupled from the equipment via the signals and the mains cables as conducted emissions. These conducted emissions may also be radiated at other different locations as further radiated emissions.

Another way of categorizing the EM disturbances is on the basis of three parameters:

- the duration,
- the repetition rate and
- the duty cycle

The disturbances can be of long or short duration. Changes of long duration are usually not included in the domain of EMC because they mainly cause alterations in the r.m.s. (root mean square) value of the mains voltage. Those with short duration last between a few seconds down to less than a microsecond. Electromagnetic disturbances with short duration can be categorized into three classes; [57]:

- *Noise* - which is a more or less permanent alteration of the voltage curve. Noise has a periodic character and its repetition rate is higher than the mains frequency. Such noise is typically generated by electric motors, welding machines, and so on. The amplitude of noise remains typically less than the peak amplitude of the mains voltage itself.

- *Impulses* - which have positive and negative peaks superimposed on the mains voltage. Impulses are characterized by having short duration, high amplitude and fast rise and/or fall times. Impulses can run synchronously or asynchronously with the mains frequency. Noises, created during various switching procedures, can exist between impulses. Typical devices that produce impulses are switches, relay controls and rectifiers.

- *Transients* - Most commonly, transients are generated by high-power switches. To be able to differentiate transients from continuous noise, the duty cycle δ is introduced and defined by Equation 11 [57]:

$$\delta = \tau \times f \qquad \text{(Eqn. 12)}$$

where,

τ - the pulse width measured at 50% height

f - the pulse repetition rate, or average number of pulses per second, at random.

An electrical equipment having a duty cycle (δ) lower than 10^{-5} can be regarded as a source of transients. When the duty cycle becomes significantly higher than 10^{-5}, as with switched mode power supplies, the emitting source is no longer regarded as transient or impulse but as continuous.

To allow a systematic approach, the IEC standard TC 77 has established a classification of electromagnetic phenomena, which is also adopted by the European standardization committee CENELEC TC 210 [IEC01] as shown in table 4.

Low Frequency		High Frequency	
Conducted phenomena	Radiated phenomena	Conducted phenomena	Conducted phenomena
Harmonics, Inter-harmonics Signalling systems Voltage fluctuations Voltage dips and interruptions Voltage unbalance Power frequency variations Induced low-frequency voltages DC in AC networks	Magnetic fields: • continuous • transient Electric fields	Directly coupled or induced voltages or currents: • continuous waves • modulated waves Undirected transients (single or repetitive) Oscillatory transients (single or repetitive)	Magnetic fields Electric fields Electromagnetic fields • continuous waves • modulated waves Transients

Table 4. Principle EMC disturbances phenomena according to IEC TC 77

In order to be able to imagine the possible sources of EM disturbances for power line communications systems and also the possible victims of the disturbances caused by PLC equipment, Table 5 summarizes some of the already existing services and equipment operating in the frequency spectrum [1.3–30MHz], where the broadband PLC systems are also operating.

Service classes	Services	Occupied bands (MHz)
Broadcasting	Medium waves (MW) and Short waves (SW) broadcasting	1.3–1.6; 3.9–4.0; 5.9–6.0, 6.0–6.2; 7.1–7.3; 7.3–7.35; 9.4–9.5; 9.5–9.9; 13.5–13.6; 13.6–13.8; 15.1–15.6; 25.6–26.1
Maritime mobile	Tactical/strategic maritime Maritime Mobile S5.90 Distress and Safety Traffic	1.6–1.8; 2.04–2.16; 2.3–2.5; 2.62–2.65; 2.65–2.8; 3.2–3.4; 4.0–4.4; 6.2–6.5; 8.1–8.8; 12.2–13.2; 16.3–17.4; 18.7–18.9; 22.0–22.8; 25.0–25.21
Radio Amateur	Naval broadcast communications	1.6-1.8
	Maritime DGPS	1.8-2.0; 2.0-2.02
	Datamode, CW, fax, phone	1.81–1.85; 3.5–3.8; 7.0–7.1; 10.1–10.15; 14.0–14.2; 14.25–14.35; 18.0–18.16; 21.0–21.4; 24.8–24.9; 28.0–29.7
Military	NATO & UK long-distance communications	2.0–2.02; 2.02–2.04; 2.3–2.5
Aeronautical	Aeronautical	2.8–3.0; 3.02–3.15; 3.4–3.5; 3.8–3.9; 4.4–4.65; 5.4–5.68; 6.6–6.7; 8.81–8.96; 10.0–10.1; 10.1–11.1; 21.0–22.0; 23.0–23.2
Radio astronomy	Radio astronomy	13.3–13.4; 25.55–25.67

Table 5. Possible EMC Victims for the PLC and their band occupations

3.2.3 EMC Standardization Organisations

EMC standards are prerequisites to insure that the numerous devices and systems do not disturb each other or give rise to malfunctioning of some of them. They lay down requirements for equipment as regards both the maximum permitted emission of parasitic conducted and radiated electromagnetic disturbances, as well as the availability of the equipment under the influence of these disturbances. To test the equipment and to check if it respects the emission limits, test setups to measure the disturbance levels are also defined by the standards. However, standards are only one aspect of the problems associated with the EMC. The EMC standardization bodies are categorized in three classes, according to the number of states in which they operate: international; regional, the most representative of which are those of the United States and the European Union and national, such as RegTP in Germany and RA (Radiocommunications Agency) in the UK. All these bodies work in a consultative and cooperative way to develop EMC standards, which try to combine the interest of all parts whose relationship is shown in figure 46.

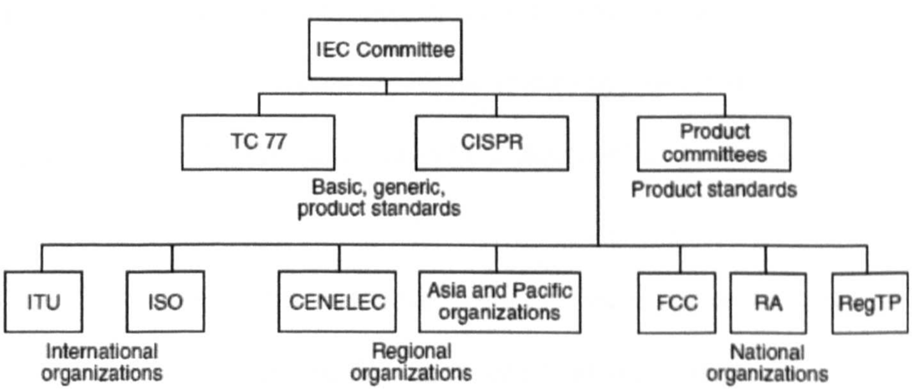


Figure 47. Organization of EMC work and liaisons between different bodies [65]

3.2.4 Noise and Disturbances on PLC Systems

Because the power cables were designed only for energy transmission, no interest has been shown in the properties of this medium in the high-frequency range. Furthermore, a wide variety of appliances, with different properties, are connected to the power network.

Therefore, before using this medium for information transmission, an intensive investigation of the phenomena present in their environment has to be achieved. Besides, the distortion of the information signal, owing to cable losses and multipath propagation, noise superposed on the useful signal energy make correct reception of information more difficult. Unlike the other telecommunications channels, the power line channel does not represent an Additive White Gaussian Noise (AWGN), whose power spectral density is constant over the whole transmission spectrum.

Investigations and measurements were achieved in order to give a detailed description of the noise characteristics in a PLC environment. An interesting description is given in [58], which classifies the noise as a superposition of five noise types, distinguished by their origin, time duration, spectrum occupancy and intensity; the approximate representation of spectrum occupation is illustrated in figure 48.

- *Coloured background noise (type 1)*: whose power spectral density (psd) is relatively lower and decreases with frequency. This type of noise is mainly caused by a superposition of numerous noise sources of lower intensity. Contrary to the white noise, which is a random noise having a continuous and uniform spectral density that is substantially independent of the frequency over the specified frequency range; the coloured background noise shows strong dependency on the considered frequency. The parameters of this noise vary over time in terms of minutes and hours.

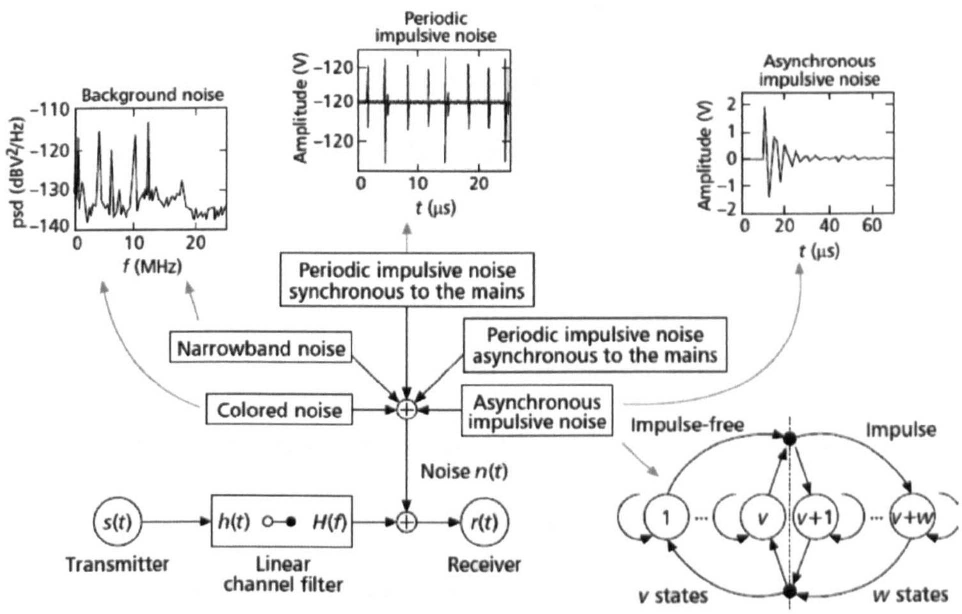


Figure 48. Noise scenario on power lines [59]

- *Narrowband noise (type 2)*: which most of the time has a sinusoidal form, with modulated amplitudes. This type occupies several sub-bands, which are relatively small and continuous over the frequency spectrum. This noise is mainly caused by the ingress of broadcast stations over medium- and shortwave broadcast bands. Their amplitude generally varies over the daytime, becoming higher by night when the reflection properties of the atmosphere become stronger.

- *Periodic impulsive noise, asynchronous to the main frequencies (type 3)*: with a form of impulses that usually has a repetition rate between 50 and 200 kHz and which results in the spectrum with discrete lines with frequency spacing according to the repetition rate. This type of noise is mostly caused by switching power supplies. A power supply is a buffer circuit that is placed between an incompatible source and load in order to make them compatible. Because of its high repetition rate, this noise occupies frequencies that are too close to each other.

- *Periodic impulsive noise, synchronous to the main frequency (type 4)*: are impulses with a repetition rate of 50 or 100 Hz and are synchronous with the main power line frequency. Such impulses have a short duration, in the order of microseconds and have a power spectral density that decreases with the frequency. This type of noise is generally caused by power supply operating synchronously with the mains frequency, such as the power converters connected to the mains supply.

- *Asynchronous impulsive noise (type 5)*: whose impulses are mainly caused by switching transients in the networks. These impulses have durations of some microseconds up to a few milliseconds with an arbitrary interarrival time. Their power spectral density can reach values of more than 50 dB above the level of the background noise, making them the principal cause of error occurrences in the digital communication over PLC networks.

The achieved measurements have generally shown that noise types 1, 2 and 3 remain usually stationary over relatively longer periods, of seconds, minutes and sometimes even of some hours. Therefore, all these three can be summarized in one noise class, which is seen as coloured PLC background noise class and is called "Generalized background noise", whose frequency occupation and mathematical model are discussed below. The noise types 4 and 5 are, on the contrary, varying in time span of milliseconds and microseconds and can be gathered in one noise class called "impulsive noise", pointed out also in other literatures as "impulse noise". Because of its relatively higher amplitudes, impulse noise is considered the main cause of burst error occurrence in data transmitted over the high frequencies of the PLC medium.

3.2.5 Generalised Background Noise

For the modelling of the generalized background noise in the PLC environment, it is considered as the superposition of the coloured background noise and the narrowband disturbances; as illustrated in figure 49. In this case, no difference is made between the shortwave radios and the other narrowband disturbances in the form of spectral lines, because normally the spectral lines are found in bundled form. For the modelling, these bundles of disturbers are approximated by their envelope. Furthermore, because of the high repetition rate noise type (3) occupies frequencies that are too close to each other, and therefore build frequency bundles that are usually approximated by a narrowband occupation. Therefore, for its modelling, this noise will be seen as a narrowband noise with very low psd.

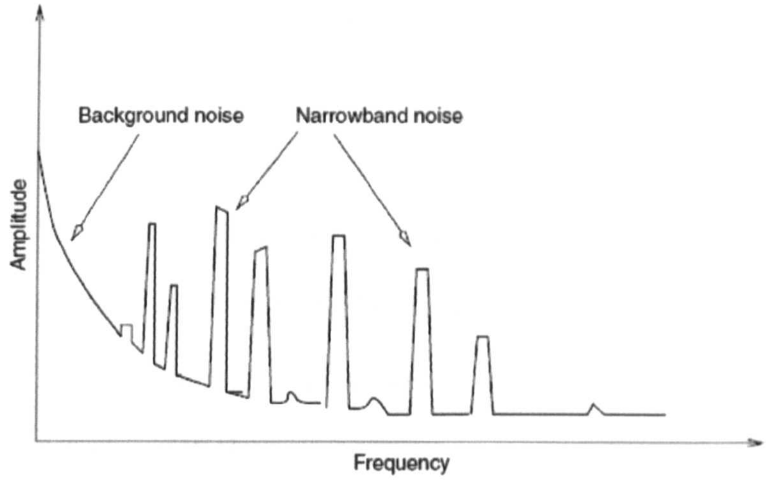


Figure 49. Spectral density model for the generalized background noise [25]

3.2.6 Impulsive Noise

The impulsive noise class is composed of the periodic impulses that are synchronous with the mains frequency and the asynchronous impulsive noise. The measurements show that this class is largely dominated by the last noise type (type 5). For this reason, the modelling of this class is based on the investigations and the measurements of type (5), of which an example is shown in figure 50.

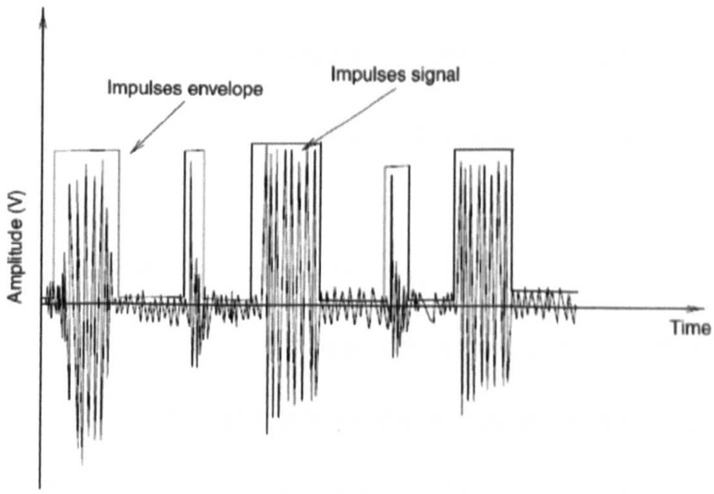


Figure 50. Example of measured impulses in the time domain in a PLC network [25]

Vines et al [27] further categorise noise as:

(a) Noise having line components synchronous with power system frequency. The usual source of this noise are triacs or silicon controlled rectifiers (SCR's), found domestically, for example, in light dimmers or photocopiers. The spectrum of this noise consists of a series of harmonics of the mains frequency (50 Hz).

There are three ways to combat this kind of noise: [24]

- As the frequency spectrum of this noise is regular, successful communication may be possible with modulation scheme that avoid, or have nulls, at these frequencies.

- Filter these noise components out using accurate notch filtering.

- Considering the time domain representation this noise, a noise pulse can be expected at equal intervals. Using fairly simple time division multiplexing (TDM) schemes and error correction, unwanted effects can be minimised.

(b) Noise with a smooth spectrum.

Noise with a smooth spectrum is generally caused by universal motors. A result of the commutation process in motor powered appliances such as blenders and vacuum cleaners, this noise has a flat spectrum in the frequency ranges used by PLC systems. It can be modelled as band limited white noise.

A characteristic of many of the appliances that contain universal motors is that they are often used for a short period of time. PLC system that does not have to function in real time can avoid this noise by operating at a time when the noise is absent. Conversely, real time systems must be able to cope with this noise

(c) Single event impulse noise.

Single event impulse noise is primarily due to switching, lightning, the closing of contacts, etc. This noise disturbs the whole frequency band for a short amount of time and often modelled as an impulse disturbance due to the relatively short times involved. This impulse noise can be overcome by error correcting codes.

(d) Non synchronous noise.

Non synchronous noise is characterised by periodic components that occur at frequencies other than harmonics of the mains frequency. Major sources of this type of noise include TV and PC monitors. The scanning and synchronisation signals in such appliances cause noise components at known frequencies. The solution to minimising such interference is to avoid data transmission at these frequencies and associated harmonics and to use a modulation scheme that is frequency diverse, thus avoiding this type of noise at any unforeseen frequencies.

But from the fact that a wide variety of loads (lights, heaters, PCs, TV, Radio, fans, air-conditioners, washing machines, cookers, ovens, microwave ovens, drills, motors, vacuum cleaners) are continuously being connected/disconnected to the network by large numbers of independent customers at their will. Each loads having its own electrical characteristics. Consequently, a communications device such as PLT modem connected to the line sees a very hostile environment which keeps changing with time. A definite pattern, however, can be discerned in the time-dependence of the line properties, patterns over a 24-hour cycle, 7-dayweek cycle, seasonal pattern, etc. This implies that all characteristics of the line have to be measured and understood under all these conditions.

From the communications point of view, there are three major aspects of the power line that must be measured, modelled and characterised.

- Impedance characteristics
- Noise behaviour
- Attenuation characteristics

The cable transitions cause reflections and changing characteristics impedance [5]. Additionally, a PLC network changes its structure (e.g. by adding new customers), especially in an in-home PLC network in which every switching event can change the network characteristics.

PLC networks are also characterized by multipath propagation because of numerous reflections caused by the joining of cables and their different impedance. This results in multipath signal propagation, with a frequency-selective fading. The most important effects influencing signal propagation are cable loses, loses due to reflections at branching points and mismatched endings of the cables as well as selective fading [2], [5], [6].

Attenuation in PLC networks depends on the line, length and changing characteristic impedance of the transmission line. Various measurements have shown that the attenuation in power lines is acceptable in relatively short cables (~ up to 200-300 m), but is very bad in longer cables [2], [5]. Therefore, longer PLC networks are expected to be equipped with the repeater.

A detailed description of the transmission features of the electrical supply networks is now given.

3.2.7 Low-voltage Supply Networks

The low-voltage supply networks are realized by the usage of various technologies (different types of cables, transformers etc.) are installed in accordance with the existing standards, which differ from country to country. There are networks realized with overhead or underground power lines, which have different transmission features, as well as combined overhead/ground cabling solutions. The layout of a low-voltage power supply network also differs from place to place and depends on several other factors, including:

- Network Location - A PLC network can be placed in a residential, industrial or business area. Furthermore, there is a difference between rural and urban residential areas. Industrial and business are characterized by a higher number of customers who are potential users of the PLC services. Also, subscribers from business areas have different requirements than industrial subscribers and especially different than subscribers from residential areas. Similar differences can be recognized between urban and rural application areas as well.

- Subscriber Density - the number of users/subscribers in a low-voltage network as well as user concentration, vary from network to network. The subscribers can be mostly placed in single houses, which is typical for a rural application areas, within small blocks including several individual customers (e.g. urban residential area), in buildings with a larger number of flats or offices, or within apartment or business towers (very high subscribers density), such as in big commercial quarters.

- Network length – the longest distance between the transformer and a customer within a low-voltage network also differs from place to place. Usually, there is a significant network length difference between urban and rural application areas.

- Network Design – Low-voltage networks usually consist of several network sections/branches of varying number, which differs from network to network, as well.

Low-voltage supply networks differ from each other and it is not possible to specify a typical network structure for them. However, it is possible to define some characteristic values and to describe an average structure of a typical PLC network in accordance with the information from [7], [8], [9] as follows:

- Number of users in the network: ~250 to 400
- Number of network sections: ~5
- Number of users in a network section: ~ 50 to 80
- Network length: ~500 m.

3.3 Transmission Line Theory

A transmission system in a communications network has to convert the information data stream in a suitable form before it is injected in the communications channel. Like all other communications channels, the PLC medium introduces attenuation and phase shift on the signals. Furthermore, the PLC medium was at the beginning designed only for energy distribution, and for this reason several types of equipment and appliances are connected to it. These activities on the power lines make this medium not adequate for information communications signals. Therefore, an investigation of the PLC channel and its characteristics are presented in this chapter. Also, PLC channel models are discussed, which describes the affect introduced on the signals that are transmitted over it. Because of the impedance discontinuities characterizing the PLC medium, the signals are reflected many times, which results in a multipath transmission, which is an effect well known in telecommunications.

3.3.1 Power Line Impedance Characteristics and Existing Research

Power line impedance is a very important parameter on the design of power line communication modem architecture. Variations on the impedance of the power line affect communications circuit performance. The distribution transformer secondary windings, entrance cables, house wiring and electrical loads determine residential impedance. The characterization of this impedance is important to the design of the PLC system. The impedance is the driving point in to which the transmitter operates and from which receiver extract the signal.

To date, various investigations and experiments have been carried out to determine the power line impedance. One of the earlier studies of power line impedance characteristics was conducted by Nicholson and Malack [13]. In 1973, they published impedance measurements of 36 commercial secondary sources. Their measurements covered the frequency range from 20-100 KHz. Later, these measurements were compared with similar measurements from Europe [15]. Figure 51 shows the frequency response plot of their findings.

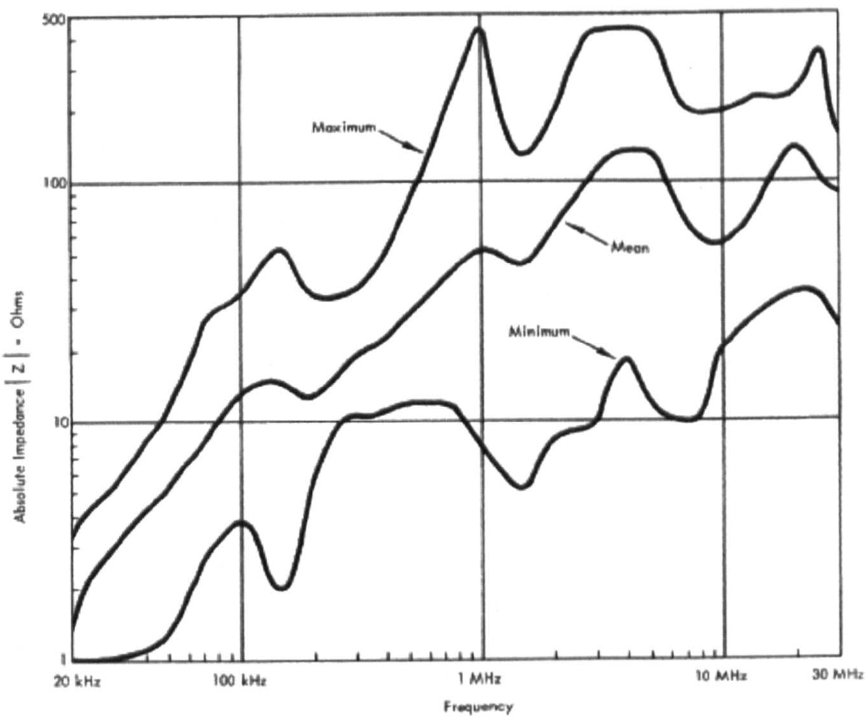


Figure 51. Power Line Impedance Measurements by Nicholson and Malack [13]

Although this paper is geared towards the validation of proposed characteristics of Line Impedance Stabilization Networks (LISN), used for measurements of conducted Electromagnetic Interference (EMI), the results shown are applicable to the scope of this thesis. Vines *et al.* [14] made impedance measurements of residential power lines at frequencies from 5-20 kHz, and reported that impedance of the residential power lines are in the range of 1-12 Ω. This validates in part the results obtained by Nicholson and Malack.

Vines' measurements were made by applying a voltage signal at the frequency of interest (through a filter) across two conductors of the secondary circuit and measuring the voltage across, and current into, the filter. The two conductors were line and neutral for the 120V measurement, and line for the 240V measurements. Details of the measurements techniques are given in [17]. Vines *et al.* described the characterization of the noise present in residential secondary power distribution circuits in the band of frequencies from 5-100 kHz [14]. These studies have proven that the residential power line can be modelled as a distributed impedance with a characteristic given by equation 13:

$$Z_o = \sqrt{\frac{L}{C}}\ \Omega \qquad \text{(Eqn. 13)}$$

Where L is in μH/foot, and

C is in μF/foot.

Vines *et al.* reports an impedance varying from 70 to 100Ω. The impedance of the 120 and 240 Volt residential power circuits increases with frequency, indicating clearly inductive behaviour as expected.

One of the concerns when considering the impedance of the power line is the affect of the household loads in the overall residential impedance. Vines *et al* [14] have reported that the impedance of most electrical loads around the house is relatively high (with the exception of high resistive loads) when compared to the unloaded power line impedance. There are however, some loads that cause resonance (either series or parallel) with the power line impedance, at frequencies above 40 kHz. This is a matter of concern, since the protocols of interest operate at frequencies above 100 kHz. In particular, Switched Mode Power Supplies (SMPS) are somewhat troublesome because of their EMI filtering. The capacitors used for the implementation of this filter bypass the communication signal, and users must avoid the connection of PLC nodes at these locations.

Malack and Engstrom [15] measured 86 commercial 50 Hz a.c. power distribution systems in six European countries and the US. These measurements show that the impedance of residential power lines increase with frequency and are in the range of 1.5 - 80 Ω at 100 kHz. The impedance of the 120V/240V residential power circuits increases with frequency, indicating inductive behaviour of the line. One interesting finding reported by Tanaka [19] indicates a drastic increase in the overall line inductance due to the outlet termination (commonly known as J-box). Each J-box termination increases the power line inductance by about 1.5 μH, with this inductance increasing as the length of the termination is increased. This affects the overall network performance, and careful termination methods are recommended to minimize this problem.

The noise spectrum of power lines at 10 kHz-100 MHz, and impedance characteristics and transmission loss on power lines in the high frequency band (10 kHz – 20 MHz) were measured by Tanaka. He measured power line impedance as 1-20 Ω for 10 kHz-150 kHz [16].

J H Bull carried out surveys of mains impedance in the UK, USA, Russia and Netherlands in the early seventies [62]. The frequency ranges covered have been different but largely concentrated in the region 10 KHz to 10 MHz. The measurements have mainly been made between phase and earth or between neutral and earth. The survey was carried out at a variety of sites including laboratories, factories, private houses, sub-station and a hospital. Measurements of the impedance of the mains supply in these countries have shown general similarities in the impedance characteristics as shown in figure 52.

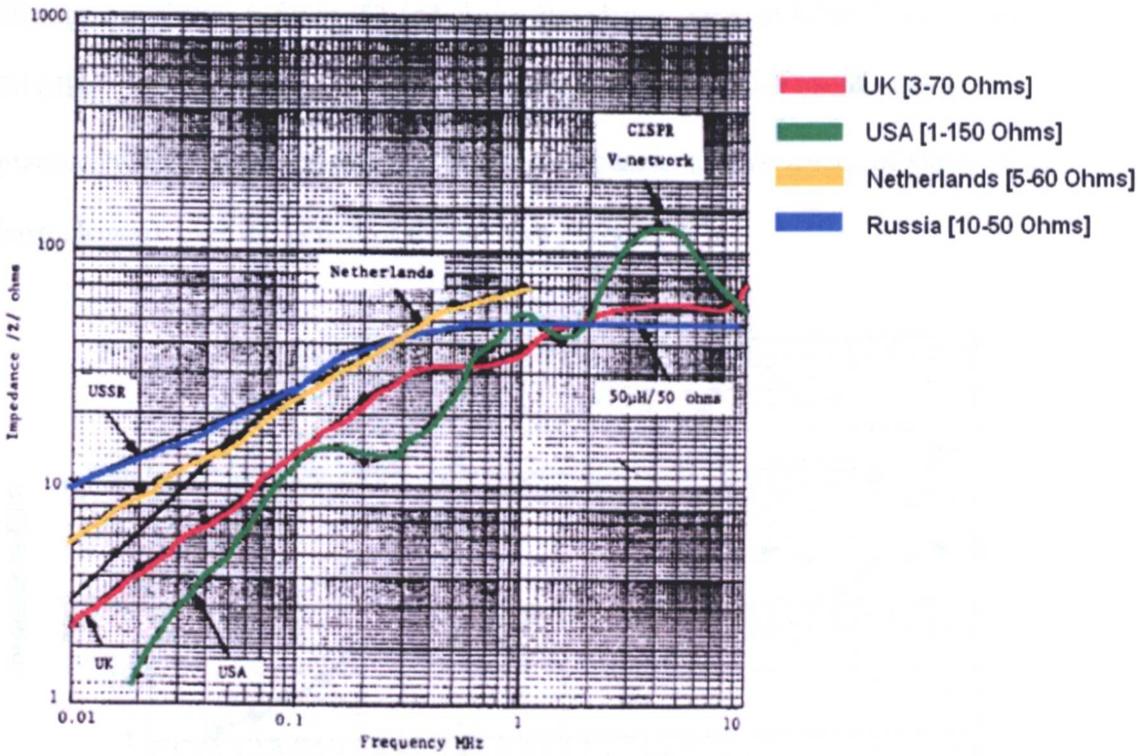


Figure 52. Mean mains impedance characteristics from UK, USA, Russia and Netherlands results compared with 50μH /50Ω and CISPR networks.

At frequencies between 10 KHz and 100 KHz the impedance is approximately proportional to frequency, indicating a substantially inductive impedance. At higher frequencies, particularly above 500 kHz, the impedance varies between low values of about 10Ω and high values of 500Ω, with mean values of 50 to 100Ω.

These impedance results validate in part the results obtained by Nicholson and Malack as shown in figure 51.

Newbury *et al* [65] carried out a series of measurements as part of CENELEC SC205A low voltage impedance measurement programmes in typical European houses and buildings in 1990 at frequencies ranging from 40 kHz to 30 MHz and their findings are shown in figure 53 and shows impedance range of 8-800 Ω for 1 MHz to 30 MHz. The discrepancies could be due to factors like, power circuit wiring practice, which varies considerably between countries, and the nature of loads, which have changed over the period of the last two decades.

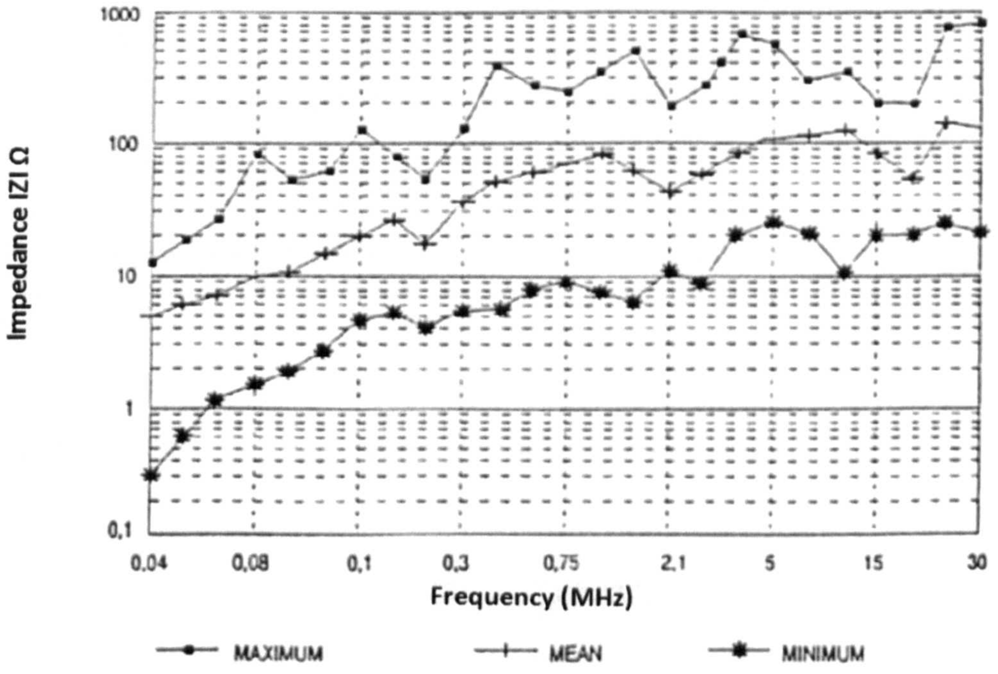


Figure 53. Aggregate European power line impedances [CENELEC SC205A]

Cavdar and Karadeniz [63] carried out impedance measurements in Trabzon, Turkey at frequencies ranging from 10 to 170 kHz (CENELEC A, B, C, D bands). Measurements were conducted in three categories: rural, urban and industrial power lines. Results are presented in graphical form as shown in figures 54, 55 and 56.

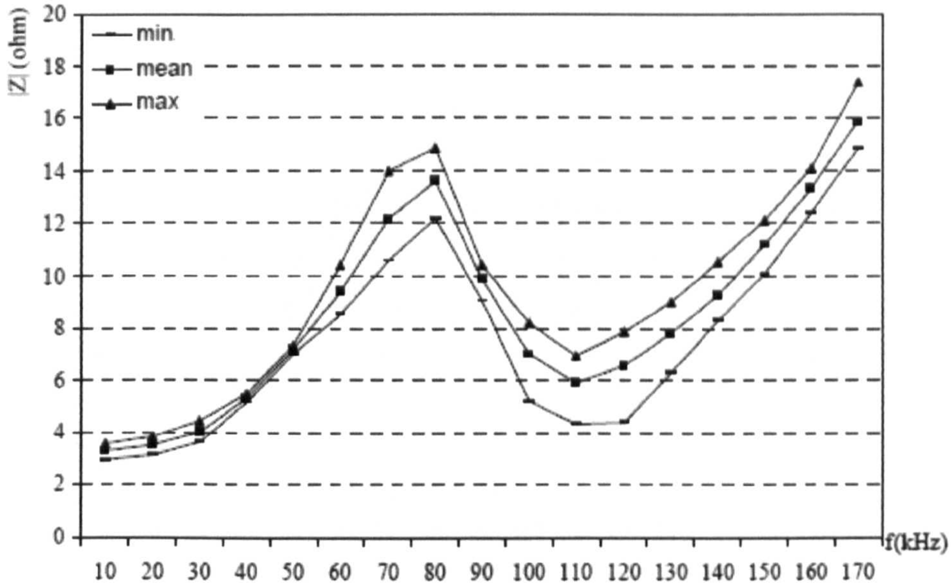


Figure 54. Impedance vs frequency for rural power lines, Trabzon, Turkey [63]

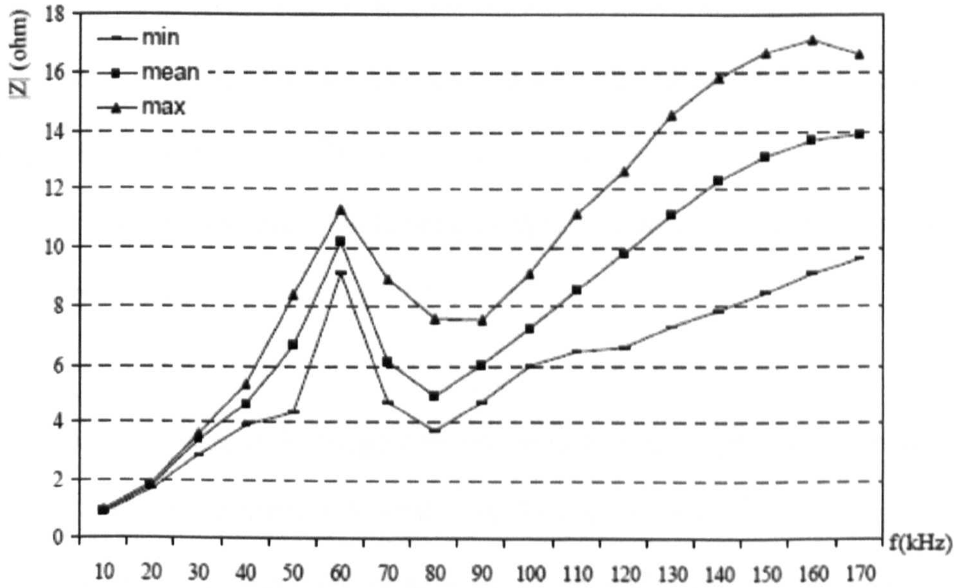


Figure 55. Impedance vs frequency for urban power lines, Trabzon, Turkey [63]

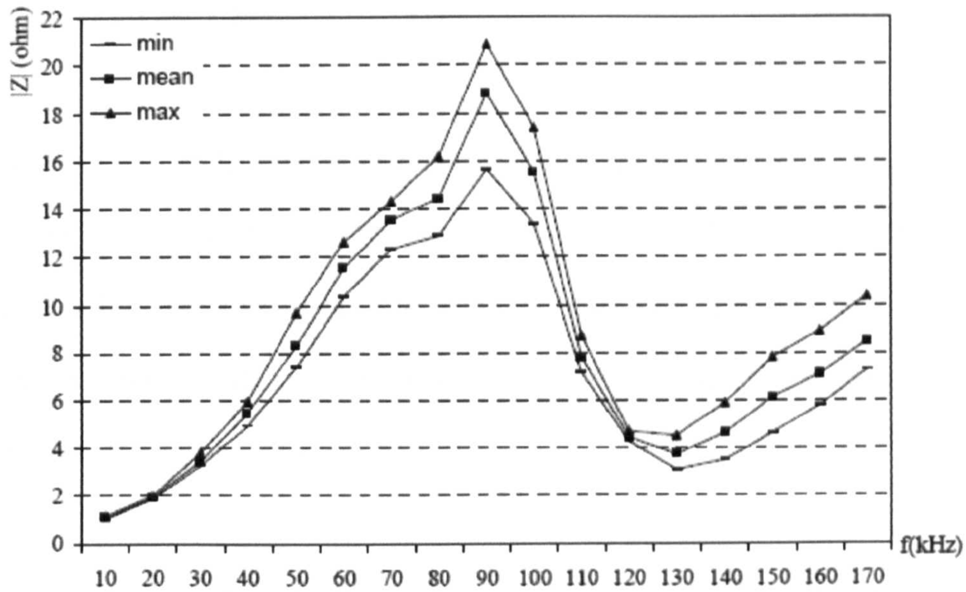


Figure 56. Impedance vs frequency for industrial power lines, Trabzon, Turkey [63]

Impedance is highly varying with frequency and ranges between a few ohms and a few kilo-ohms with peaks at some frequencies where the network behaves like a parallel resonant circuit. The net impedance is strongly influenced by the network topology and connected load. The low-voltage mains does not have essentially a characteristic impedance since loads being switched on and off randomly introduce a change in impedance.

Although there are various investigations on the power line impedance mentioned above, PLC modem designers still need more data on the power line impedances for the optimum modem design. The main target of this study is to realize measurements and obtain some useful data about the power line impedance in low voltage distribution networks.

3.3.2 Transmission Lines

A Transmission Line is a system of conductors connecting one point to another and along which electromagnetic energy can be sent. Telephone lines and power distribution lines are typical examples of transmission lines. Components of transmission lines include parallel wires, co-axial cables, optical fibres, electrical power lines.

Modelling the power line channel is not an easy task because of its unpredictable nature with frequency, time of day and geographic location. For the purposes of analysis, an electrical transmission line can be modelled as a two-port network as shown in figure 57.

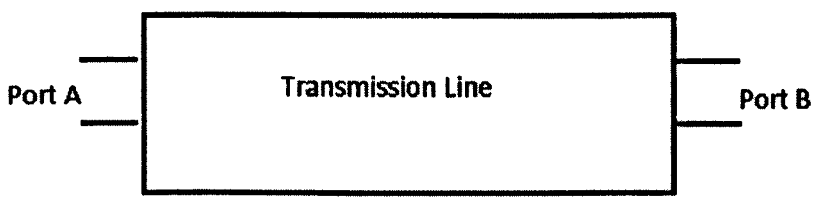


Figure 57. Transmission Line as a two-port network

The network is assumed to be linear (i.e. the complex voltage in either port is proportional to the complex current flowing into it when there are no reflections), and the two ports are interchangeable. If the transmission line is uniform along its length, then its behaviour is largely described by a single parameter called *characteristic impedance*, Z_0. This is the ratio of the complex voltage of a given wave to the complex current of the same wave at any point on the line.

Mathematical analysis of the behaviour of electrical transmission lines grew out of the research by James Clerk Maxwell, Lord Kelvin and Oliver Heaviside. In 1885 Lord Kelvin formulated a diffusion model of the current in a submarine cable. The model exactly predicted the poor performance of the 1885 Trans-Atlantic submarine telegraph cable. In 1885, Heaviside published the first papers that described his analysis of propagation in cables and the modern form of the telegrapher's equation based on Maxwell's Equations [10].

Since each conductor has a certain length and diameter, it must have resistance and inductance, since there are two wires close to each other, there must be capacitance between them. The wires are separated by a medium called the *dielectric*, which cannot be perfect in its insulation; the current leakage through it can be represented by a shunt conductance. The resulting equivalent circuit is shown in Figure 58.

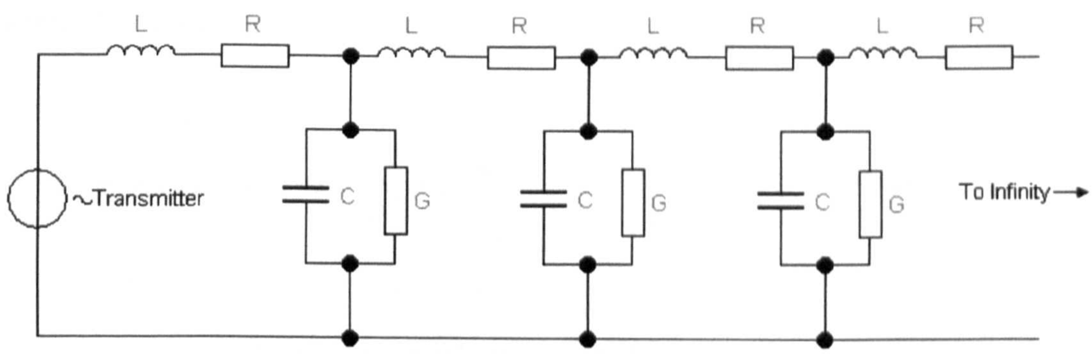


Figure 58. General equivalent circuit of transmission line

All the quantities shown in Figure 58 are proportional to the length of the line, and unless measured and quoted per unit length, they are meaningless. At radio frequencies, the inductive reactance is much larger than the resistance. The capacitive susceptance is also much larger than the shunt conductance. Thus both R and G may be ignored, resulting in a line that is considered lossless (as a very good approximation for RF calculations). The simplified equivalent circuit is shown in Figure 59.

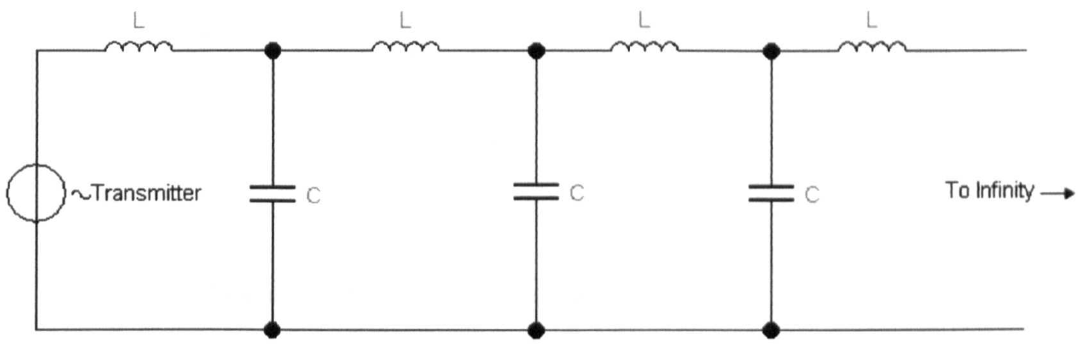


Figure 59. Transmission-line RF equivalent circuit

The quantities R, L, C and G are all measured per unit length (e.g. per metre), because they occur continuously along the line. They are thus distributed throughout the length of the line.

- Resistance R is given by $R = \frac{\rho l}{A}$ (Eqn. 14)

  Where,

  ρ is the resistivity of the conductor material

  A is the cross-sectional area of each conductor

  l is the length of conductor (for a two-wire system, l represents twice the length of the line).

  Resistance is stated in ohms per metre length of a line and represents the imperfection of the conductor.

- Inductance L is due to the magnetic field surrounding the conductors of a transmission line when a current flows through them.

  The inductance of an isolated twin line is given by the equation 15:

$$L = \frac{\mu_o \mu_r}{\pi}\left[\frac{1}{4} + \ln\frac{D}{a}\right] \text{ H/m} \qquad \text{(Eqn. 15)}$$

  Where,

  D is the distance between centres of the conductor

  a is the radius of each conductor

  μ_o=4π x 10^{-7} H/m, known as permeability of free space or magnetic space constant. In most practical lines μ_r = 1, known as relative permeability.

  An inductance stated in henrys per loop metre takes into consideration the fact that there are two conductors in a particular length of line.

- Capacitance C exists as a result of the electric field between conductors of a transmission line. The capacitance of an isolated twin line is given by the equation 15:

$$C = \frac{\pi\varepsilon_0\varepsilon_r}{\ln(D/a)} \text{ F/m} \qquad \text{(Eqn. 16)}$$

  Where,

  ε_0=8.85 pF/m, known as permittivity of free space.

  In most practical lines ε_r= 1, known as relative permittivity.

- Conductance G is due to the insulation of the line allowing some current leak from one conductor to the other. Conductance (leakance) is measured in Siemens per metre length of line and represents imperfection of the insulation.

3.3.3 Characteristic Impedance

Any circuit that consists of series and shunt impedances must have an input impedance. For the transmission line this input impedance will depend on the type of line, its length and the termination at the far end. To simplify description and calculation, the input impedance under certain standard, simple and easily reproducible conditions are taken as the reference and is called *characteristic impedance* of that line. Characteristic impedance of a transmission line Z_0, is the impedance measured at the input of this line when its length is infinite. Under these conditions the type of termination at the far end has no effect.

The characteristic impedance of a line is measured at its input when the line is terminated at the far end in an impedance equal to Z_0, no matter what length the line has. This is important, because such a situation is far easier to reproduce for measurement purposes than a line of infinite length.

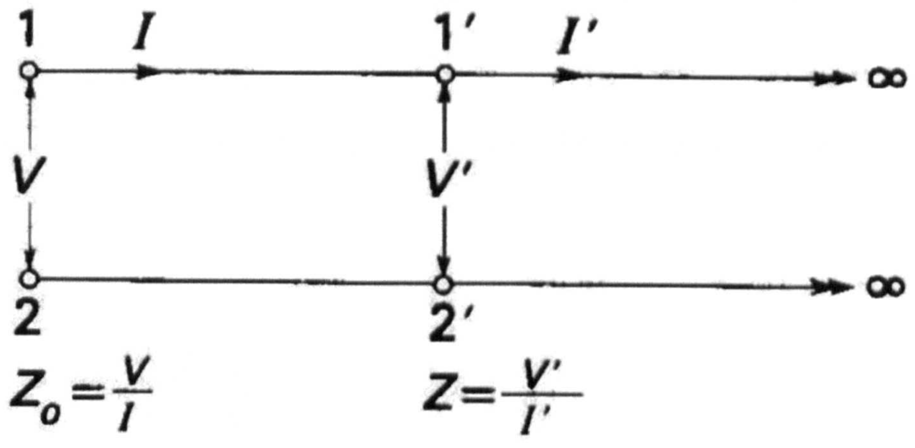


Figure 60. Infinite transmission line [12]

If a line has infinite length, all the power fed into it will be absorbed. It's fairly obvious that as one move away from the input, voltage and current will decrease along the line, as a result of the voltage drops across the inductance and current leakage through the capacitance. The points of 1' – 2' of figure 60 are just as far from the far end of this line as the points 1 – 2. Thus the impedance seen at 1' – 2' (looking into the right) is also Z_0 , although the current and voltage are lower than at 1 – 2. We can thus say that the input terminals see a piece of line up to 1' – 2', followed by a circuit which has the input impedance equal to Z_0. It does not matter what the circuit to the right of 1' – 2' consist of, provided that it has an input impedance equal to the impedance of the line.

It follows from filter theory that the characteristic impedance of an iterative circuit consisting of series and shunt elements is given by [12]:

$$Zo = \sqrt{\frac{Z}{Y}}$$

Where Z = series impedance per section = R + j ωL (Ω/m) and is the series impedance per unit length.

Y = shunt admittance per section = G + j ωC (S/m) and is the shunt admittance per unit length.

Thus, $$Zo = \sqrt{\frac{R + j\omega L}{G + j\omega C}}\ \Omega \qquad \text{(Eqn. 17)}$$

Where,

R = Resistance per unit length

L = Inductance per unit length

G = Leakage conductance per unit length

C = Leakage capacitance per unit length

ω = $2\pi f$ (angular frequency)

$j = \sqrt{-1}$ (imaginary unit)

Impedance is a complex quantity, with a resistive and reactive component. It is a function of the frequency of the applied signal, and is unrelated to length of the line. Line impedance is of prime importance for good transmission. Maximum power transfer occurs when the source has the same impedance as the load. For sending signals over a line, the transmitting equipment must have the same characteristic impedance as the line to get the maximum signal into the line. At the other end of the line, the receiving equipment must also have the same impedance as the line to be able to get the maximum signal out of the line.

Where impedances do not match, some of the signal is reflected back towards the source. In many cases this reflected signal causes problems and is therefore, undesirable. Impedance changes considerably with frequency.

At radio frequencies (above 100 kHz), however, as already mentioned, the resistive components of the circuit become insignificant, and the expression for Z_o

reduces to $Zo = \sqrt{\frac{L}{C}}\ \Omega.$ (Eqn. 18)

Where,

L is measured in henrys/m, and

C in farads/m.

3.3.4 General Characteristics of Power Cables

When developing power line communication systems for operating over standard transmission and distribution networks, an accurate knowledge of the channel parameters are required and in particular the channel impedance of the power line. This is extremely important because the signal power at the receiver reaches a maximum when the impedance of the transmitter, receiver and channel of communication are matched as perfectly as possible for circuit.

The impedance of the line varies with the operating frequency that power line systems operate. The channel impedance is a strongly fluctuating variable and depends on the loads connected to the power line and amount of time it is connected for. Although these results in the fact that a single value for the channel impedance rarely be given, it is still possible to predict the range of impedance.

From the predictions it is possible to say that the overall impedance of the power line network depends on:

- The impedance of the medium/low-voltage distribution transformer in the power line circuit.

It has been shown that for a number of distribution transformers used, confirms that the impedance of the secondary transformer increases with frequency of operation. However, this dependency decreases with smaller power rated transformers. Within the various transformers, the various phases are coupled, resulting in the signal propagating between the phases. Consequently, in principle this results in the fact that a signal may be transmitted across phases without coupling the circuits between phases.

- The characteristics impedance of the cables (s) in the circuit.

A wide range and variety of power cables are used in both underground and overhead networks in the medium- and low-voltage distribution networks. For this single reason it is very difficult to assess and predict the impedance of the low-voltage networks. The capacitance of the cable network is much smaller than the capacitance of the transformer. Therefore, it is possible to model the cable as a series circuit of inductors and resistors in series. Typical impedance is in the range 70 Ω to 100 Ω [22].

- The impedance of the different equipment connected to the power line network.

Typical impedance values for the different devices and equipment connected with the standard house operating on a 230 V/50 Hz network varies between 800 Ω for a light bulb operating at 60 Watts to 35 Ω for a 1400 Watt vacuum cleaner. However, in considering heavy load appliances connected between two phases can have much smaller impedance, for example, a water heater exhibiting an impedance of 32 Ω or 12 Ω for an electric heater. Further, due to the overall impedance of an electrical power network being determined by the parallel impedances of the devices connected to the household. Therefore, the small impedances of the devices have a major and dominant affect on the impedance and propagation of signals along the power distribution network.

3.3.5 Equivalent Circuit for the Power Line

A power line can be represented as an R-L-C circuit. However, since the capacitance value is negligible, some authors choose to ignore it. Forti [53] concludes that the power line can be represented as frequency-dependent resistance in series with a constant inductance:

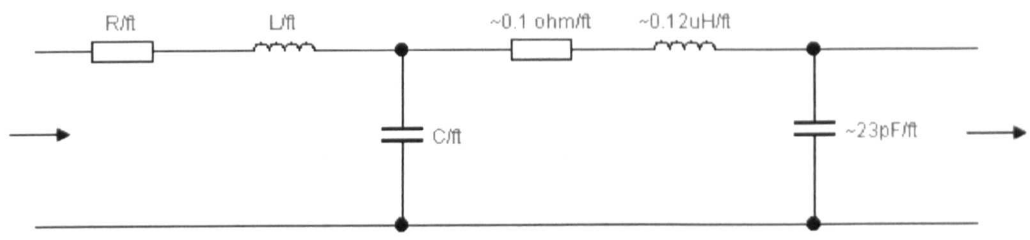


Figure 61. Power Line Model by Downey and Sutterlin [50]

$$Z = R(f) + sL \qquad \text{(Eqn. 19)}$$

A more practical approach is given by Downey and Sutterlin [50], in which the power line modelled as a distributed R-L-C network as shown in Figure 61. Using the model for a 30 feet length of 12-2 BX cable, yields the following values:

Series inductance: 3.6 μH

Shunt Capacitance: 690 pF

Series Resistance: 0.3 Ω

Using equation 19, $Z_o \approx 74\ \Omega$

The significance of this information is that the power line circuit will exhibit a different characteristic impedance depending of the type of impedance (load) into which it is terminated: It will look inductive when terminated with a low impedance and it will look capacitive when terminated with a high impedance. Also, it can be seen that the power line acts as a voltage divider (attenuates the communication signal), together with the different loads that are connected to the network, with the attenuation increasing with frequency for frequencies above 100 kHz (increase of 0.25 dB/kHz is reported) [25]. The power of the signal at the receiver side is maximum when the impedance of the transmitter, receiver and the power line are matched. Therefore, it is important to study carefully the signal coupling mechanisms that optimize the transfer of information. Considering all the facts already discussed, it is almost impossible to decide which is the best value of the power line impedance to use for the design of the coupling circuit, since this value depends on the type of wire, the length of the cable and the type of loads connected to it. However, the range of values given by Nicholson and Malack [13] are a good starting point.

3.3.6 Access Impedance

The transmitter of a PLT modem has the task of injecting a voltage into the mains that reaches an amplitude as specified in CENELEC EN50065. The required transmission power directly depends on the access impedance, in particular on its real part, as only active power is able to propagate along a line. The smaller the impedance, the more power is required.

The required transmission power can be calculated when the input impedance of the mains is known. The most unfavourable conditions are found at the crossbar system of a transformer station. Among other factors, the parallel connection of a large number of outgoing trunks causes very low impedances [2]. Two examples of access impedance of transformer stations are shown in figure 62. In both cases the magnitudes are extremely small at the lower end of the frequency range. With less than 0.5 Ω, the injection of significant signal amplitudes causes tremendous effort, so that using higher frequencies is always desirable [61].

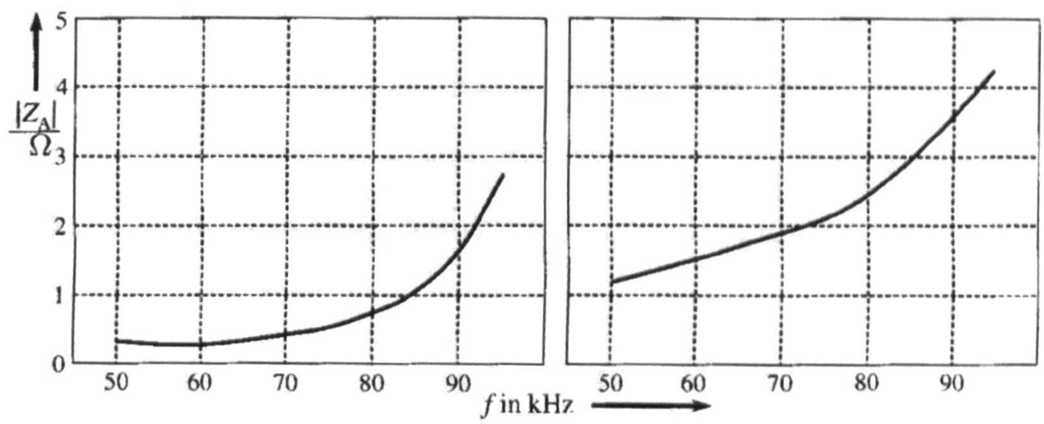


Figure 62. Access impedance records within transformer stations. [61]

Very low impedance leads to costly transmitter output stages in practical applications. Moreover, the design of the coupler components, in particular the capacitor, leads to higher costs. The measurement location also has considerable influence on the value of access impedance.

In a transformer station, the value is much lower than it is at a wall socket inside a building. The typical house service connection has much higher access impedance than the crossbar system of a transformer station, so that transformer output stages, which can supply a maximum power of a few watts, will be sufficient for the operation of modems on the electricity customer side [2].

3.3.7 Signal Attenuation

The low impedance of the distribution network potentially causes high signal attenuation. This consequently will lead to a mismatch between transmitter, channel and receiver impedances and contribute to the attenuation. For low-voltage distribution networks, this is in the order of 100 dB/km and for medium voltage networks 10 dB/km [22]. Due to the high level of attenuation on the low voltage distribution networks; repeaters are used in many cases. For the high voltage distribution networks, with lower attenuation, signals may propagate distances of the order of hundreds of kilometres without the use of repeaters [22].

3.3.8 Time and Frequency Dependency of Signal Attenuation

For any power line circuit, underground or overhead, there is a clear connection between the network impedance and the signal attenuation. Time dependency is a considerable function between the signal attenuation and the variable impedance of the line. The fact that many appliances are only switched on during the working day and not in the night time may result in a variation of sensitivity. Further it has been shown that for frequencies below 100 kHz the signal attenuation is independent of frequency. For frequencies above 100 kHz the attenuation is 0.25dB/kHz [22].

The amount of signal attenuation within any network will depend on the number of lines in the network and the impedance between the phases of the system. Generally, the signal attenuation between any two points on the distribution power line network connected to the same phase is normally smaller than the signal attenuation between two points at the same distance connected to different phases.

3.3.9 Differential Mode and Common Mode Signals

Another important aspect of power cables is to understand the distinction between the possible modes of coupling. The basis for this distinction is the idea that two separate circuit paths can co-exist in the same set of conductors. One of these is the circuit that was intended by the designer – signal and return, or power and return, along which the desired signal currents flow, "differentially", that is in opposition to each other.

The other is the parasitic circuit that is formed between this desired circuit and the structure within which it is located. This is called "common mode" circuit, because the currents in the conductors are all following in the same direction. Figure 63 illustrates these different modes for generalized appliances with a mains power supply and a signal line.

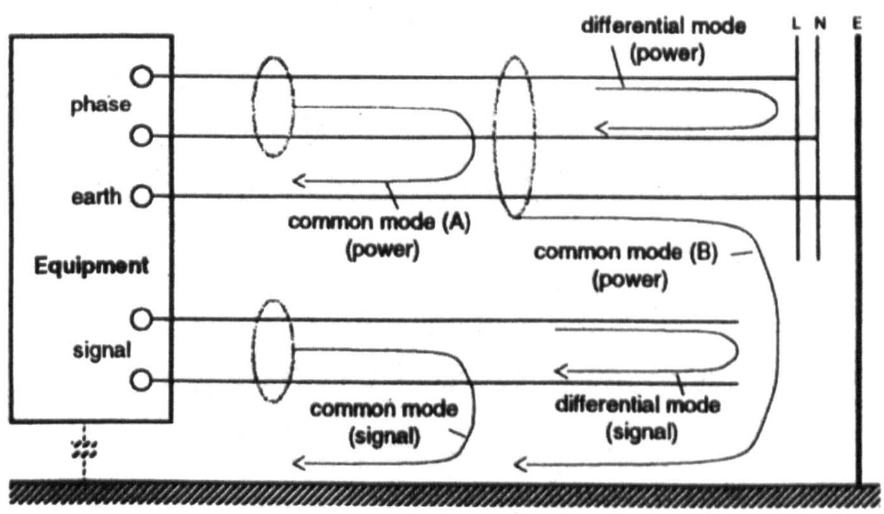


Figure 63. Differential and common mode concepts [23]

In the transmission of the power line signal over the power line network, the signal is normally transmitted in differential mode (DM). The signals flow is along the live conductor and flow back along the return conductor(s). For circuits with a single end topology, all the return currents share a common conducting structure which is usually the 0V conductor of the DC power distribution line. For this balanced line or differential signaling there is a dedicated conductor for the return circuit as well as the send path. For good signal quality and EMC effects the two are routed together as a twisted pair.

Unfortunately, due to imbalances in the physical structure of the interconnections and cables, they cause Common Mode (CM) noise voltages and currents. Common Mode currents flow out on both the send and return paths at the same time and return via another electrical route which is normally the protective safety earth and or the mains power distribution circuit. These noise currents and voltages have small magnitudes of the order of milliamps and millivolts compared with the signal currents. However, the very large loop areas associated with common mode noise currents and voltages makes them extremely important for the EMC quality of the circuit. Generally, for power line carrier systems operating in the frequency band above 1MHz the unwanted emissions are usually attributed to the Common Mode currents and voltages.

Considerable design expertise is currently being used to produce PLC systems that are balanced with respect to signal propagation along the low and medium voltage distribution line. This is normally described as the Longitudinal Conversion Loss (LCL). This term relates the amount of signal energy that is converted into unwanted energy that potentially may radiate and cause interference with established radio services. The lower the LCL of a power system, the further the actual signal will propagate and the potential to transmit higher frequencies over the same distance. For this reason there is considerable drive from the communications industry to drive to category 5 and 6 and higher classifications of cable and the consequent better signal balance and therefore increased LCL at higher frequencies and reduction on the CM currents and voltages. Due to the CM and DM signals in power communication networks it is necessary to introduce filter networks to help minimize the imbalance of the circuit.

Therefore, the transfer function between two points on electrical network carrying digital information will be determined by the key electrical parameters of cable length, cable type, and the degree of branching within the topology of electrical distribution system. Due to the impedance characteristics of inductance, capacitance and resistance of the electrical distribution system that the transfer function of the power line system will vary according to the type of architecture. For example, there will be a difference between the Medium voltage system, low voltage, including access and in-house systems.

Since the power line for both medium and low voltage systems has a unique value of the inductance, capacitance and conductivity they behave as lossy conductors that will have inherent attenuation that will increase with length of the line. The conductivity depending on the coating of the conductors, which is a form of polyvinyl chloride (PVC). Cables with oil paper insulation material exhibiting lower attenuation than PVC constructed cables. Due to the ohmic losses and leakage conductivity for the cables they show an attenuation constant that increases with frequency. Therefore, the bandwidth available for PLC systems decreases with distance.

Overhead cables, which are used in abundance in the North American continent and to a lesser extent in other regions of the world, exhibit lower attenuation due to the dielectric losses. Generally in low and medium voltage systems the cable types have varied over the years as materials used for there construction has improved. However, matching cables of different construction has proved impossible. Consequently multi path propagation takes place leading to frequency fading at different frequencies.

From the discussion so far it is seen that the EMC is one of the key factors in developing PLC systems. As has been raised the cables carrying the communication signals over the power line radiate part of the signal transmitted down the line and therefore become "leaky", a term to describe that not all the signal injected onto the cable will reach the receiver end and part emanates from the cable as electromagnetic radiation. Due to this mechanism, the power cable may be considered as a form of antenna with low efficiency. The fraction of the injected signal power transmitted will be determined by the type of cable, the symmetry of the cable and the type of system network topology. The symmetry of the transmission system is determined by the impedance between the conductors and ground. For example, for a two wire line system the impedance between each conductor and ground is equal or balanced. These type of balanced lines, using differential mode transmission; achieve excellent signal propagation with minimum common mode signal. The unbalanced line does not have good signal propagation because of the Common mode signal that emanates from the cable and therefore, is considered as unbalanced.

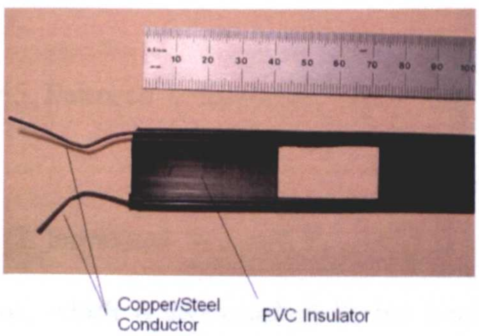
Therefore, common mode currents generated are uniquely responsible for the unsymmetrical balance of the line and the potential radiation from the line. Whereas, differential mode currents are equal in magnitude and flow in opposite directions along the signal conductors. A line that behaves highly symmetrical has a high differential mode to common mode ratio and therefore, has negligible radiated emission from the power line. An unbalanced line will have a very low differential mode to common mode ratio, showing that the cable is leaky and potentially radiating and causing interference to established radio services.

To provide a measure for the disturbance of the power line, the transmission is compared with that of an AM transmission broadcast system. Spuriously emitted electromagnetic radiation is measured within a standard 9 kHz bandwidth which represents the typical and standard AM radio receiver bandwidth. The frequency range from 9 kHz to 30 MHz is normally investigated using a standard magnetic loop antenna.

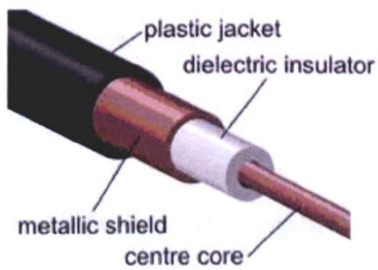
3.3.10 Realistic Power Line Communication Propagation

Wired communications systems intended to carry radio frequency generally use one of two types of cables (figure 64):

- Balanced parallel wire line
- Co-axial line



(a) Parallel twin-wire



(b) Co-axial pair

Figure 64. Types of transmission lines (Parallel twin-wire and Co-axial pair)

Within each broad grouping or type of transmission line there is variety of different kinds, dictated by various applications. Balanced two-wire lines normally consist of open wires with consistent spacing and distance from other metallic objects and earth, to maintain the balance by equalizing stray capacitance. Coaxial cable consists of an inner conductor surrounded by a dielectric material, which is in turn surrounded by a conducting outer sheath, which may be continuous or woven depending on the quality of the cable.

A balanced line is fed with a differential mode signal, which is balanced with respect to earth, as shown in Figure 65.

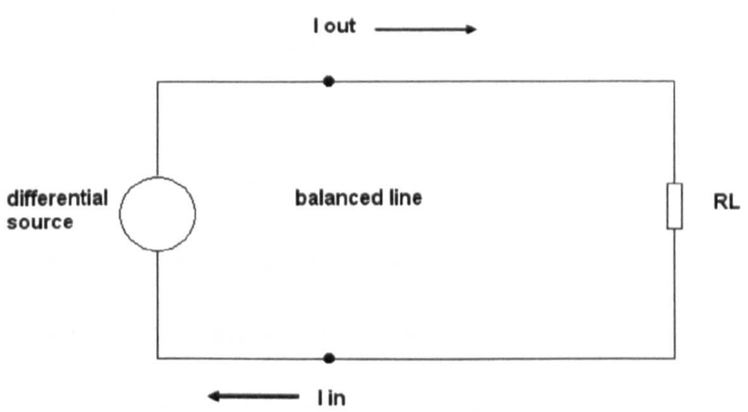


Figure 65. Balanced transmission Line

The line is terminated in a load R_L, which is matched to the characteristic impedance of the line, which is also matched by the source impedance. If the line, the source and the load are perfectly balanced current I_{out} will be the same as current I_{in}. This means that the electromagnetic fields surrounding the conductors will have the same magnitude but opposite polarities; hence they will cancel out and the net emission of power from the line will be zero. If the line or its terminations become unbalanced I_{in} and I_{out} will no longer be equal in magnitude, and the line will radiate. The difference between the two currents, $I_{out} - I_{in}$ is known as the *common mode current* (aka antenna mode current) and flows in the earth between the source or load and the point of unbalance, rather than in the line.

The difference between the differential voltage applied to the line and the (unwanted) common mode voltage between the line and earth is called the Longitudinal Conversion Loss (LCL) and is defined as follows:

$$LCL = 20log\left(\frac{developedcommon\ mode\ voltage}{applied\ differential\ mode\ voltage}\right) \qquad \text{(Eqn.20)}$$

Figure 66 shows how stray impedances can convert differential mode signals to common mode. In this equivalent circuit the components C_C are stray capacitances between the conductors of the line and earth, while Z_S and Z_L are stray impedances in the source and load respectively. It is stated that these capacitances will dominate, but that inductive effects will also be involved, especially where the line passes close to other metallic structures. These inductive effects are represented in Figure 66 by the components L_C.

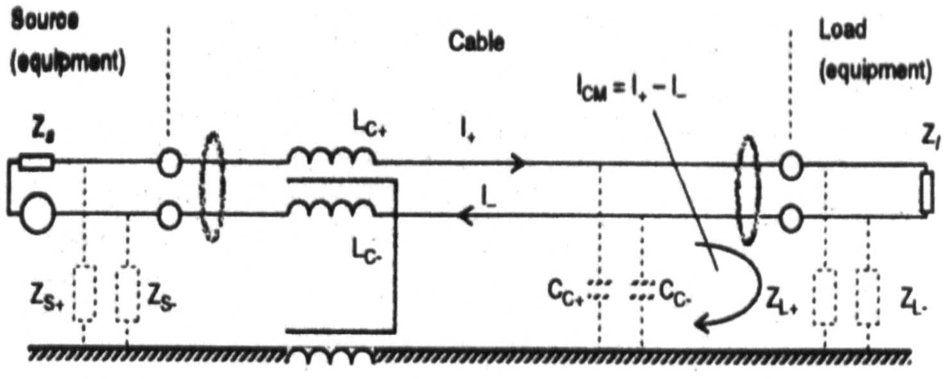


Figure 66. Differential to Common Mode Conversion Mechanisms [23]

Although most RF feeders now use co-axial cable, computer Local Area Networks have moved away from co-ax (IEEE 802.3/1986) to twisted pair (10BASE-T) in both screened and unscreened formats, unscreened being the most common implementation on the grounds of cost and compatibility with telephone wiring. The adoption of twisted pair wiring for LANs can be seen as a retrograde step because the type of unbalance shown in Figure 66 leads to high levels of signal radiation, as anyone who has tried to use portable band 2 VHF receivers in an office with a 100Mbps LAN can testify.

Figure 67. Example of poor wiring practice in a large building

In addition to the likelihood of unbalance being caused by the installation of the wiring, there are two other reasons why PLC systems are unlikely to behave in the same way as balanced telecommunications feeders. The first is that lighting circuits separate the live and neutral conductors at the ceiling rose, extending the live wire down to a switch. This means that for each fixed lighting point there is a substantial length of what, in signaling terms, is a single wire circuit. Power circuit wiring practice varies considerably between countries but in the UK ring circuits are used in domestic premises, as shown in Figure 68.

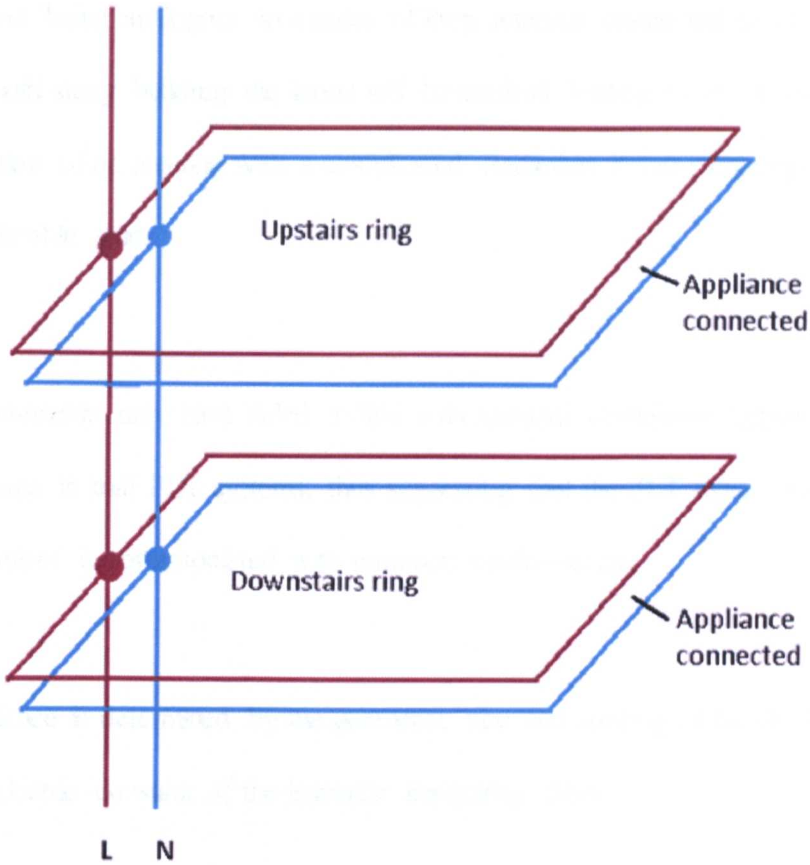


Figure 68. UK Ring Main Circuit Configuration

With no appliances connected, each ring circuit consists of a loop connected to the live conductor and a separate loop connected to the neutral conductor, these being contained in the same cable in domestic wiring. When an appliance is introduced, the live and neutral conductors are joined via low impedance depending on the power consumption of the device and its internal circuitry. This impedance may be very low at HF, especially if the appliance contains capacitors for interference suppression. If the HF impedance of the live conductor is not the same as that of the neutral conductor between the feed and the point at which the appliance is connected, the HF signals may flow in different directions around the loop, thus converting it to a loop antenna. In this case, emission is possible without common mode currents, the situation being analogous to a series of loop antennas connected to a balanced feeder. In a multi-story building the loops will be stacked, leading to the potential for formation of an antenna with a complicated Radiation Pattern Envelope and considerable gain.

Measurements may have failed to find a meaningful correlation between LCL and emissions in trial PLT systems, thus suggesting that the PLT signal radiation mechanism is not associated with common mode current.

Impedance is determined by the geometry, size and spacing of the conductors, and by the dielectric constant of the insulator separating them.

(a) Parallel wire line (b) Co-axial line

Figure 69. Characteristic impedance of transmission lines.

For a parallel-wire line with air insulation as shown in figure 69 the impedance can be calculated as:

$$Z_o = \frac{276}{\sqrt{\varepsilon_r}} \log \frac{d}{r} \quad \text{(Eqn. 21)}$$

Where,

Z_o = Characteristic impedance of the line

d = Distance between conductor centres

r = Conductor radius

ε_r = Relative permittivity of insulation between conductors

For co-axial line, it follows a different equation:

$$Z_o = \frac{138}{\sqrt{\varepsilon_r}} \log \frac{d_1}{d_2} \qquad \text{(Eqn. 22)}$$

Where,

Z_o = Characteristic impedance of the line

d_1 = inside diameter of the outer conductor

d_2 = outside diameter of the inner conductor

ε_r = Relative permittivity of insulation between conductors

For a high value of characteristic impedance, it is seen that the conductors must be very small to give large inductance per unit length. As well, the distance between them must be very large to yield as small a shunt capacitance per unit length as possible.

3.3.11 Losses in Transmission Lines

There are mainly three ways in which energy, applied to a transmission line, dissipated before reaching the load:

- Copper loss
- Radiation or Induction Losses
- Dielectric loss

Conductor heating, or I^2R loss, is proportional to current and therefore inversely proportional to characteristic impedance. Another type of copper loss is due to *skin effect*. As frequency is increased, the opposition to the flow of current in the centre of the wire increases. Current in the centre of the wire becomes smaller and most current flow on the wire surface. *Skin effect* increases with increased frequency and hence more power loss.

Radiation loss arises because transmission lines act as an antenna if the separation of the conductors is an appreciable fraction of wavelength. They increase with frequency for any given transmission line.

Dielectric heating is proportional to voltage across the dielectric and hence inversely proportional to the characteristic impedance for any power transmitted. It again increases with frequency (for solid dielectric lines) because of gradually worsening properties with increasing frequency for any given dielectric medium.

3.3.12 Reflections from an Imperfect Termination

If a lossless transmission line has infinite length or is terminated in its characteristics impedance, all the power applied to the line by the transmitter at one end is absorbed by the load at the other end. Conversely, if a finite piece of line is terminated in an impedance not equal to the characteristic impedance, some of the applied power will be absorbed by the termination. The remaining power will be *reflected.*

When a transmission line is incorrectly terminated, the power not absorbed by the load is sent back toward the transmitter, so that an obvious inefficiency exists. The greater the difference between the load impedance and the characteristic impedance of the line, the larger this inefficiency.

A line terminated in its characteristic impedance is called a *non-resonant*, or *Flat* line. The voltage and current in such a line are constant throughout its length if the line is lossless, or are reduced exponentially (as the load is approached) if the line has losses. When a line is terminated in a short circuit or open circuit, none of the power will be dissipated in such a termination, and all of it will be reflected back to the transmitter. If the line is lossless, it should be possible to send a signal out and then quickly replace the transmitter by a short circuit. The power in the line would shunt back and forth, never diminishing because the line is lossless. The line is then called *resonant* because of its similarity to a resonant *LC* circuit, in which the power shunts back and forth between the electric and magnetic fields.

3.3.13 Standing Waves

When power is applied to a transmission line by a transmitter, a voltage and a current appear whose value depends on the characteristic impedance and the applied power. The voltage and current waves travel to the load at a speed slightly less than the speed of light (3×10^8 m/s). If Z_L (load impedance) is equal to Z_0 (characteristic impedance), the load absorbs all the power, and none is reflected. The only waves present are the voltage and current *travelling waves* from the transmitter to load.

If Z_L is not equal to Z_0, some power is absorbed, and the rest is reflected. We then have one set of waves, V and I, travelling toward the load, and the reflected set travelling back to the transmitter. These two sets of travelling waves, going in opposite directions, set up an interference pattern known as *standing waves* along the line as shown in figure 70.

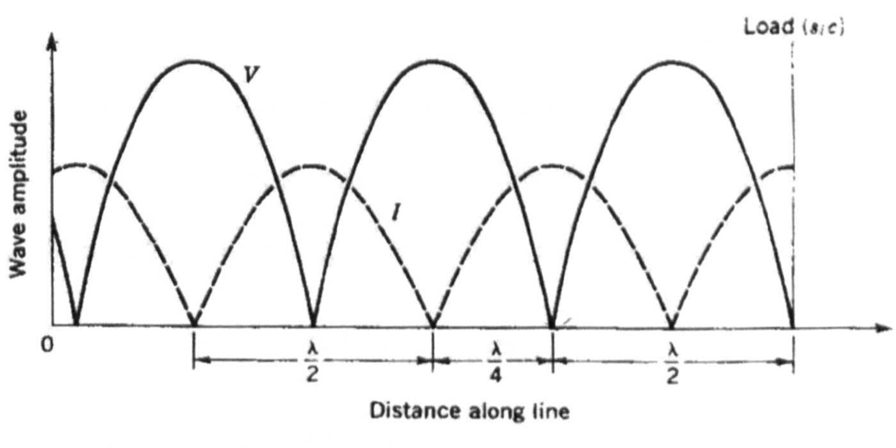


Figure 70. Standing wave patterns on a length of short-circuited transmission line [11]

It is seen that stationary voltage and current minima (nodes) and maxima (antinodes) have appeared. They are separated by half the wavelength of the signal. The voltage nodes and current nodes coincide on the line, as do current nodes and voltage antinodes. At the load, the voltage will be zero and the current a maximum because the load is a short circuit. The current has a finite value since the line has an impedance. At that instant of time, the same conditions also apply at a point exactly one wavelength on the transmitter side of the load. The current at the load is always a maximum, although the size of this maximum varies cyclically with time.

The reflection that takes place at the short circuit affects both voltage and current. The current now starts travelling back to the transmitter, unchanged in phase, but the voltage is reflected with 180° phase reversal.

3.3.14 Standing Wave Ratio

The ratio of maximum current to a minimum current along a transmission line is called the *standing-wave ratio*, as is the ratio of maximum to minimum voltage, which is equal to the current ratio. The SWR is a measure of the mismatch between the load and the line, and is the first and most important quantity calculated for a particular load. The SWR is equal to unity when the load is perfectly matched. When the line is terminated in a purely resistive load, the standing-wave ratio is given by: $SWR = \frac{Z_0}{R_L}$ or $SWR = \frac{R_L}{Z_0}$ (whichever is larger), where R_L is the load resistance. If the load is purely reactive, SWR will be infinity, the same can be seen to apply for a short-circuit or open-circuit termination. Since in all three cases no power is absorbed, the reflected signal has the same size as the forward signal. Somewhere along the line the complete cancellation will occur, giving a voltage zero, and hence

SWR will be infinite. Figure 71 shows standing wave pattern on a transmission line terminated with $R_L > Z_0$.

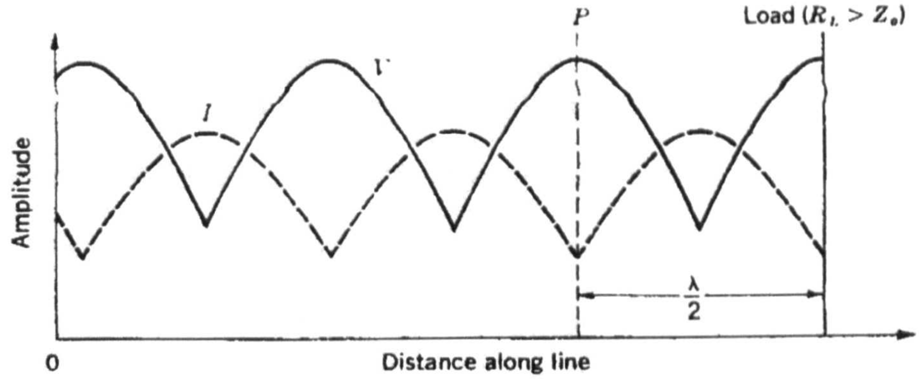


Figure 71. Standing wave patterns of transmission line terminated with $R_L > Z_0$. [11]

When the load is complex, SWR can still be computed, but it is much easier to determine it from a transmission-line calculator or to measure it. The higher the SWR, the greater the mismatch between line and load or, for that matter, between transmitter and line. In practical lines, power loss increases with SWR, and so a low value of standing-wave ratio is always sought, except when the transmission line is being used as a pure reactance or as tuned circuit.

3.3.15 Return Loss of a Transmission Line

One measure of the amount of reflected power is return loss, which is a logarithm ratio of the power of the signal reflected back to the source to the power output by the source. Values for return loss range from infinity, for a perfectly matched system, to zero for open or short circuit. It is usually expressed as a ratio in decibels (dB).

$$\text{ReturnLoss(dB)} = 10\log_{10}\frac{P_i}{P_r} \qquad \text{(Eqn. 23)}$$

Where, P_i is the incident power and P_r is the reflected power.

Two lines are well matched if the return loss is high. Higher the value, the less power is reflected. A high return loss is therefore desirable as it results in a lower insertion loss. Figure 72 illustrates power flow for a transmission line. Figure 73 illustrates return loss and its effect upon original signal respectively. In the top portion, the signal is injected upon the pair. As the signal travels down the pair portions of the signal are reflected back to the transmitter. These reflections are caused by impedance discontinuities in the line.

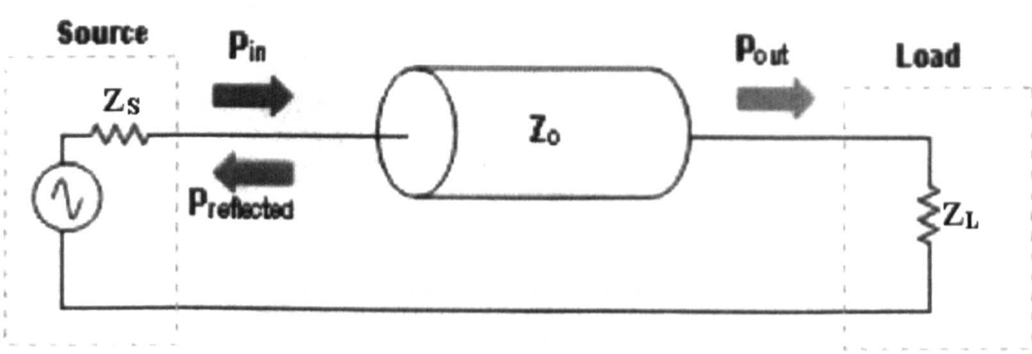


Figure 72. Illustration of power flow for a simple transmission line.

These discontinues may be due to several things such as mismatch with the terminating load, improper installations, poor connections, device insertion.

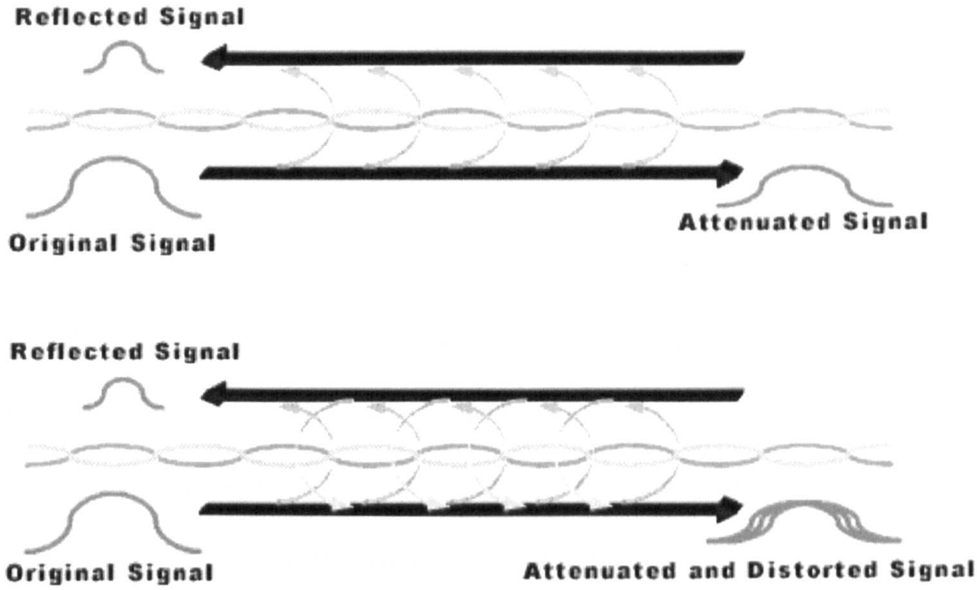


Figure 73. Illustration of Return Loss

3.3.16 Reactance Properties of Transmission Lines

Just as a suitable piece of transmission line may be used as a transformer, so other chosen transmission-line configurations may be used as series or shunt inductive or capacitive reactance. The input impedance of a quarter-wave of transmission line, short-circuited at the far end, is infinity, and the line has transformed a short circuit into an open circuit. However, this applies only at the frequency at which the piece of line is exactly $\lambda/4$ in length. At some frequency near this, the line will be just a little longer or shorter than $\lambda/4$, so that at this frequency the impedance will not be infinity. The further we move, in frequency, away from the original, the lower will be the impedance of this piece of line [11]. We, therefore, seem to have a parallel-tuned circuit, or at least something that behave as one.

If the quarter-wave line is open circuited at the far end, then by a similar process of reasoning, a series-tuned circuit is obtained. Similarly, a short-circuited half-wave line will behave as a series tuned circuit.

3.4 Summary

In this chapter various aspects of EMC and noise are discussed. The theory of transmission line and characteristic impedance of transmission lines have been highlighted. Various research to date on measurements of impedance are discussed. Chapter 4 details the development of experimental program that was designed to measure the impedance in the low voltage distribution lines.

Chapter 4: Experimental Work

4.1 Introduction

This chapter describes the practical experiments undertaken in this thesis to investigate the impedance variation in low voltage distribution network. The initial research work started with investigation into the Radiated Emission of PLC system. Open University PLC Research Group members have taken numerous measurements in various parts of UK and abroad. These are reported in various seminars and published PhD thesis by other members of the group. The members of the group also published a paper, "Evaluation of Key parameters for Determining the Efficiency of Signal propagation in Broadband PLT Systems". International Symposium on PLC and its Applications, IEEE. May 2005. [Appendix 2]

Simultaneously, a measurement programme for investigating the impedance characteristics of the low-voltage distribution line in Bridgwater College buildings and residential houses were established, which constitute this thesis.

4.2 Impedance Measurement Techniques

There are many measurement methods to choose from when measuring impedance, each of which has advantages and disadvantages. In this thesis a Network Analysis method was selected. This method has the advantage of wide frequency range (300 kHz -100 MHz) and good accuracy.

4.2.1 Network Analysis

Network analysis is the process by which designers and manufacturers measure the electrical performance of the components and circuits used in more complex electrical systems. When these systems are conveying signals with information content, we are most concerned with getting the signal from one point to another with maximum efficiency and minimum distortion. Network analysis is a method of accurately characterizing such components by measuring their effect on the amplitude and phase of swept-frequency and swept power test signals.

Commercially available network analysers are very expensive pieces of precision equipment, costing thousands of pounds. These instruments provide tremendous dynamic range (approaching 90 to 100 dB), a high degree of accuracy, and many software options for manipulating and displaying data. It's possible to sacrifice some of the dynamic range and precision to save a lot on the cost and complexity of the measurement hardware. Today's personal computers and laptops, however, provide extensive ability to manipulate and display data for virtually no additional cost—just the time and effort of creating the software. So the instrument itself is kept as simple as possible by offloading much of the work to the host computer.

Figure 74 is a block diagram of the low cost Vector Network Analyser (VNA) measurement device. The equipment consists of a direct digital synthesiser (DDS) to generate an RF test signal, a reflection measurement circuit, a transmission measurement circuit, a pair of phase/ magnitude RF detectors (one for transmission and one for reflection), a multi-channel analogue-to-digital converter (ADC), and a specialized USB aware microprocessor. Additionally, a +3.3 V regulator and a +5 to –5 V inverter provide the digital and analogue supply voltages for the board.

The direct digital synthesizer (DDS) circuits generate an RF test signal and an LO signal for down-converting the tested component/circuit's response signals to zero IF. The dc IF signals are then digitized by appropriate analogue-to-digital converters (ADC). The digital numbers are fed into a standard personal computer (PC) for further processing and imaging.

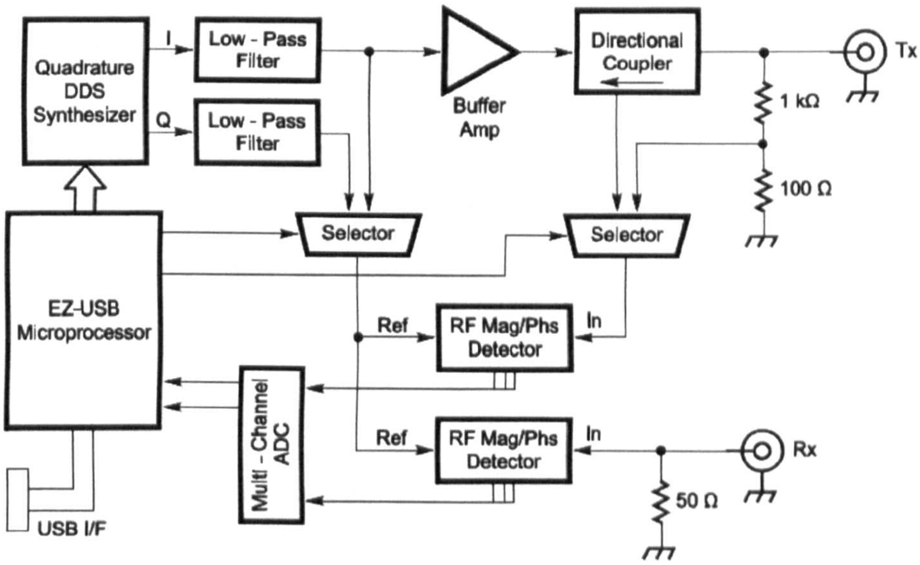


Figure 74. Block diagram of Vector Network Analyser [31]

This mini Vector Network Analyser (AD 83020+AD9851) intended for amateur radio enthusiast market is selected for the impedance measurements on LV distribution networks. The VNA unit as shown in figure 75 is connected to a PC parallel port. It performs a scan through a programmable frequency limits and acquires impedance parameters in the frequency domain.

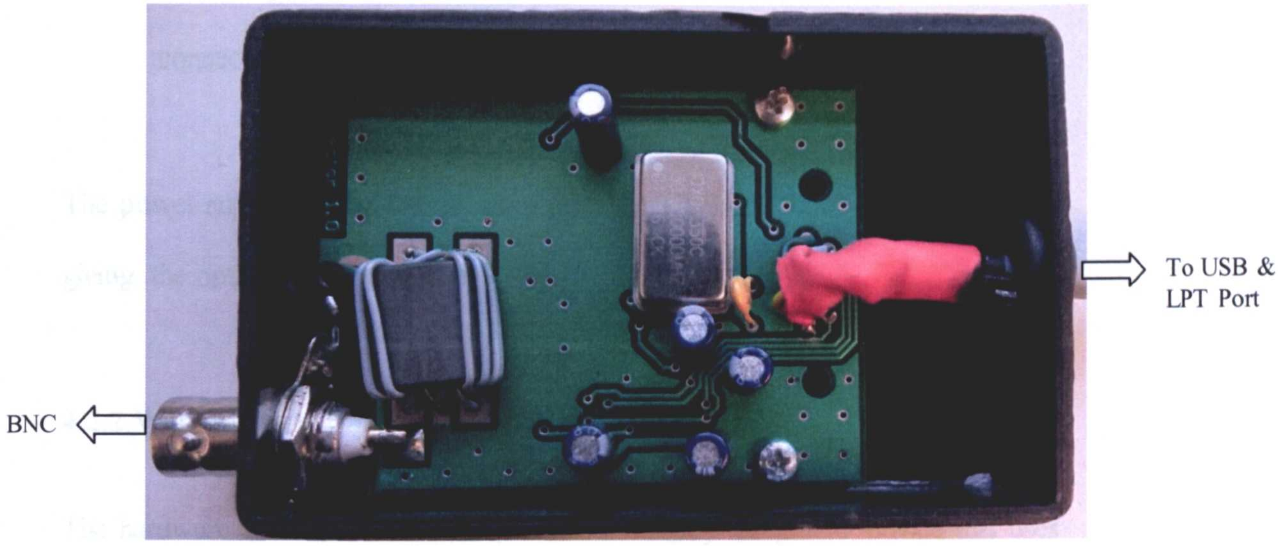


Figure 75. Vector Network Analyser (AD 83020+AD9851)

Adaption of this VNA allows the following parameter to be measured which is detailed in the technical specification:

- Analyser with the following measurements: Return Loss, SWR, Z, X, R
- Real time measurement, scans the full HF range (0.1- 60 MHz) in 0.3 seconds per screen with 500-point resolution.
- DDS generator (0.1-60 MHz) with P_{out} -5 dBm @ 50 Ω
- Measurements of capacitor and inductor, balun, resistors, etc.
- Programmable maximum and minimum sweep frequency
- Programmable number of samples per screen
- Programmable LPT address
- Measurements of coaxial cable
- Software compatible with Win95/98/ME/2000/XP

- Power supply from the PC, from PS2 (external keyboard connector) or USB connector, no external power required.

The power supply for the unit is taken from the USB or PS2 of the connected PC giving the option of portable use.

4.2.2 Working of the Analyser (AD8302+AD9851)

The hardware is based on AD9851, which is a highly integrated device that uses advanced Direct Digital Synthesis (DDS) technology, coupled with an internal high speed, high performance D/A converter, and comparator, to form a digitally programmable frequency synthesizer and clock generator function. AD9851 generates a stable frequency and phase-programmable digitized analogue output sine wave. This sine wave is used directly as a frequency source, or internally converted to a square wave for agile-clock generator applications. The AD9851's high speed DDS core accepts a 32-bit frequency tuning word, which results in an output tuning resolution of approximately 0.04 Hz with a 180 MHz system clock.

The output of AD9851 feeds a directional coupler; the two coupled outputs are compared in phase and amplitude as shown in the circuit diagram in figure 76. In reflection mode the Return Loss and the phase of the reflection coefficient is used to calculate the impedance, while in transmission mode the coupler is used as a power splitter which sends power to the load and creates a reference for the first port of the AD8302. The AD8302 measures the magnitude ratio, defined here as gain, and phase difference between two signals. A pair of matched logarithmic amplifiers provides the measurement, and their hard-limited outputs drive the phase detector.

The hardware also contains a microcontroller, which acts as an interface between the DDS and the USB converter, first the CPU will receive via USB/RS232 the command to carry out a sweep, and then the CPU will send back the results of the two internal analogue to digital converters (magnitude and phase) values for each generated frequency sample.

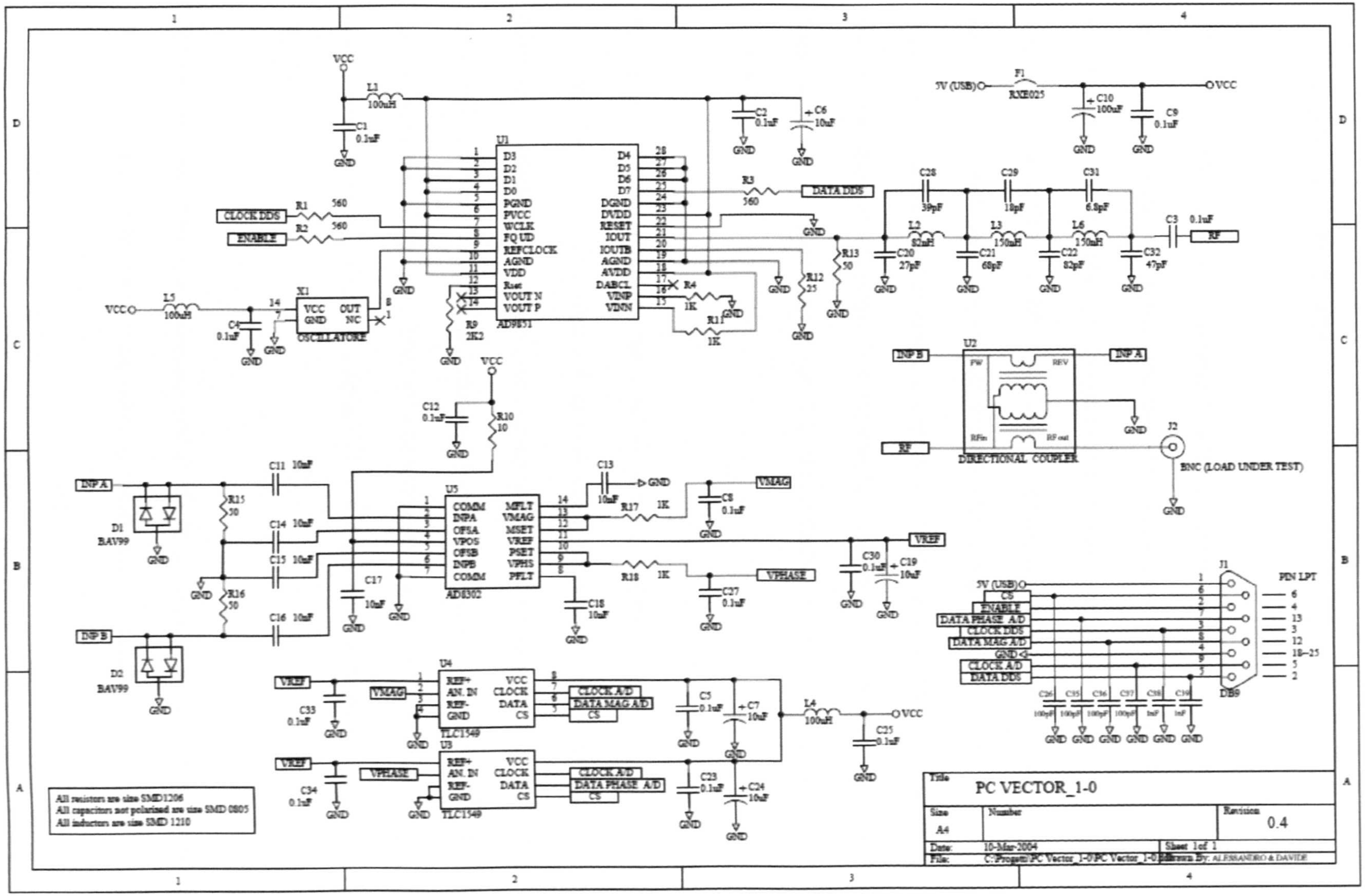


Figure 76. Circuit Diagram of Impedance Anayser (AD8302+AD9851)

4.2.3 Coupling Circuits for PLC

The basic VNA is designed to connect to a passive circuit. In order to connect to the power lines a coupler is designed and built. One of the most critical components of any Power Line Communication (PLC) system is its interface circuit (or coupling circuit) with the power distribution network. This is by no means a simple unit considering the challenging characteristics of the PLC channel. Due to high voltages, varying impedances, high amplitudes and time dependent disturbances, coupling circuits need to be carefully designed to provide both the specific signal transmission with the appropriate bandwidth, and the safety level required by the applicable domestic or international standard.

Coupling circuit has to provide the necessary galvanic isolation of the PLC system from the power line. Inductive coupling is known to be rather lossy up to several decibels. However, it avoids physical connection to the network, which makes it safer and often easier to install than the capacitive coupling. Capacitive coupling, on the other hand, realizes the required high-pass filtering with a straight-forward electronics that is easy and compact to design. Practical coupling circuits often apply a combination of both techniques.

The arrangement of the signal coupler used in this research programme is shown in figure 77. This coupler can be used for reception or transmission of signals.

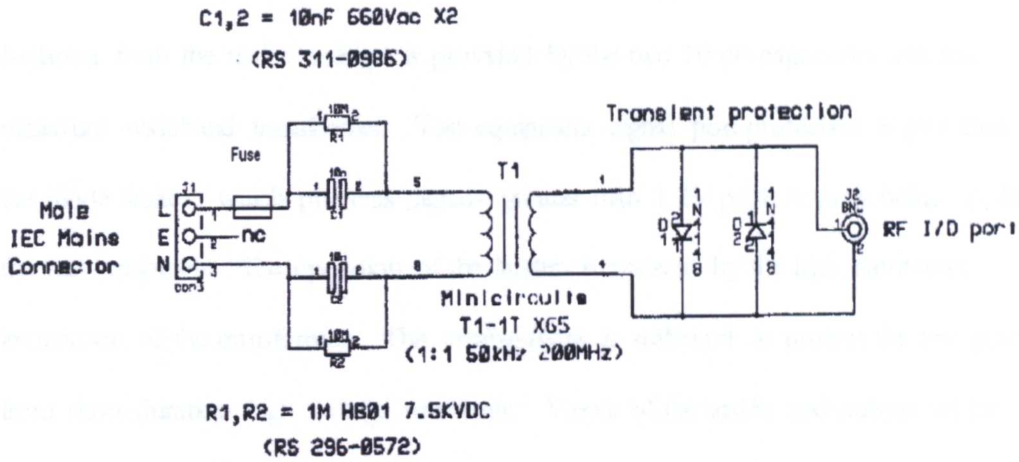


Figure 77. Low-voltage PLT Coupler circuit

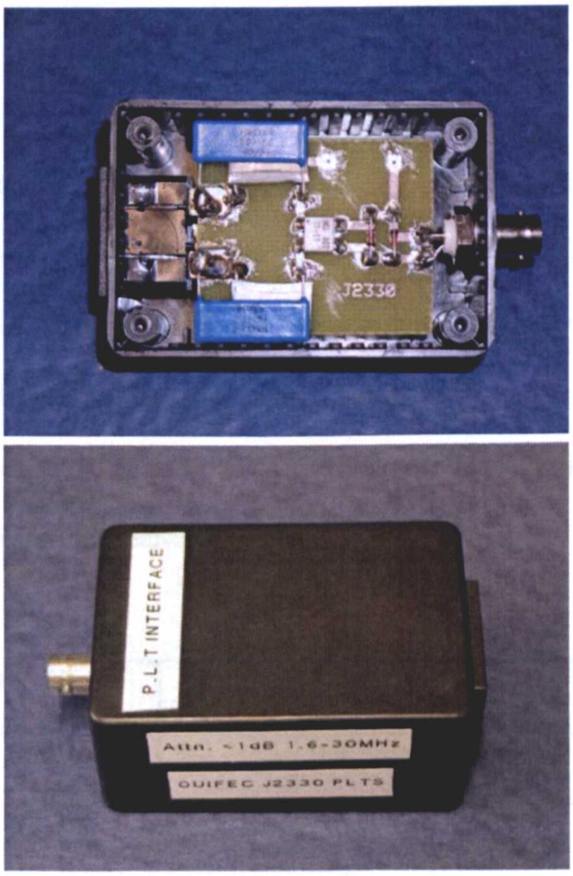


Figure 78. Low-voltage coupler inside (top) and outside (bottom).

Isolation from the mains voltage is provided by the two 10 nF capacitors and the miniature wideband transformer. Test equipment signal port protection is provided by the diode limiter, which prevents signals greater than 1.2V peak to peak being applied to the test equipment. The operation of the limiter is assisted by the high saturation impedance of the transformer. This arrangement is sufficient to protect the test gear ports from short-duration high voltage transients. Views of the inside and outside of the coupler are shown in figure 78. The coupler is equipped with a BNC socket for connection to the test equipment and an IEC mains socket for connection to the network under test, the short lead being chosen to minimize attenuation between the coupler and the network.

The coupler was calibrated before use by connecting a pair back to back (by linking their mains ports) and performing a frequency run using a signal generator and the measuring receiver. In this test setup the maximum loss across the frequency range 1.6 - 30MHz was found to be 1dB per coupler. The actual losses were as shown in table 6 and were used as a transducer factor, so that the loss was compensated in the measurement file from the receiver.

Frequency (MHz)	1.6	2.2	5.0	12.0	16.5	30
Attenuation (dB)	0.75	0.5	0.4	0.4	0.5	1.0

Table 6. Transducer factors for the coupler.

The measurement error associated with this procedure is related to the unknown source impedance of the mains and the 50Ω impedance of the test equipment.

A calibration check of the impedance analyser was done using a 50 Ω load terminator and its impedance was measured instead of power line. Figure 79 shows the variation of impedance. Impedance recorded is approximated to 50 Ω within the selected frequency of 1MHz-30MHz.

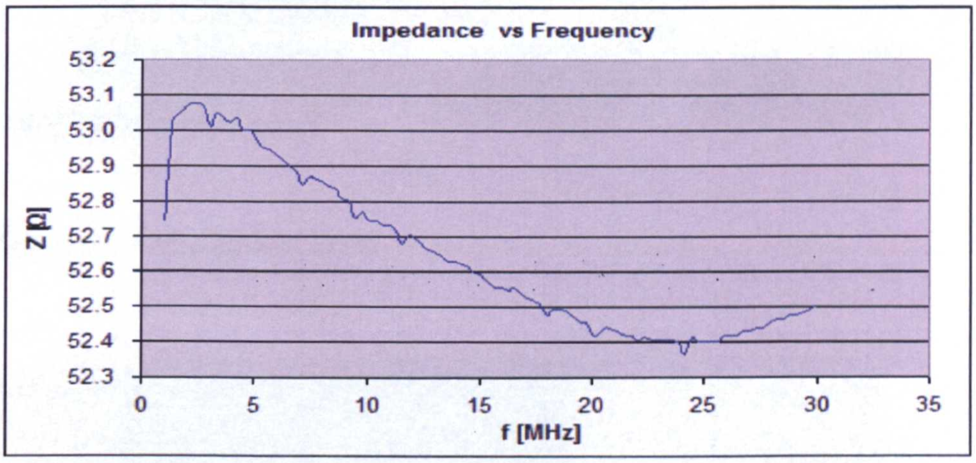


Figure 79. Calibration check of Impedance Analyser with 50 ohms load.

4.3 Experimental Set Up

The experimental set-up used is shown in the following diagram.

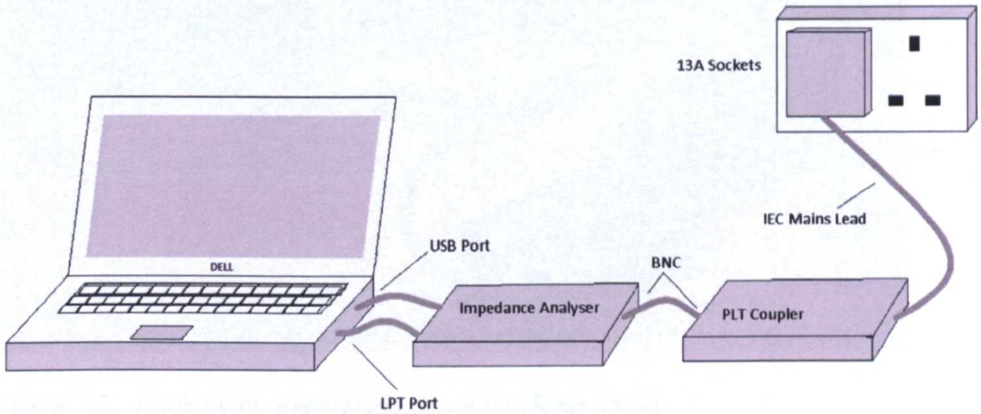


Figure 80. Experimental set-up.

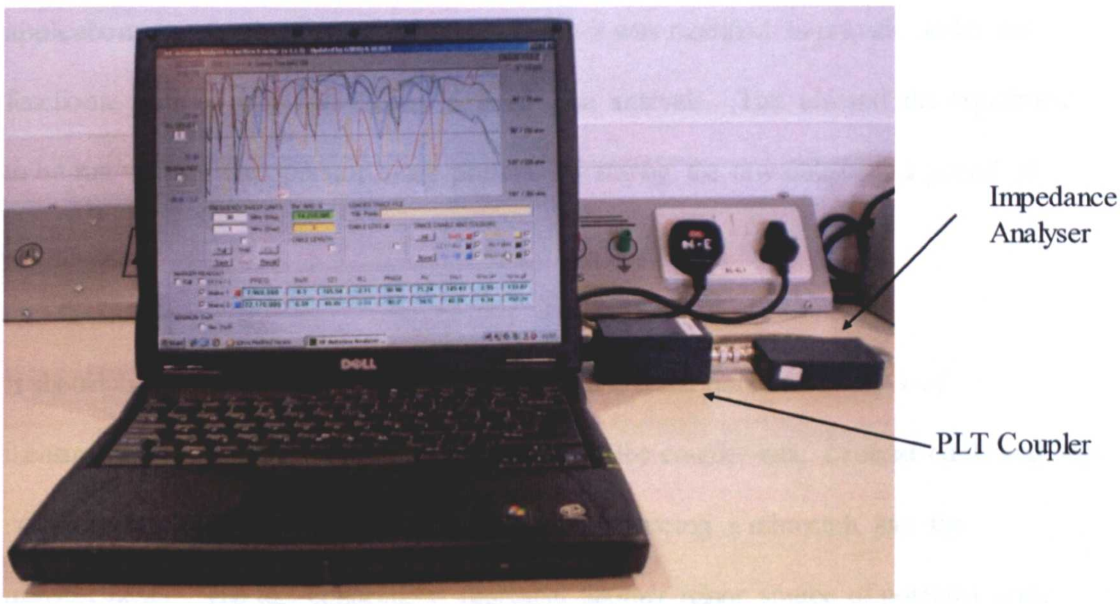


Figure 81. Equipment experimental set-up (Front view)

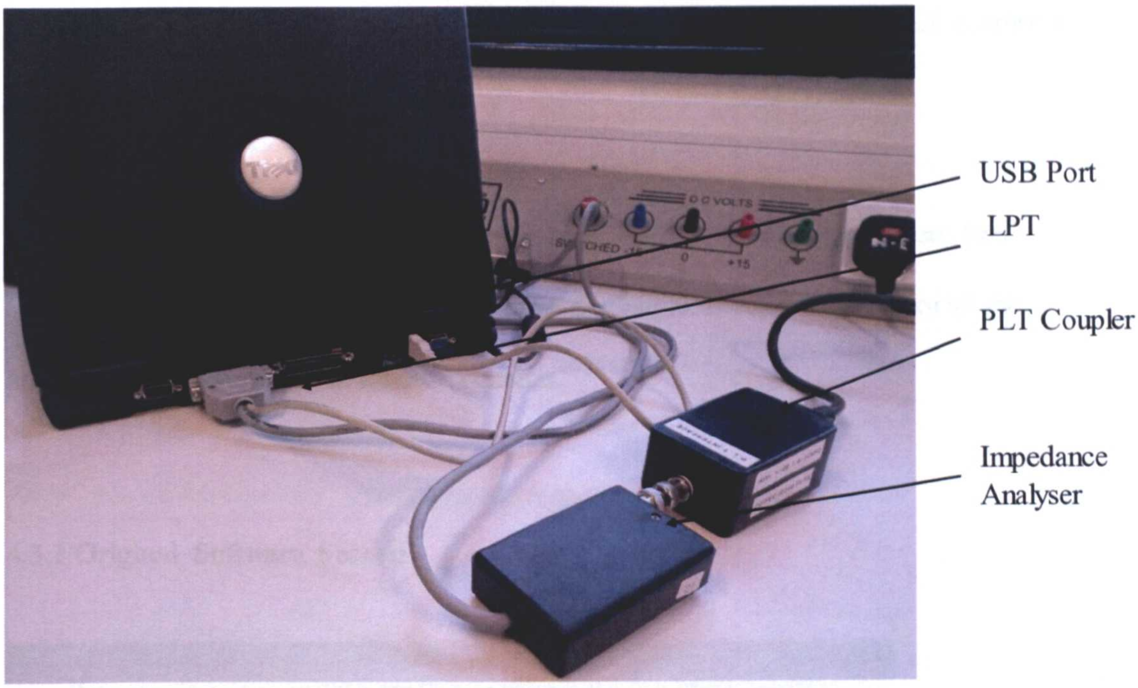


Figure 82. Equipment experimental set up (Rear view)

The original software supplied with the VNA kit is perfectly adequate for amateur radio application, but for the purpose of this research it was modified to provide additional functions, such as auto save facility at fixed time intervals. This allowed the experiment to be run without the operator being present, by storing the raw data over a period of time.

It should be noted that this experimental set-up has some potential sources of measurement uncertainty, related to the effects of the coupler unit, co-axial cable and test connections. The coupler has the potential for introducing a mismatch into the measurements. The test connections represent another minor source of potential error. Efforts were made to minimize these potential errors by placing the equipment near to the measuring power socket and a shorter 0.5 metre IEC lead is used for the PLT coupler to the socket.

The set up captured and stored data every hour of the day. The raw data were then formulated in Excel spread sheets which gave the graphical representation of all the impedance measurements at various locations.

4.3.1 Original Software Screen

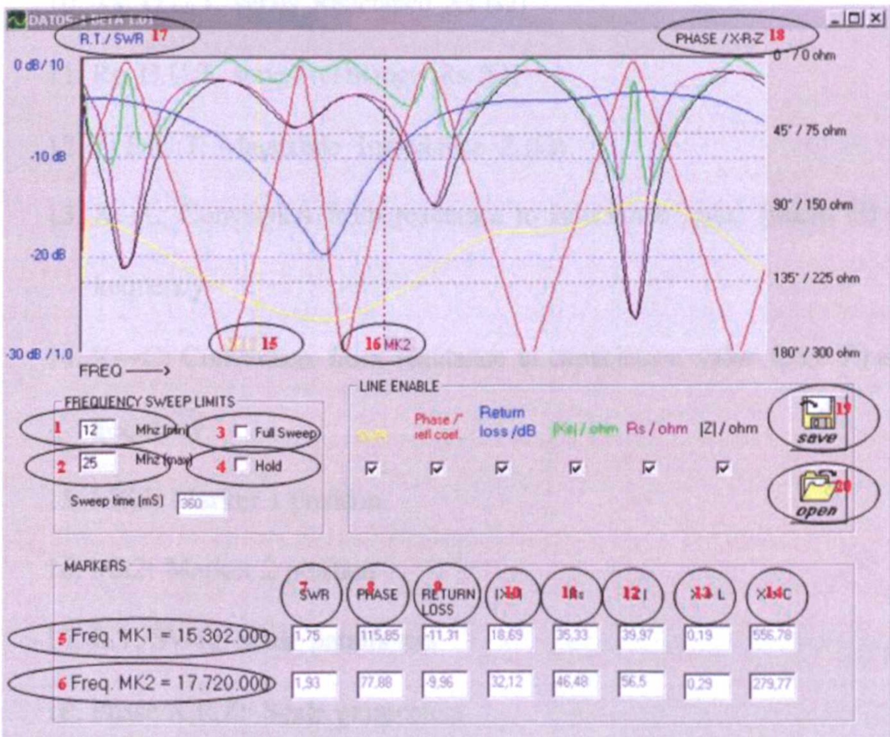
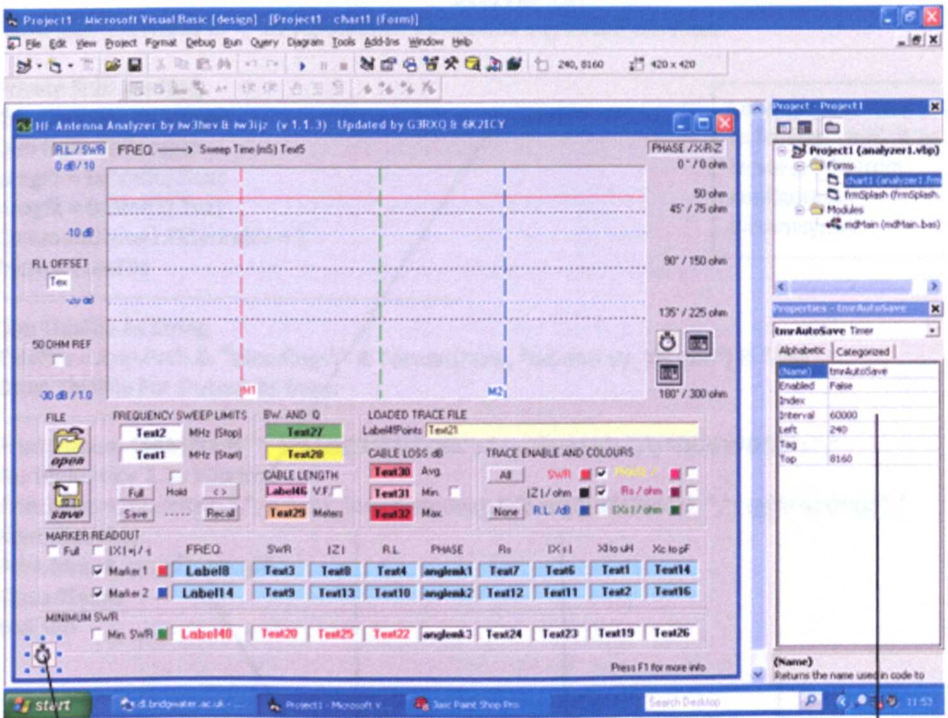


Figure 83. Original Software Screen

1. Fmin: (MHz) start frequency sweep
2. Fmax: (MHz) stop frequency sweep

3. Full Sweep: Set the maximum sweep (minimum and maximum values programmed in to analyz.ini).
4. Hold: Turn on to disable the reading updating, suggesting to display saved files.
5. Freq.MK1: Frequency value pointed by marker 1
6. Freq.MK2: Frequency value pointed by marker 2
7. SWR: $SWR = \frac{1+|\rho|}{1-|\rho|}$
8. Phase: Phase of the reflection co-efficient 0-180°
9. Return Loss: RL = -20 log |ρ|
10. Xs: D.U.T. series Reactance Xs (Ω)
11. Rs: D.U.T. series resistance Rs (Ω)
12. Z: D.U.T. Magnitude Impedance Z (Ω)
13. X→L: Conversion from reactance to inductance value (micro H) at given marker frequency
14. X→C: Conversion from reactance to capacitance value (pico F) at given marker frequency
15. MK1: Marker 1 position
16. Mk2: Marker 2 position
17. R.T./SWR: Scale parameters
18. Phase/X,R,Z: Scale parameters
19. Save: for saving data into .vec format and .csv format
20. open: for restoring files .vec format

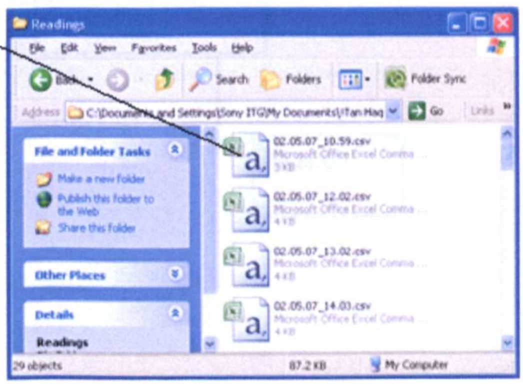
4.3.2 Software Modification Details




```
tmrAutoSave: save at hourly intervals
Private Sub tmrAutoSave_Timer()
TimeCounter = TimeCounter + 1
If TimeCounter = 60 Then
   TimeCounter = 0
   savefile
End If
End Sub
```

Timer tick event set at maximum available interval of 1 minute 60,000 millisecs.

The modifications were to automatically save the measured impedance at hourly intervals. Calculated values were saved in comma separated value format:




```
SAMPLE N°,RETURN LOSS,PHASE,DDS WORD,
 1 , 484 , 37 , 30779400 ,
 2 , 483 , 18 , 37698800 ,
 3 , 483 , 16 , 44618200 ,
 4 , 483 , 15 , 51537600 ,
 5 , 484 , 14 , 58457000 ,
 6 , 485 , 14 , 65376400 ,
 7 , 485 , 13 , 72295800 ,          etc.
```

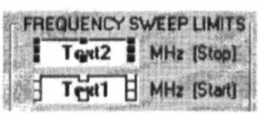
The sub-routine to save the data in CSV format:

```
'************************************* Save File .CSV ***********************************
' Now has "," instead of ";" as separators - i.e Comma separated variables

Private Sub savefile()
Dim fileindex As Integer
Dim fnum As Integer
progf1 = txtVal(0).Text
progf2 = txtVal(1).Text
CommonDialog1.FilterIndex = 1
fnum = FreeFile
'-------------------------------------------------------------------------
Dim ThisFile As String
ThisFile = App.Path & "\Readings\" & Format(Now, "dd.mm.yy_hh.mm") & ".csv"
Open ThisFile For Output As fnum
'---------------------------------------------
Print #fnum, "SAMPLE N°"; ","; "RETURN LOSS"; ","; "PHASE"; ","; "DDS WORD"; ","
For fileindex = 1 To lChamp
Print #fnum, fileindex; ","; return_loss(fileindex); ","; angle(fileindex); ","; sg(fileindex); ","
Next fileindex
Print #fnum, progf1, progf2
Close #fnum
End Sub
```

Loop counter from 1 to lchamp - Initialised to value 100 from configuration file:analyz.ini

progf1 & progf2
Form global variables to store the sweep limits.



return_loss array

angle array

sg array

4.3.3 Modified Software Screen

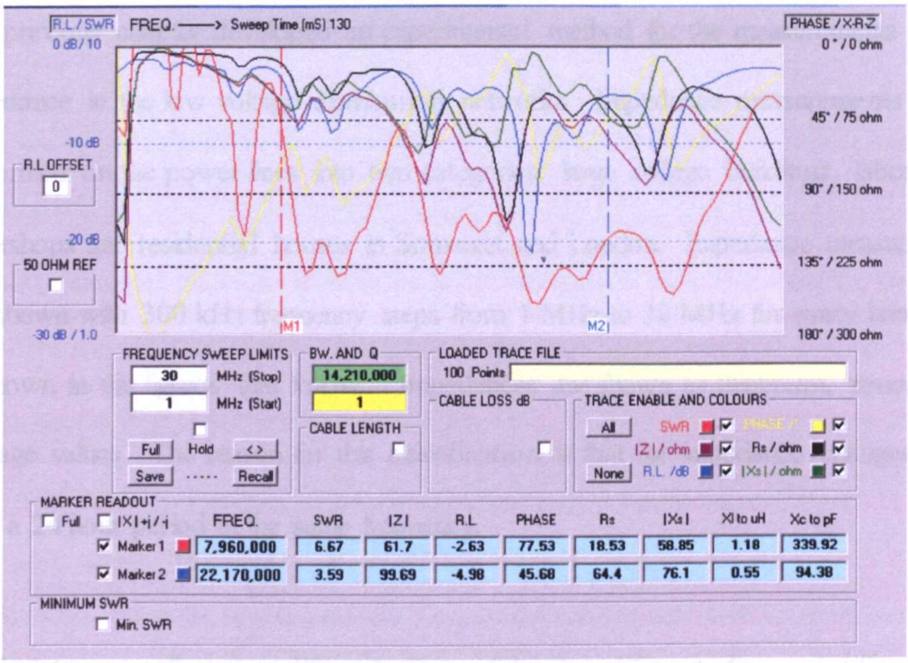


Figure 84. Modified Software Screen

4.4 Summary

This chapter described the development of an experimental method and software modification details and that was used to measure the impedance of low voltage distribution networks. A series of experiments have been carried out over a period of time in various engineering workshops, laboratories, computer classrooms in Bridgwater College and some residential houses in Somerset and London. The experimental set up was connected to the power lines socket and left to capture and store data over a period of time. Chapter 5 discusses the results of this experimental programme.

Chapter 5: Experimental Results

The previous chapter developed an experimental method for the measurements of impedance in the low voltage distribution networks. Impedance measurements are performed on the power lines into two categories: large college buildings, laboratories, workshops and residential houses in Somerset and London. Impedance measurements are shown with 300 kHz frequency steps from 1 MHz to 30 MHz for every hour in a day as shown in the figures that follow. Impedances are shown as minimum, maximum and average values. The reason for this classification is that the impedance changes with time over a 24 hour period at the same frequency.

Much data was collected at different times of the day, different days and different places. In all the measurements, impedances are observed for 24 hours a day, and sometimes up to seven days of the week. Measurements were recorded automatically. In addition I had set up the capability to remotely log on to the host PC/laptop to monitor the measurements using Microsoft Remote Desk Top client application.[10] This chapter describes the results obtained in various locations.

---

[10] Microsoft Remote Desktop is a client application that allows a user to access and control the resources and data of a remote computer using an internet connection. It is, in essence, remote control software. Once logged on, display data and keyboard strokes transmit from the host to the client computer, allowing the user to view and work with the host computer as if the user were sitting directly in front of it.

5.1 Results 1 : Semi - Rural premises – Bridgwater College Buildings

5.1.1 Single Phase Measurements

The first sets of measurements presented in this chapter are taken at Bridgwater College in Somerset, England. It is a tertiary college and one of the largest in South West of England. Because of its geographic location, Bridgwater can be considered to be semi-rural as it is a small town but some distance from any major towns and cities. Bridgwater is a market town and the administrative centre of the Sedgemoor district. Bridgwater is located on the major communication routes through South West England. According to the 2001 census, the town had a population of 33698.

The college is an interesting test premises because it has both three-phase and single-phase architectures and a range of classrooms with computers, laboratories and electrical and mechanical workshops. The original campus was built in early eighties and the other buildings were constructed around the main buildings over the last 30 years. The new state of the art engineering department building was opened in 2011. Figure 85 shows the location of the main campus of the college and the buildings in question where impedance measurements are taken.

Figure 86 shows the layout of the college buildings. The buildings included various electronics laboratories, computer classrooms and welding workshops. Most of the single phase measurements are carried out between terminals of Line and Neutral that is "normal mode" or "differential mode" impedance. The measurements were taken over a period of time at Bridgwater College buildings. The test equipments were left on during the normal working hours as well as during the evening and night. The impedance analyser performs a scan through a programmable frequency limits and acquires impedance parameters in the frequency domain.

Measurements were also taken during the weekend with no college activities. All the measurements were time and date stamped by the software used. Obtained results from the impedance experiments are presented graphically and discussed in this chapter and detailed results are included in appendix 1.

Figure 85. Bridgwater College, Somerset, UK – Site location.

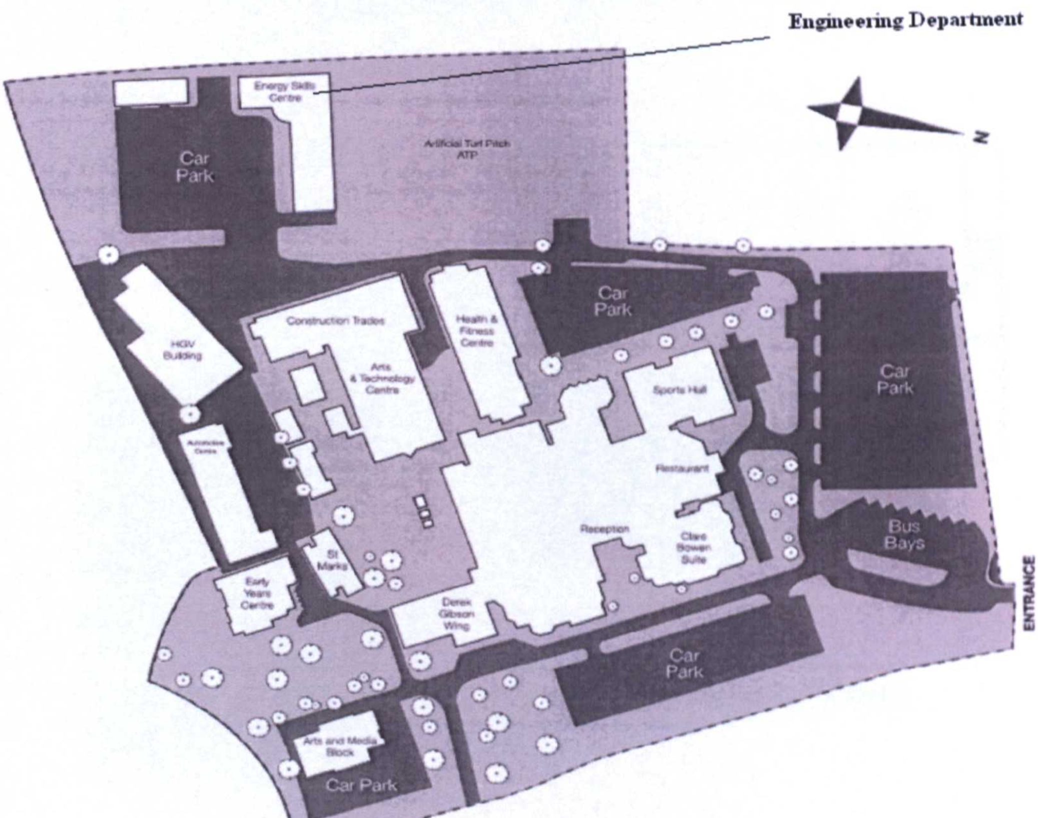


Figure 86. Aerial view and layout of the buildings of Bridgwater College Main campus.

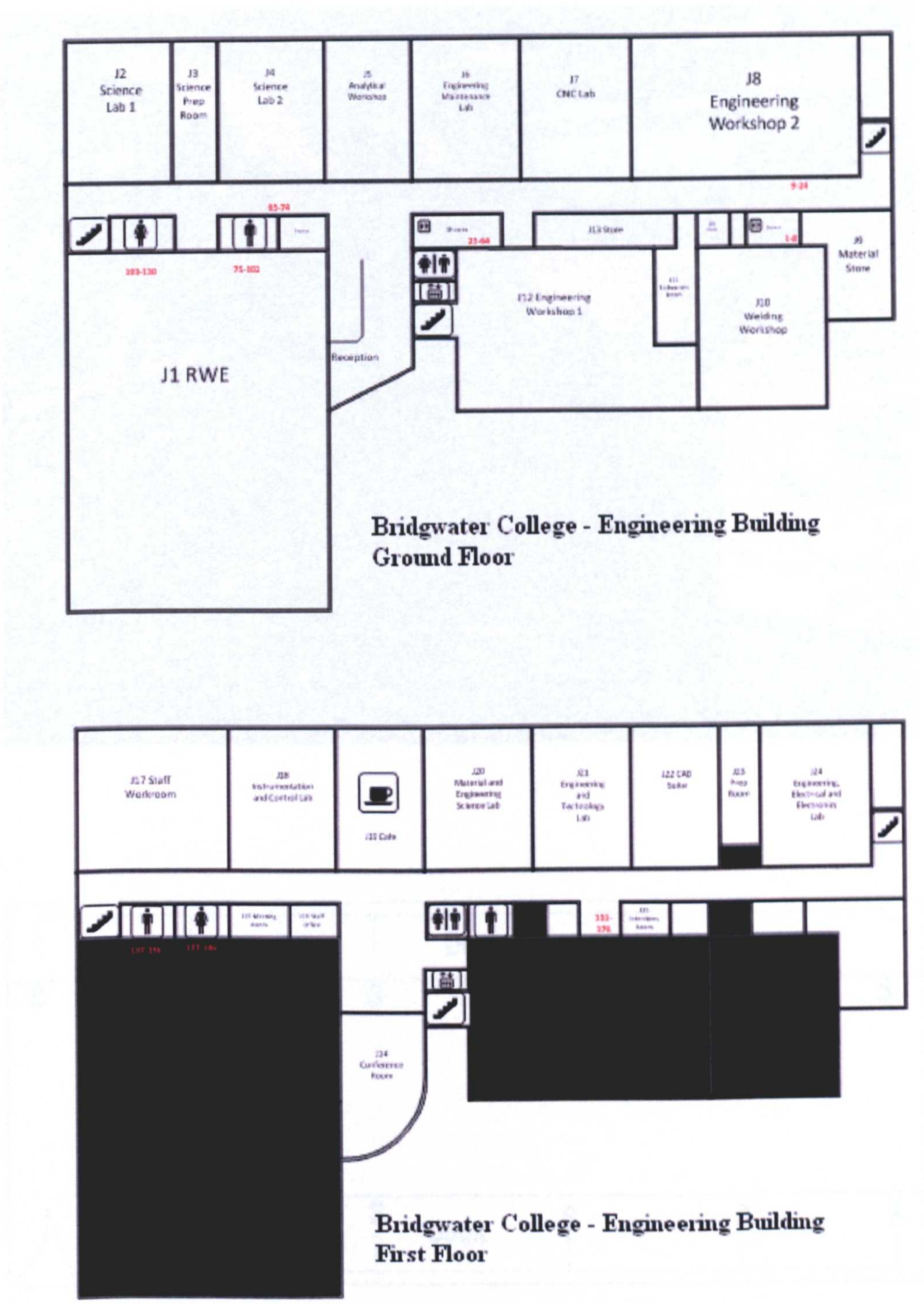


Figure 87. Rooms Layout of the New Engineering Building of the College.

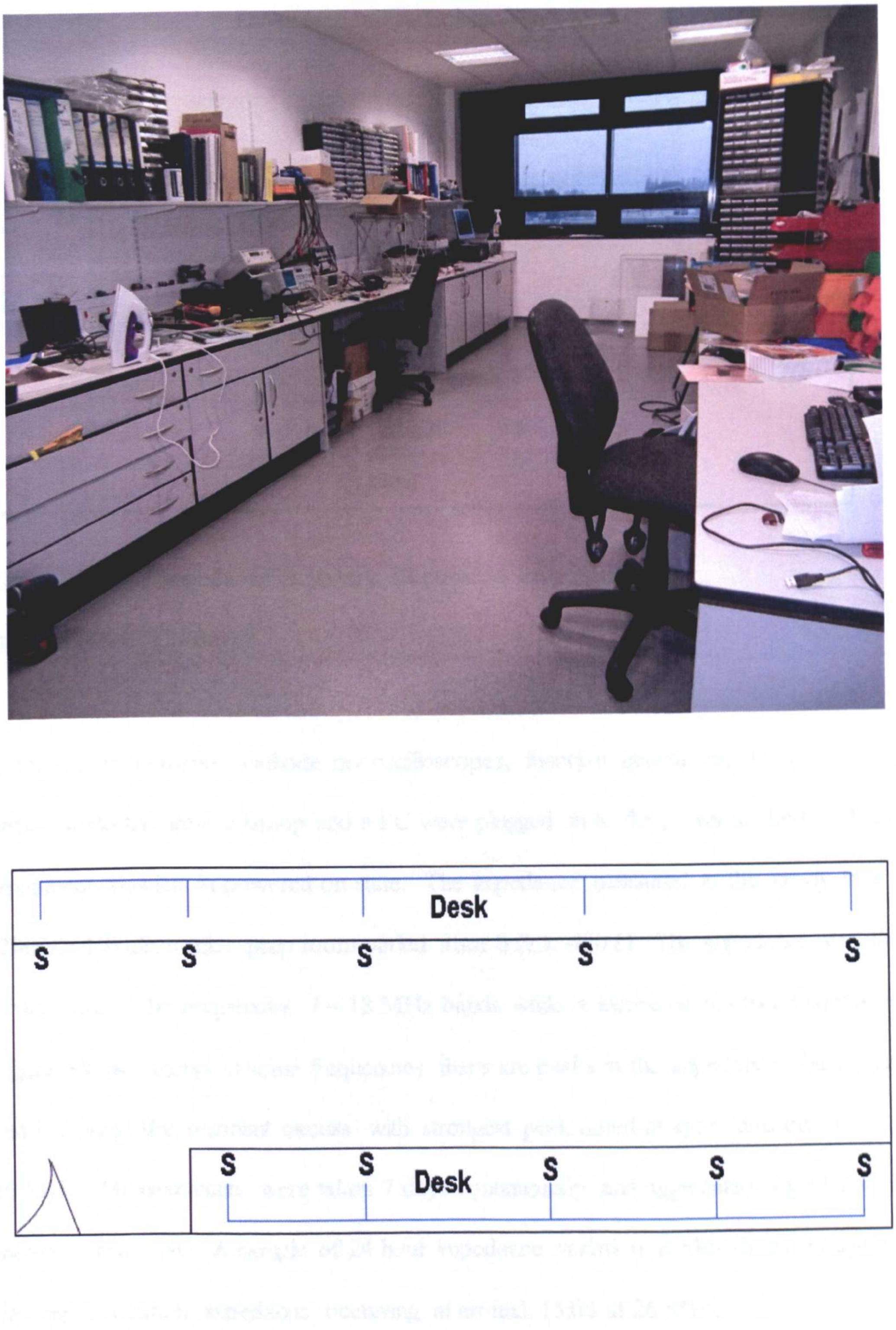


Figure 88. Electronics Prep Room J24 and Electrical Socket Diagram

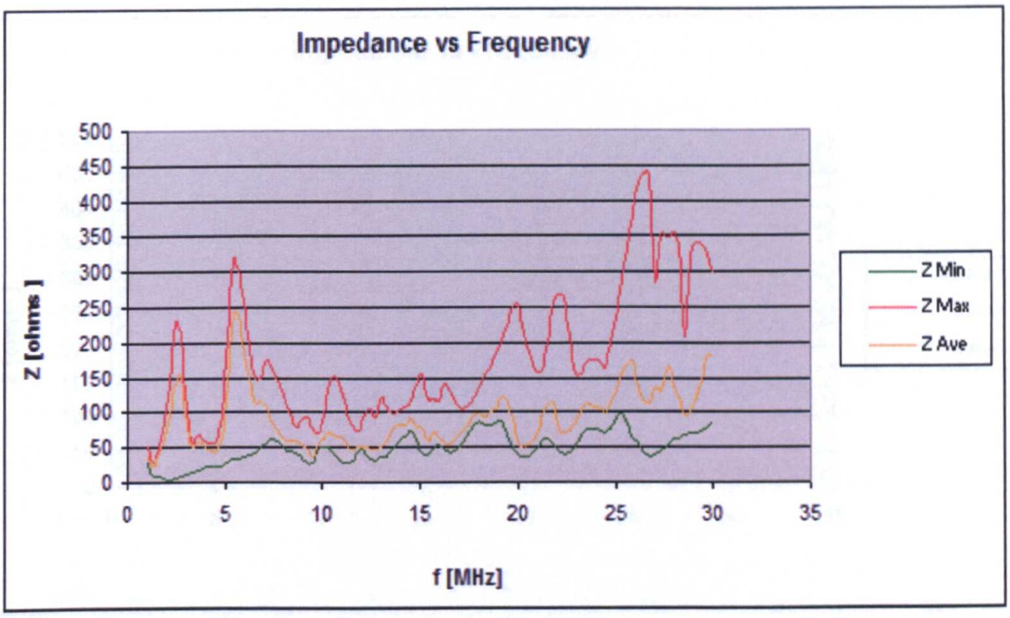


Figure 89. Day Impedance Summary Electronics Prep Room J24.

Date 24/06/2011 (Friday)

In these measurements, cathode ray oscilloscopes, function generators, d.c. power supply units, an electric iron, a laptop and a PC were plugged in to the power sockets. All the equipment was left in powered on state. The impedance measured in this newly built (2009/2010) electronics prep room varied from 0 Ω to 450 Ω. The impedance was found to decrease at the frequencies 7 – 18 MHz bands while it increased at other frequencies. Figure 89 also shows at some frequencies there are peaks in the impedance characteristics and behaving like resonant circuits with strongest peak noted at approximately at 26 MHz. Measurements were taken 7 days continuously and aggregated impedance is shown in figure 90. A sample of 24 hour impedance variation is also shown in figure 91 showing maximum impedance occurring at around 15:00 at 26 MHz.

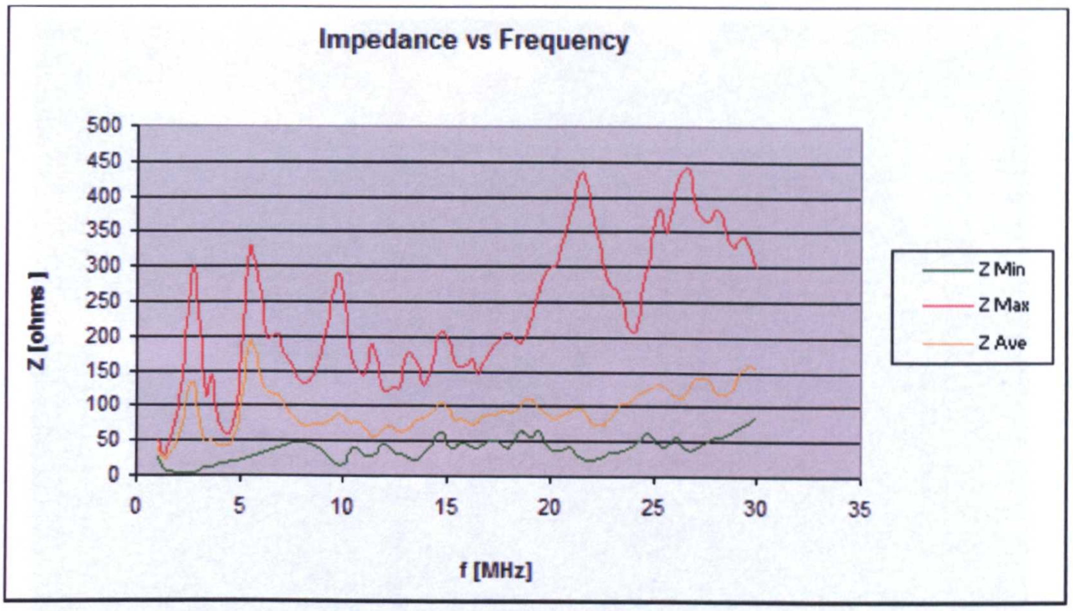


Figure 90. Aggregate 7 days impedance summary

Electronics Prep Room J24 Date 24/06/11 – 30/06/11

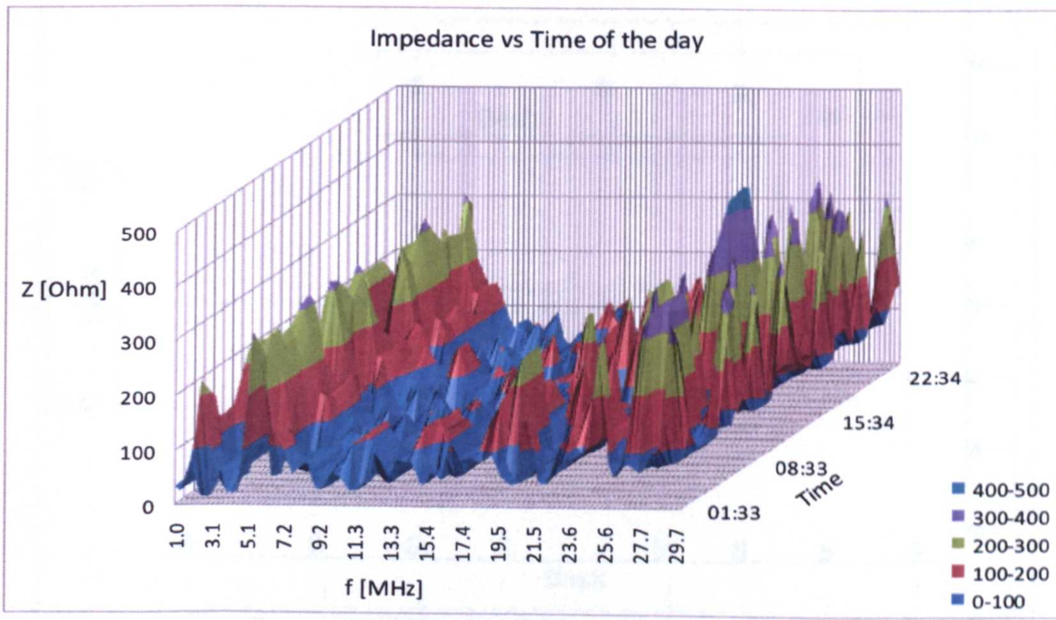


Figure 91. 24 hour impedance variation - Electronics Prep Room J24

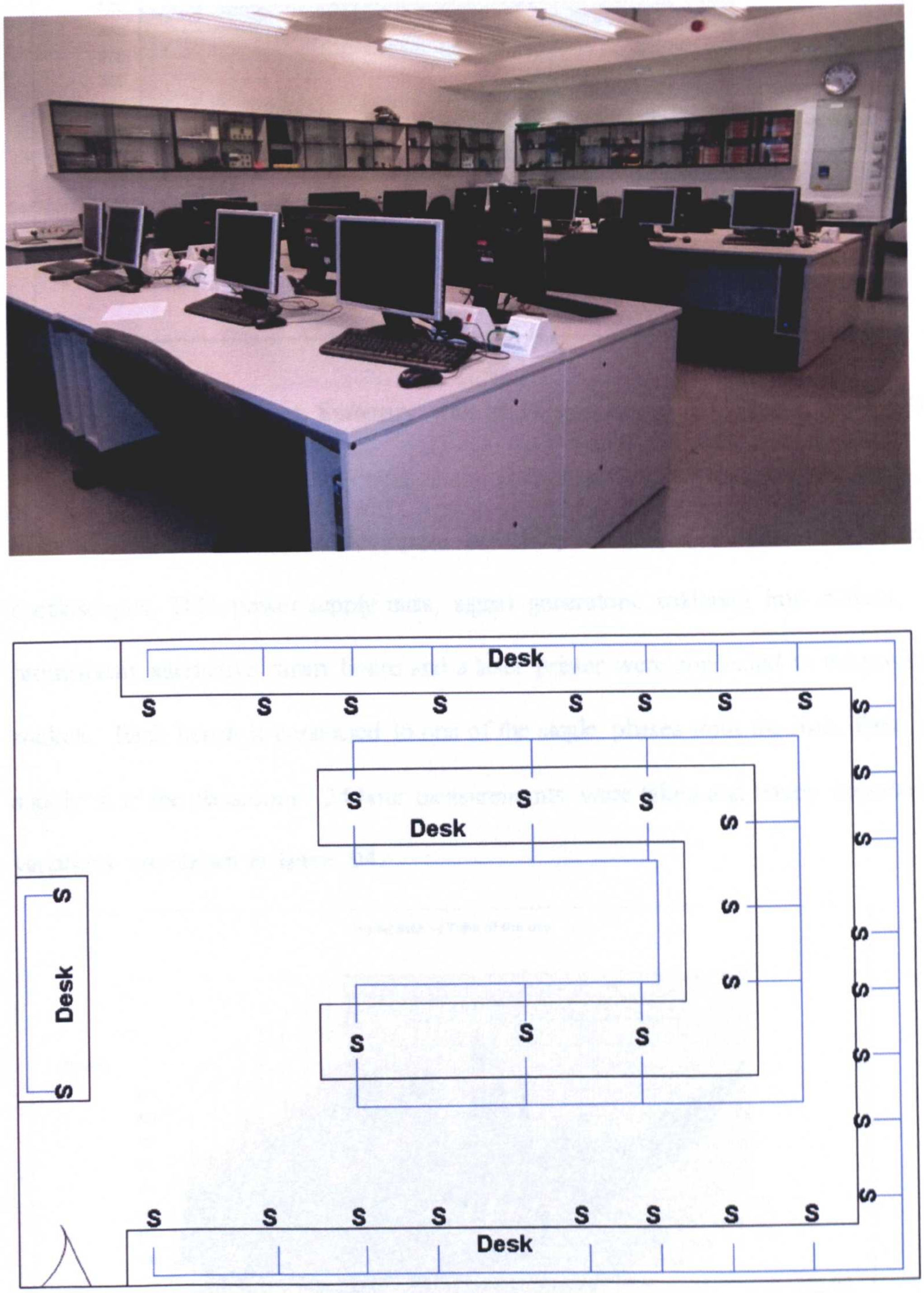


Figure 92. Electronics Laboratory J24 and Electrical Socket Diagram

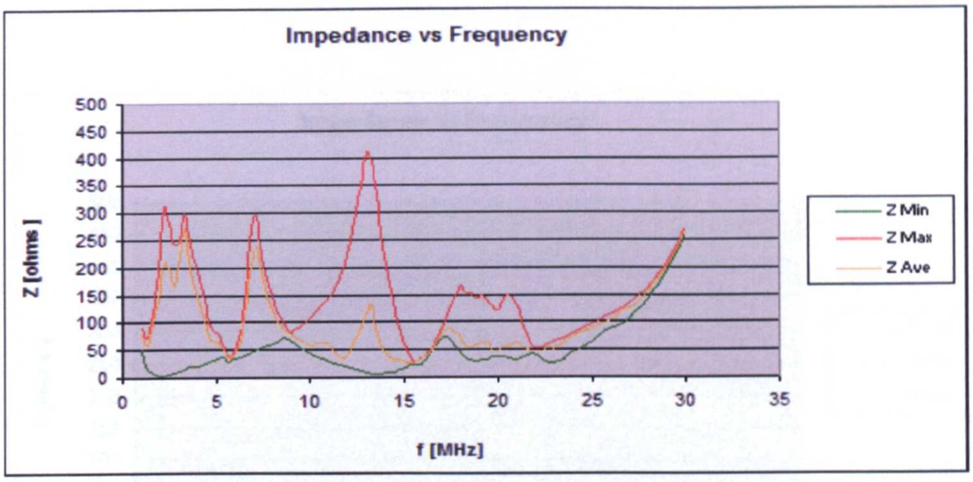


Figure 93. Day Impedance Summary with all PCs on Room J24. Date 22/06/11(Tuesday)

In these measurements in the electronics laboratory classroom, PCs and cathode ray oscilloscopes, D.C. power supply units, signal generators, soldering iron stations, promethean interactive smart board and a laser printer were connected to the power sockets. Each bench is connected to one of the single phases from the main three phase supply in to the classroom. 24 hour measurements were taken and hourly impedance variations are shown in figure 94.

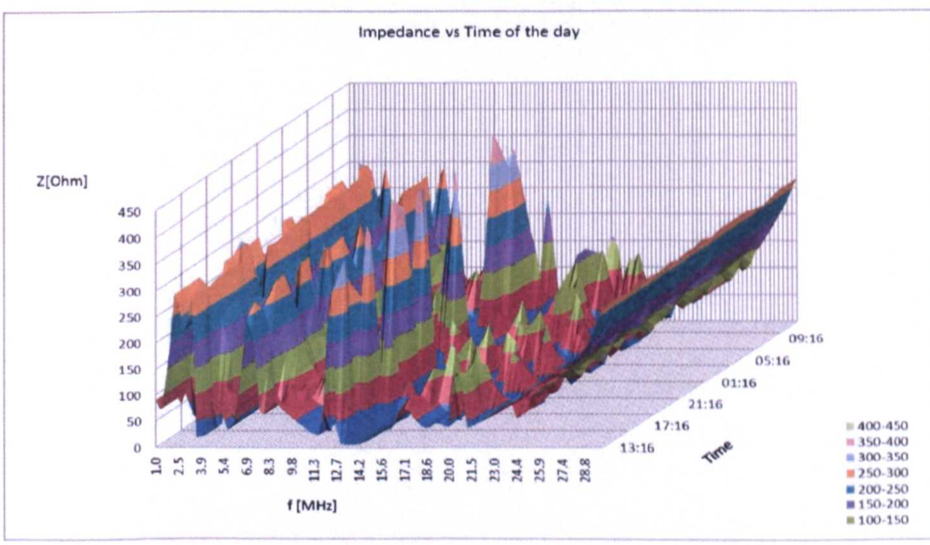


Figure 94. 24 hour impedance variation – Electronics laboratory J24

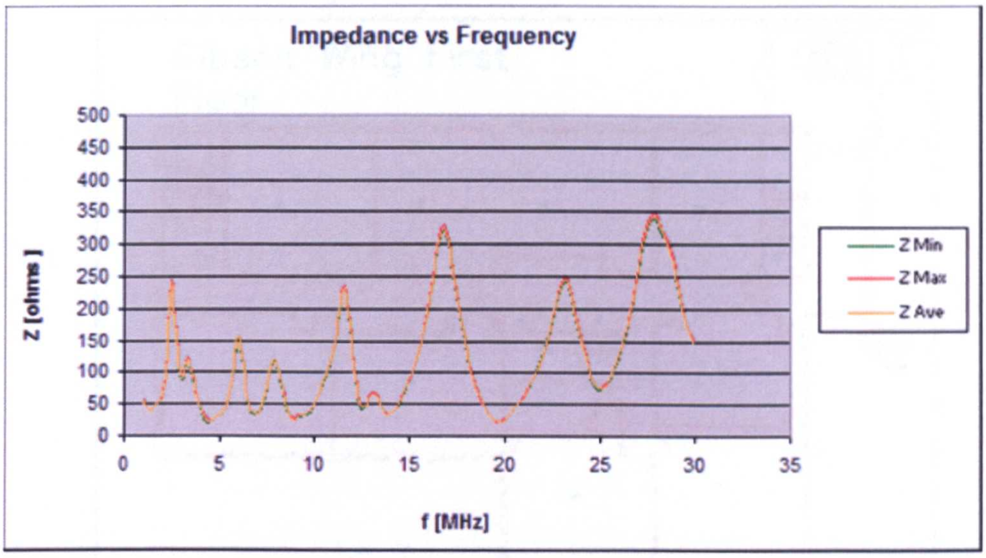


Figure 95. Day Impedance Summary with no power in the socket. Date 27/06/11 (Monday).

Measurements were also taken with all sockets disconnected of their equipment and impedance variation with no electrical power in the sockets are shown in figure 95.

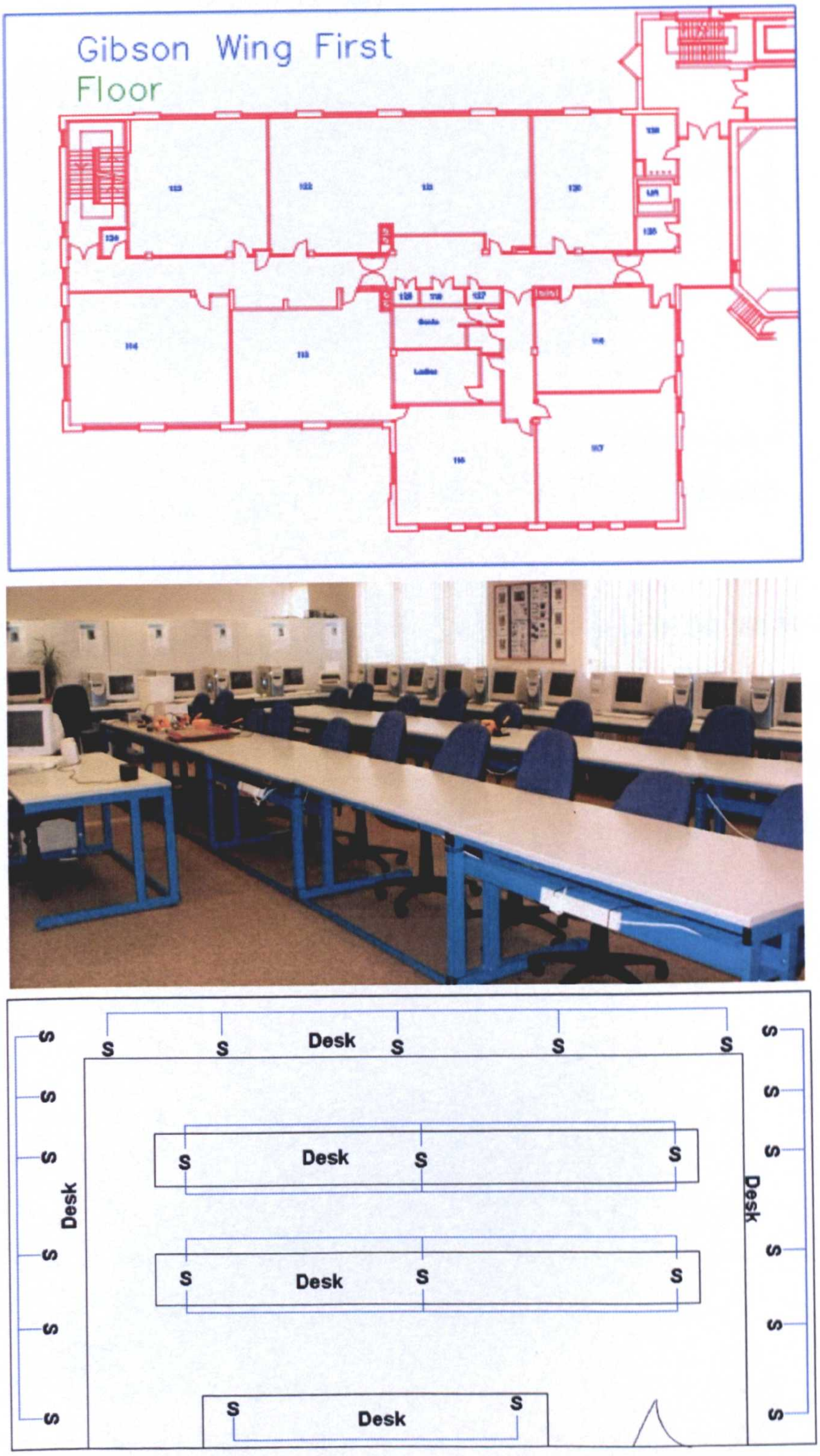


Figure 96. Computer Workshop Room 123 (Gibson Wing) and Socket Diagram

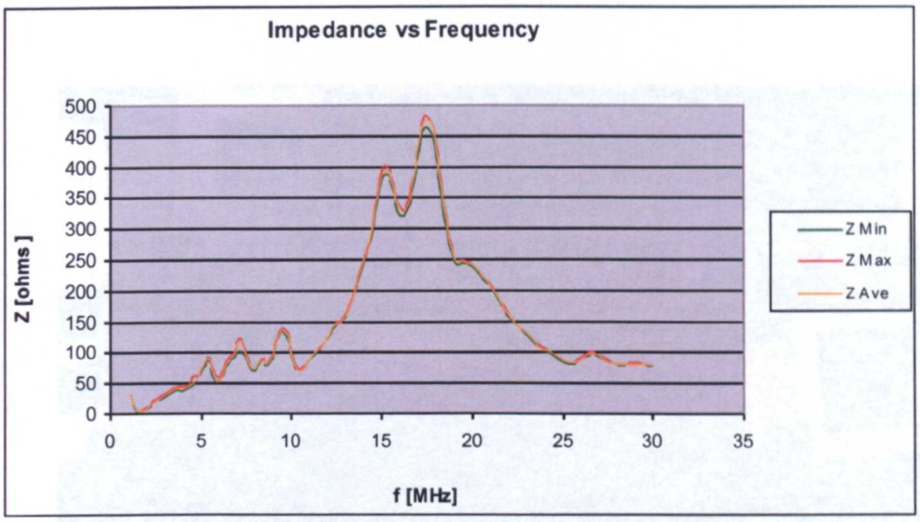


Figure 97. Day Impedance Summary (Room 123). Date 23/11/06 (Thursday)

In these measurements all the PCs were powered on performing normal classroom activities. There is no significant variation of impedance over time in this case and this could be due to the fact that only PCs are in use. The PCs could be considered as light stable loads and also the fact that the classroom is electrically isolated from the other rooms. 24 hour impedance variation is also shown in figure 98.

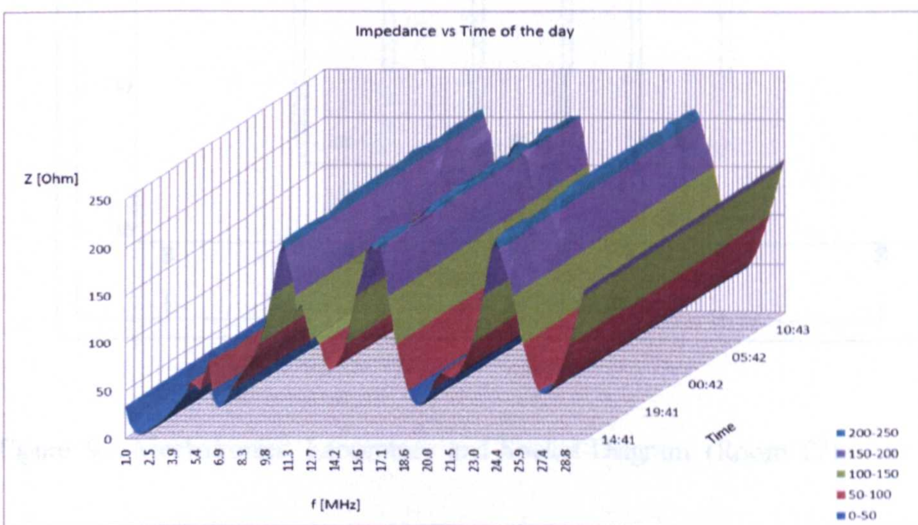


Figure 98. 24 hour impedance variation – Computer workshop Room 123

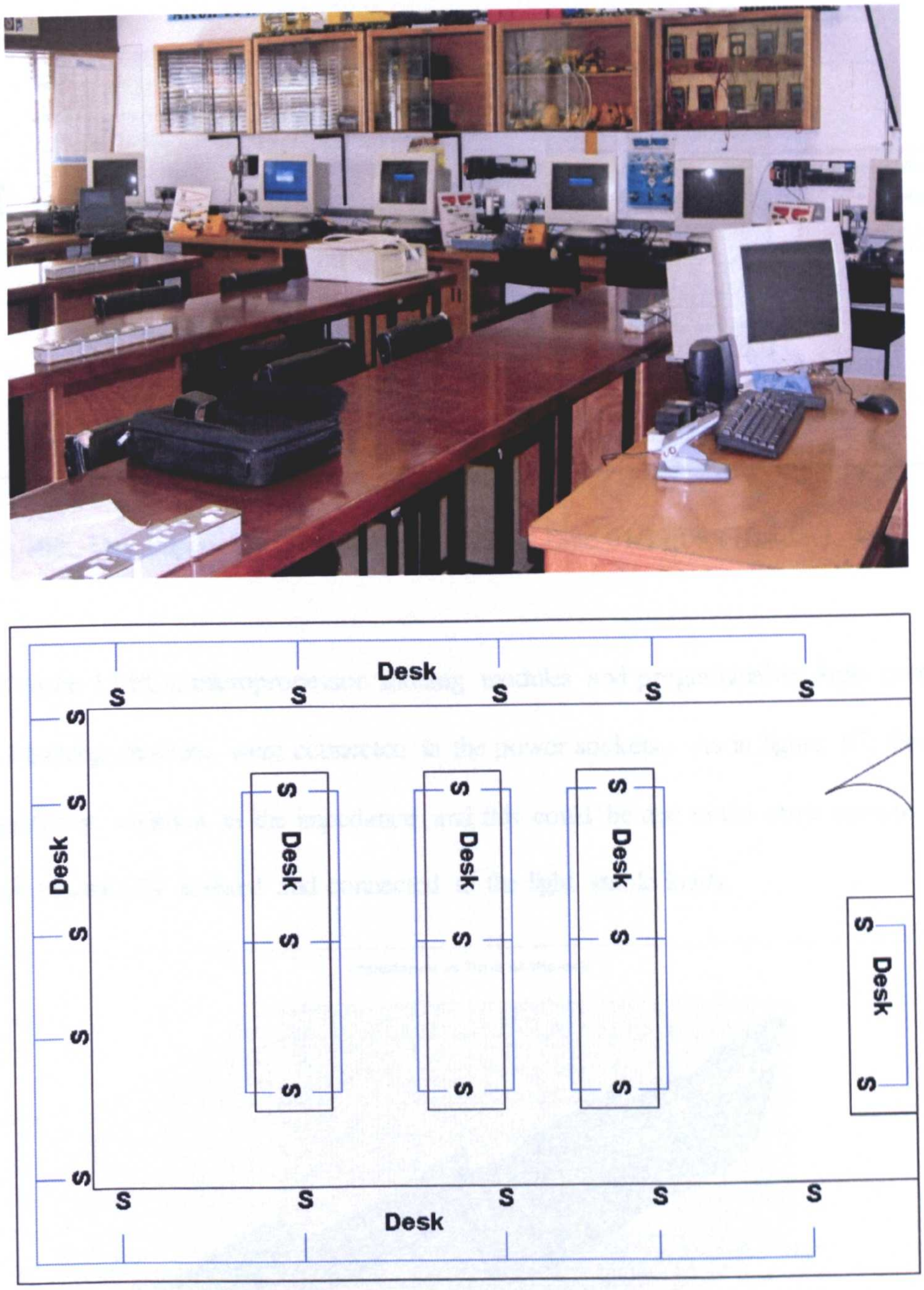


Figure 99. Mechatronics Laboratory and Socket Diagram (Room T7)

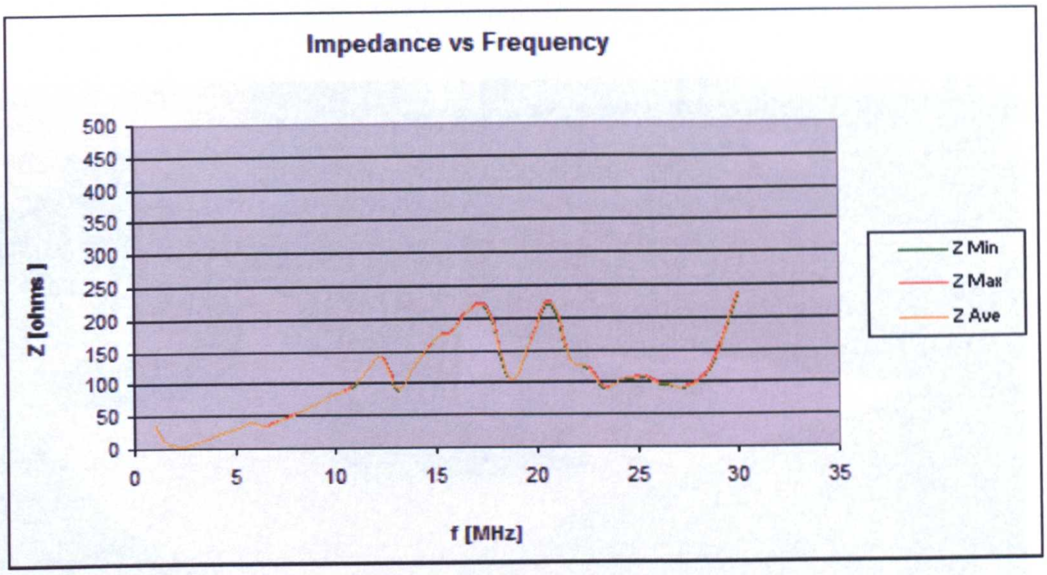


Figure 100. Day Impedance Summary (RoomT7). Date 01/11/06 (Tuesday)

In this room 15 PCs, microprocessor training modules and programmable logic controller (PLC) training modules were connected in the power sockets. As in figure 97, there is no significant variation in the impedance and this could be due to the same reasons, as the room is electrically isolated and connected to the light stable loads.

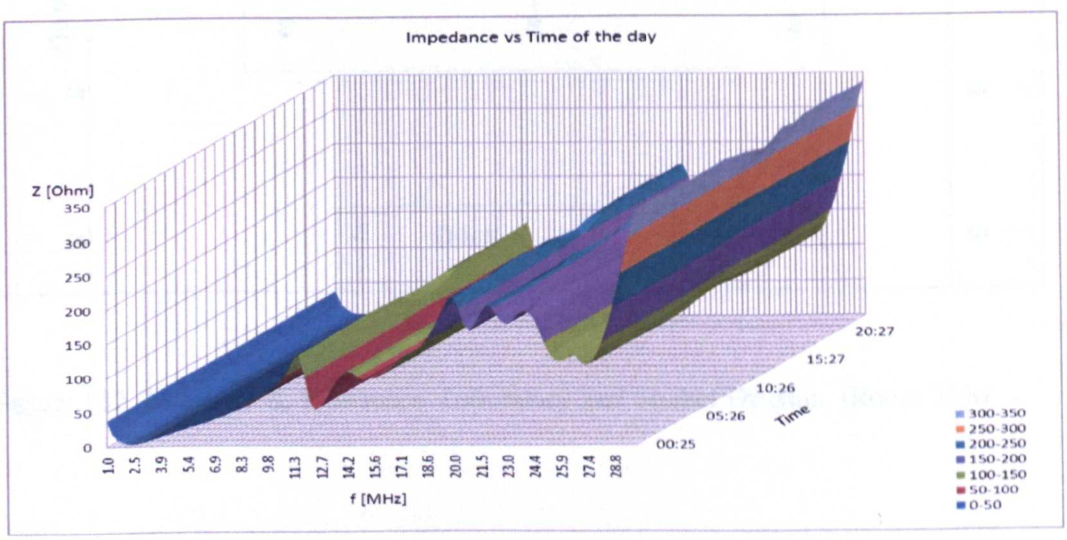


Figure 101. 24 hour impedance variation – Room T7

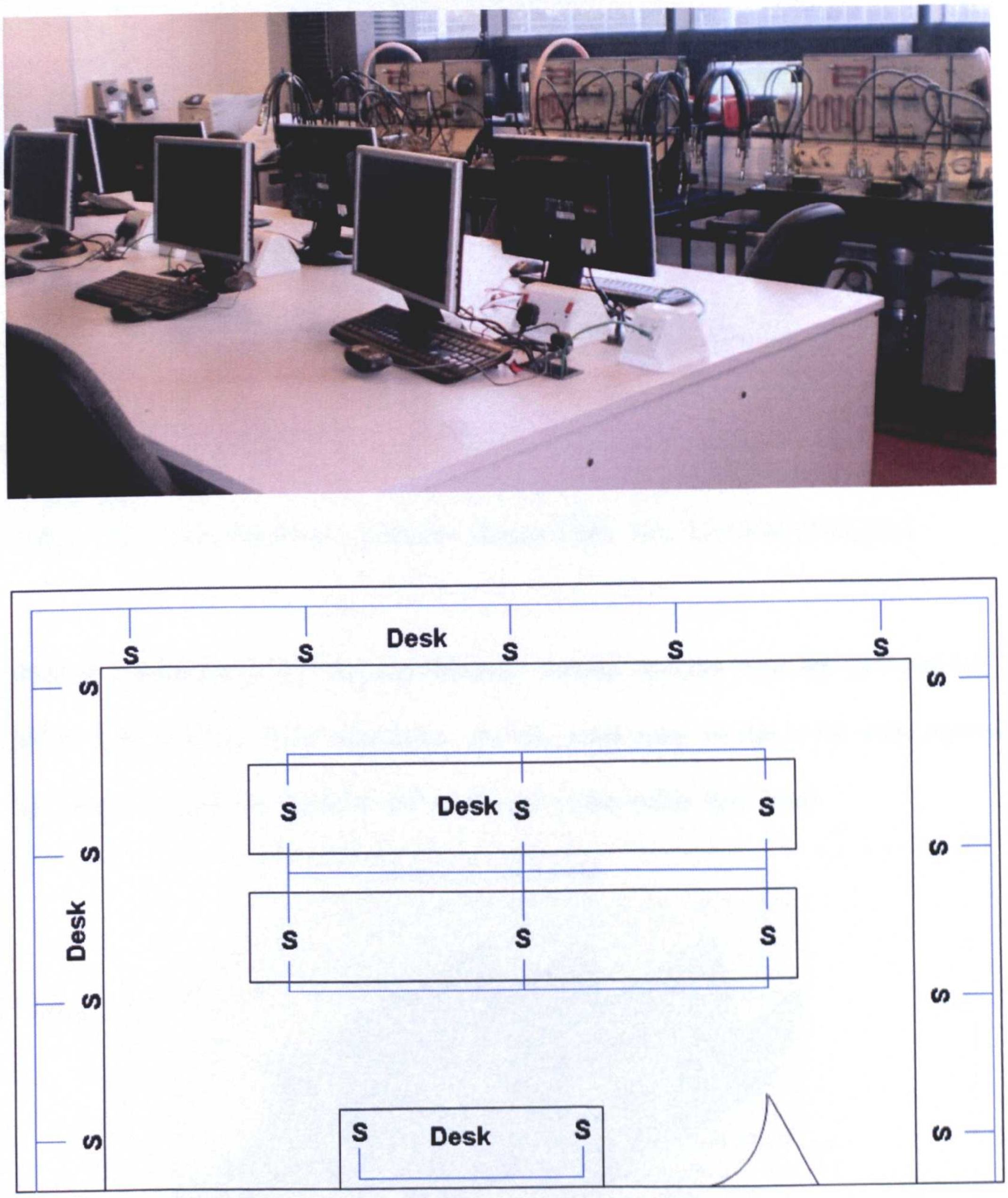


Figure 102. Electrical & Hydraulics Laboratory and Socket Diagram (Room T28)

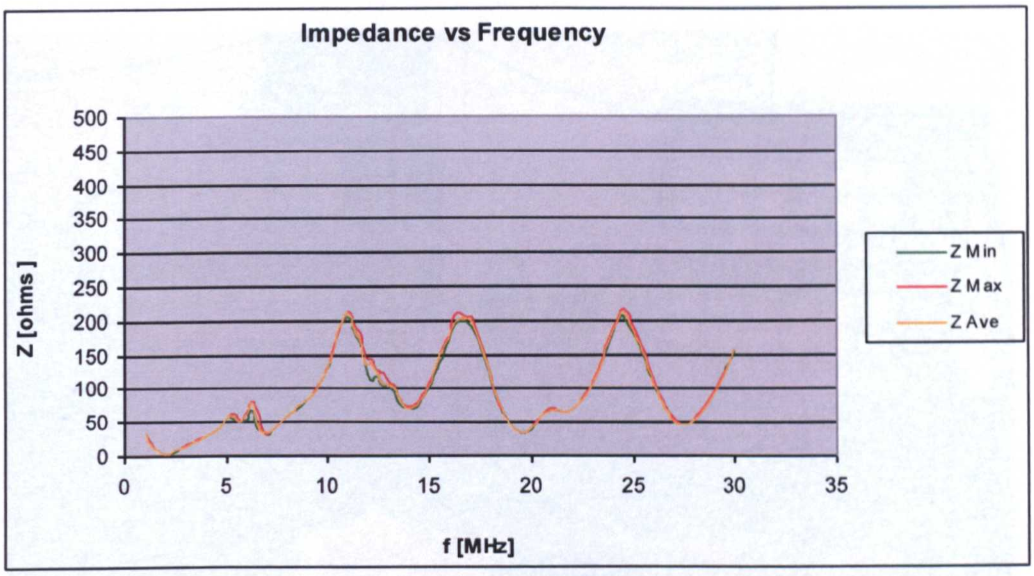


Figure 103. Day Impedance Summary (Room T28). Date 12/10/06 (Thursday)

In these measurements all PCs and hydraulic training modules were left powered on. There is no variation in the impedance and this could again be due to the same reasons, as the room is electrically isolated and connected to the stable light loads.

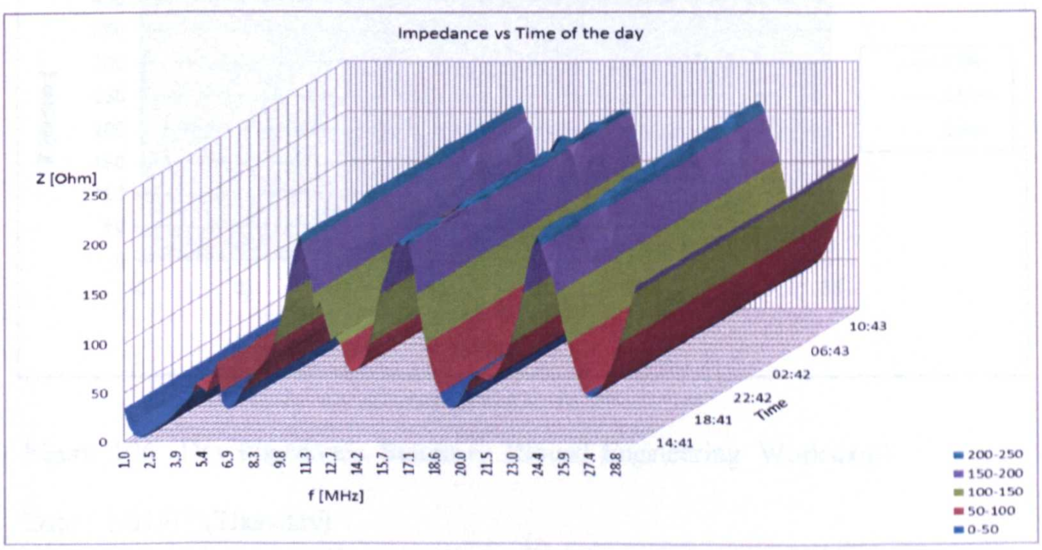


Figure 104. 24 hour impedance variation – Room T28

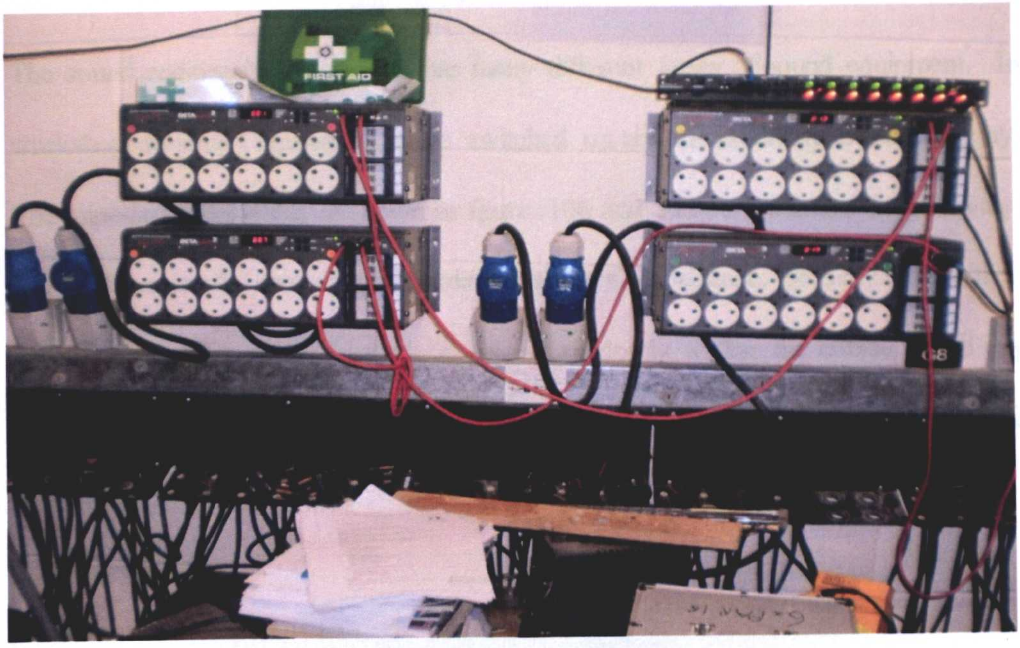


Figure 105. Sound Engineering Workshop

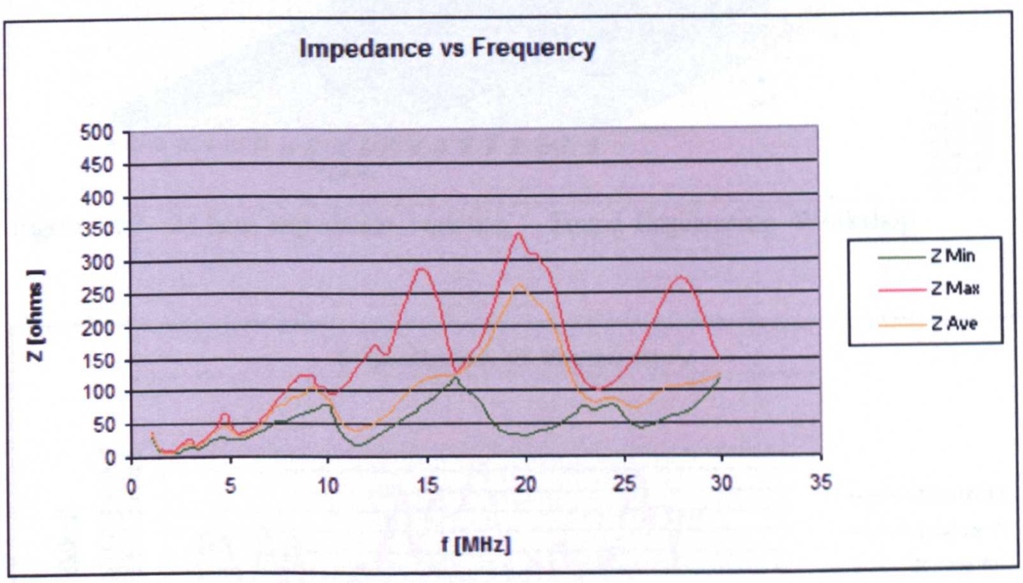


Figure 106. Day Impedance Summary (Sound Engineering Workshop) Date 11/01/07 (Thursday).

The sound engineering workshop has many different types of sound equipment. In this workshop all sound equipment were switched on and off randomly during the day time. The impedance variation is shown in figure 106 and 24 hour variation is shown in figure 107. These results show considerable variation in impedance, possibly due to the fact that the equipment were switched on and off randomly during the course of the day. Aggregate power line impedance of all the single phase measurements are shown in figure 108.

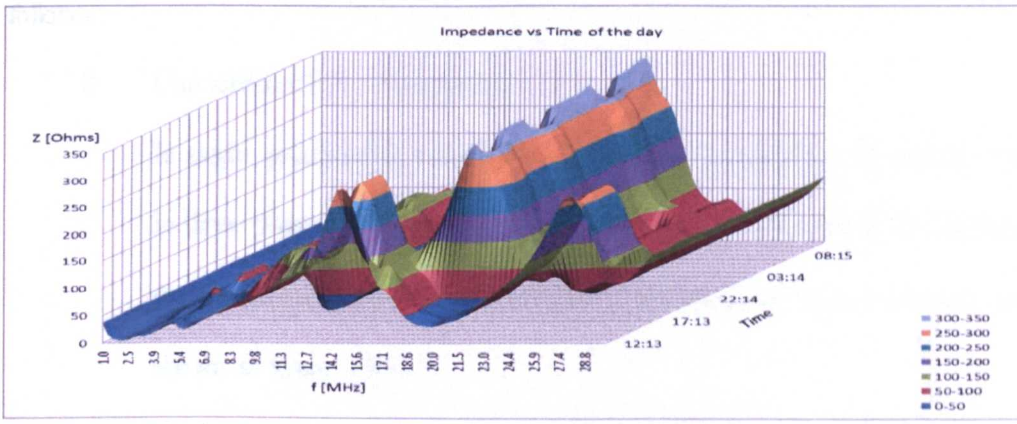


Figure 107. 24 hour impedance variation – Sound Engineering Workshop

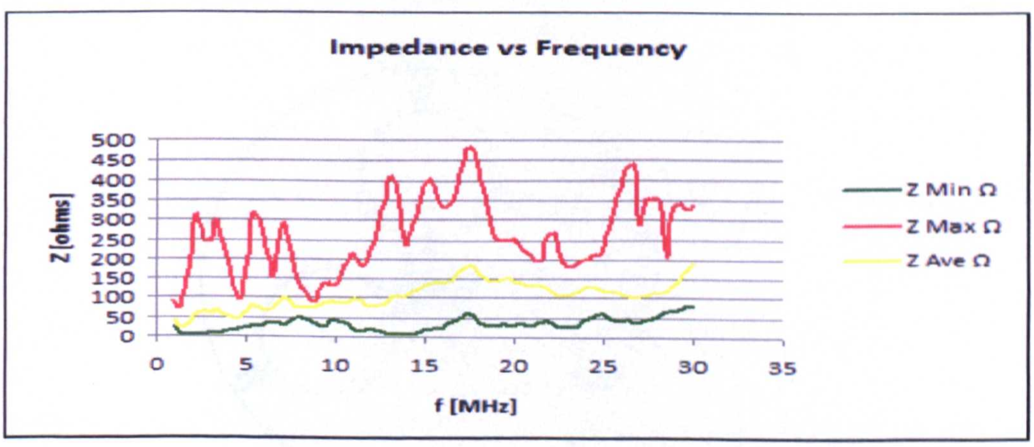


Figure 108. Aggregate power line impedance of all single phase measurements of college buildings.

5.1.2 Three Phase Measurements

As part of this investigation some three phase measurements were also taken. The three phase network topology was explained in chapter 2. In a three-phase system the values for impedance and admittance can be calculated from the physical structure of the multiphase cable, recognising the multipath propagation, though because of the increased number of conductors each parameter, R, L, G, C, is replaced with multiple values as follows.

i) Capacitance (C) / Conductance (G)

   In single phase cable admittance is present between the core and the screen. In three phase cables there are admittance values between each conductor and the screen and between each conductor and the other two conductors as shown in figure 109.

ii) Resistance (R) / Inductance (L)

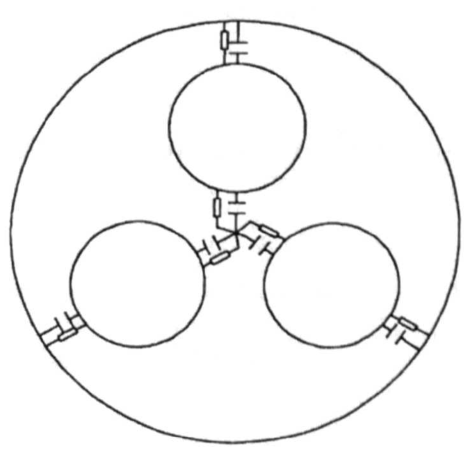


Figure 109. Three-phase cable showing capacitance and conductance positions

With a single phase cable there is only one current path. In a three phase cable, resistance and inductance is present for each of the current paths within the cable. For the purpose of calculation these have been reduced to the three paths, out via the central conductor and return via the screen as shown in figure 110.

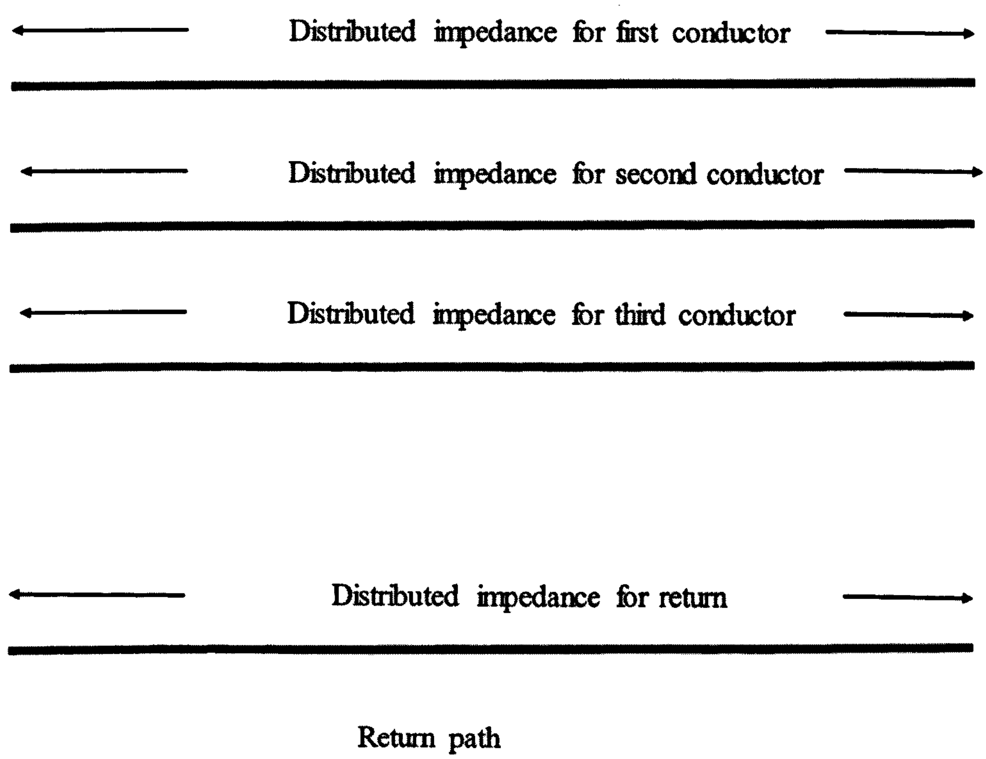


Figure 110. Schematic of three-phase cable showing how series parameters are present.

These cable parameters can be included in a model for calculating the required propagation characteristics as follows.

Equations for solving multiphase transmission line systems were derived by Riddle et. al. [66]. These equations are reproduced here with reference to figure 111.

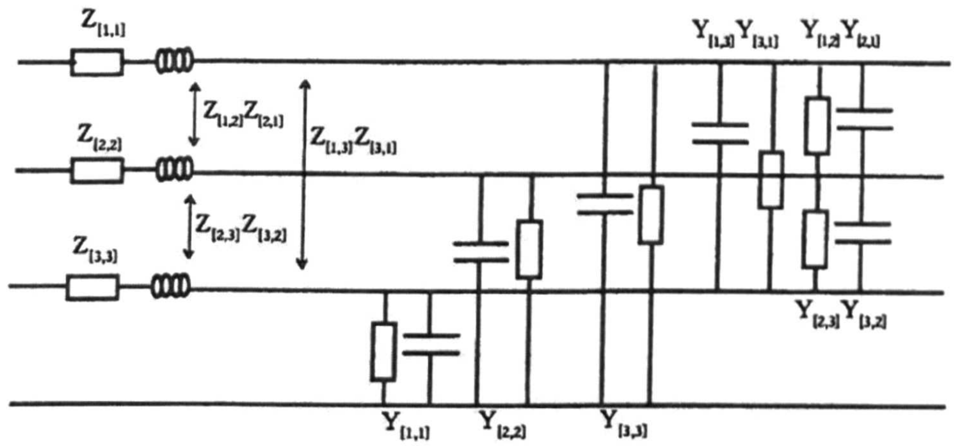


Figure 111. Schematic of three phase cable.

Impedance per unit length matrix

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad \text{Eqn. 24}$$

Admittance per unit length matrix

$$Y = \begin{bmatrix} Y_{11}+Y_{12}+Y_{13} & -Y_{12} & -Y_{13} \\ -Y_{21} & Y_{22}+Y_{21}+Y_{23} & -Y_{23} \\ -Y_{31} & -Y_{32} & Y_{33}+Y_{31}+Y_{32} \end{bmatrix}$$ Eqn. 25

Voltage at some distance 'x' from sending end

Eqn. 26

$$V_{(x)} = \begin{bmatrix} v_1(x), & v_2(x), & v_3(x) \end{bmatrix}^T$$

Current at some distance 'x' from sending end

Eqn. 27

$$I_{(x)} = \begin{bmatrix} i_1(x), & i_2(x), & i_3(x) \end{bmatrix}^T$$

Propagation matrix

Eqn. 28

$$\gamma^2 = Z \times Y$$

Characteristic admittance

Eqn. 29

$$Y_0 = Z^{-1} \times \gamma$$

Reflection coefficient at the load

Eqn. 30

$$\Gamma_L = \Gamma[L] = [Z_L \times Y_0 + I]^{-1} \times [Z_L \times Y_0 - I]$$

The conductor voltage at distance ‘x’ from sending end

Eqn. 31

$$V_{(x)} = \left[I + e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right] e^{-\gamma X}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S$$

The conductor current at distance ‘x’ from sending end

$$I_{(x)} = Y_0\left[I - e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right] e^{-\gamma X}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S$$

Eqn. 32

The input impedance at distance ‘x’ from sending end,

looking towards load

Eqn. 33

$$Z_{in(x)} = \left[I + e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right]\left[I - e^{\gamma(X-L)}\Gamma_L e^{\gamma(X-L)}\right]^{-1} Y_0^{-1}$$

Because the only interest is in the voltage, current and impedance at ends of cables (X=L or X=0) equations 31, 32 and 33 can be simplified to give the following:

The receiving end voltage

$$V_{(L)} = \left[I + \Gamma_L\right] e^{-\gamma L}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0 \left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S$$

Eqn. 34

The receiving end current

$$I_{(L)} = Y_0[I - \Gamma_L]e^{-\gamma L}\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\left[Z_S + \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Z_0\right]^{-1} V_S$$

Eqn. 35

The sending end impedance looking towards load

$$Z_{in(0)} = \left[I + e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]\left[I - e^{-\gamma L}\Gamma_L e^{-\gamma L}\right]^{-1} Y_0^{-1}$$

Eqn. 36

For symmetrical three phase cables the following is true:

$$Z_{11}=Z_{22}=Z_{33} \text{ and } Z_{12}=Z_{13}=Z_{21}=Z_{23}=Z_{31}=Z_{32}$$

Eqn. 37

$$Y_{11}=Y_{22}=Y_{33} \text{ and } Y_{12}=Y_{13}=Y_{21}=Y_{23}=Y_{31}=Y_{32}$$

Eqn. 38

Therefore these matrix equations can be simplified as follows:

Given that

$$A = \begin{bmatrix} x & y & y \\ y & x & y \\ y & y & x \end{bmatrix}$$

Eqn. 39

and that

$$B = \begin{bmatrix} v & w & w \\ w & v & w \\ w & w & v \end{bmatrix}$$

Eqn. 40

$$[A\times B]_{ii} = xv + 2yw \text{ and } [A\times B]_{ij} = xw + yw + yv, \ (i \neq j)$$ Eqn. 41

Similarly from equation 38

$$[A^{-1}]_{ii} = \frac{x^2 - y^2}{x^3 + 2y^3 - 3xy^2} \text{ and } [A^{-1}]_{ij} = \frac{xy - y^2}{x^3 + 2y^3 - 3xy^2}, \ i \neq j$$

Eqn. 42

And given that

$$A^2 = \begin{bmatrix} x & y & y \\ y & x & y \\ y & y & x \end{bmatrix}$$ Eqn. 43

Equation 42 can be solved to give:

$$[A]_{ij} = \frac{\left[\pm\sqrt{x+2y} \pm \sqrt{x-y}\right]}{3}, \ i \neq j \text{ and } [A]_{ii} = \frac{y - [A]_{ij}^2}{2[A]_{ij}}$$

Eqn. 44

Using the statements in equations 37 and 38 and applying 41 to 28 gives:

$$[\gamma^2]_{ii} = Z_{11}[Y_{11} + 2Y_{12}] + 2Z_{12}[-Y_{12}]$$

Eqn. 45

$$[\gamma^2]_{ij} = Z_{11}[-Y_{12}] + Z_{12}[-Y_{12}] + Z_{12}[Y_{11} + 2Y_{12}], \ i \neq j$$

Inverting the Z matrix gives:

$$\left[Z^{-1}\right]_{ii} = \frac{Z_{11}^{\ 2} - Z_{12}^{\ 2}}{Z_{11}^{\ 3} + 2Z_{12}^{\ 3} - 3Z_{11}Z_{12}^{\ 2}} \text{ and } \left[Z^{-1}\right]_{ij}$$

$$= \frac{Z_{11}Z_{12} - Z_{12}^{\ 2}}{Z_{11}^{\ 3} + 2Z_{12}^{\ 3} - 3Z_{11}Z_{12}^{\ 2}},\ i \neq j \qquad \text{Eqn. 46}$$

and equation 29 becomes

$$\left[Y_0\right]_{ii} = \left[Z^{-1}\right]_{11}\gamma_{11} + 2\left[Z^{-1}\right]_{12}\gamma_{12} \text{ and}$$

$$\left[Y_0\right]_{ij} = \left[Z^{-1}\right]_{11}\gamma_{12} + \left[Z^{-1}\right]_{12}\gamma_{12} + \left[Z^{-1}\right]_{12}\gamma_{11},\ i \neq j \qquad \text{Eqn. 47}$$

These equations can be incorporated into a computer programme to provide the voltages and currents for three phase transmission lines.

The following measurements were taken in Bridgwater College Fabrication and Welding workshop where three-phase Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) welding are carried out.

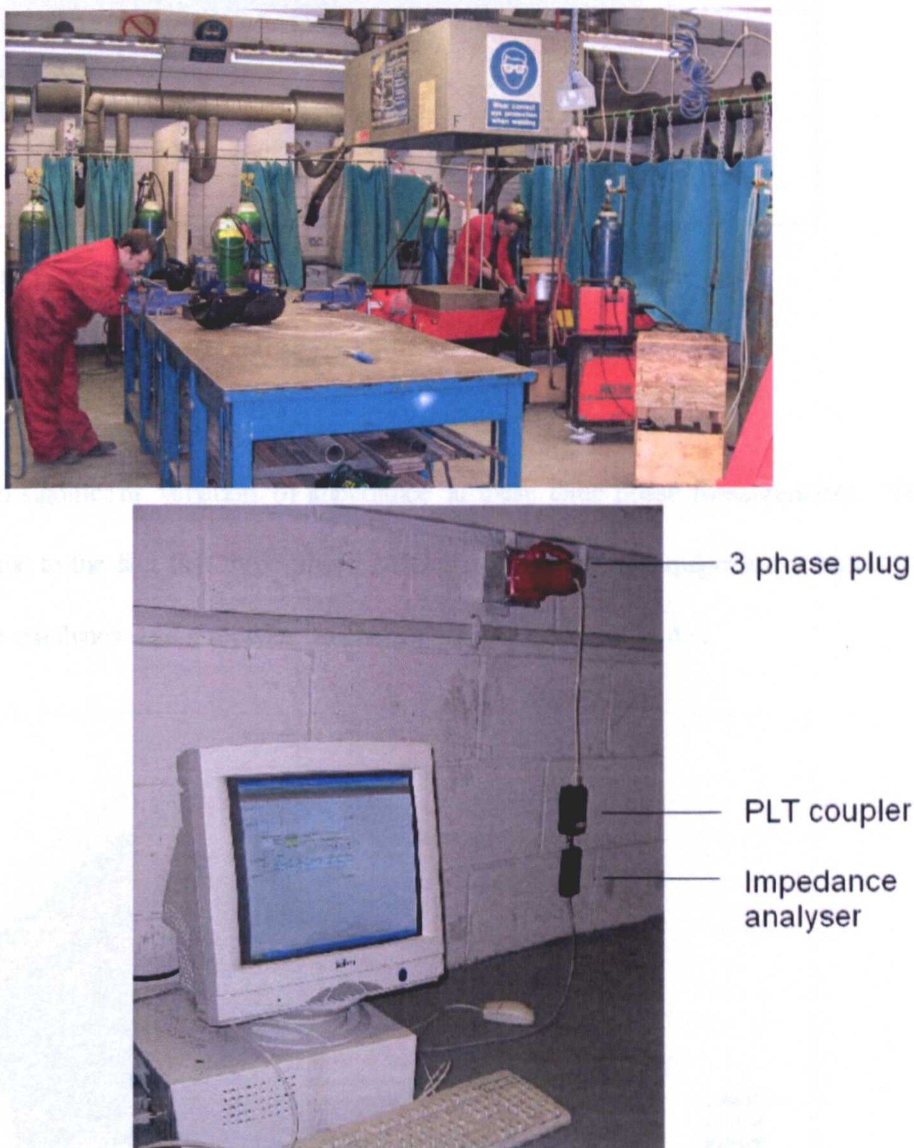


Figure 112. Fabrication and Welding Workshop – Three Phase (Room T21)

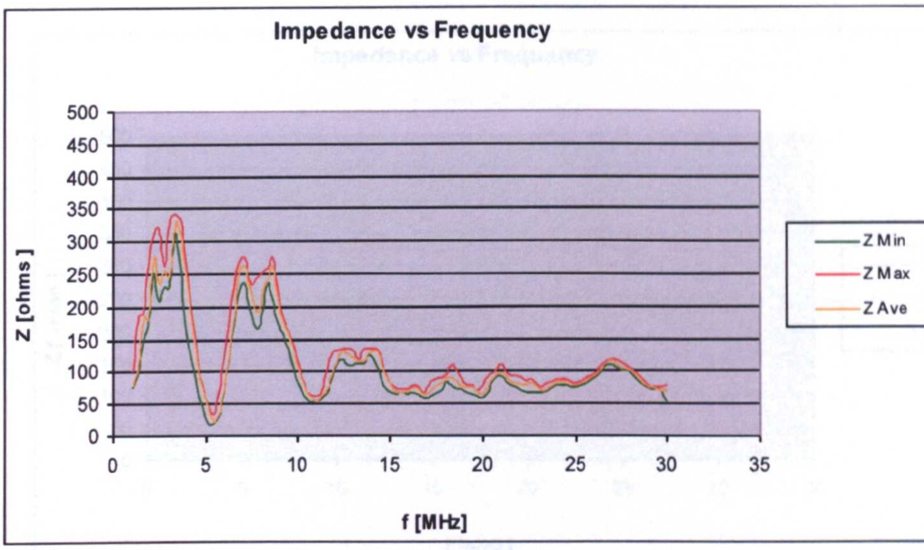


Figure 113. Day Impedance Summary of 3 Phase Measurements between L1 and N. Date 17/04/07 (Tuesday)

There is no significant variation of impedance in these three phase measurements. This could be due to the fact that three-phase MIG and TIG welding equipment is based on d.c. These machines use a rectifier to change three-phase a.c. to d.c.

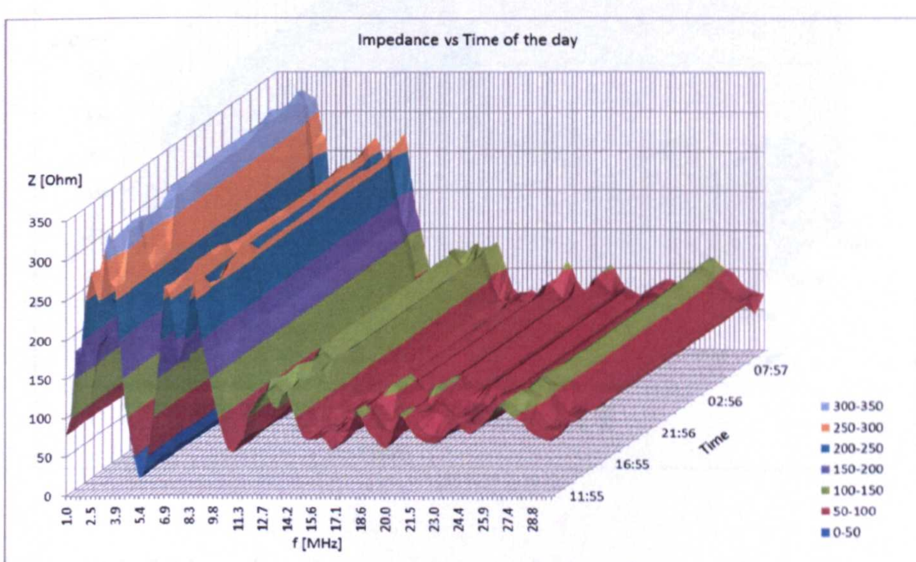


Figure 114. 24 hour impedance variation – 3 Phase between L1 and N

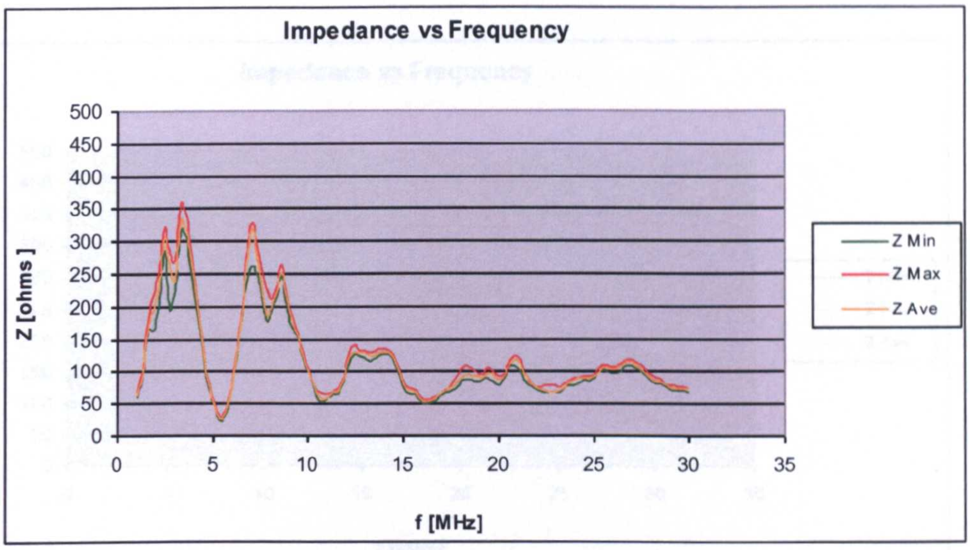


Figure 115. Day Impedance Summary of 3 Phase Measurements between L2 and N cables. Date 01/05/07 (Tuesday)

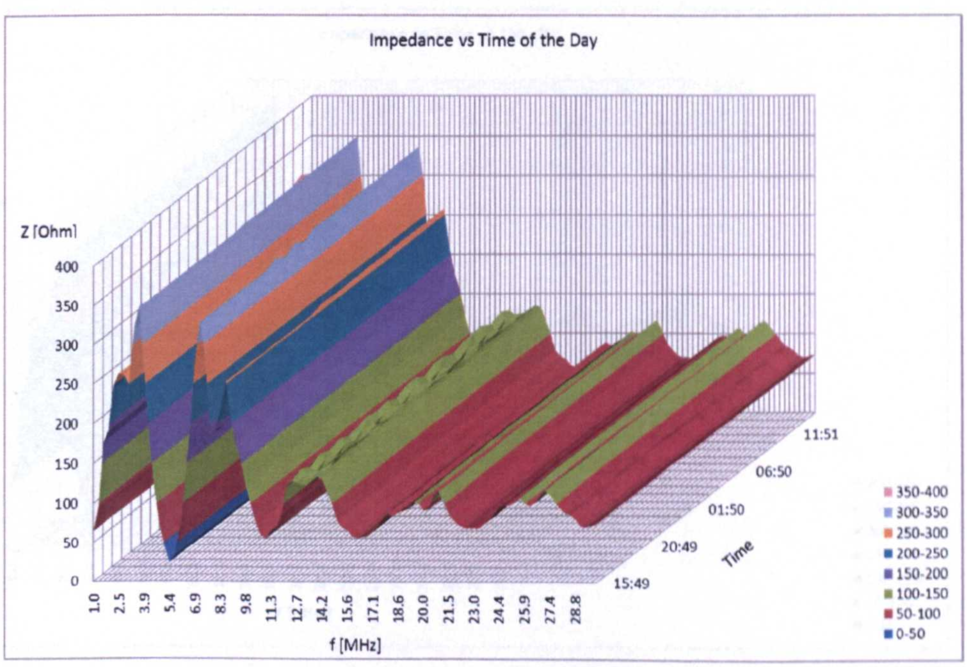


Figure 116. 24 hour impedance variation – 3 phase between L2 and N

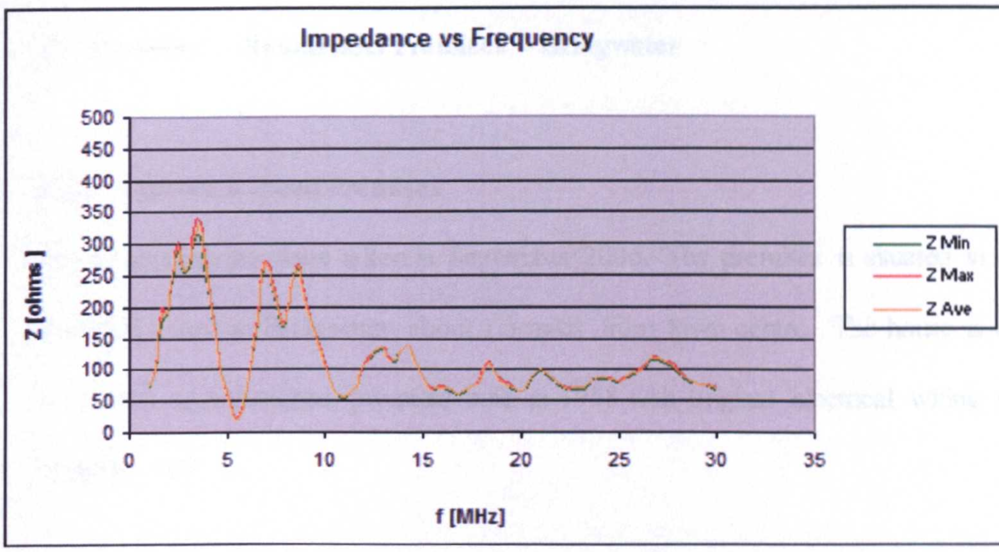


Figure 117. Day Impedance Summary of 3 Phase Measurements between L3 and N cables. Date: 26/04/07 (Thursday)

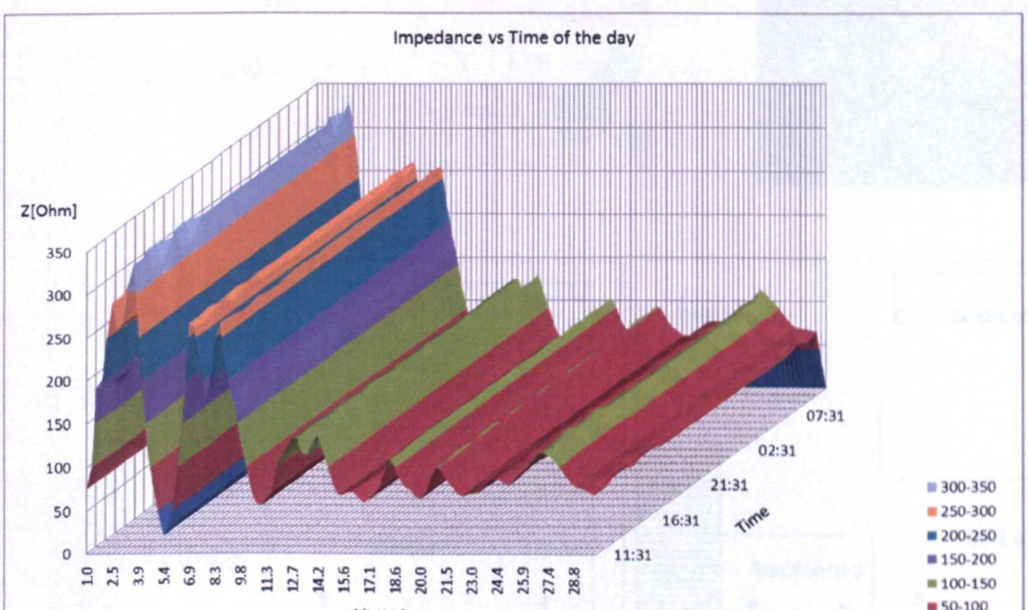


Figure 118. 24 hour impedance variation - 3 phase between L3 and N

5.2 Results 2 – Residential Premises – Bridgwater

5.2.1 Alfoxton Road Premises

The measurements were taken in September 2006. The premises is situated in a quiet residential area in Bridgwater about 1.5 miles from town centre. The house is three bedrooms semi-detached premises built in 1958 with original electrical wiring as shown in figure 119.

Figure 119. Alfoxton Road Premises and socket Diagram

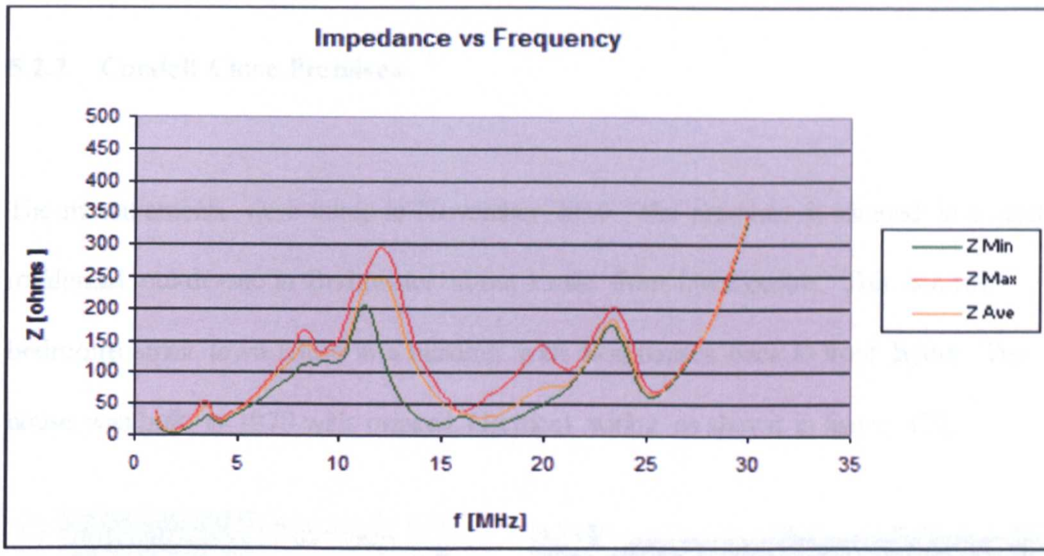


Figure 120. Day Impedance Summary of Alfoxton Road Premises.

Date: 22/09/06 (Friday). The measurements were carried out in the lounge where equipment such as TV, VCR, DVD/CD Players and lights are connected to the sockets. The lounge is isolated through a circuit breaker. Day impedance summary is shown in figure 120. Maximum impedance of 348 Ω occurring at 30 MHz. 24 hour impedance variation is also shown in figure 121.

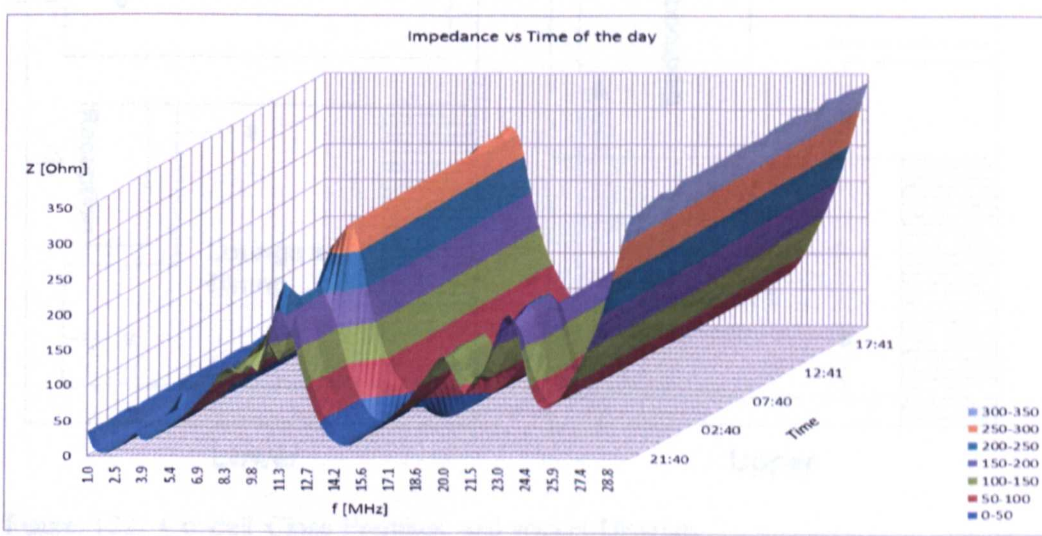


Figure 121. 24 hour impedance variation – Alfoxton Road Premise

5.2.2 Condell Close Premises

The measurements were taken in November 2010. The premises is situated in a quiet residential cul-de-sac in Bridgwater about 1 mile from town centre. This is a two bedrooms small town house in a building with four houses back to front layout. The house was built in 1970 with original electrical wiring as shown in figure 122.

Figure 122. Condell Close Premises and socket Diagram

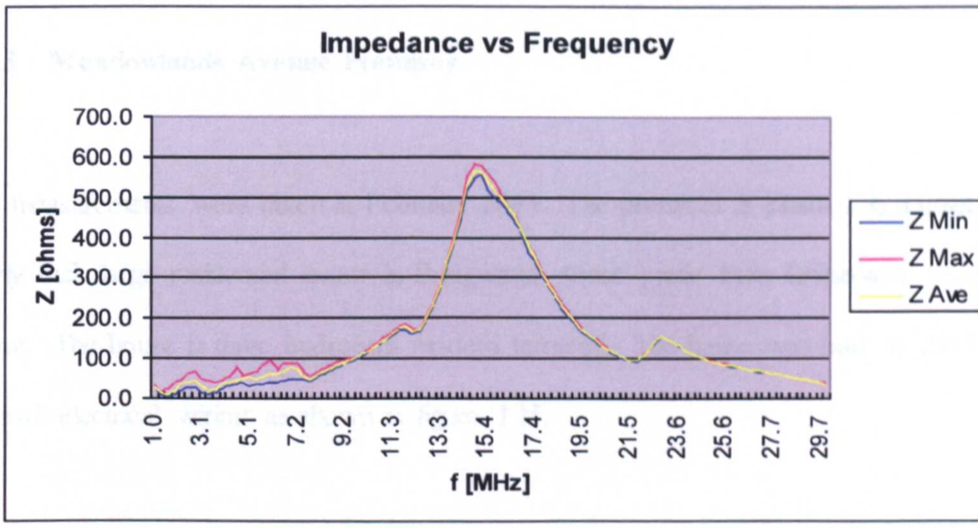


Figure 123. Day Impedance Summary of Condell Close Premises.

Date: 18/11/10 (Thursday)

The measurements were carried out in the small bedroom without any electrical equipment connected to the socket as there were only one socket available. The maximum impedance of 554 Ω is noted at frequency of 15.4 MHz. 24 hour impedance variation is also shown in figure 124.

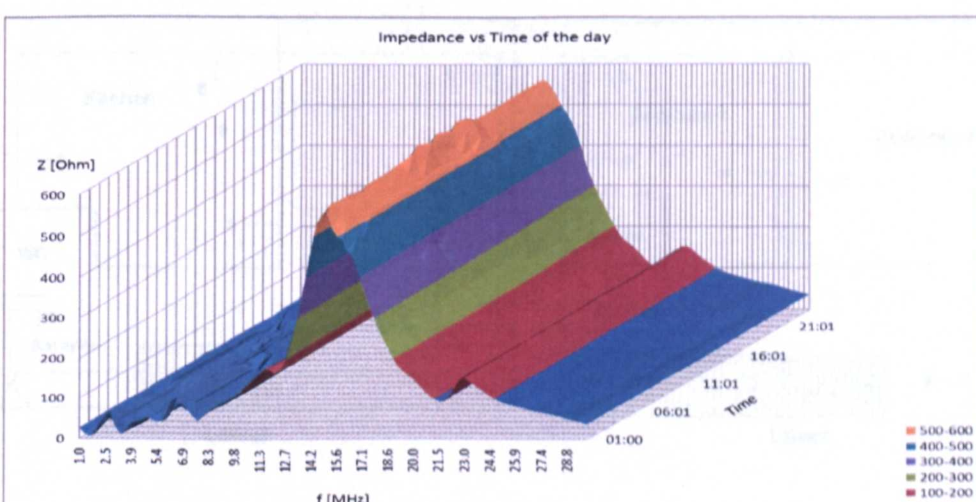


Figure 124. 24 hour impedance variation – Condell Close Premises

5.2.3 Meadowlands Avenue Premises

The measurements were taken in February 2011. The premises is situated in a quiet newly built large residential estate in Bridgwater about 1 mile from Bridgwater town centre. The house is three bedrooms modern terraced. The house was built in 2005 with original electrical wiring as shown in figure 125.

Figure 125. Meadowlands Avenue Premises and socket Diagram.

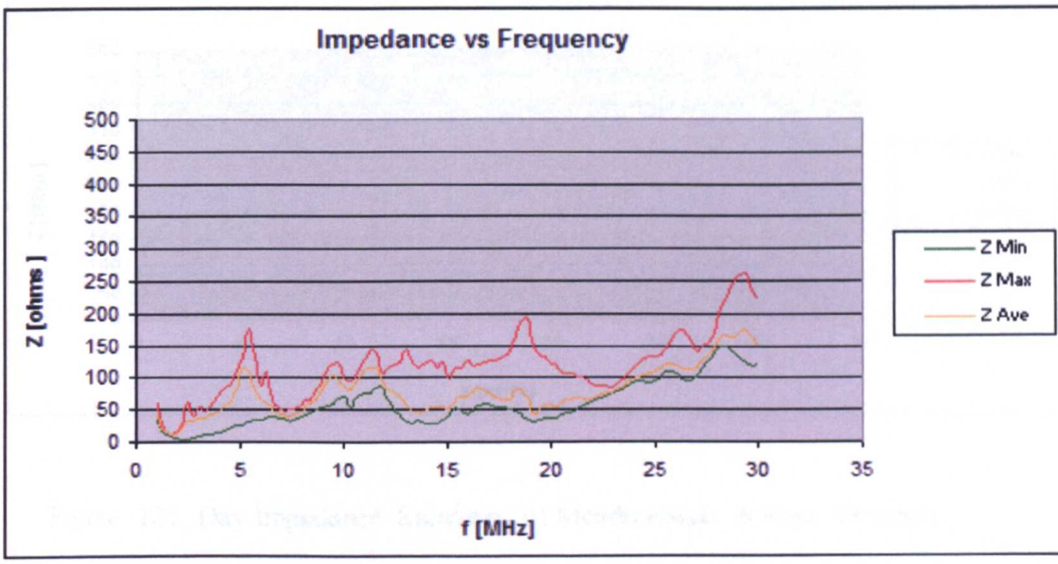


Figure 126. Day Impedance Summary of Meadowlands Avenue Premises. (Lounge) Date 01/02/11 Tuesday.

In these measurements, equipment such as TV, DVD player, SKY satellite TV receiver unit, BT telephone and internet wireless unit charger, lights and laptop chargers were connected to the power sockets. The impedance variation is shown in figure 126, showing peaks at frequencies of 5 MHz, 18 MHz and 30MHz.

Measurements were also done in the lounge, with all electrical equipment disconnected and all sockets without power, and the day impedance variations are shown in figure 127. The impedance was almost constant around 50 Ω at all the frequencies. Similar measurements were also taken in a bedroom, and the impedance variation is shown in figure 128 and figure 129.

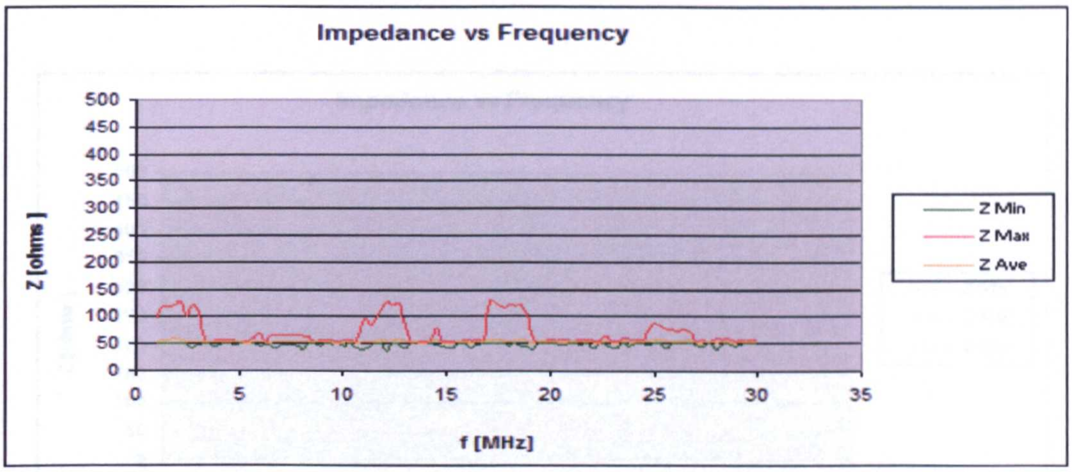


Figure 127. Day Impedance Summary of Meadowlands Avenue Premises.

(Lounge with no load – all sockets were disconnected and power off)

Date 10/02/12 Friday

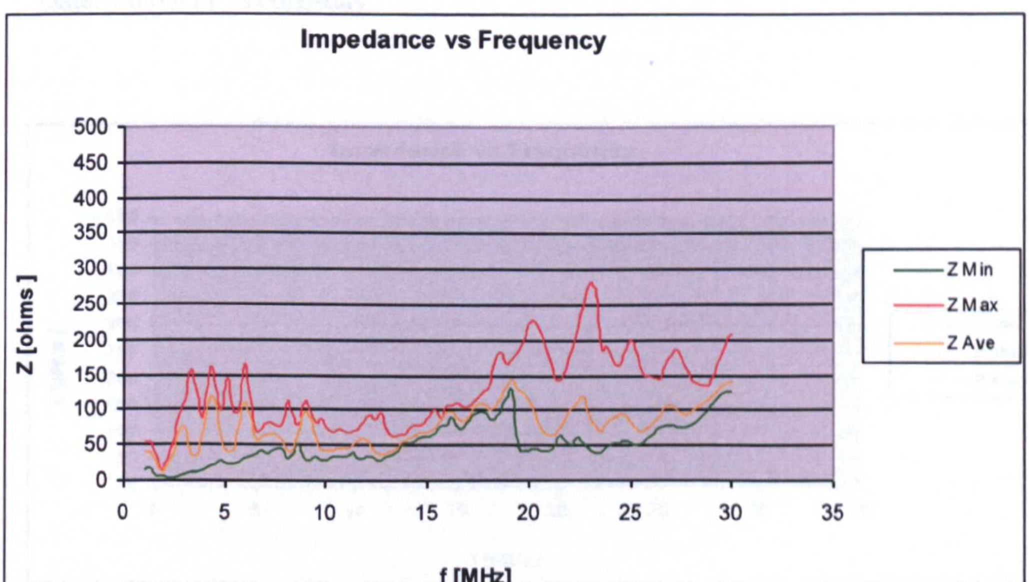


Figure 128. Day Impedance Summary of Meadowlands Avenue Premises.

(Bedroom 3) Date 02/07/11 (Saturday)

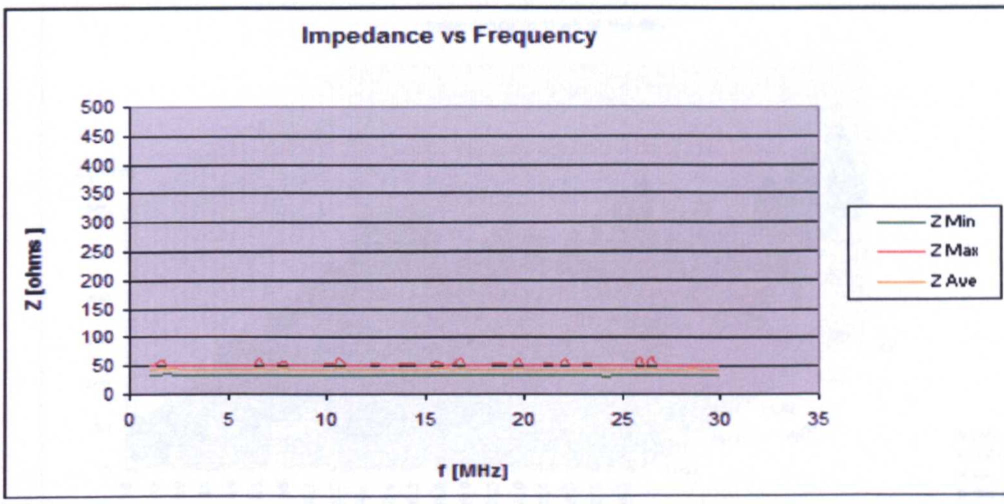


Figure 129. Day Impedance Summary of Meadowlands Avenue Premises

(Bedroom 3 with no load-all sockets were disconnected and power off)

Date: 06/07/11 Wednesday

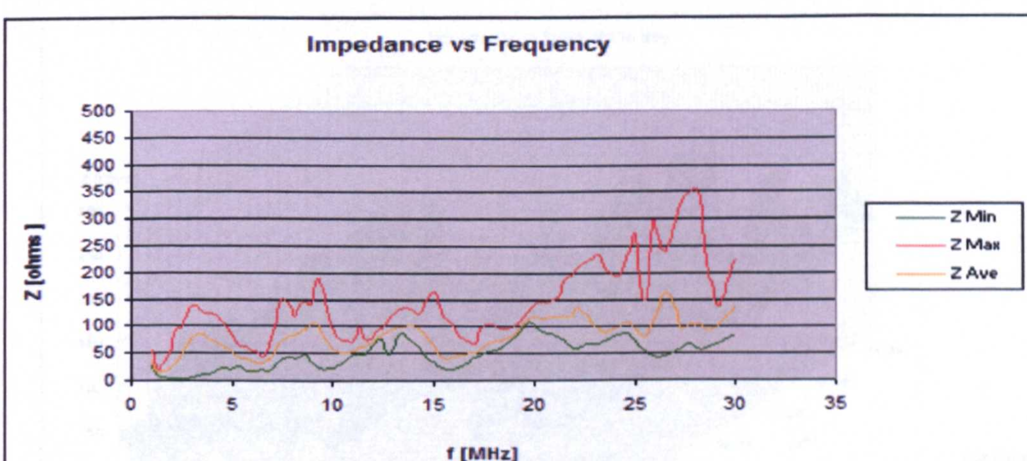


Figure 130. Day Impedance Summary of Meadowlands Avenue Premises (Kitchen). Date 04/07/11 (Monday). Sockets were connected to fridge/freezer, toaster, rice cooker, blender, kettle, washing machine, dish washer, microwave oven and a radio charger.

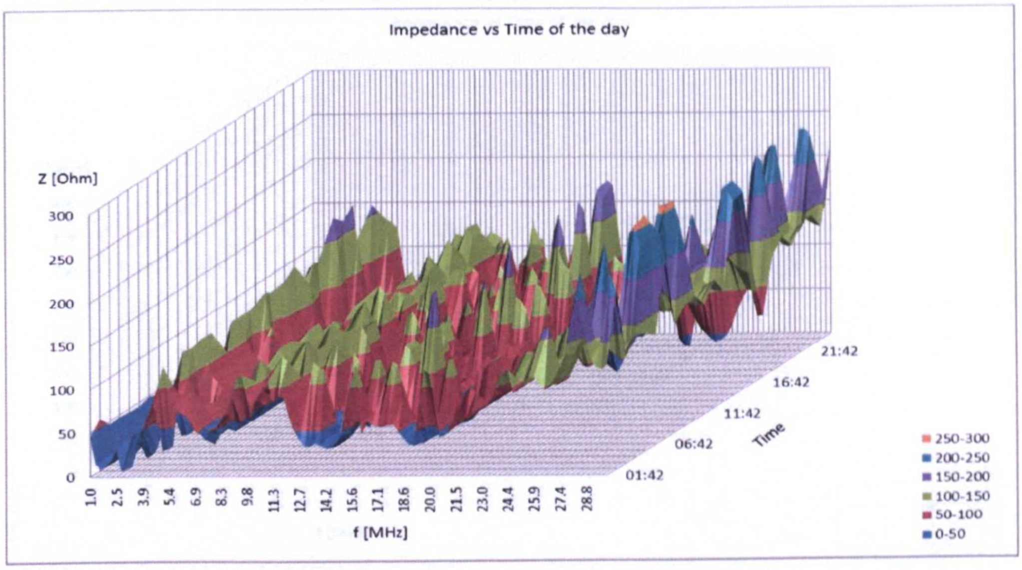


Figure 131. 24 hour impedance variation – Meadowlands Avenue Premises (Lounge)

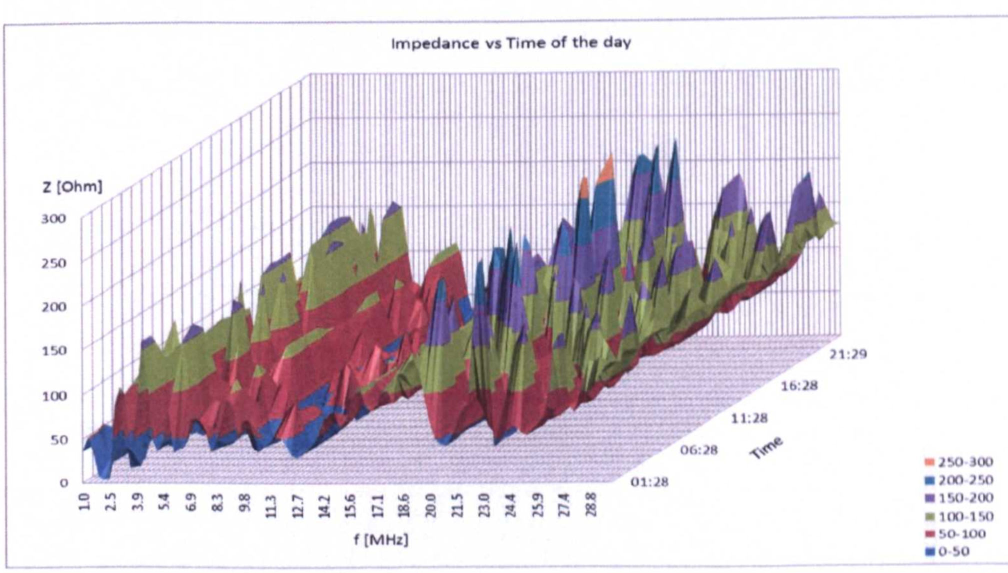


Figure 132. 24 hour impedance variation – Meadowlands Avenue Premises (Bedroom 3)

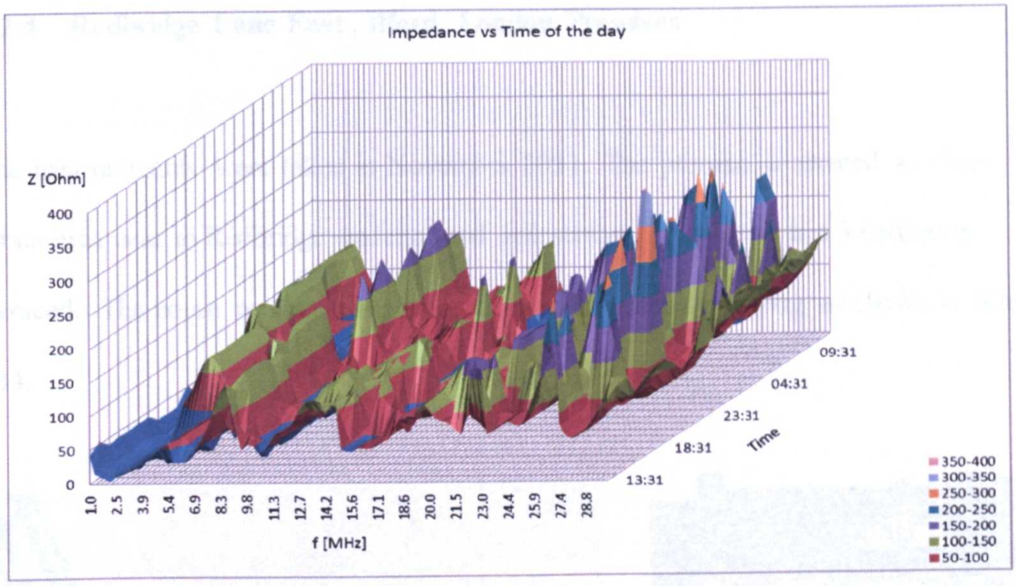


Figure 133. 24 hour impedance variation – Meadowlands Avenue Premises (Kitchen)

5.2.4 Redbridge Lane East , Ilford, London Premises

The measurements were taken in November 2011. The premise is situated in a busy urban area near to Redbridge underground rail station. The house is a 3 bedrooms terraced. The house was built in 1960 with original electrical wiring as shown in figure 134.

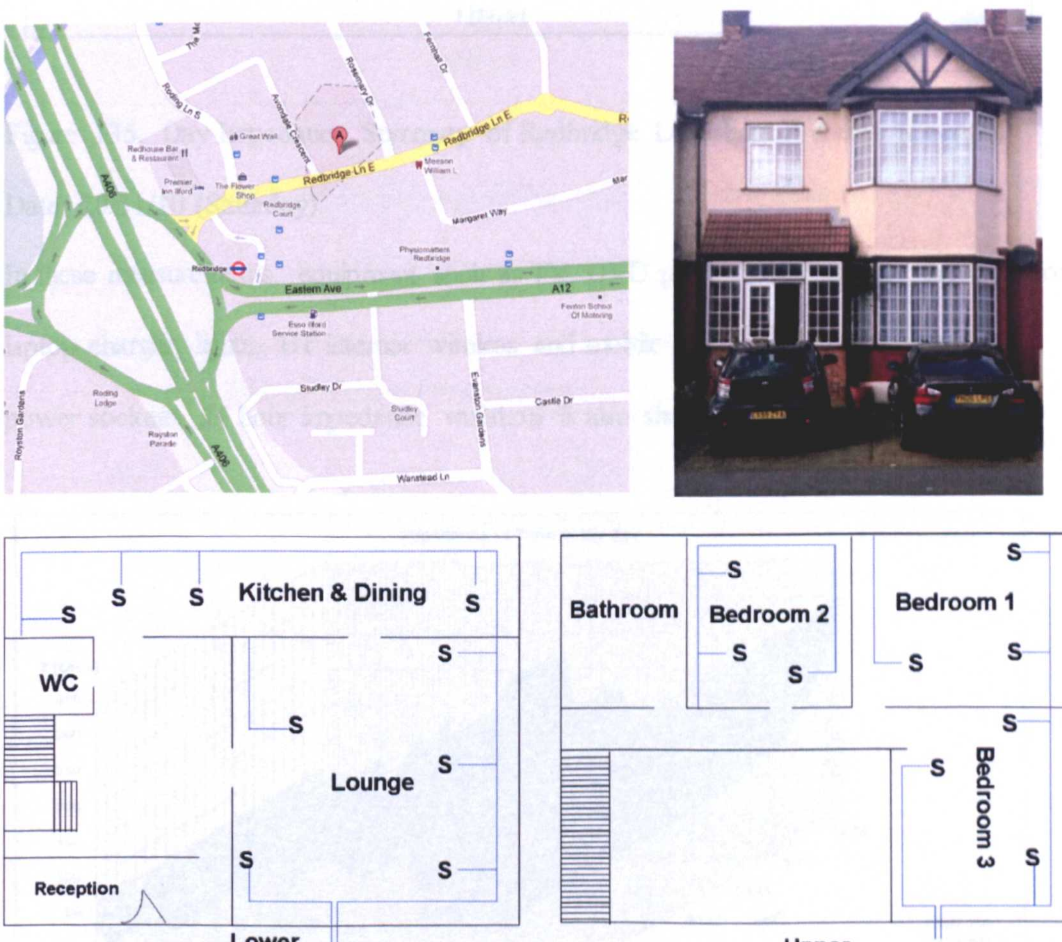


Figure 134. Redbridge Lane East Premises and socket Diagram

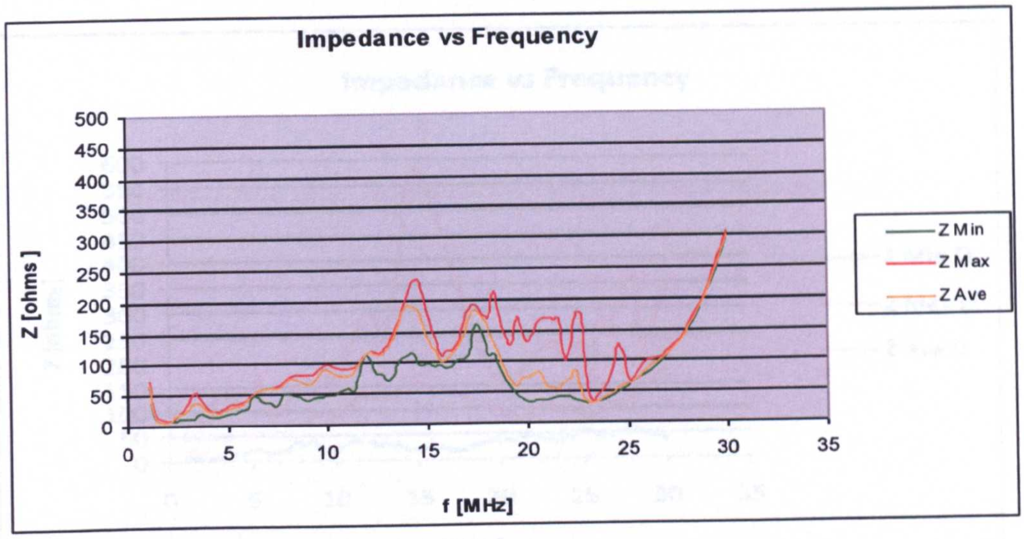


Figure 135. Day Impedance Summary of Redbridge Lane East Premises (Lounge)

Date: 20/11/10 (Saturday).

In these measurements, equipment such as TV, DVD player, SKY satellite receiver box, laptop charger, lights, BT internet wireless and mobile charger were connected to the power sockets. 24 hour impedance variation is also shown in figure 136.

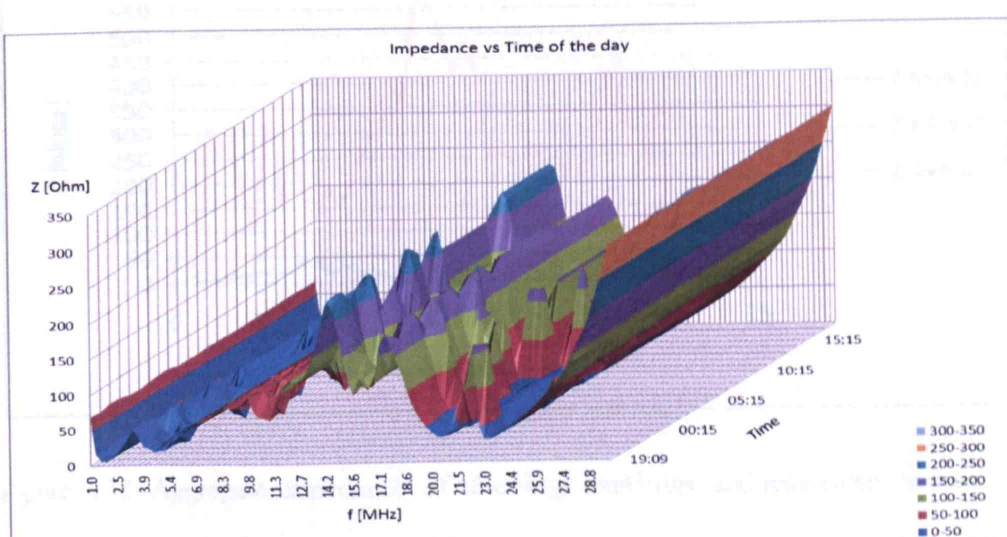


Figure 136. 24 hour impedance variation – Redbridge Lane East Premises.

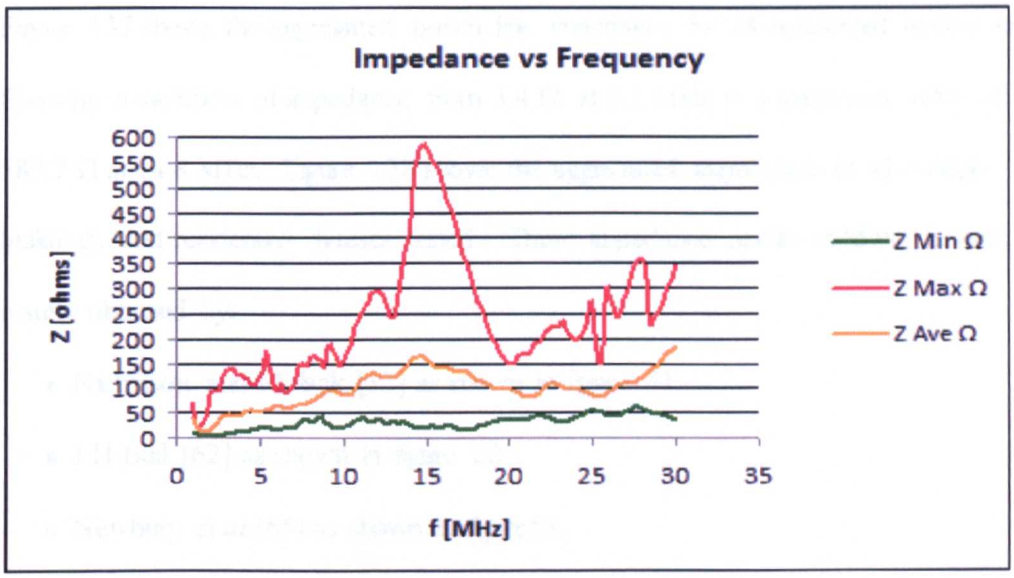


Figure 137. Aggregate power line impedance of all residential houses.

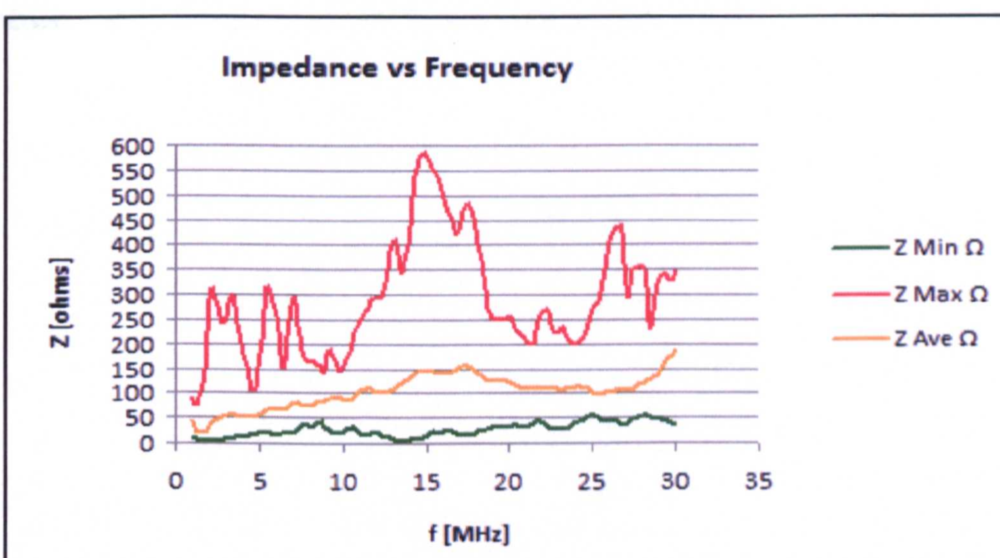


Figure 138. Aggregate impedance of all college buildings and residential houses.

Figure 137 shows the aggregated power line impedance for all residential houses tested, Showing a variation of impedance from 3.4 Ω at 2.2 MHz to a maximum value of 583.7 Ω at 14.8 MHz. Figure 138 shows the aggregated impedance of all college buildings and residential houses tested. These impedance results validate, in part, the results obtained by;

- Nicholson and Malack [13] as shown in figure 51
- J H Bull [62] as shown in figure 52
- Newbury *et al* [65] as shown in figure53.

The discrepancies could be due to the fact that power circuit wiring practice varies considerably between countries and also nature of loads have changed over the period of times.

5.3 Summary

In this chapter all the impedance measurements of Bridgwater College buildings and residential houses are presented in graphical format. Aggregated impedance results are also shown for all the measurements. 24 hour variations of impedance are also shown. It has been noted that the wide variations of impedance with frequency are apparent. Figure 108 shows aggregated power line impedance of all single phase measurements of college buildings, showing variation of impedance from 3 Ω at 2.2 MHz to a maximum value of 584 Ω at 14.8 MHz. Figure 108 also shows at some frequencies there are other local peaks in the impedance characteristics, indicating that power lines behave like resonant circuits. Three phase measurements show variation from 21 ohms to 334 Ω with higher impedance values occurring within the frequency range of 1MHz-8.9MHz. Figure 136 shows aggregated power line impedance of all the residential houses, showing variation of impedance from 3.4 Ω at 2.2 MHz to a maximum value of 583.7 Ω at 14.8 MHz. Figure 137 shows aggregated impedance of all college buildings and residential houses.

Chapter 6: Conclusion and Further Work

6.1 Conclusion

In this study, some new empirical data on the impedance of the low voltage power lines in the UK are presented. Aggregated impedances in single-phase measurements of all large buildings and residential houses are varied in the range of 3-584 Ω for the frequency range of 1MHz-30MHz. Measurements at various locations are taken and the trend is more or less similar in nature, which is an increasing and fluctuating function. Impedances in three-phase measurements varied from 21-340 Ω. Power lines behaving largely as inductive loads and value of impedance increasing with frequency. As the frequency goes up, repeated local peaks are observed depending on the loads indicating that the power lines behave like a resonant circuit.

These impedance results validate in part the results obtained by Nicholson and Malack [13] as shown in figure 51. Their measurements show the impedance range of 4-450 Ω for the frequency range of 1 MHz - 30MHz. These results also validate in part the results obtained by J H Bull [62] in UK, USA, Russia and Netherlands as shown in figure 52. The frequency ranges covered by Bull have been different but largely concentrated in the region of 10kHz - 10MHz. Also, their measurements have mainly been made between phase and earth or between neutral and earth. Their measurements show that the impedance varies between low values of about 10 Ω and high values of 500 Ω.

These measurements also validate in part the results found by Newbury *et al* [65] in typical European houses and buildings as shown in figure 53. Their measurements are done in the frequency ranging from 40 kHz to 30 MHz and shows impedance range of 8 – 800 Ω for 1MHz to 30 MHz. The discrepancies could be due to the fact that power circuit wiring practice varies considerably between countries. In the UK, ring circuits are used and tree and branch circuits are used in European countries.

The problems associated with the use of power lines for communication purposes do not originate from the transmission conductor per-se, but from the fact that a wide range and variety of loads are continuously being connected and disconnected to the network by large number users making the medium non-linear, dispersive, randomly time-varying, noisy, and entirely beyond control of the communications engineer – all of which in turn stemming from the fact that its use for communication purposes was never an objective.

The impedance of the low-voltage power line can be categorised into line impedance and load impedance. For PLC the problem arises when the load impedance is low. When load impedance is low the PLC signal tends to flow to ground through load –following the path of least resistance – causing significant attenuation of the PLC signal.

For the transmitter and the receiver, the output impedance is designed to a fixed value according to a given line impedance. But actually, the impedance is time varying. It changes continuously and unpredictably, and the value of impedance varies too largely to ignore when the system is designed. The transmitter and the receiver cannot match the load impedance, and there are reflections on the interfaces of the communications modem and power line.

Since the variation of the power line impedance mainly depends on the external circumstances and all the load of power line, we can hardly control the variation. On the other hand the transmitter and receiver can hardly be designed to fit a time varying load impedance. Therefore, we have only one way to solve this problem, using a method to adapt the interface impedance of the communication equipment to the varying power line impedance. Classical adaptor or impedance matcher can not fit the time varying impedance. Dynamic output-impedance modems or "Auto Adapted Impedance Matching" may be designed using a combined real time impedance detector of the power line and the adjustable output impedance-power amplifier. Real time impedance detectors and adjustable output impedance power amplifiers may be applied to an error amplifier-comparator; therefore modem output impedance may be matched to the real time line impedance. If PLC modem includes this technique, PLC system performance may be increased.

Although PLC systems present economical solutions for home automation and industrial control applications without extra wires and cables, there is not enough data for different specific power networks around the world to facilitate system design. In light of this, current study is performed to contribute to the existing literature of measured network data. It could be said that the carrier frequency is an important parameter for the impedance and the relation between frequency and impedance are not linear. If it is assumed that the power lines in different countries are similar to each other, obtained results from these measurements may be universally used in PLC system design.

The main target of this study is to realize measurements and obtain some useful data about the power line impedance in power distribution networks. Results from this study may give some contributions to the literature, especially original data in UK. The data may be used by system designers in countries that has similar power network to facilitate designing standard system for general use.

Power lines cannot be modelled as single line with single load. In a typical in-house network there exist a number of branches going to different rooms. Low voltage mains network propagation differs from the matched lines, numerous reflections are caused by joints of house services cables, connection boxes and the joints at series connection of cables with different characteristics impedance. Signal propagation does not only take place along a direct 'line of sight' path between the transmitter and the receiver, but also additional propagation paths echoes must be considered.

6.2 Further Work

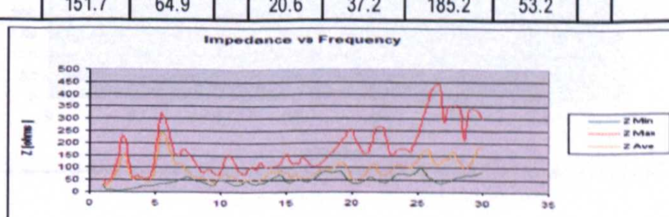
Although there are some investigations on the power line impedance explained in this study. To date, most of these measurements concentrated in the narrowband PLC CENELEC (3 kHz – 148.5 kHz) frequency bands. Aside from this work there are relatively few measurements in the range of 1-30MHz. PLC modem designers still need more data on the power line impedances for the optimum design. Experimental studies like this may be repeated in other locations such as industrial and commercial premises in other areas in other countries to understand the impedance patterns. This study looked at frequencies in the broadband PLC system 1MHz - 30MHz. Measurements could be carried out in other frequency ranges such as 30 MHz – 70MHz. All characteristics of the power line have to be measured and understood under its worst-case condition, best-case condition, as well as typical conditions. These data will also contribute towards the understanding of the capabilities of the smart grid.

Appendix 1: Detailed Experimental Results

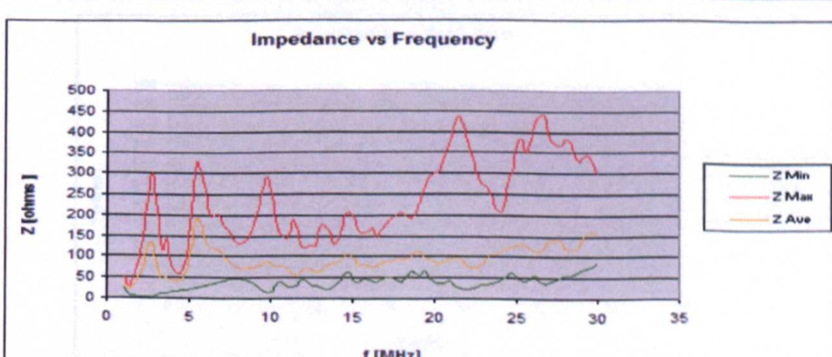
The spread sheet data shown below are from the graphical representations of all the impedance readings given in chapter 5.

Day Summary. Location: Bridgwater College Electronics Prep Room J 24. Date: 24/06/2011 (Friday)

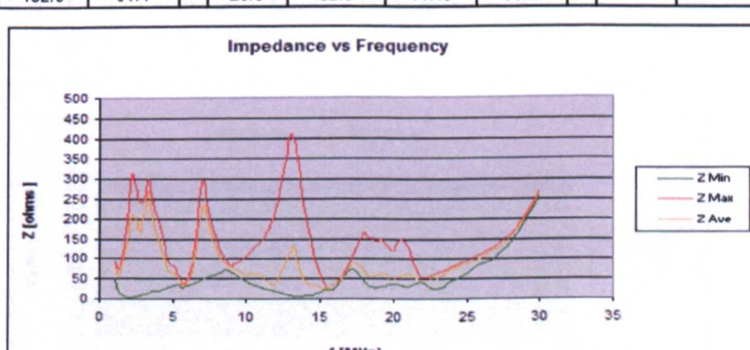
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	27.5	50.1	36.8	11.0	28.4	122.8	60.8	20.9	48.2	158.2	66.5
1.3	8.7	27.0	23.4	11.3	27.4	93.9	49.2	21.2	59.0	160.7	94.1
1.6	9.2	51.3	42.8	11.5	31.9	79.3	46.0	21.5	60.7	199.0	108.6
1.9	4.2	84.0	57.9	11.8	45.0	72.2	50.0	21.8	52.3	256.9	111.7
2.2	3.4	137.5	94.8	12.1	44.1	95.7	51.0	22.1	44.6	267.2	77.1
2.5	4.3	230.5	139.4	12.4	34.7	104.4	48.1	22.4	37.9	263.5	71.1
2.8	8.0	212.6	151.1	12.7	31.2	91.3	47.7	22.7	41.2	208.2	72.3
3.1	11.7	99.0	77.8	13.0	35.7	119.7	51.1	23.0	51.5	154.2	84.7
3.3	14.3	57.2	51.8	13.3	37.6	107.3	60.2	23.3	64.8	154.8	100.7
3.6	17.6	66.2	60.0	13.6	47.9	98.1	77.1	23.6	74.4	170.2	113.6
3.9	19.3	59.6	52.1	13.9	56.9	101.5	82.8	23.8	76.8	174.4	105.5
4.2	21.4	55.9	44.8	14.2	63.5	107.8	80.3	24.1	73.5	171.8	103.0
4.5	21.2	59.6	45.0	14.5	74.1	116.3	91.0	24.4	71.2	163.7	99.6
4.8	23.8	95.4	64.5	14.8	61.7	136.8	79.3	24.7	77.0	196.3	113.7
5.1	27.6	206.7	136.8	15.1	42.1	155.3	74.7	25.0	89.6	232.4	128.3
5.4	32.6	316.7	242.6	15.4	40.6	117.7	59.2	25.3	99.3	285.8	153.9
5.7	34.5	302.0	237.8	15.6	47.1	117.8	70.8	25.6	83.2	329.0	168.6
6.0	37.8	258.5	185.0	15.9	52.4	114.9	61.9	25.9	63.0	378.3	172.5
6.3	40.6	195.3	148.5	16.2	47.5	140.8	55.5	26.2	57.2	423.6	134.1
6.6	42.8	148.3	113.5	16.5	41.4	128.6	53.4	26.5	43.5	437.0	114.2
6.9	50.4	148.0	114.8	16.8	46.0	115.5	60.8	26.8	35.7	436.9	111.2
7.2	55.0	172.9	107.9	17.1	50.9	105.1	69.5	27.1	39.5	287.2	134.3
7.4	60.9	163.6	85.0	17.4	63.7	107.6	79.3	27.4	45.6	352.4	129.7
7.7	57.4	136.9	67.9	17.7	80.3	120.5	94.4	27.7	53.3	348.4	166.7
8.0	47.4	115.3	58.6	18.0	87.6	137.8	98.7	27.9	60.4	353.9	138.0
8.3	45.6	98.5	58.1	18.3	80.8	152.6	93.5	28.2	62.4	339.3	120.2
8.6	43.1	79.8	59.2	18.6	82.0	162.8	100.6	28.5	66.7	206.8	95.7
8.9	35.5	88.9	54.4	18.9	84.8	181.5	103.9	28.8	69.5	319.9	102.0
9.2	27.3	92.4	48.2	19.2	85.8	203.3	120.9	29.1	70.7	340.3	116.7
9.5	28.8	75.4	36.9	19.5	69.0	223.0	114.5	29.4	73.5	337.9	147.2
9.8	47.1	69.4	53.4	19.7	49.9	249.2	89.6	29.7	79.6	326.0	180.1
10.1	50.5	96.0	62.5	20.0	39.8	252.0	55.3	30.0	88.2	298.4	180.2
10.4	50.6	139.2	69.3	20.3	36.5	212.9	46.7				
10.7	40.5	151.7	64.9	20.6	37.2	185.2	53.2				



Aggregate 7 Days summary . Location: Bridgwater College Electronics Prep Room J 24. Date:24.06.11 -30.06.11											
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	25.5	51.1	38.4	11.0	28.3	146.0	68.2	20.9	40.8	376.8	91.8
1.3	8.2	28.0	21.3	11.3	27.2	187.9	57.5	21.2	31.5	417.1	98.4
1.6	6.2	51.7	32.2	11.5	31.9	171.5	56.8	21.5	25.2	434.8	95.2
1.9	4.1	84.4	45.8	11.8	44.9	123.9	65.0	21.8	22.9	413.7	86.3
2.2	3.2	140.4	72.8	12.1	43.4	119.5	69.2	22.1	23.1	368.6	71.9
2.5	3.2	247.5	123.0	12.4	34.7	125.0	66.6	22.4	25.2	333.3	72.3
2.8	4.1	301.4	132.2	12.7	31.2	126.0	62.7	22.7	28.8	293.2	73.9
3.1	6.4	211.7	76.2	13.0	29.2	174.1	64.3	23.0	32.9	271.8	84.5
3.3	9.8	116.0	48.9	13.3	21.1	173.4	69.6	23.3	35.1	268.0	94.2
3.6	11.6	142.9	51.1	13.6	21.8	159.7	79.1	23.6	35.7	247.5	103.0
3.9	14.1	78.2	42.0	13.9	30.7	128.9	82.4	23.8	40.0	213.5	105.2
4.2	16.8	59.5	41.1	14.2	42.7	155.5	89.2	24.1	46.6	210.9	114.8
4.5	18.7	63.3	44.0	14.5	58.8	200.6	100.8	24.4	52.3	275.7	119.6
4.8	21.0	96.4	65.8	14.8	61.1	207.6	104.1	24.7	60.8	302.4	123.5
5.1	23.8	207.8	120.6	15.1	42.1	194.0	94.1	25.0	52.8	364.2	128.0
5.4	26.1	326.2	191.7	15.4	40.6	161.8	79.0	25.3	45.4	381.2	131.8
5.7	28.7	302.0	179.1	15.6	46.7	158.4	80.2	25.6	42.8	347.6	125.5
6.0	31.1	258.5	136.8	15.9	45.0	161.1	76.1	25.9	49.0	378.3	117.9
6.3	33.7	195.3	122.0	16.2	43.4	167.9	73.2	26.2	56.5	423.6	113.8
6.6	36.2	200.0	114.1	16.5	38.7	146.5	76.4	26.5	43.5	437.0	111.0
6.9	38.9	203.4	115.4	16.8	43.6	164.4	83.4	26.8	35.7	436.9	125.6
7.2	41.5	172.9	103.5	17.1	50.9	179.5	86.9	27.1	39.5	389.0	139.5
7.4	44.9	163.6	87.1	17.4	50.8	191.7	88.0	27.4	44.3	371.8	140.6
7.7	47.6	136.9	77.2	17.7	40.9	202.4	94.0	27.7	49.7	364.9	136.5
8.0	47.3	131.0	70.7	18.0	38.6	205.5	91.1	27.9	57.0	380.9	121.0
8.3	45.3	134.2	70.2	18.3	51.6	197.0	91.7	28.2	55.8	376.7	117.6
8.6	42.7	148.4	73.5	18.6	64.1	191.8	100.5	28.5	59.8	345.1	117.5
8.9	35.5	175.7	73.5	18.9	58.5	204.6	108.5	28.8	65.8	328.8	125.5
9.2	27.1	215.8	77.1	19.2	56.0	233.6	109.3	29.1	70.4	340.3	145.5
9.5	20.2	263.7	80.7	19.5	65.9	265.6	99.3	29.4	73.5	341.9	153.3
9.8	13.5	288.8	87.0	19.7	49.4	288.3	90.2	29.7	79.6	326.0	159.8
10.1	16.8	243.0	80.6	20.0	39.7	300.6	83.3	30.0	88.2	298.4	155.5
10.4	34.3	173.9	74.4	20.3	36.5	304.4	80.9				
10.7	40.0	151.7	76.4	20.6	37.2	337.1	88.3				

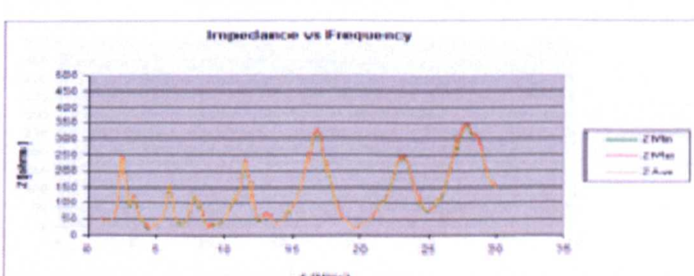


Day Summary. Location: College Room J 24 New Electronics Lab. all PCs on								Date: 22.06.11/23.06.11 (Tuesday/Wednesday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	50.5	90.5	78.3	11.0	28.9	146.0	60.0	20.9	31.5	131.4	62.1
1.3	17.0	73.1	60.0	11.3	26.1	159.1	46.3	21.2	33.8	100.1	57.0
1.6	9.2	115.4	94.7	11.5	23.5	179.8	37.6	21.5	38.0	79.0	50.6
1.9	4.2	191.5	139.1	11.8	20.6	204.1	34.6	21.8	42.0	54.8	47.1
2.2	3.3	309.4	208.4	12.1	17.6	244.8	47.7	22.1	38.4	52.3	47.0
2.5	4.3	278.0	200.1	12.4	13.5	298.1	71.4	22.4	29.6	54.5	48.7
2.8	7.4	242.7	166.1	12.7	10.8	349.0	89.5	22.7	26.2	60.4	53.3
3.1	10.4	248.0	218.6	13.0	7.8	408.8	116.0	23.0	25.7	63.4	51.2
3.3	13.6	300.5	270.1	13.3	5.8	393.6	129.3	23.3	26.8	67.9	56.0
3.6	20.1	240.7	192.6	13.6	5.7	330.4	76.8	23.6	31.7	71.2	60.6
3.9	20.3	204.3	158.6	13.9	5.7	238.7	53.9	23.8	41.4	76.6	69.0
4.2	23.7	155.2	111.6	14.2	7.0	167.3	32.4	24.1	48.4	81.5	76.8
4.5	27.3	104.2	77.1	14.5	9.7	117.6	29.9	24.4	53.2	86.0	80.1
4.8	30.6	85.1	66.0	14.8	13.3	81.1	29.9	24.7	58.4	91.5	84.3
5.1	33.8	79.9	63.1	15.1	17.3	53.7	26.3	25.0	65.4	96.5	86.5
5.4	37.8	55.2	49.7	15.4	21.8	33.4	25.1	25.3	73.1	101.5	91.6
5.7	29.4	37.7	34.3	15.6	22.3	27.8	26.9	25.6	81.1	107.2	97.6
6.0	34.5	46.7	43.1	15.9	22.8	33.7	32.3	25.9	86.2	111.4	101.6
6.3	36.0	82.5	65.3	16.2	35.1	41.6	40.1	26.2	90.1	115.5	107.0
6.6	39.8	155.2	124.7	16.5	50.4	52.0	51.0	26.5	93.3	120.0	112.4
6.9	44.7	275.5	206.4	16.8	62.4	73.2	66.1	26.8	97.8	126.2	119.5
7.2	49.8	294.8	235.6	17.1	74.3	95.0	82.0	27.1	106.5	133.5	124.7
7.4	54.2	220.0	188.6	17.4	70.6	120.0	87.9	27.4	116.9	142.0	133.3
7.7	58.6	166.4	138.8	17.7	55.6	145.9	79.9	27.7	128.1	151.1	142.8
8.0	62.9	133.9	111.2	18.0	44.0	166.8	71.3	27.9	139.7	160.4	153.3
8.3	67.6	111.9	94.2	18.3	34.6	152.1	55.3	28.2	153.3	172.2	167.8
8.6	72.1	95.4	83.9	18.6	31.9	152.6	52.9	28.5	166.8	184.1	179.9
8.9	68.8	82.8	78.0	18.9	28.7	143.4	58.5	28.8	183.0	197.4	193.3
9.2	60.6	85.9	73.0	19.2	31.3	150.0	63.1	29.1	199.1	212.4	208.0
9.5	53.2	92.8	67.9	19.5	32.3	137.7	63.0	29.4	217.7	229.6	225.1
9.8	46.7	100.8	61.5	19.7	35.8	126.6	48.3	29.7	237.3	247.6	243.3
10.1	41.6	109.7	57.4	20.0	36.0	121.8	46.9	30.0	258.6	269.8	266.1
10.4	36.7	120.0	60.6	20.3	35.9	139.5	54.4				
10.7	32.6	132.9	61.1	20.6	32.9	147.9	56.0				

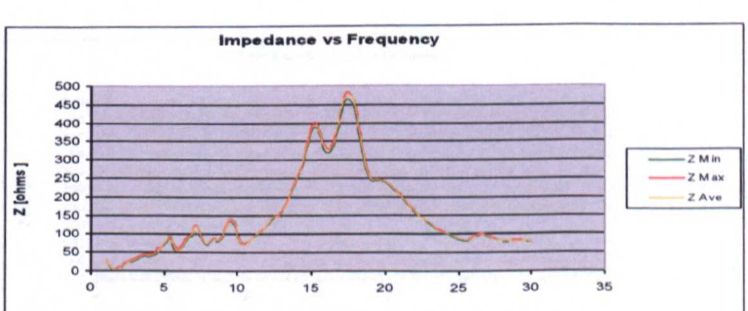


Day Summary. Location: College Room J24 w ith no pow er readings | Date:27.06.11 (Monday)

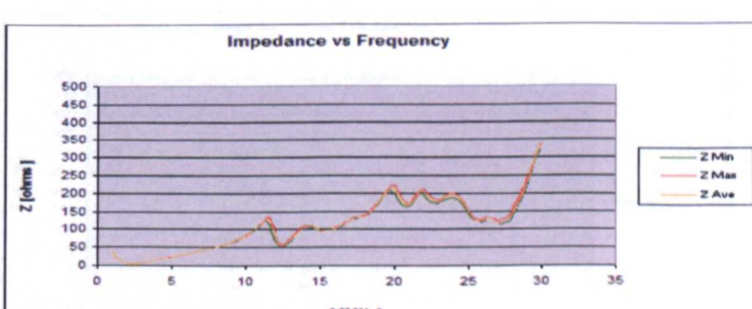
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	54.1	55.0	54.5	11.0	134.1	135.2	134.5	20.9	59.7	61.3	60.2
1.3	39.0	39.2	39.1	11.3	192.4	194.2	193.2	21.2	74.4	75.1	74.8
1.6	47.0	47.5	47.2	11.5	232.8	236.6	234.3	21.5	91.7	92.5	92.1
1.9	56.0	56.5	56.3	11.8	172.3	177.0	174.6	21.8	112.0	112.6	112.3
2.2	86.9	89.1	88.0	12.1	90.0	92.4	91.2	22.1	136.4	137.5	137.0
2.5	242.1	243.6	242.6	12.4	42.7	47.5	46.7	22.4	167.1	168.1	167.5
2.8	151.3	153.9	152.7	12.7	46.4	46.9	46.6	22.7	202.6	204.4	204.0
3.1	88.2	90.6	88.9	13.0	65.2	66.8	65.9	23.0	234.2	238.1	235.2
3.3	120.9	124.4	122.1	13.3	62.4	63.6	63.0	23.3	242.1	246.3	244.8
3.6	93.5	94.7	94.4	13.6	44.1	45.1	44.5	23.6	217.6	220.7	218.4
3.9	53.3	53.8	53.6	13.9	33.4	34.1	33.7	23.8	174.7	178.8	176.6
4.2	21.5	29.8	28.5	14.2	40.8	41.4	41.0	24.1	131.2	135.5	133.0
4.5	21.3	21.6	21.5	14.5	56.1	59.3	56.5	24.4	96.0	99.0	97.7
4.8	31.9	32.2	32.0	14.8	74.3	75.0	74.6	24.7	76.7	78.0	77.4
5.1	33.3	33.9	33.5	15.1	96.0	96.6	96.3	25.0	73.8	76.0	74.9
5.4	47.4	48.2	47.8	15.4	121.1	121.6	121.4	25.3	77.8	81.2	79.3
5.7	88.3	89.5	88.8	15.6	151.0	152.3	151.6	25.6	93.9	96.2	95.0
6.0	155.2	157.7	156.4	15.9	190.9	192.8	191.3	25.9	115.6	118.1	117.2
6.3	110.9	112.7	111.9	16.2	243.5	246.0	244.4	26.2	142.1	144.4	143.4
6.6	45.5	46.1	45.8	16.5	301.1	307.8	303.9	26.5	174.5	176.6	175.7
6.9	35.1	35.6	35.4	16.8	320.7	328.0	323.4	26.8	211.9	217.3	215.4
7.2	35.5	36.0	35.7	17.1	299.8	306.4	302.6	27.1	256.9	264.2	261.5
7.4	63.2	64.5	63.8	17.4	239.3	243.5	242.0	27.4	306.6	314.9	310.1
7.7	116.7	118.0	117.4	17.7	174.4	177.2	176.5	27.7	338.5	346.8	341.2
8.0	105.3	106.6	105.8	18.0	127.4	130.0	128.7	27.9	336.2	344.3	339.7
8.3	70.5	73.3	72.5	18.3	93.4	94.5	94.0	28.2	314.1	320.7	319.5
8.6	35.6	36.4	36.0	18.6	67.5	68.4	68.0	28.5	300.6	306.4	301.2
8.9	25.8	26.7	26.2	18.9	47.8	48.3	48.1	28.8	272.4	276.9	273.7
9.2	32.1	32.6	32.3	19.2	33.0	33.3	33.1	29.1	228.5	233.2	230.7
9.5	32.4	33.2	32.8	19.5	24.1	24.3	24.2	29.4	190.1	192.6	191.7
9.8	37.6	38.3	37.9	19.7	23.1	23.4	23.3	29.7	163.4	166.2	164.7
10.1	52.8	53.6	53.2	20.0	26.4	26.9	26.6	30.0	145.8	147.6	146.3
10.4	71.4	72.4	71.8	20.3	35.3	36.3	35.6				
10.7	96.5	97.6	97.0	20.6	46.6	47.3	47.0				



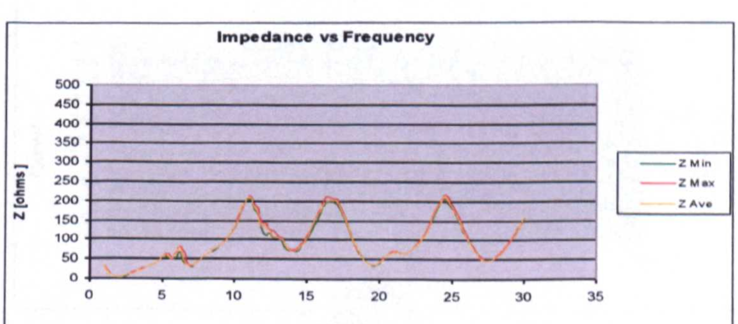
Day Summary. Location: College Computer Laboratory Room 123								Date: 23.11.06 & 24.11.06 (Thursday/Friday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	31.2	31.6	31.4	11.0	89.0	90.8	89.7	20.9	207.2	211.1	209.1
1.3	9.7	10.1	9.9	11.3	99.2	100.4	100.0	21.2	193.8	197.2	195.8
1.6	3.2	3.4	3.4	11.5	107.3	109.5	108.1	21.5	180.6	183.6	182.7
1.9	5.7	7.2	6.8	11.8	117.6	119.3	118.3	21.8	168.0	170.6	169.5
2.2	12.6	15.3	14.6	12.1	130.5	132.6	131.5	22.1	155.4	157.5	157.2
2.5	18.6	22.2	21.0	12.4	143.9	145.8	145.1	22.4	145.2	147.1	146.6
2.8	23.5	26.8	25.1	12.7	145.6	148.1	146.9	22.7	137.2	138.9	138.5
3.1	27.2	34.2	30.4	13.0	157.7	162.1	159.6	23.0	129.4	131.5	131.0
3.3	33.1	40.0	35.9	13.3	178.9	182.7	180.1	23.3	120.9	123.2	122.2
3.6	39.0	44.5	41.1	13.6	202.6	207.4	204.1	23.6	112.8	114.6	114.1
3.9	36.8	45.3	42.2	13.9	233.9	239.6	235.5	23.8	106.5	108.7	107.7
4.2	43.5	46.7	44.6	14.2	268.7	272.5	270.9	24.1	101.8	104.3	103.0
4.5	47.3	62.2	49.7	14.5	304.4	313.3	309.2	24.4	96.6	98.5	97.7
4.8	60.5	62.6	61.5	14.8	348.3	359.6	353.3	24.7	90.3	92.6	91.7
5.1	75.8	79.9	77.4	15.1	383.9	397.8	389.8	25.0	85.0	87.4	86.3
5.4	87.0	92.2	90.4	15.4	386.7	399.2	394.6	25.3	82.2	83.9	82.9
5.7	57.4	66.3	63.6	15.6	358.7	367.3	365.1	25.6	82.9	84.7	83.5
6.0	52.0	57.7	54.3	15.9	322.1	336.2	333.9	25.9	87.3	89.0	88.0
6.3	64.9	72.4	66.8	16.2	320.7	329.0	326.7	26.2	91.5	95.2	93.7
6.6	83.7	91.3	86.1	16.5	336.2	351.1	343.1	26.5	95.7	100.4	98.3
6.9	93.7	101.1	98.7	16.8	378.4	388.1	387.5	26.8	97.3	100.6	98.9
7.2	105.0	123.4	119.4	17.1	432.1	445.7	443.2	27.1	92.0	96.0	94.4
7.4	96.0	104.9	101.7	17.4	463.1	482.7	475.4	27.4	86.5	89.1	88.3
7.7	71.4	73.8	72.6	17.7	454.6	473.0	470.7	27.7	83.1	84.5	83.8
8.0	76.9	79.8	77.8	18.0	413.0	431.9	426.4	27.9	80.8	81.8	81.2
8.3	86.6	90.9	88.4	18.3	351.4	369.7	366.3	28.2	79.9	81.2	80.4
8.6	78.4	82.8	80.2	18.6	298.4	311.1	308.1	28.5	81.3	82.2	81.7
8.9	90.1	94.5	91.9	18.9	259.8	266.1	265.0	28.8	82.2	83.2	82.8
9.2	120.3	122.2	121.3	19.2	242.5	248.0	246.1	29.1	82.0	83.1	82.5
9.5	135.4	140.3	137.8	19.5	245.1	249.3	246.2	29.4	80.9	81.7	81.2
9.8	124.3	132.7	130.0	19.7	244.0	246.7	245.5	29.7	79.6	80.7	80.1
10.1	87.0	91.6	90.1	20.0	238.5	241.0	240.2	30.0	78.5	79.4	79.1
10.4	69.9	71.8	70.9	20.3	231.0	232.4	232.0				
10.7	72.5	74.9	73.4	20.6	220.5	223.1	221.8				



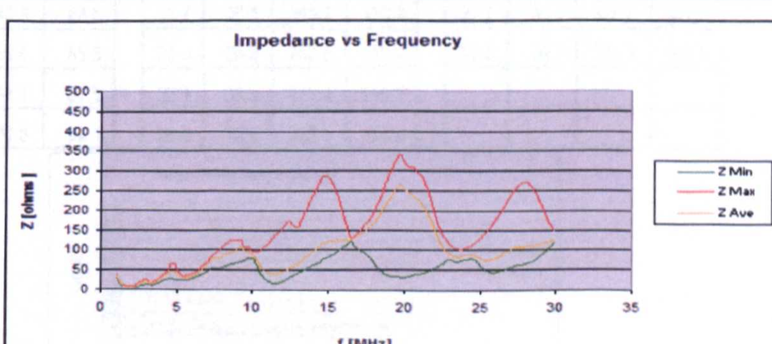
Day Summary. Location: College Mechatronics/Electronics Laboratory Room T7								Date : 01.11.06 (Tuesday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	36.3	37.5	37.1	11.0	112.6	115.4	113.4	20.9	162.5	167.2	165.7
1.3	16.8	17.6	17.4	11.3	126.1	129.1	128.3	21.2	172.3	179.3	174.7
1.6	9.9	10.5	10.3	11.5	113.9	136.1	130.3	21.5	188.3	196.6	191.2
1.9	5.0	5.6	5.4	11.8	79.9	105.4	98.5	21.8	201.0	207.5	203.8
2.2	3.2	3.2	3.2	12.1	57.8	64.0	61.8	22.1	190.2	207.6	202.1
2.5	3.4	3.4	3.4	12.4	52.1	56.1	52.9	22.4	177.1	194.2	189.1
2.8	3.7	4.1	3.8	12.7	56.2	64.5	58.3	22.7	173.2	182.3	178.5
3.1	6.0	6.3	6.1	13.0	67.7	75.6	69.6	23.0	172.6	178.7	175.6
3.3	8.4	8.8	8.5	13.3	80.2	86.9	81.9	23.3	177.0	182.2	180.6
3.6	11.0	11.3	11.0	13.6	92.7	97.5	94.0	23.6	183.2	193.5	189.9
3.9	13.4	13.9	13.5	13.9	103.4	105.8	103.9	23.8	184.0	198.5	194.8
4.2	15.9	16.3	16.0	14.2	107.3	109.0	108.4	24.1	182.1	196.8	193.0
4.5	18.4	18.8	18.5	14.5	103.2	107.6	105.7	24.4	175.9	186.8	184.7
4.8	20.7	21.2	20.9	14.8	98.0	100.7	99.8	24.7	162.5	171.2	168.1
5.1	23.2	23.6	23.3	15.1	96.0	97.4	96.8	25.0	144.2	150.8	147.6
5.4	25.8	26.1	25.8	15.4	97.4	98.6	98.1	25.3	130.5	134.0	132.3
5.7	28.3	28.6	28.4	15.6	97.6	98.8	98.2	25.6	123.4	126.3	124.2
6.0	30.3	30.8	30.5	15.9	99.6	101.8	100.3	25.9	120.3	127.5	122.5
6.3	33.0	33.3	33.0	16.2	103.9	106.4	104.9	26.2	124.8	132.2	127.1
6.6	35.6	36.1	35.7	16.5	110.2	113.0	111.3	26.5	130.7	133.3	131.7
6.9	38.4	38.8	38.5	16.8	117.5	120.1	118.7	26.8	126.0	128.6	127.6
7.2	41.2	41.6	41.3	17.1	125.2	127.6	126.3	27.1	117.4	123.4	119.1
7.4	44.1	44.7	44.3	17.4	130.0	133.7	131.9	27.4	115.1	125.1	118.0
7.7	47.3	47.7	47.4	17.7	134.1	135.6	134.7	27.7	121.6	134.5	125.1
8.0	50.5	51.1	50.7	18.0	137.4	140.2	138.3	27.9	135.7	150.2	139.4
8.3	54.0	54.7	54.1	18.3	143.8	149.3	145.4	28.2	155.5	170.5	159.5
8.6	57.7	58.4	57.9	18.6	153.5	159.6	155.2	28.5	180.9	196.8	184.6
8.9	61.7	62.4	61.9	18.9	166.0	172.5	168.1	28.8	208.3	222.0	212.2
9.2	65.8	66.8	66.1	19.2	182.7	186.2	184.2	29.1	238.2	252.1	242.3
9.5	70.5	71.8	70.8	19.5	198.3	201.9	200.1	29.4	271.5	281.1	274.8
9.8	75.6	77.2	76.1	19.7	207.7	216.4	214.5	29.7	305.3	312.1	308.5
10.1	81.4	83.2	82.0	20.0	198.5	221.4	215.6	30.0	322.4	339.6	336.5
10.4	89.1	91.5	89.9	20.3	180.1	201.7	196.3				
10.7	99.3	102.5	100.2	20.6	166.0	180.1	175.6				



Day Summary. Location: College Electrical & Hydraulics Lab. Room T28								Date: 12.10.06/13.10.06 (Thursday/Friday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	33.6	34.0	33.8	11.0	205.3	212.9	209.5	20.9	68.5	69.0	68.8
1.3	15.3	15.5	15.4	11.3	185.8	192.8	189.3	21.2	67.6	68.5	68.0
1.6	7.4	7.5	7.5	11.5	168.5	182.0	172.1	21.5	64.7	65.5	65.0
1.9	3.9	4.1	3.9	11.8	132.4	146.1	135.9	21.8	64.3	64.9	64.6
2.2	4.1	4.1	4.1	12.1	111.7	143.0	137.6	22.1	69.1	70.0	69.5
2.5	6.9	7.2	7.1	12.4	117.9	126.5	122.5	22.4	78.4	79.8	79.1
2.8	11.2	11.7	11.6	12.7	102.7	122.8	106.5	22.7	89.9	91.4	90.5
3.1	15.3	15.5	15.4	13.0	106.0	110.1	107.7	23.0	102.6	104.9	103.2
3.3	18.8	19.4	18.9	13.3	94.1	102.7	100.3	23.3	119.6	122.6	120.7
3.6	23.6	24.1	23.6	13.6	76.0	82.1	80.6	23.6	143.7	146.2	144.5
3.9	28.2	29.1	28.9	13.9	70.0	71.9	71.0	23.8	169.9	173.2	171.2
4.2	33.9	34.3	34.3	14.2	71.2	76.2	73.5	24.1	196.0	199.5	197.6
4.5	40.1	40.6	40.2	14.5	78.8	84.8	80.6	24.4	208.9	215.0	212.4
4.8	46.5	46.9	46.8	14.8	92.0	96.5	92.9	24.7	194.9	210.1	203.3
5.1	58.1	59.5	58.7	15.1	106.3	115.7	109.2	25.0	178.6	187.1	183.2
5.4	54.2	61.1	56.5	15.4	129.8	138.6	136.4	25.3	161.8	167.3	164.7
5.7	49.9	51.4	50.7	15.6	145.2	160.9	157.9	25.6	139.3	148.1	143.2
6.0	52.0	65.1	62.7	15.9	172.2	177.4	173.7	25.9	115.4	120.7	117.6
6.3	66.9	80.8	78.2	16.2	193.8	208.1	196.2	26.2	95.4	98.4	96.9
6.6	40.3	65.3	43.8	16.5	199.6	210.6	203.5	26.5	78.1	81.0	79.3
6.9	32.5	33.3	32.8	16.8	198.6	203.9	201.1	26.8	63.6	64.9	64.3
7.2	31.9	34.3	33.7	17.1	191.9	204.7	200.6	27.1	50.7	52.6	51.9
7.4	42.5	43.5	43.1	17.4	173.1	181.1	177.8	27.4	46.5	48.5	47.5
7.7	52.4	53.4	53.0	17.7	139.3	147.2	142.1	27.7	46.6	47.9	47.2
8.0	60.7	60.9	60.9	18.0	109.5	113.8	111.3	27.9	52.8	54.3	53.4
8.3	67.5	68.0	67.7	18.3	85.5	87.9	86.7	28.2	61.5	63.4	62.5
8.6	73.5	74.8	74.5	18.6	64.8	67.0	66.0	28.5	72.6	75.6	74.0
8.9	80.4	80.9	80.7	18.9	49.8	51.0	50.4	28.8	86.1	89.2	87.3
9.2	89.2	90.8	89.4	19.2	39.3	39.9	39.6	29.1	101.3	104.1	102.5
9.5	101.5	102.7	101.9	19.5	34.3	34.7	34.4	29.4	118.0	120.2	119.2
9.8	116.6	118.8	118.1	19.7	34.6	35.0	34.8	29.7	136.2	138.8	137.7
10.1	135.9	138.9	137.8	20.0	40.7	41.9	41.3	30.0	155.6	157.5	156.8
10.4	162.5	167.4	163.3	20.3	51.0	52.4	51.7				
10.7	193.3	195.1	194.1	20.6	61.9	63.1	62.5				

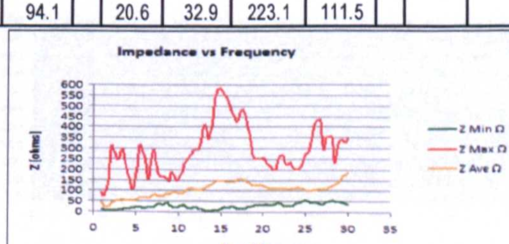


Day Summary. Location: Sound Engineering Lab. Bridgwater College								Date: 11.01.07/12.01.07(Thursday/Friday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	33.6	37.1	34.6	11.0	23.0	115.2	42.9	20.9	38.4	292.1	223.5
1.3	15.0	16.4	15.5	11.3	16.7	128.2	39.9	21.2	40.9	279.9	210.8
1.6	6.4	8.6	7.0	11.5	15.7	139.8	40.3	21.5	44.8	254.1	193.6
1.9	5.6	7.2	6.4	11.8	19.6	150.2	43.7	21.8	49.8	218.9	168.1
2.2	4.7	7.6	6.6	12.1	25.2	163.1	48.5	22.1	55.6	180.4	140.6
2.5	6.3	15.7	12.7	12.4	30.3	170.5	53.4	22.4	62.2	151.4	117.8
2.8	11.1	21.1	16.9	12.7	35.8	159.4	59.0	22.7	68.7	132.0	102.3
3.1	13.1	25.0	19.4	13.0	41.7	158.0	65.9	23.0	74.9	118.0	91.9
3.3	11.4	17.0	14.6	13.3	47.6	179.7	74.1	23.3	74.4	107.6	84.7
3.6	15.4	21.6	19.8	13.6	53.5	203.3	83.5	23.6	69.7	103.1	82.8
3.9	20.3	30.6	28.1	13.9	59.2	230.0	92.9	23.8	73.0	100.2	85.3
4.2	25.6	42.6	37.3	14.2	65.0	259.2	102.8	24.1	76.8	105.6	88.1
4.5	27.6	60.3	46.1	14.5	70.9	281.5	111.4	24.4	80.0	113.1	88.5
4.8	25.6	63.6	48.3	14.8	77.4	285.5	117.2	24.7	72.1	120.8	85.4
5.1	26.6	43.8	37.8	15.1	84.1	281.2	120.0	25.0	60.2	129.7	79.3
5.4	26.6	34.0	30.4	15.4	91.0	260.8	122.0	25.3	50.2	140.7	73.7
5.7	25.0	37.4	30.4	15.6	98.4	232.3	122.7	25.6	44.0	153.0	72.8
6.0	28.8	40.2	33.0	15.9	105.9	194.5	122.5	25.9	43.1	166.6	75.6
6.3	33.1	46.2	39.6	16.2	113.6	158.1	123.3	26.2	43.9	181.2	81.1
6.6	37.7	54.3	47.9	16.5	121.7	128.1	126.2	26.5	46.6	199.0	87.5
6.9	42.1	63.5	56.6	16.8	106.9	139.0	131.5	26.8	50.4	216.9	94.5
7.2	47.3	74.2	66.5	17.1	98.4	150.0	138.7	27.1	54.8	236.1	101.3
7.4	52.3	86.7	75.8	17.4	92.5	162.3	146.9	27.4	58.5	252.9	105.5
7.7	53.5	97.3	78.7	17.7	81.2	178.3	156.4	27.7	60.9	266.7	107.1
8.0	56.4	108.6	85.9	18.0	66.4	198.3	168.7	27.9	63.4	272.8	107.6
8.3	61.3	115.8	89.6	18.3	52.7	222.1	183.7	28.2	67.6	268.1	108.9
8.6	63.8	122.4	93.7	18.6	43.6	247.0	201.2	28.5	73.9	253.7	110.6
8.9	66.4	122.8	97.8	18.9	37.6	277.2	220.0	28.8	81.8	233.6	112.6
9.2	70.0	122.5	105.4	19.2	34.0	301.3	236.9	29.1	90.4	206.6	114.3
9.5	74.2	108.0	98.9	19.5	32.3	325.2	253.5	29.4	99.2	182.9	116.8
9.8	78.2	105.7	93.8	19.7	30.1	339.5	260.1	29.7	109.5	159.6	121.1
10.1	77.7	94.6	87.0	20.0	30.3	324.3	252.6	30.0	120.5	146.5	127.4
10.4	58.3	94.9	70.2	20.3	33.4	308.7	246.3				
10.7	37.8	103.6	53.6	20.6	36.5	308.3	236.7				

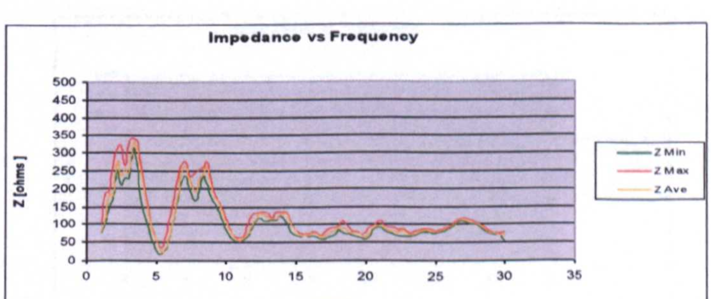


Aggregate impedance measurements of all college single phase measurements.

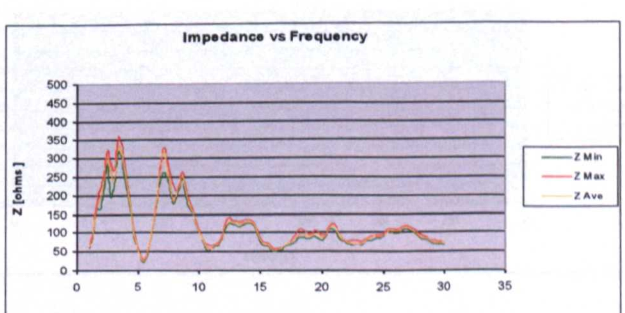
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	13.5	90.5	41.2	11.0	23.0	239.6	102.3	20.9	31.5	211.1	107.7
1.3	8.5	73.1	20.9	11.3	16.7	259.4	106.0	21.2	33.8	197.2	107.7
1.6	3.2	115.4	19.8	11.5	15.7	274.4	107.5	21.5	38.0	199.0	107.4
1.9	3.7	191.5	24.2	11.8	19.6	291.5	103.4	21.8	42.0	256.9	108.3
2.2	3.2	309.4	38.1	12.1	17.6	290.8	101.5	22.1	38.4	267.2	107.7
2.5	3.4	278.0	47.4	12.4	13.5	298.1	101.0	22.4	29.6	263.5	108.9
2.8	3.7	242.7	51.9	12.7	10.8	349.0	101.8	22.7	26.2	223.0	108.0
3.1	6.0	248.0	53.7	13.0	7.8	408.8	108.3	23.0	25.7	226.6	105.1
3.3	8.0	300.5	54.7	13.3	5.8	393.6	115.5	23.3	26.8	234.2	106.3
3.6	10.2	240.7	50.9	13.6	5.7	342.1	119.2	23.6	31.7	207.7	108.3
3.9	12.2	204.3	49.5	13.9	5.7	401.8	127.3	23.8	37.3	198.5	110.6
4.2	12.7	155.2	51.4	14.2	7.0	476.3	134.8	24.1	42.5	199.5	112.1
4.5	13.9	105.8	50.3	14.5	9.7	552.3	142.9	24.4	48.1	215.0	110.8
4.8	15.7	109.2	50.6	14.8	13.3	583.7	145.7	24.7	54.1	241.9	107.9
5.1	18.9	206.7	59.9	15.1	17.3	577.2	145.2	25.0	53.8	270.5	102.0
5.4	19.2	316.7	68.0	15.4	21.6	558.5	143.3	25.3	50.2	285.8	99.1
5.7	17.9	302.0	65.5	15.6	19.7	536.9	141.1	25.6	44.0	329.0	98.9
6.0	17.1	258.5	65.1	15.9	19.5	510.6	139.8	25.9	43.1	378.3	101.6
6.3	17.9	195.3	66.5	16.2	23.5	478.2	140.5	26.2	41.7	423.6	102.1
6.6	19.0	155.2	66.6	16.5	24.4	453.2	142.6	26.5	43.5	437.0	104.6
6.9	18.1	275.5	76.8	16.8	19.9	419.5	147.3	26.8	35.7	436.9	106.1
7.2	25.0	294.8	83.0	17.1	17.2	445.7	154.6	27.1	39.5	294.7	106.8
7.4	29.6	220.0	78.1	17.4	16.7	482.7	157.6	27.4	45.6	352.4	105.8
7.7	37.1	166.4	73.2	17.7	16.6	473.0	153.0	27.7	46.6	349.4	113.0
8.0	30.9	161.8	74.5	18.0	18.7	431.9	143.5	27.9	52.8	354.8	116.8
8.3	35.5	165.2	76.8	18.3	22.4	369.7	134.7	28.2	55.0	342.0	123.3
8.6	43.1	157.1	80.1	18.6	27.0	311.1	128.5	28.5	51.3	231.4	127.8
8.9	29.7	141.1	85.2	18.9	28.7	266.1	124.8	28.8	48.5	319.9	137.2
9.2	25.4	188.7	89.4	19.2	29.8	248.0	123.6	29.1	46.3	340.3	149.2
9.5	20.6	168.0	89.0	19.5	32.3	249.3	124.3	29.4	43.5	337.9	163.4
9.8	21.4	143.9	88.5	19.7	30.1	249.2	123.9	29.7	38.2	326.0	177.0
10.1	21.6	156.6	85.5	20.0	30.3	252.0	119.2	30.0	36.2	348.3	188.0
10.4	29.0	184.1	87.5	20.3	33.4	232.4	115.1				
10.7	32.6	220.8	94.1	20.6	32.9	223.1	111.5				



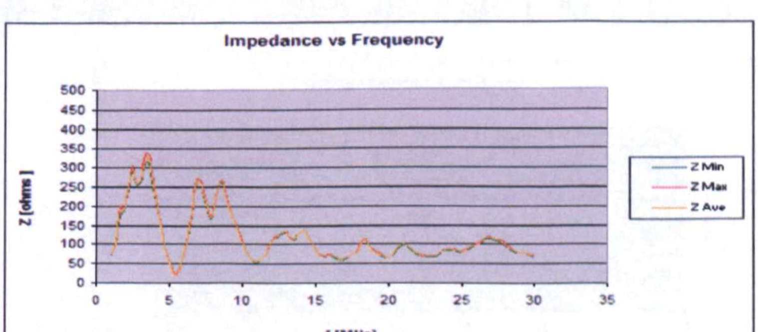
Day Summary. Location: College Welding Workshop 3-phase betw een L1 & N								Date: 17.04.07-18.04.07 (Tuesday/Wednesday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	76.2	102.2	78.8	11.0	53.5	61.7	54.5	20.9	91.8	109.8	98.9
1.3	99.5	185.6	105.2	11.3	59.9	72.9	64.5	21.2	84.4	99.0	93.4
1.6	145.9	191.1	185.8	11.5	67.8	102.8	72.0	21.5	80.0	92.6	85.3
1.9	171.2	263.0	178.8	11.8	93.3	130.3	98.0	21.8	75.9	92.0	80.1
2.2	253.6	313.1	277.4	12.1	112.2	133.2	116.4	22.1	71.2	89.4	78.6
2.5	207.0	319.0	233.4	12.4	117.6	135.7	131.1	22.4	68.3	85.2	80.0
2.8	230.4	261.6	256.4	12.7	109.9	136.2	126.7	22.7	67.2	86.8	80.7
3.1	230.9	335.2	243.6	13.0	109.7	132.8	121.8	23.0	66.3	78.9	74.6
3.3	315.3	342.7	329.8	13.3	112.1	118.7	113.8	23.3	67.2	74.9	70.1
3.6	264.0	335.4	311.8	13.6	111.5	135.0	115.7	23.6	71.4	80.4	73.1
3.9	169.0	266.0	254.1	13.9	125.9	135.7	128.3	23.8	76.2	83.4	79.1
4.2	112.5	177.9	169.7	14.2	109.7	134.7	131.1	24.1	79.2	87.5	83.6
4.5	73.9	113.9	109.0	14.5	86.0	114.3	110.3	24.4	77.5	86.7	83.7
4.8	43.8	77.0	73.7	14.8	73.2	94.0	90.4	24.7	76.9	84.6	82.3
5.1	20.7	46.5	43.7	15.1	68.5	80.0	74.4	25.0	74.8	82.2	78.6
5.4	20.9	32.9	21.7	15.4	64.2	73.0	66.8	25.3	77.9	85.5	81.5
5.7	31.3	69.1	33.7	15.6	66.3	72.2	68.7	25.6	82.2	89.3	85.7
6.0	66.3	122.3	69.5	15.9	64.9	72.8	70.8	25.9	87.6	94.1	89.9
6.3	117.6	176.6	121.7	16.2	66.8	77.8	75.4	26.2	93.2	99.3	96.4
6.6	174.8	234.0	182.3	16.5	65.1	75.7	72.4	26.5	102.3	108.2	104.0
6.9	225.7	270.5	258.6	16.8	58.3	68.5	64.4	26.8	110.1	116.2	112.8
7.2	236.7	275.3	260.7	17.1	60.2	77.7	67.9	27.1	109.6	118.4	114.4
7.4	193.7	233.2	225.9	17.4	64.8	86.9	75.9	27.4	105.1	115.4	108.0
7.7	164.8	244.4	190.6	17.7	70.5	90.2	81.3	27.7	99.9	110.0	103.4
8.0	193.4	252.3	225.5	18.0	85.6	95.6	89.2	27.9	97.2	103.1	100.1
8.3	236.6	259.8	241.5	18.3	78.8	110.6	90.5	28.2	89.4	98.3	95.7
8.6	210.2	274.0	260.8	18.6	72.9	102.3	83.0	28.5	81.3	89.0	87.1
8.9	173.4	221.6	211.4	18.9	72.6	87.6	76.3	28.8	75.5	80.4	79.3
9.2	157.5	180.4	174.4	19.2	67.1	77.8	76.2	29.1	74.1	76.2	75.8
9.5	135.2	159.5	157.0	19.5	65.5	79.9	75.5	29.4	72.7	75.2	73.6
9.8	104.8	136.2	131.5	19.7	61.7	70.6	67.4	29.7	70.0	75.7	71.6
10.1	78.2	106.0	102.4	20.0	59.5	77.4	65.3	30.0	53.3	77.4	70.9
10.4	61.6	80.1	77.3	20.3	68.4	92.9	74.9				
10.7	52.5	64.8	61.9	20.6	88.2	98.3	90.5				



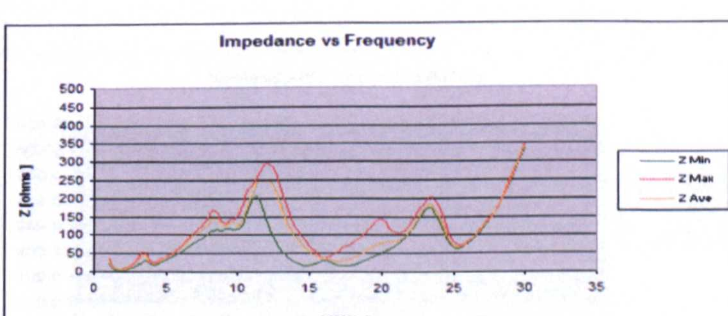
Day Summary. Location: College Welding Workshop 3-phase between L2-N								Date : 01.05.07/ 02.05.07 (Tuesday/Wednesday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	58.7	67.0	62.4	11.0	57.6	64.2	58.3	20.9	107.2	124.1	117.5
1.3	90.6	99.9	93.4	11.3	64.1	68.5	66.2	21.2	94.4	107.0	104.5
1.6	164.9	180.6	170.4	11.5	65.9	72.5	67.8	21.5	82.7	91.3	88.9
1.9	163.8	219.7	193.0	11.8	83.4	90.9	86.3	21.8	76.1	79.3	78.1
2.2	205.3	255.7	229.9	12.1	112.7	128.5	120.1	22.1	69.7	76.6	72.1
2.5	286.7	323.6	308.7	12.4	125.4	139.9	130.3	22.4	66.3	79.2	68.9
2.8	196.0	280.9	258.4	12.7	124.5	131.5	128.8	22.7	66.1	79.2	67.1
3.1	224.3	271.0	241.4	13.0	121.3	133.0	129.8	23.0	66.1	77.6	67.6
3.3	318.3	357.2	330.2	13.3	116.0	129.3	124.2	23.3	68.0	75.9	70.0
3.6	305.7	339.9	318.0	13.6	120.5	131.2	127.3	23.6	75.9	81.1	76.9
3.9	243.8	274.3	266.4	13.9	127.1	134.3	129.6	23.8	77.8	85.8	84.4
4.2	173.4	185.5	181.5	14.2	127.6	132.1	130.1	24.1	82.5	90.2	88.6
4.5	114.1	124.2	121.4	14.5	111.2	121.7	118.9	24.4	85.8	91.5	89.4
4.8	70.3	77.6	75.9	14.8	92.0	102.5	99.4	24.7	84.6	92.8	88.6
5.1	44.4	46.9	45.7	15.1	71.3	78.5	77.1	25.0	89.0	95.9	91.8
5.4	23.3	27.9	24.7	15.4	65.8	73.0	70.4	25.3	99.8	105.7	102.4
5.7	34.5	38.7	35.5	15.6	64.3	69.5	66.8	25.6	102.7	109.8	107.7
6.0	72.3	76.4	73.6	15.9	54.2	59.4	56.2	25.9	99.1	105.6	103.0
6.3	126.3	131.4	128.3	16.2	51.7	55.9	52.9	26.2	97.8	106.2	103.1
6.6	188.7	196.3	192.2	16.5	52.3	59.0	56.9	26.5	101.7	112.2	109.6
6.9	243.4	296.3	284.2	16.8	56.6	62.3	60.4	26.8	109.0	118.8	116.2
7.2	261.6	328.5	319.1	17.1	64.8	67.6	66.3	27.1	110.5	117.2	115.4
7.4	244.3	281.7	261.9	17.4	68.7	74.4	71.9	27.4	103.3	111.5	107.5
7.7	179.5	229.4	188.5	17.7	73.5	88.7	81.8	27.7	96.2	104.0	99.6
8.0	190.9	210.3	195.7	18.0	84.0	102.8	91.2	27.9	87.7	95.4	91.2
8.3	216.9	230.1	222.6	18.3	87.6	108.5	94.7	28.2	80.9	88.8	84.8
8.6	246.2	262.7	254.0	18.6	88.0	104.6	93.4	28.5	80.3	85.8	83.3
8.9	194.5	213.8	210.0	18.9	85.2	97.5	91.3	28.8	76.9	80.0	78.9
9.2	166.3	181.9	177.7	19.2	86.9	95.8	90.6	29.1	70.4	77.4	73.0
9.5	152.5	156.8	154.8	19.5	88.5	105.5	97.1	29.4	69.9	76.1	72.2
9.8	118.9	126.6	120.9	19.7	85.4	101.7	95.7	29.7	69.0	75.3	73.1
10.1	97.3	100.7	99.4	20.0	78.9	91.6	88.3	30.0	68.0	74.4	73.1
10.4	72.2	76.0	74.9	20.3	91.2	96.3	93.4				
10.7	54.7	67.2	58.7	20.6	108.2	118.4	111.4				



Day Hour Summary. Location: College Room Welding Workshop. 3-Phase Between L3-N								Date:26.04.07			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	74.4	76.1	75.2	11.0	54.7	56.5	55.4	20.9	99.7	102.5	100.9
1.3	97.6	100.2	99.5	11.3	63.6	64.2	63.9	21.2	96.3	96.7	96.5
1.6	176.3	199.3	191.3	11.5	70.4	71.4	70.8	21.5	85.4	86.0	85.9
1.9	186.9	191.4	189.9	11.8	100.6	101.5	101.1	21.8	77.8	78.4	78.1
2.2	244.2	249.5	248.7	12.1	111.8	114.0	113.3	22.1	71.5	73.7	72.1
2.5	290.6	304.2	293.9	12.4	122.1	124.2	123.4	22.4	67.2	68.9	67.8
2.8	255.2	259.8	257.7	12.7	130.6	133.1	132.1	22.7	68.3	69.7	69.1
3.1	261.8	266.6	265.8	13.0	131.4	133.7	133.0	23.0	68.0	70.9	69.5
3.3	308.3	336.2	315.3	13.3	115.5	116.6	115.9	23.3	68.7	70.8	69.9
3.6	311.2	333.7	328.5	13.6	113.5	115.0	114.1	23.6	76.7	79.1	77.5
3.9	250.0	265.2	259.0	13.9	128.0	130.2	128.6	23.8	83.6	84.5	84.0
4.2	172.5	176.0	175.3	14.2	136.4	138.6	137.3	24.1	84.5	86.5	85.7
4.5	112.8	113.9	113.5	14.5	117.1	117.6	117.4	24.4	84.1	86.7	85.3
4.8	76.1	76.7	76.5	14.8	98.4	99.3	98.8	24.7	81.8	83.5	82.9
5.1	45.5	46.5	46.0	15.1	80.2	81.0	80.4	25.0	79.0	81.8	79.6
5.4	20.9	21.4	21.1	15.4	67.3	69.4	68.5	25.3	84.4	85.9	85.1
5.7	31.4	32.6	32.2	15.6	68.3	69.2	68.9	25.6	91.2	92.1	91.6
6.0	66.6	67.9	67.4	15.9	70.8	72.1	71.5	25.9	96.0	98.3	96.9
6.3	117.6	120.2	118.4	16.2	68.0	71.0	70.2	26.2	101.3	104.0	102.5
6.6	174.4	181.7	176.5	16.5	62.8	65.4	64.3	26.5	108.1	110.6	109.2
6.9	266.5	269.5	267.1	16.8	58.8	59.1	59.0	26.8	116.1	120.6	117.0
7.2	260.5	266.1	262.2	17.1	63.0	63.9	63.7	27.1	116.4	117.9	116.8
7.4	217.2	225.1	223.0	17.4	69.3	69.9	69.6	27.4	110.2	112.8	112.0
7.7	168.6	173.8	171.4	17.7	76.2	76.6	76.2	27.7	104.8	108.2	106.8
8.0	196.0	198.6	197.9	18.0	96.0	97.4	96.4	27.9	96.8	100.5	99.1
8.3	247.5	247.7	247.6	18.3	109.2	111.2	110.1	28.2	89.2	92.4	91.2
8.6	262.5	266.5	265.4	18.6	99.9	101.2	100.3	28.5	81.7	84.4	83.3
8.9	218.0	224.0	220.3	18.9	84.6	85.7	84.9	28.8	77.4	79.0	78.5
9.2	181.4	184.4	182.3	19.2	75.7	77.4	76.8	29.1	76.7	77.2	76.8
9.5	158.7	160.8	160.2	19.5	71.4	74.8	73.9	29.4	74.6	75.9	75.0
9.8	127.1	128.1	127.6	19.7	65.9	67.8	67.0	29.7	70.6	74.1	71.7
10.1	100.2	101.1	100.7	20.0	64.2	65.3	64.6	30.0	68.8	73.9	70.1
10.4	74.3	75.1	74.7	20.3	71.5	72.9	71.9				
10.7	57.7	59.4	59.0	20.6	87.1	91.0	88.6				

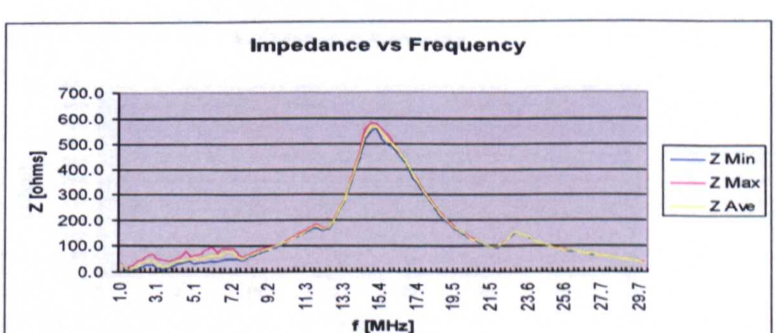


Day Summary. Location: Alfoxton Road Premises , Bridgwater (Lounge)								Date: 22.09.06/23.09.06 (Friday/Saturday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	28.0	35.4	32.0	11.0	200.7	239.6	215.2	20.9	70.7	105.9	79.2
1.3	9.1	13.8	11.0	11.3	205.8	259.4	243.3	21.2	79.5	104.9	83.7
1.6	4.1	6.1	4.6	11.5	190.9	274.4	246.7	21.5	89.7	110.4	91.8
1.9	3.7	5.3	4.7	11.8	159.4	291.5	248.1	21.8	101.0	121.8	103.0
2.2	4.2	11.2	9.0	12.1	125.8	290.8	246.8	22.1	114.1	136.2	116.5
2.5	8.6	17.7	14.9	12.4	98.2	284.3	235.6	22.4	129.0	152.5	132.2
2.8	13.5	25.6	21.9	12.7	76.8	260.5	210.0	22.7	145.6	170.2	150.1
3.1	19.2	35.9	30.6	13.0	59.7	226.1	178.7	23.0	162.2	181.7	167.9
3.3	26.5	52.5	43.4	13.3	47.1	188.4	147.4	23.3	173.8	196.7	181.2
3.6	32.2	49.5	43.2	13.6	36.8	156.7	121.7	23.6	171.4	203.1	181.1
3.9	22.1	28.1	25.7	13.9	28.7	130.5	100.7	23.8	151.5	188.5	162.3
4.2	20.4	26.0	23.4	14.2	23.0	109.6	83.8	24.1	121.9	157.9	131.9
4.5	25.8	32.3	29.9	14.5	19.3	92.2	70.5	24.4	93.8	124.5	102.7
4.8	30.6	37.6	35.3	14.8	17.7	77.7	60.0	24.7	74.9	96.5	81.1
5.1	36.1	45.1	42.0	15.1	18.3	65.7	51.6	25.0	63.4	78.2	69.0
5.4	41.6	51.9	48.9	15.4	21.6	55.0	45.1	25.3	62.5	69.8	64.7
5.7	47.3	59.8	56.0	15.6	26.2	45.8	40.0	25.6	65.5	70.9	66.8
6.0	53.3	68.2	63.8	15.9	31.6	37.7	35.8	25.9	73.0	76.9	73.7
6.3	60.1	77.9	72.7	16.2	30.2	38.0	32.5	26.2	81.8	86.1	83.3
6.6	67.9	89.1	82.9	16.5	24.4	43.6	30.0	26.5	92.9	96.8	94.3
6.9	76.5	101.9	94.1	16.8	19.9	50.1	28.6	26.8	105.2	108.9	106.5
7.2	82.5	112.9	103.7	17.1	17.2	55.7	28.4	27.1	119.1	121.5	120.1
7.4	88.3	123.7	111.3	17.4	16.7	63.3	30.0	27.4	133.4	136.8	134.3
7.7	99.4	141.6	123.0	17.7	16.6	69.5	32.1	27.7	149.0	153.8	150.1
8.0	110.7	161.8	139.5	18.0	18.7	77.3	36.0	27.9	165.8	169.1	167.0
8.3	113.5	165.2	142.8	18.3	22.4	87.4	41.2	28.2	185.4	188.4	186.5
8.6	114.4	157.1	141.6	18.6	27.0	95.8	47.2	28.5	205.8	210.8	207.9
8.9	111.6	135.3	128.9	18.9	32.0	106.5	53.8	28.8	230.3	238.1	231.8
9.2	118.7	133.0	126.5	19.2	36.7	119.0	60.5	29.1	255.2	261.8	257.3
9.5	119.1	142.3	134.8	19.5	41.1	129.5	67.0	29.4	283.1	288.7	285.5
9.8	113.9	143.9	132.4	19.7	45.3	141.1	72.9	29.7	310.4	317.3	313.6
10.1	118.2	156.6	127.5	20.0	50.2	143.5	77.2	30.0	337.7	348.3	344.0
10.4	129.3	184.1	140.3	20.3	56.0	134.5	78.7				
10.7	162.2	220.8	172.9	20.6	62.9	115.3	78.2				

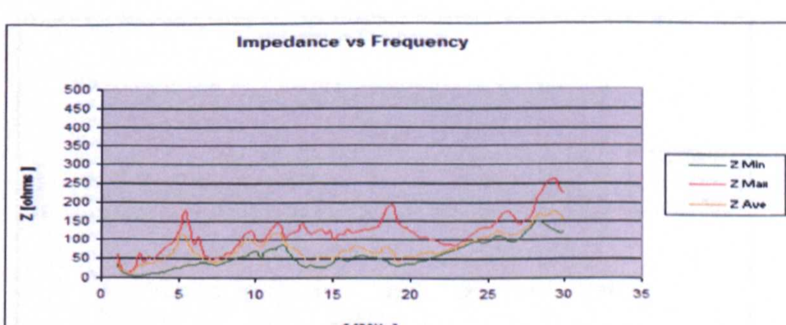


Day Summary. Location: Condell Close Premises, Bridgwater (Lounge) | Date: 18.11.10 (Thursday)

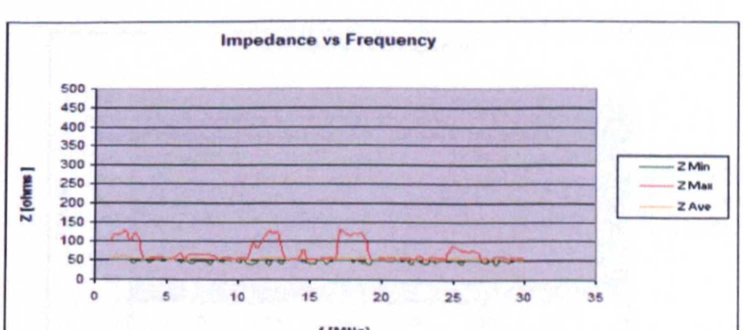
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	24.2	31.7	27.2	11.0	142.8	153.0	146.3	20.9	109.2	114.5	112.0
1.3	10.5	13.8	12.4	11.3	156.0	164.9	160.0	21.2	100.5	104.3	102.9
1.6	5.4	21.1	10.1	11.5	170.4	178.2	174.5	21.5	94.1	97.4	94.6
1.9	9.3	40.9	19.2	11.8	170.0	182.4	177.4	21.8	93.0	98.1	94.2
2.2	17.1	42.0	33.3	12.1	161.7	168.9	166.1	22.1	103.2	107.7	105.5
2.5	25.1	61.1	40.6	12.4	166.9	171.6	168.6	22.4	125.0	128.6	126.7
2.8	26.1	65.1	43.0	12.7	192.8	200.6	196.0	22.7	145.9	148.8	147.5
3.1	14.6	48.1	28.7	13.0	232.8	240.7	236.5	23.0	151.1	153.8	152.6
3.3	9.8	44.5	18.7	13.3	280.5	287.1	283.3	23.3	143.7	146.3	145.1
3.6	15.0	39.4	23.3	13.6	329.2	342.1	336.1	23.6	132.6	134.7	134.0
3.9	20.8	42.3	33.3	13.9	387.5	401.8	393.9	23.8	122.1	124.7	123.4
4.2	29.0	51.7	41.3	14.2	452.5	476.3	463.5	24.1	113.1	115.5	114.2
4.5	35.5	78.3	45.0	14.5	514.7	552.3	527.7	24.4	105.3	107.0	106.3
4.8	40.6	54.7	47.8	14.8	546.3	583.7	564.5	24.7	99.0	100.2	99.7
5.1	29.9	62.5	50.6	15.1	554.0	577.2	562.8	25.0	91.9	94.6	93.9
5.4	36.7	64.3	49.9	15.4	520.5	558.5	540.4	25.3	87.9	89.5	89.0
5.7	34.5	82.4	52.4	15.6	500.1	536.9	517.7	25.6	83.7	86.1	85.3
6.0	41.4	94.2	59.6	15.9	490.1	510.6	502.0	25.9	80.6	82.9	82.2
6.3	37.2	70.2	62.7	16.2	464.4	478.2	476.5	26.2	77.5	79.4	78.8
6.6	42.1	87.6	67.3	16.5	438.6	453.2	451.0	26.5	74.0	75.5	75.1
6.9	48.2	87.6	76.6	16.8	416.4	419.5	418.2	26.8	70.6	72.1	71.6
7.2	49.5	88.8	73.6	17.1	364.9	382.6	379.9	27.1	67.0	69.0	68.5
7.4	48.5	63.8	57.0	17.4	337.3	350.7	346.7	27.4	64.2	66.0	65.5
7.7	44.1	55.3	48.5	17.7	308.0	319.2	315.3	27.7	62.4	62.9	62.7
8.0	56.8	65.5	59.8	18.0	278.7	290.1	283.7	27.9	59.1	60.6	59.6
8.3	63.0	74.0	65.5	18.3	250.2	259.8	255.6	28.2	55.0	57.7	56.1
8.6	69.3	83.5	73.0	18.6	225.2	234.3	231.2	28.5	51.3	53.8	52.3
8.9	80.8	90.7	84.1	18.9	201.8	211.6	209.0	28.8	48.5	49.8	49.2
9.2	85.8	96.0	89.1	19.2	182.4	190.5	188.0	29.1	46.3	47.5	47.2
9.5	91.6	100.1	94.1	19.5	166.6	171.2	169.9	29.4	43.5	45.0	44.6
9.8	100.4	107.2	103.3	19.7	154.0	158.1	155.6	29.7	38.2	41.5	40.5
10.1	110.6	116.9	113.8	20.0	140.5	148.1	143.3	30.0	36.2	37.5	36.8
10.4	125.6	130.8	128.6	20.3	129.2	135.3	131.1				
10.7	136.1	145.4	138.2	20.6	117.9	121.7	121.0				



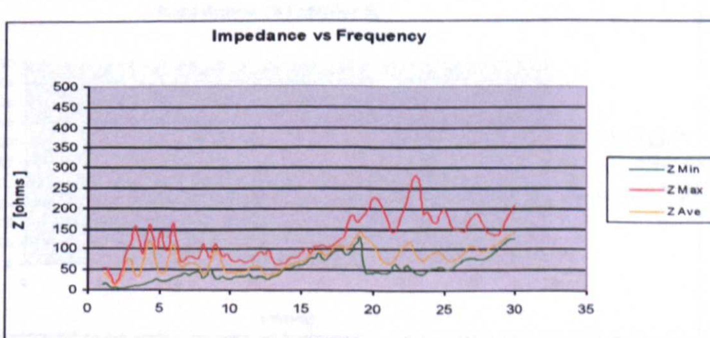
Day Summary. Location: Meadowlands Avenue Premises, Bridgwater (Lounge)								Date : 01.02.11 (Tuesday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	33.5	59.6	41.4	11.0	75.7	128.7	111.4	20.9	45.8	105.4	64.6
1.3	14.7	19.4	16.7	11.3	76.9	142.7	116.4	21.2	50.7	102.5	67.3
1.6	8.0	12.3	10.4	11.5	83.2	136.6	114.9	21.5	55.6	100.3	65.6
1.9	5.4	14.7	10.9	11.8	85.5	107.9	95.8	21.8	60.3	95.6	65.9
2.2	3.9	26.1	19.6	12.1	63.2	115.2	80.6	22.1	63.4	88.1	68.0
2.5	3.7	61.4	31.0	12.4	49.2	120.7	76.6	22.4	67.5	88.0	73.8
2.8	5.3	40.2	31.8	12.7	41.1	123.3	69.2	22.7	71.0	88.3	76.0
3.1	7.8	53.3	37.4	13.0	32.0	143.3	56.9	23.0	74.6	84.8	77.1
3.3	10.2	47.8	37.9	13.3	29.2	127.5	47.1	23.3	78.8	92.8	81.2
3.6	12.4	55.0	43.2	13.6	32.6	115.6	43.8	23.6	84.8	98.4	87.3
3.9	14.9	69.0	45.8	13.9	29.5	120.0	46.9	23.8	91.3	108.3	94.6
4.2	18.2	84.3	56.0	14.2	27.2	125.4	54.0	24.1	95.9	120.9	101.2
4.5	21.5	89.2	62.2	14.5	28.3	115.6	53.2	24.4	96.6	128.1	102.8
4.8	24.2	109.2	80.1	14.8	33.9	123.2	52.5	24.7	93.7	133.3	106.4
5.1	26.5	133.1	115.5	15.1	43.0	97.0	51.4	25.0	96.5	132.1	110.1
5.4	29.9	175.8	109.4	15.4	53.4	113.9	62.6	25.3	102.0	135.2	114.2
5.7	33.0	131.6	81.3	15.6	48.4	116.3	69.2	25.6	109.5	146.2	120.2
6.0	33.9	86.1	63.8	15.9	42.9	127.1	71.1	25.9	109.6	163.3	120.6
6.3	35.8	110.0	60.3	16.2	46.6	119.2	75.8	26.2	102.7	175.1	114.6
6.6	38.2	65.4	53.3	16.5	56.9	122.0	83.5	26.5	96.9	170.4	112.3
6.9	37.8	52.2	46.3	16.8	57.9	123.0	80.0	26.8	95.5	157.7	112.7
7.2	36.1	49.2	41.5	17.1	55.9	127.1	73.1	27.1	102.2	141.8	115.1
7.4	29.6	49.5	39.1	17.4	54.0	125.4	67.1	27.4	114.7	148.1	125.9
7.7	37.1	54.1	43.9	17.7	53.2	132.2	65.0	27.7	130.0	156.6	136.4
8.0	42.1	64.5	50.6	18.0	51.5	141.5	66.0	27.9	144.3	184.0	152.6
8.3	45.8	65.3	57.6	18.3	48.9	166.5	80.9	28.2	149.7	213.8	164.6
8.6	49.8	78.5	65.4	18.6	41.8	188.1	79.9	28.5	144.9	231.4	162.9
8.9	53.9	93.1	78.9	18.9	33.0	191.2	67.4	28.8	136.8	250.6	163.5
9.2	57.3	112.9	96.9	19.2	29.8	150.1	43.2	29.1	130.1	257.2	171.5
9.5	59.6	120.8	103.5	19.5	33.7	135.9	50.8	29.4	122.8	260.7	173.0
9.8	68.0	120.1	94.4	19.7	36.6	130.9	55.7	29.7	117.9	235.1	164.1
10.1	69.2	97.3	83.9	20.0	36.2	119.6	55.4	30.0	122.0	223.0	150.0
10.4	53.6	95.2	82.7	20.3	37.7	119.4	54.2				
10.7	71.3	107.8	95.9	20.6	41.5	106.6	61.6				



Day Summary. Location: Meadowlands Avenue premises -Lounge (no power - all socket off)								Date: 09.02.12 & 10.02.12			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	50.8	98.0	54.3	11.0	40.3	94.8	53.3	20.9	50.5	54.1	52.1
1.3	50.8	119.0	57.4	11.3	45.9	85.5	53.0	21.2	51.0	55.8	52.2
1.6	50.8	118.3	57.2	11.5	49.7	95.2	53.9	21.5	48.1	55.3	52.1
1.9	50.7	119.7	60.2	11.8	49.4	111.6	54.8	21.8	50.9	55.2	52.3
2.2	49.7	127.0	55.1	12.1	35.6	125.6	54.5	22.1	42.0	53.5	51.1
2.5	49.7	101.4	54.0	12.4	49.7	119.9	55.0	22.4	50.9	53.5	51.9
2.8	40.9	120.7	54.4	12.7	50.6	124.4	55.2	22.7	47.4	62.4	53.4
3.1	49.0	109.2	54.5	13.0	42.7	85.2	53.2	23.0	42.8	54.0	51.7
3.3	49.4	54.9	52.1	13.3	50.7	54.0	52.1	23.3	41.9	54.0	50.8
3.6	48.1	54.5	52.1	13.6	50.8	53.6	52.0	23.6	50.1	57.6	52.3
3.9	46.1	55.7	52.1	13.9	50.1	53.7	51.7	23.8	45.8	56.7	51.6
4.2	49.5	55.7	52.2	14.2	50.9	57.5	52.3	24.1	49.7	56.7	52.4
4.5	50.7	55.3	52.3	14.5	48.0	78.4	55.0	24.4	49.4	57.3	52.4
4.8	48.5	54.3	52.1	14.8	43.6	54.0	51.4	24.7	46.7	76.6	53.9
5.1	50.8	53.7	52.1	15.1	42.4	53.9	51.5	25.0	50.3	87.5	55.4
5.4	50.5	54.1	51.9	15.4	42.0	54.7	51.1	25.3	51.1	82.1	54.9
5.7	50.6	57.7	52.1	15.6	49.9	54.4	52.2	25.6	43.3	76.0	53.8
6.0	45.4	67.6	53.6	15.9	49.5	56.5	52.3	25.9	50.5	75.9	53.9
6.3	47.2	53.2	51.9	16.2	41.9	53.6	51.5	26.2	50.3	72.3	53.7
6.6	44.7	64.3	51.5	16.5	47.3	55.2	52.0	26.5	49.7	77.2	53.9
6.9	42.6	65.1	52.2	16.8	50.7	53.6	52.1	26.8	51.0	70.1	55.0
7.2	48.5	65.1	52.7	17.1	50.9	130.3	55.5	27.1	48.1	53.5	51.8
7.4	47.6	65.3	52.4	17.4	50.4	122.6	55.0	27.4	46.1	56.2	51.1
7.7	45.5	63.3	52.4	17.7	50.6	116.0	54.7	27.7	50.2	53.0	52.1
8.0	40.7	61.2	52.0	18.0	46.0	122.0	54.3	27.9	40.6	59.6	50.9
8.3	49.9	62.2	52.5	18.3	50.9	117.1	54.6	28.2	47.4	55.0	52.2
8.6	50.9	53.8	52.2	18.6	44.4	120.4	56.9	28.5	49.5	57.7	52.4
8.9	45.8	55.3	52.1	18.9	44.4	104.5	53.5	28.8	46.0	54.7	51.7
9.2	50.8	55.3	52.4	19.2	40.3	57.7	51.3	29.1	48.8	55.0	52.1
9.5	47.5	55.4	52.0	19.5	49.8	53.6	52.2	29.4	50.5	53.4	52.2
9.8	50.9	54.0	52.0	19.7	49.4	53.7	52.1	29.7	50.6	56.2	52.3
10.1	45.9	54.9	51.8	20.0	49.5	55.3	52.3	30.0	49.9	53.7	52.0
10.4	50.7	56.9	52.6	20.3	49.8	53.7	52.2				
10.7	41.0	53.9	50.4	20.6	48.1	56.0	51.9				

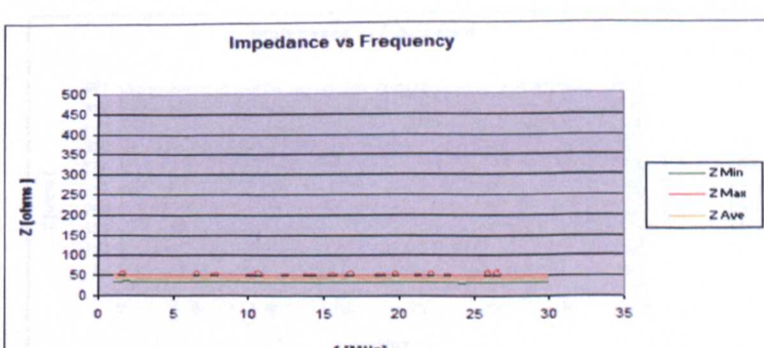


Day Summary. Location: Meadowlands Avenue Premises, Bridgwater (Bed Room 3)								Date: 02.07.11 (Saturday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	13.5	53.0	39.2	11.0	35.0	68.5	45.3	20.9	42.2	174.0	65.3
1.3	17.4	52.4	39.3	11.3	39.6	70.2	49.7	21.2	50.9	144.7	65.6
1.6	6.5	34.2	25.0	11.5	32.0	72.4	57.1	21.5	65.0	143.5	75.7
1.9	5.7	13.6	11.1	11.8	29.8	83.3	58.9	21.8	57.4	161.2	90.9
2.2	3.6	28.1	21.8	12.1	34.9	93.1	53.5	22.1	49.9	187.1	104.7
2.5	3.6	52.1	35.9	12.4	30.0	86.4	40.4	22.4	62.4	218.6	111.1
2.8	5.6	93.9	69.3	12.7	28.1	95.5	35.9	22.7	54.3	254.2	116.9
3.1	8.3	111.2	74.1	13.0	33.3	70.4	39.1	23.0	44.6	280.4	91.9
3.3	11.1	155.9	36.5	13.3	37.4	60.7	41.3	23.3	38.4	272.1	77.8
3.6	12.3	123.2	34.5	13.6	43.3	64.1	47.7	23.6	40.2	186.3	69.9
3.9	15.2	86.9	66.5	13.9	52.1	65.5	56.4	23.8	48.2	192.3	82.1
4.2	19.1	160.4	119.0	14.2	54.4	77.9	63.0	24.1	54.0	164.9	91.0
4.5	23.6	129.8	107.2	14.5	58.0	79.4	67.1	24.4	52.1	165.1	95.2
4.8	27.4	98.3	55.5	14.8	63.2	81.3	68.6	24.7	55.6	187.4	92.9
5.1	23.5	146.4	38.5	15.1	61.0	93.6	69.2	25.0	53.8	198.5	80.9
5.4	22.6	95.0	41.1	15.4	66.9	100.7	74.9	25.3	51.8	177.2	72.3
5.7	26.1	98.3	78.1	15.6	79.9	89.7	85.7	25.6	54.4	150.6	68.8
6.0	29.8	165.8	110.8	15.9	79.7	105.7	98.2	25.9	61.5	149.9	74.7
6.3	34.1	115.4	90.0	16.2	90.4	106.9	99.1	26.2	68.5	145.5	84.1
6.6	37.1	66.2	56.1	16.5	77.2	109.8	87.6	26.5	74.7	144.8	92.2
6.9	41.8	72.2	62.3	16.8	76.6	104.4	83.5	26.8	78.3	168.0	106.0
7.2	36.9	80.3	65.0	17.1	86.7	107.0	92.2	27.1	78.2	180.2	108.1
7.4	40.9	79.1	63.3	17.4	94.4	115.1	107.7	27.4	76.0	184.7	100.9
7.7	44.7	77.4	55.3	17.7	97.7	127.7	110.5	27.7	75.0	159.5	93.7
8.0	30.9	111.4	41.7	18.0	89.2	135.5	101.6	27.9	77.8	142.9	97.8
8.3	35.5	93.9	43.3	18.3	87.7	170.0	105.2	28.2	84.2	136.5	104.2
8.6	49.2	78.4	70.5	18.6	97.3	181.6	118.0	28.5	92.1	135.7	109.5
8.9	29.7	113.0	97.6	18.9	118.5	166.9	135.3	28.8	101.5	135.8	114.8
9.2	27.4	99.6	86.1	19.2	128.8	173.8	142.7	29.1	111.7	151.9	122.3
9.5	34.2	80.8	59.3	19.5	46.4	185.7	130.6	29.4	120.6	172.8	131.2
9.8	29.5	86.7	42.4	19.7	42.9	202.2	122.7	29.7	125.5	193.6	136.4
10.1	27.4	73.2	41.4	20.0	43.1	224.2	112.1	30.0	125.9	206.5	140.7
10.4	34.0	68.5	42.3	20.3	46.2	223.9	95.9				
10.7	33.6	72.4	44.8	20.6	42.3	206.9	74.1				

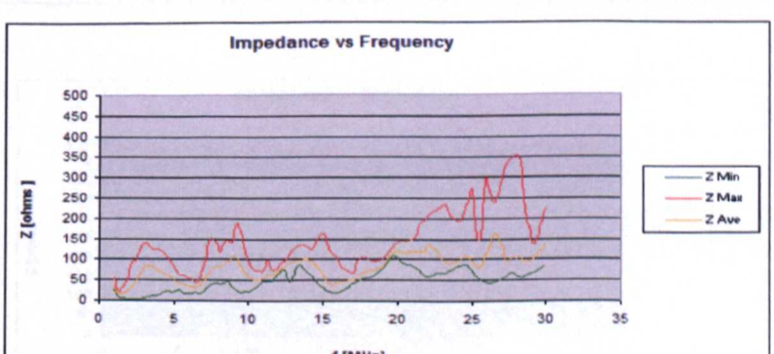


Day Summary. Location: Meadowlands Avenue premises Bedroon-3 with no power | Date:06.07.11 (Wednesday)

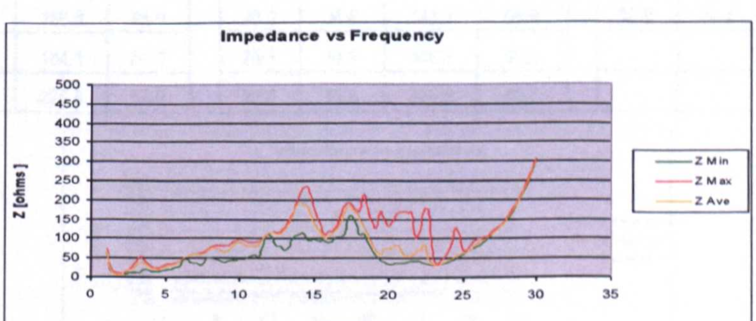
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	34.4	51.1	42.9	11.0	34.0	51.0	43.3	20.9	33.9	52.0	42.5
1.3	34.4	51.1	42.9	11.3	33.8	50.8	43.2	21.2	33.4	52.0	42.5
1.6	34.4	58.1	43.6	11.5	34.0	51.3	43.3	21.5	34.5	51.1	42.6
1.9	36.1	51.7	43.5	11.8	32.7	51.3	43.3	21.8	33.3	51.0	42.8
2.2	34.2	51.9	43.6	12.1	32.9	51.9	43.2	22.1	34.2	60.9	43.4
2.5	34.1	51.0	43.3	12.4	33.7	54.3	43.1	22.4	34.5	51.3	43.1
2.8	34.5	51.1	43.3	12.7	32.7	51.3	43.0	22.7	33.8	51.7	43.3
3.1	34.4	50.9	43.3	13.0	33.4	51.3	42.7	23.0	33.9	51.6	43.4
3.3	33.9	51.0	43.2	13.3	32.9	51.1	42.6	23.3	33.9	52.3	43.3
3.6	33.9	50.9	43.0	13.6	34.4	51.1	42.7	23.6	33.6	51.6	43.3
3.9	33.3	51.0	42.8	13.9	33.7	52.0	43.1	23.8	32.4	51.1	43.3
4.2	33.8	51.1	42.8	14.2	34.2	52.4	42.9	24.1	31.9	51.1	43.4
4.5	34.7	51.1	43.0	14.5	34.8	52.0	43.0	24.4	34.1	51.0	43.4
4.8	34.6	51.4	43.0	14.8	34.0	51.2	43.4	24.7	32.5	50.9	43.0
5.1	34.3	51.4	42.7	15.1	32.8	51.0	43.2	25.0	33.6	51.1	42.7
5.4	34.1	51.5	42.9	15.4	32.6	53.6	43.4	25.3	33.5	51.1	42.3
5.7	33.8	51.7	43.2	15.6	34.0	56.6	43.6	25.6	33.3	51.2	42.3
6.0	34.4	51.7	43.1	15.9	34.0	51.0	43.7	25.9	35.0	65.4	43.9
6.3	34.6	51.7	43.3	16.2	32.9	51.5	43.2	26.2	33.4	51.9	43.2
6.6	34.1	62.5	43.8	16.5	33.5	52.0	43.0	26.5	34.2	65.3	43.7
6.9	34.4	50.9	43.3	16.8	33.9	61.7	43.9	26.8	34.2	53.2	43.2
7.2	34.6	51.0	43.5	17.1	34.0	51.6	42.7	27.1	34.6	51.6	43.2
7.4	34.2	51.1	43.5	17.4	34.6	50.8	42.6	27.4	34.9	51.6	43.2
7.7	33.8	55.9	43.8	17.7	34.3	50.9	42.8	27.7	33.7	50.9	43.1
8.0	33.6	51.1	42.8	18.0	34.1	51.4	42.6	27.9	33.8	50.9	43.3
8.3	32.8	51.5	42.6	18.3	34.6	51.7	42.9	28.2	34.0	51.3	43.5
8.6	34.4	51.2	42.5	18.6	34.8	52.5	43.1	28.5	32.6	51.8	43.6
8.9	34.4	51.2	42.8	18.9	34.7	52.2	43.5	28.8	32.4	51.5	43.3
9.2	34.3	51.0	42.9	19.2	34.7	51.6	43.3	29.1	32.4	51.4	43.0
9.5	34.4	50.6	42.8	19.5	33.3	51.4	43.3	29.4	33.7	50.8	42.6
9.8	34.2	51.6	43.1	19.7	34.2	61.9	44.1	29.7	33.9	51.0	42.7
10.1	34.5	52.4	43.1	20.0	34.9	51.0	43.5	30.0	34.0	51.0	42.6
10.4	34.5	52.6	43.2	20.3	34.0	51.1	43.4				
10.7	34.3	61.9	44.1	20.6	33.4	51.3	43.1				



Day Summary. Location: Meadow lands Avenue premises - Kitchen								Date: 04.07.11(Monday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	25.5	54.5	35.1	11.0	48.7	72.7	54.5	20.9	84.6	149.9	118.4
1.3	8.5	18.9	14.2	11.3	48.3	98.5	61.7	21.2	79.6	158.1	118.2
1.6	6.4	29.5	15.7	11.5	47.4	74.6	63.0	21.5	72.5	187.1	116.7
1.9	4.1	47.6	19.5	11.8	57.8	76.6	67.5	21.8	62.3	194.1	117.6
2.2	3.4	93.8	32.2	12.1	69.8	88.5	76.1	22.1	58.4	207.7	133.5
2.5	3.6	94.7	46.0	12.4	74.9	96.7	85.0	22.4	60.9	216.3	127.2
2.8	4.0	118.9	61.8	12.7	48.4	108.3	89.1	22.7	66.2	223.0	121.2
3.1	6.8	137.0	78.0	13.0	58.1	123.4	95.4	23.0	67.7	226.6	100.9
3.3	8.0	136.2	83.2	13.3	83.1	131.1	99.2	23.3	68.6	234.2	94.3
3.6	10.2	123.7	85.2	13.6	83.3	135.3	98.7	23.6	73.6	207.7	87.7
3.9	12.2	122.8	72.8	13.9	72.4	133.3	100.1	23.8	77.3	198.1	91.9
4.2	20.8	118.0	67.2	14.2	61.6	122.7	96.0	24.1	84.3	194.7	99.7
4.5	23.9	105.8	62.0	14.5	50.7	139.2	86.7	24.4	87.3	214.4	106.1
4.8	21.0	92.1	55.6	14.8	37.4	156.8	72.5	24.7	83.9	241.9	107.9
5.1	22.1	77.0	47.1	15.1	30.0	164.0	59.4	25.0	74.2	270.5	96.4
5.4	24.8	62.3	40.3	15.4	23.3	130.5	42.9	25.3	59.9	152.6	80.8
5.7	17.9	61.2	38.5	15.6	19.7	112.2	37.7	25.6	49.7	151.0	81.6
6.0	17.1	53.4	32.6	15.9	19.5	102.6	41.3	25.9	44.1	294.2	105.8
6.3	17.9	51.8	31.7	16.2	23.5	84.6	44.0	26.2	41.7	265.2	
6.6	19.0	41.6	31.8	16.5	29.1	75.5	48.0	26.5	43.6	239.9	160.3
6.9	18.1	62.8	36.7	16.8	35.0	70.3	49.6	26.8	47.6	257.9	156.0
7.2	25.0	98.6	50.1	17.1	41.2	67.3	51.3	27.1	52.7	294.7	130.9
7.4	36.9	149.6	68.9	17.4	47.0	98.8	58.7	27.4	59.2	330.4	96.8
7.7	41.5	144.0	81.0	17.7	52.4	103.3	66.2	27.7	67.1	349.4	104.0
8.0	39.5	117.3	82.4	18.0	57.2	101.7	72.2	27.9	60.5	354.8	100.7
8.3	42.8	138.2	88.5	18.3	58.1	96.8	72.4	28.2	56.8	342.0	102.6
8.6	47.0	147.4	92.9	18.6	66.2	94.8	75.2	28.5	58.3	215.6	92.2
8.9	34.8	141.1	103.1	18.9	74.9	99.5	80.4	28.8	63.3	178.7	94.6
9.2	25.4	188.7	104.8	19.2	85.5	103.8	90.1	29.1	68.3	138.2	100.5
9.5	20.6	168.0	84.3	19.5	98.4	117.4	103.0	29.4	73.1	154.3	112.3
9.8	21.4	121.0	67.4	19.7	108.8	129.0	114.6	29.7	78.6	194.0	124.7
10.1	21.6	93.3	56.2	20.0	104.1	139.8	117.5	30.0	85.4	224.9	137.0
10.4	29.0	76.8	50.9	20.3	92.9	146.3	115.2				
10.7	37.8	74.1	51.6	20.6	86.8	142.0	114.4				

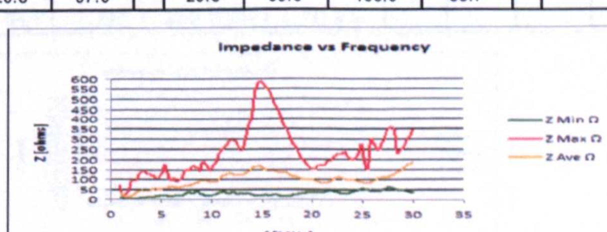


Day Summary. Location: Redbridge Lane East, Ilford (Lounge)								Date : 20.11.10/21.11.10 (Saturday/Sunday)			
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	65.3	71.7	68.1	11.0	57.9	90.1	78.7	20.9	36.8	167.9	56.8
1.3	14.9	18.9	15.6	11.3	54.2	94.1	88.3	21.2	39.1	166.0	54.9
1.6	5.5	12.6	6.1	11.5	83.9	101.9	100.0	21.5	41.0	168.6	52.1
1.9	5.0	9.6	5.5	11.8	111.6	112.8	112.5	21.8	42.3	101.2	63.2
2.2	8.3	9.7	9.5	12.1	102.6	117.7	116.8	22.1	41.5	121.2	70.2
2.5	9.1	17.2	16.2	12.4	82.8	115.8	112.5	22.4	37.0	175.9	83.7
2.8	10.6	26.4	20.4	12.7	80.3	117.7	113.5	22.7	33.6	173.9	49.2
3.1	11.0	38.5	28.3	13.0	70.1	128.6	123.2	23.0	30.7	56.8	32.7
3.3	11.8	52.3	36.3	13.3	79.4	147.6	141.5	23.3	30.6	34.5	31.5
3.6	18.6	41.4	33.4	13.6	104.6	169.8	165.9	23.6	33.3	44.1	34.5
3.9	16.8	30.5	26.6	13.9	108.8	199.5	189.2	23.8	37.3	52.9	39.4
4.2	12.7	23.4	21.6	14.2	114.7	229.7	189.0	24.1	42.5	81.0	45.7
4.5	13.9	23.8	20.3	14.5	97.5	232.2	181.8	24.4	48.1	125.8	53.6
4.8	15.7	28.9	24.6	14.8	94.3	206.0	157.8	24.7	54.1	113.1	59.7
5.1	18.9	33.1	28.1	15.1	98.3	167.0	131.6	25.0	60.2	68.5	62.7
5.4	19.2	34.3	30.4	15.4	92.9	136.5	118.5	25.3	66.2	72.7	68.6
5.7	24.1	36.4	35.0	15.6	94.3	108.8	101.9	25.6	72.4	85.9	74.4
6.0	26.8	42.9	41.6	15.9	89.4	117.9	104.6	25.9	78.5	98.9	84.0
6.3	48.6	50.5	49.7	16.2	93.8	118.4	111.9	26.2	83.5	101.6	91.7
6.6	45.7	56.9	55.7	16.5	104.6	132.9	123.1	26.5	92.3	103.6	97.6
6.9	37.3	60.1	57.8	16.8	105.3	162.5	142.0	26.8	101.6	106.7	104.4
7.2	35.6	59.8	57.7	17.1	113.2	184.5	170.3	27.1	111.2	116.8	113.5
7.4	32.1	62.5	59.6	17.4	159.9	190.5	181.9	27.4	122.4	127.2	123.5
7.7	50.6	70.9	68.6	17.7	142.3	174.7	168.8	27.7	134.6	137.4	136.2
8.0	49.7	78.0	75.5	18.0	110.2	170.4	147.8	27.9	148.7	153.8	150.9
8.3	49.1	81.5	71.9	18.3	111.7	212.7	130.2	28.2	164.1	170.8	166.3
8.6	44.7	81.3	69.0	18.6	90.7	170.7	105.9	28.5	180.6	184.5	182.6
8.9	40.1	80.3	64.4	18.9	70.0	141.8	85.4	28.8	201.0	203.7	202.0
9.2	41.3	82.9	66.8	19.2	56.2	125.8	67.9	29.1	223.1	226.2	224.9
9.5	46.2	89.0	78.1	19.5	45.5	170.9	59.1	29.4	245.5	255.2	249.4
9.8	44.8	95.9	89.1	19.7	40.6	146.2	72.7	29.7	272.7	279.1	274.4
10.1	46.6	97.2	86.7	20.0	34.6	132.6	72.8	30.0	300.4	306.8	301.8
10.4	48.1	93.9	80.7	20.3	34.9	146.8	78.5				
10.7	53.3	90.1	78.3	20.6	35.6	166.0	82.9				

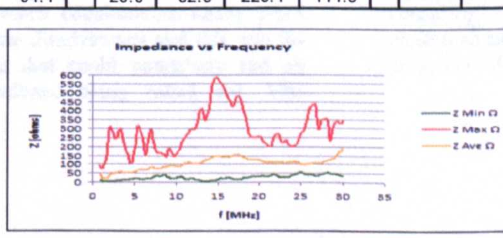


Aggregate impedance measurements of all residential houses in Somerset and London.

Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	13.5	71.7	40.5	11.0	35.0	239.6	108.6	20.9	36.8	167.9	82.7
1.3	8.5	19.4	18.2	11.3	39.6	259.4	119.9	21.2	39.1	166.0	82.1
1.6	4.1	29.5	12.0	11.5	32.0	274.4	126.0	21.5	41.0	187.1	82.8
1.9	3.7	47.6	11.8	11.8	29.8	291.5	126.7	21.8	42.3	194.1	89.1
2.2	3.4	93.8	20.9	12.1	34.9	290.8	123.3	22.1	41.5	207.7	99.8
2.5	3.6	94.7	30.8	12.4	30.0	284.3	119.8	22.4	37.0	216.3	109.1
2.8	4.0	118.9	41.4	12.7	28.1	260.5	118.9	22.7	33.6	223.0	110.2
3.1	6.8	137.0	46.2	13.0	32.0	240.7	121.6	23.0	30.7	226.6	103.8
3.3	8.0	136.2	42.7	13.3	29.2	287.1	126.6	23.3	30.6	234.2	101.8
3.6	10.2	123.7	43.8	13.6	32.6	342.1	135.7	23.6	33.3	207.7	99.1
3.9	12.2	122.8	45.1	13.9	28.7	401.8	147.9	23.8	37.3	198.1	99.0
4.2	12.7	118.0	54.8	14.2	23.0	476.3	158.2	24.1	42.5	194.7	97.3
4.5	13.9	105.8	54.4	14.5	19.3	552.3	164.5	24.4	48.1	214.4	94.4
4.8	15.7	109.2	49.8	14.8	17.7	583.7	162.6	24.7	54.1	241.9	91.3
5.1	18.9	133.1	53.6	15.1	18.3	577.2	154.3	25.0	53.8	270.5	85.5
5.4	19.2	175.8	53.3	15.4	21.6	558.5	147.4	25.3	51.8	152.6	81.6
5.7	17.9	131.6	56.9	15.6	19.7	536.9	142.0	25.6	49.7	151.0	82.9
6.0	17.1	94.2	62.0	15.9	19.5	510.6	142.2	25.9	44.1	294.2	90.2
6.3	17.9	110.0	61.2	16.2	23.5	478.2	140.0	26.2	41.7	265.2	97.6
6.6	19.0	89.1	57.9	16.5	24.4	453.2	137.2	26.5	43.6	239.9	105.3
6.9	18.1	101.9	62.3	16.8	19.9	419.5	133.7	26.8	47.6	257.9	109.5
7.2	25.0	112.9	65.3	17.1	17.2	382.6	132.5	27.1	52.7	294.7	109.4
7.4	29.6	149.6	66.5	17.4	16.7	350.7	132.0	27.4	59.2	330.4	107.8
7.7	37.1	144.0	70.0	17.7	16.6	319.2	126.3	27.7	62.4	349.4	113.8
8.0	30.9	161.8	74.9	18.0	18.7	290.1	117.9	27.9	59.1	354.8	121.4
8.3	35.5	165.2	78.3	18.3	22.4	259.8	114.2	28.2	55.0	342.0	130.0
8.6	44.7	157.1	85.4	18.6	27.0	234.3	109.6	28.5	51.3	231.4	134.5
8.9	29.7	141.1	92.8	18.9	32.0	211.6	105.2	28.8	48.5	250.6	142.6
9.2	25.4	188.7	95.0	19.2	29.8	190.5	98.7	29.1	46.3	261.8	153.9
9.5	20.6	168.0	92.4	19.5	33.7	171.2	96.7	29.4	43.5	288.7	166.0
9.8	21.4	143.9	88.2	19.7	36.6	158.1	99.0	29.7	38.2	317.3	175.6
10.1	21.6	156.6	84.9	20.0	34.6	148.1	96.4	30.0	36.2	348.3	185.1
10.4	29.0	184.1	87.6	20.3	34.9	146.8	92.3				
10.7	33.6	220.8	97.0	20.6	35.6	166.0	88.7				



Aggregate impedance measurements of all college buildings and residential houses measurements											
Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave	Freq	Z Min	Z Max	Z Ave
MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω	MHz	Ω	Ω	Ω
1.0	13.5	90.5	41.2	11.0	23.0	239.6	102.3	20.9	31.5	211.1	107.7
1.3	8.5	73.1	20.9	11.3	16.7	259.4	106.0	21.2	33.8	197.2	107.7
1.6	3.2	115.4	19.8	11.5	15.7	274.4	107.5	21.5	38.0	199.0	107.4
1.9	3.7	191.5	24.2	11.8	19.6	291.5	103.4	21.8	42.0	256.9	108.3
2.2	3.2	309.4	38.1	12.1	17.6	290.8	101.5	22.1	38.4	267.2	107.7
2.5	3.4	278.0	47.4	12.4	13.5	298.1	101.0	22.4	29.6	263.5	108.9
2.8	3.7	242.7	51.9	12.7	10.8	349.0	101.8	22.7	26.2	223.0	108.0
3.1	6.0	248.0	53.7	13.0	7.8	408.8	108.3	23.0	25.7	226.6	105.1
3.3	8.0	300.5	54.7	13.3	5.8	393.6	115.5	23.3	26.8	234.2	106.3
3.6	10.2	240.7	50.9	13.6	5.7	342.1	119.2	23.6	31.7	207.7	108.3
3.9	12.2	204.3	49.5	13.9	5.7	401.8	127.3	23.8	37.3	198.5	110.6
4.2	12.7	155.2	51.4	14.2	7.0	476.3	134.8	24.1	42.5	199.5	112.1
4.5	13.9	105.8	50.3	14.5	9.7	552.3	142.9	24.4	48.1	215.0	110.8
4.8	15.7	109.2	50.6	14.8	13.3	583.7	145.7	24.7	54.1	241.9	107.9
5.1	18.9	206.7	59.9	15.1	17.3	577.2	145.2	25.0	53.8	270.5	102.0
5.4	19.2	316.7	68.0	15.4	21.6	558.5	143.3	25.3	50.2	285.8	99.1
5.7	17.9	302.0	65.5	15.6	19.7	536.9	141.1	25.6	44.0	329.0	98.9
6.0	17.1	258.5	65.1	15.9	19.5	510.6	139.8	25.9	43.1	378.3	101.6
6.3	17.9	195.3	66.5	16.2	23.5	478.2	140.5	26.2	41.7	423.6	102.1
6.6	19.0	155.2	66.6	16.5	24.4	453.2	142.6	26.5	43.5	437.0	104.6
6.9	18.1	275.5	76.8	16.8	19.9	419.5	147.3	26.8	35.7	436.9	106.1
7.2	25.0	294.8	83.0	17.1	17.2	445.7	154.6	27.1	39.5	294.7	106.8
7.4	29.6	220.0	78.1	17.4	16.7	482.7	157.6	27.4	45.6	352.4	105.8
7.7	37.1	166.4	73.2	17.7	16.6	473.0	153.0	27.7	46.6	349.4	113.0
8.0	30.9	161.8	74.5	18.0	18.7	431.9	143.5	27.9	52.8	354.8	116.8
8.3	35.5	165.2	76.8	18.3	22.4	369.7	134.7	28.2	55.0	342.0	123.3
8.6	43.1	157.1	80.1	18.6	27.0	311.1	128.5	28.5	51.3	231.4	127.8
8.9	29.7	141.1	85.2	18.9	28.7	266.1	124.8	28.8	48.5	319.9	137.2
9.2	25.4	188.7	89.4	19.2	29.8	248.0	123.6	29.1	46.3	340.3	149.2
9.5	20.6	168.0	89.0	19.5	32.3	249.3	124.3	29.4	43.5	337.9	163.4
9.8	21.4	143.9	88.5	19.7	30.1	249.2	123.9	29.7	38.2	326.0	177.0
10.1	21.6	156.6	85.5	20.0	30.3	252.0	119.2	30.0	36.2	348.3	188.0
10.4	29.0	184.1	87.5	20.3	33.4	232.4	115.1				
10.7	32.6	220.8	94.1	20.6	32.9	223.1	111.5				



Appendix 2 – Published paper

Evaluation of Key Parameters for Determining the Efficiency of Signal Propagation in Broadband PLT Systems

Ray Brannon, Tan Haq, John Newbury, Kerry Morris, Fraser Robertson, Lister Wills, Iain Summers,

The Open University, Power Communications Systems Research Group

Email: j.e.newbury@open.ac.uk

Abstract

The key considerations for developing and delivering a full International standard for Broadband power line communications and other wire-line systems of XDSL and cable modem systems is well overdue. This is due to standards committees throughout the World discussing, determining and evaluating the key conditions responsible for signal propagation along the low voltage distribution cable (LVDN) and considering other parameters and the quality of cables used for this type of communication. This paper gives some insight into the work of the committees the problems they are debating and the way to evaluate cardinal parameters to establish a seamless communication system for wire-line communications systems.

Towards Standardisation

Some ten years has passed since the first investigations and experimental trials for Broadband PLT systems in different parts of the World. The key to these experiments of transmitting and receiving data over the LVDN in the frequency range from 1.6 MHz to 30 MHz were limited to establishing the throughput of the data from the transmitter (Modem) to the receiving end (Modem).The results of these initial experiments were encouraging in so far that data rates of 1Mbit/second and higher were transmitted and received efficiently for both underground and overhead electrical systems.

The results of data transmission rates were very encouraging and acted as a catalyst for other organisations to become involved including vendors, manufacturers and utilities. In addition national and international consortia were formed principally to allow easy access to the utility companies who control the LVDN. With these advantages and much collaboration taking place there has to be one disadvantage and this was the radiated emission that could potentially end all chances of broadband being rolled out. This problem has dominated all aspects of broadband development to this day and attracted a range of insinuations from around the world some of which were partly justified and others completely unfounded.

To resolve many of the key problems of broadband PLT a series of technical committee's were formed originating at both Government , utility and manufacturer level. Due to the attention this type of technology was and is still attracting, international bodies were asked to become involved. Principal among these organisations was the European Commission for Electro-technical standardisation CENELEC, which deals with low frequency and now high frequency power line systems. From this spawned a series of committee's including that of the European Telecommunications Standards Institute (ETSI).They investigated the possibility of a joint committee with CENELEC. Unfortunately due one body being representative of the European Union and the other representing a trading organisation with fees and voting rights this was not possible. However it was agreed that both committees would exchange work programmes with the aim of developing all aspects of Broadband PLT systems. Both committees are producing good work and many participants are active in both committees.

Due to the dominance of the radiated emissions a joint working group for investigating electromagnetic compatibility of not only broadband PLT but the two other key wire-line technologies of xDSL systems and cable modem systems was initiated. This committee attracted members from both CENELEC and ETSI together with other key interested parties including radio operators, broadcasting organisations such as the BBC, British Telecommunications, Radio communication agencies of UK and the Netherlands and amateur radio organisations. Each organisation has there own vested interest in this technology, with some making unjustified comments that take an inordinate amount of time to resolve if ever.

CISPR22, before Broadband PLT, was responsible for all aspects of signal propagation for xDSL and cable modem systems. To incorporate a third wire-line system, that of Broadband PLT, an official modification to the statutes of this committee was required. This was passed and the task of specifying the same technical standard for all three communications systems commenced. Unfortunately, many problems ensued taking an inordinate amount of time without resolution. In addition the time scale for integrating all three technologies is close to passing and therefore we may be back where we started from several years ago.

The advancement and resolution of the radiated emissions from these three systems has attracted considerable attention from leading governments in the world particularly Japan and UK. The Japanese Parliament announced some two years ago that no commercial licences would be made available to companies until CISPR 22 had resolved the issue of radiated emission and a standard issued for the World. This also applies to other countries in the world and until such time only trials are being carried out even though customers both industrial, commercial and residential are paying monthly fees for there service, therefore giving a false view of operation.

The connection between the different organisations and government bodies responsible for Broadband PLT systems is shown in Figure 1.It is not complete but provides the most significant outline of developments today.

Figure1 Standards Bodies of the World

Technological Challenges for Broadband Systems

In considering the different standards bodies in Europe and the rest of the World, they all have one aim and that is to establish sensible and workable radiated emission limits from wire-line systems that will not cause any interference to the established radio services. This includes the following services:

Broadcasting
Mobile communications
Distress frequencies
Space and radio astronomy
Military communications

As shown in Figure 2

Figure2 Established communications Services

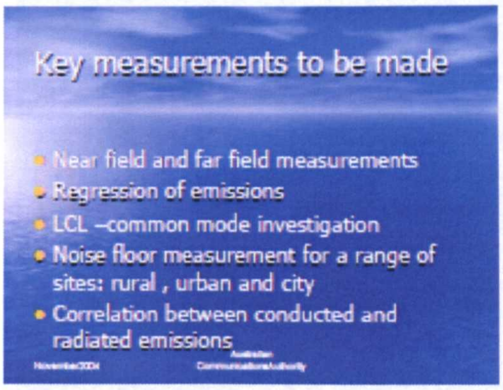
High frequency Parameters

In order to establish a coordinated response to the radiated emissions limit within the standards bodies it is absolutely essential to understand and measure key parameters associated with the emissions from Broadband PLT systems.

In particular the key measurement parameters that determine the transmission and reception of broadband PLT systems in operation include the following:

Longitudinal coupling Loss
Conducted emissions
Radiated emissions
Noise floor

As shown figure3



It is with these parameters, that the radiated emission limits may be established and understood with respect to transmission and reception.

It is extremely important to establish the range of values for these parameters and over as wide a geographical area as possible. For this reason we are carrying out a measurement campaign in the United Kingdom, Europe and other parts of the world. Even within these locations it is essential to carry out measurements in rural, semi- urban, and urban city areas.

Measurement Programme

To undertake such a measurement programme it is essential to have the most accurate equipment and be able to set it up so that measurements over a long period can be obtained. The equipment used in our experimental programme included:

Measuring receiver – Rhode and Schwartz
Signal generator
Low voltage coupler
LCL probe
Wideband antennae
Resonant Antennae

In addition to this equipment, that must be accurately calibrated, there is the software development for recording the measurements. Our measurement centred on a number of sites using a range of modems systems including MAINNET and ASCOM systems.

The LCL probe, developed in-house within our research group laboratories, was based on the McFarlane (reference1).

With this equipment all the key measurement parameters would be able to be measured very accurately. The frequency range covered 1MHz to 30MHz split as follows:

Access band: 1MHz to 10MHz
In-house band: 10MHz to 30MHz

Field strength measurements enable the following parameters to be established:

PLT emissions
Manmade background noise caused by intentional radiators due to broadcast stations
Natural background noise: it was necessary to make measurements at different times of the day to establish an increase or decrease due to the ionosphere
Increase in background at various distances from radiating structures, caused by the operation of the PLT system
Regression rate of the signal strength with increasing distance from the radiating structures.

Evaluating and assessing Key Parameters of Broadband PLT Systems.

Unlike other standards, Broadband PLT systems, knows no boundaries and therefore radiated emission and hence propagation emanates all over the world. The propagation of broadband power line signals leads to three components, namely, ground wave, sky wave and space wave when transmitting in the frequency range 1.6 MHz to 30 MHz as shown in Figure4

Figure 4 Signal Propagation for Broadband PLT systems

Although the signal propagation conditions are well established they provide a source of potential interference when detected by wire-line systems and therefore contribute to the noise ingress at the receiving end. In addition the general electromagnetic interference between the wire-line cables and the general power distribution network provides further interaction which is detrimental to signal propagation as shown in Figure5

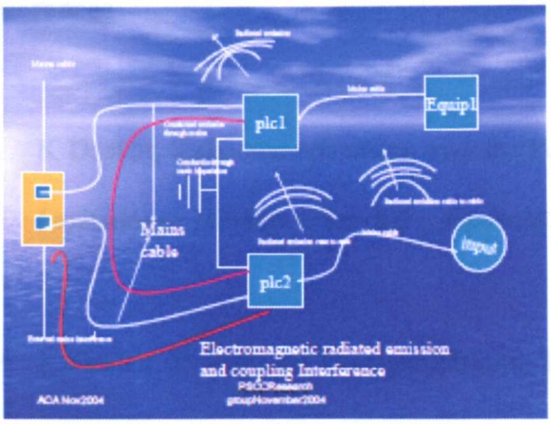


Figure 5 Electromagnetic Radiated Emissions and Coupling Interference

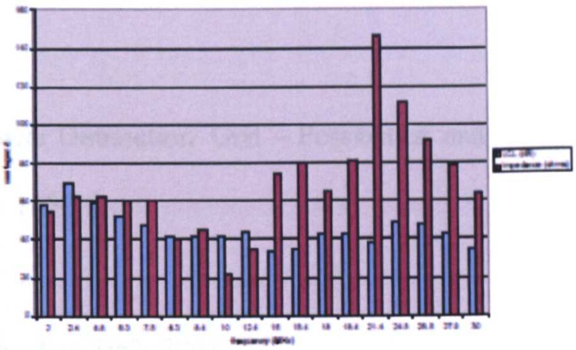


Figure 6 Longitudinal Conversion Losses and Impedance for a Kitchen

The relationship of the conducted current from the modem distributed through the power line will be determined by the number of devices connected to the LVDN cable. The mismatch in the impedance of the cable between equipment nodes will give rise to a common mode current that emanates from the cable in the form of electromagnetic radiation producing an electromagnetic field E. Here a potential problem exists of establishing the relationship between the common mode current and the Electric field E generated and the accuracy to which these two key parameters may be measured. The relationship of these two parameters leads to the longitudinal conversion loss which may be defined as follows in equation 1:

$$\text{Longitudinal Conversion Loss (LCL)} = \frac{\text{Modem Voltage}}{\text{Common Mode Current}} \quad \ldots\ldots\ldots 1$$

From equation 1, subject to the modem voltage remaining reasonably constant, a small common mode current will lead to a large LCL and sound transmission conditions. However a low LCL will give rise to a high common mode current and a high radiated emission from the electricity cable. In practice from measurements carried out over a number of sites LCL values of the order of 35dB are being achieved.

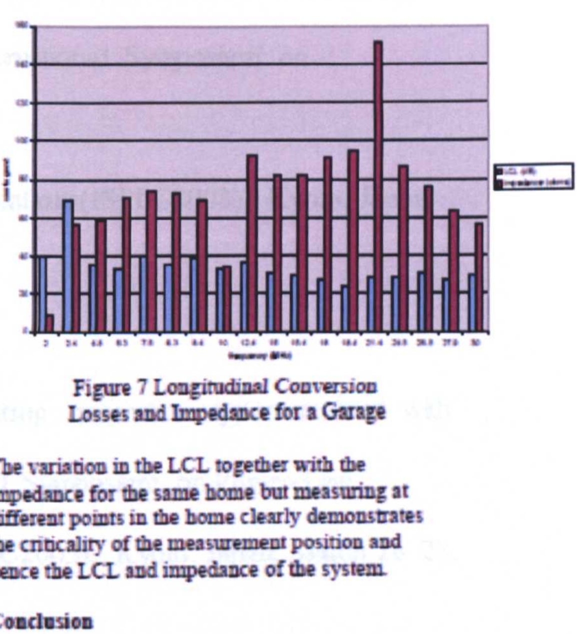


Figure 7 Longitudinal Conversion Losses and Impedance for a Garage

The variation in the LCL together with the impedance for the same home but measuring at different points in the home clearly demonstrates the criticality of the measurement position and hence the LCL and impedance of the system.

Conclusion

The establishment of a full empirical model for the behaviour of broadband PLT systems must take into consideration the measurement position and the actual equipment connected in the network so that variation in the common mode current and the resulting electric field may be established. In addition, the measurement of parameters to establish the ingress noise, the regression rate of the electric field against different noise floor levels according to the time of day and geographical location are essential. Until a full experimental programme is established the work of the different standard bodies at all levels will be severely impeded.

References

1. K Dostert, Telecommunication over the Power Distribution Grid – Possiblities and Limitations, IIR-Powerline 6/97, Germany, 1997

2. K Dostert, Power Line Communications, Prentice Hall, 2001

3. G Bumiller, System architecture for power-line communications and consequence for modulation and multiple access, 7th International Symposium on

4. Power-Line Communications and its Applications(ISPLC2003), Kyoto, Japan, March 26-28, 2003

5. G Bumilar, N Pirschel, Airfield ground lighting automation system realised with power-line communication, 7th International Symposium on Power-Line Communications and its Applications(ISPLC2003), Kyoto, Japan, March 26-28, 2003

6. M Zimmermann, K Dostert, The low voltage distribution network as last mile access network – signal propagation and noise scenario in the HF-range, AEU international journal of Electronics and Communications,(1), 13-22 2000.

7. M Zimmermann, K Dostert, A Multipath model for the powerline channel, IEEE Transcation on Communications, 50(4), 553-557 April 2002

8. O G Hooijen, On the channel capacity of the residential power circuit used as a digital communications medium, IEEE Communications Letters, 2(10), October 1998

9. H Hrasnica, R Lehnert, Powerline communications in telecommunication access area (Powerline Communications im TK-Zugangsbereich), VDE World Microtechnologies Congress (MICRO.tec 2000), ETG-fachtagung und orum:Vertelungsnetze im liberalisierten Markt, Expo 2000, Hanover, Germany, September 25-27, 2000

10. H Hrasnica, A. Haidine, R. Lehnert, Powerline Communications im Anschlussbereich, VDE Verlag, Germany, 48-53 NTZ 7-8/2001, in Germany

11. E weber and F Neveker, The evolution of Electrical Engineering, IEEE Press, Piscataway, New Jersey USA, 1994 ISBN 0-7803-1066-7

12. G Kennedy, Electronic Communication Systems, McGraw-Hill International Editions, 1984

13. J R Nicholson and J A Malack, "RF Impedance of Power Lines and Line Impedance Stabilization Networks in Conducted Interference Measurements", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC – 15, No.2 , pp 84-86, May 1973

14. R M Vines, H J Trusssel, K C Shuey and J B O'Neil, "Impedance of the Residential Power-Distribution Circuit", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-27, No.1, PP 6-12, February 1985

15. J A Malack, J R Engstrom, "RF Impedance of United States and European Power Lines", IEEE Transaction on Electromagnetic Compatibility. 1976, 18, 36-38

16. M Tanaka, "High frequency Noise Power Spectrum, Impedance and Transmission Loss Power Line in Japan on Intra-building Power Line Communications", IEEE Transaction on Consumer Electronics, Vol. 34, PP 321-326, May 1988

17. R M Vines, H J Trussell, L J gale, J B O'Neil, "Noise on Residential Power Distribution Circuit", IEEE Transaction IEEE Transaction on Electromagnetic Compatibility, Vol. 26, pp 161-168, 1985

18. R M Vines, "The Characterization of Residential Impedances and Noise Sources for Power Line Communications", Centre for communications and signal processing, North Carolina State University, Raleigh, NC, June 10, 1983

19. M Tanaka, "Transmission Characteristics of a Power Line Used for Data Communications at High Frequencies", IEEE Transactions on Consumer Electronics, Vol.35, No.1, pp 6-12, February 1985.

20. J Tengdin, "Distribution Line Carrier Communications – an Historical Perspective," IEEE Transaction on Power Delivery, 1998, PP. 321-26

21. S Agarwal, Power Line Communications: The other PLC. http://www.frost.com/prod/servlet/market-insight-top.pag?docid=8328821&ctxixpLink=FcmCtx5&ctxixpLabel=FcmCtx6 (18/11/2010)

22. B E Eyre, "Results of a comprehensive field trial of a United Kingdom customer telemetry system using mains borne signalling," Proceedings of the sixth International Conference on Metering Apparatus and Tariffs for Electricity Supply, IEE Conference Publications

23. Power Line Communications Assessment: EP –P25824/C1248 [Report by Electric Power Research Institute (EPRI) and Power Communications Systems Research Group (Open University, UK), 2009.

24. T Williams and K Armstrong, EMC for Systems and Installations, Newness, 2000.

25. H Hrasnica, A Haidine & R Lehnert, Broadband Powerline Communications Networks, Wiley, 2004.

26. H C Ferreira and O Hooijen, "Power Line Communications: An Overview", Transactions of the S.A. Institute of Electrical Engineers, September 1995.

27. R M Vines, H J Trussel, L J Gale and J B O' Neal, "Noise on Residential Power Distribution Circuits", IEEE Transactions on EMC, Vol. EMC -27, No.1, February 1995, pp 6-12.

28. L Cimini, Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing, IEEE Transaction Communications, COM-33 (7), pp665-675, July 1985.

29. M R D Rodrigues, Modelling and Performance Assessment of OFDM Communications Systems in the Presence of Non-linearities, PhD Thesis, Department of Electronic and Electrical Engineering, University College, London, UK, 1999.

30. Tutorial by C Langton, www.complextoreal.com, Tutorial 22 - Orthogonal Frequency Division Multiplex (OFDM, DMT), (27/11/ 2010).

31. National Semiconductor, Cyplex et al. IC/SS-Integrated Circuit/Spread Spectrum, Power Line Communications. 1991.

32. National Semiconductor, ICSS1001, ICSS1002, and ICSS1003, IC/SS Power Line Carrier, Local Area Network Chip Set, September 1993

33. J Meel, Spread spectrum: Applications, De Nayer Institute, Belgium, October 1999.

34. S Nomura, T Shirai, M Itami, K Etoh, A study on controlling transmission power of carriers of OFDM signal, proceedings of the 5th International Symposium on Power-Line Communications and its Applications (ISPLC), Malmo, Sweden, April 4-6, 2001.

35. T Nishiyama, S Nomura, M Itami, K Itoh, H Aghvami, A study on controlling transmission power of carriers of OFDM signal combined with data symbol spreading in frequency domain, *Proceeding of the 6th Internationsl Symposium on Power-Line Communications and its Applications (ISPLC),* Athens, Greece, March 27-29, 2002.

36. T Nishiyama, T Shirai, M Itami, K Itoh, H Aghvami, A study on controlling transmission power of carriers of OFDM signal combined with data symbol spreading using optimal data reconstruction, *Proceedings of the 7th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Kyoto, Japan, March 26–28, 2003.

37. K Kuri, Y Hase, S Ohmori, F Takahashi, R Kohno, Power channel coding and modulation considering frequency domain error characteristics, *Proceedings of the 7th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Kyoto, Japan, March 26–28, 2003.

38. T Shirai, S Nomura, M Itami, K Itoh, Study on reduction of the affectation of impulse noise in OFDM transmission, *Proceedings of the 6th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Athens, Greece, March 27–29, 2002.

39. H Matsuo, D Umehara, M Kawai, Y Morihiro, An iterative detection for OFDM over impulsive noise channel, *Proceedings of the 6th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Athens, Greece, March 27–29, 2002.

40. M Ferreiro, M Cacheda, C Mosquera, A low complexity all-digital ds-ss transceiver for power-line communications, *Proceedings of the 7th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Kyoto, Japan, March 26–28, 2003.

41. D Umehara, M Kawai, Y Morihiro, An iterative detection for M-ary SS system over impulsive noise channel, *Proceedings of the 6th International Symposium on Power-Line Communications and its Applications (ISPLC)*, Athens, Greece, March 27–29, 2002.

42. B H Walke, *Mobile Radio Networks – Networking and Protocols*, John Wiley & Sons Ltd, Chichester, UK, 1999, ISBN 0-471-97595-8.

43. M. Zimmermann, *Energieverteilnetze als Zugangsmedium f'ur Telekommunikationsdienste*, Dissertation, Shaker Verlag, Aachen, Germany, 2000, ISBN 3-8265-7664-0, ISSN 0945-0823, inGerman.

44. M A Kousa, A K. Elhakeem, H Yang, Performance of ATM networks under hybrid ARQ/FEC error control scheme, *IEEE/ACM Transactions on Networking*, 7(6), 917–925 December 1999.

45. I. Joe, A novel adaptive hybrid ARQ scheme for wireless ATM networks, *Wireless Networks*, 6, 211–219 2000.

46. C. E. Shanon, The Mathematical Theory of Communication, Illinois Press, 1949.

47. P K Van der Gracht and R W Donaldson, "Communications Using Pseudonoise Modulation on Electric Power Distribution Circuits", IEEE Transaction Communications, Vol. COM-33, Sept. 1985, pp. 964-74.

48. N Pavlidou, A J Han Vinck, J Yazdani and B Honary, IEEE Communications Magazines, pp. 34- 40, April 2003.

49. CENELEC, "Part 1: General Requirements, Frequency Bands and Electromagnetic Disturbances in Signalling on Low-Voltage Electrical installations in the Frequency Range 3 KHz to 148.5 KHz," 1991

50. P Sutterlin and W Downey, "A Power Line Communication Tutorial – Challenges and Technology", Echelon Corporation, USA.

51. H Ferreira, H Grove, O Hooijen and A Vinck, "Power Line Communications: An Overview," Africon 1996, Stellenbosch, pp558-563

52. H K Podszeck, "Carrier Communication over Power Lines," 4th Edition, New York: Springer-Verlag, 1972.

53. IEEE Guide for Power-Line Carrier Applications", IEEE Standard 643-1980.

54. ANSI C93. 1-1972, Requirements for Power Line Coupling Capacitors.

55. A Petrus, J V Rensburg and H C Ferreira, "Practical Aspects of Component Selection and Circuit Layout for Modem and Coupling Circuitry", Proceeding of 7^{th} ISPLC-2003, Kyoto, Japan, pp. 197-209, March 26-28, 2003.

56. W Hagman, "Installation and Net Conditioning manual for Power line Infrastructure Units", Ascom Powerline, pp.8-13, 2000.

57. J Goedbloed, Electromagnetic Compatibility, Prentice Hall, New York, 1995.

58. L Tihanyi, Electromagnetic Compatibility in Power Electronics , IEEE Press, The Institute of Electrical & Electronic Engineers, new York, 1995.

59. M Zimmermann, K Dostert, The voltage distribution network as last mile access network – signal propagation and noise scenario in the HF- range, AEÜ International Journal of Electronics and Communications, (1), 13-22 2000.

60. M Gotz, M Rapp and K Dostert, "Power Line Channel Characteristics and their Effect on Communication System Design", pp. 78-86, IEEE Communications Magazine, April 2004.

61. C Ferreira, L Lampe, J Newbury & T G Swart, Power Line Communications, Willey, 2010.

62. J H Bull, "Impedance of the Supply Mains at Radio Frequencies." 1st Symposium on EMC, Montreux, 1975.

63. H Cavdar and E Karadeniz, "Measurements of Impedance and Attenuation at CENELEC Bands for Power Line Communication Systems". Sensors, Published 8 December 2008, ISSN 1424-8220.

64. Alan Symonds, Electrical Power Equipment and Measurements, Second Edition, McGraw-Hill, 1980.

65. John Newbury, Broadband developments, Keynote speech on ISPLC 2005 Vancouver, Canada 2005.

66. M Riddle, S Ardalan & J Suh, "Derivation of voltage and current transfer functions for multi-conductor transmission lines" IEEE Circuits & Systems 1989. IEEE International Symposium.

67. K K Yeung, 'Detailed OFDM Modelling in Network Simulation of Mobile Ad Hoc Network". MSc Thesis. University of California, 2003.