CHAPTER 1
INTRODUCTION

1.1 Introduction to Power Line Communication (PLC)

Digital communication over power lines is an idea that dates back to the early 1920s. Since then, utility companies around the world have successfully used this technology for remote metering and control. These applications, however, required very low bit rates of the order of Kbps. More recently, there has been a growing interest in the possibility of exploiting the power grid to provide broadband access to residential customers [1-9] or Broadband distribution over ‘last mile’ and ‘last feet. The attractive feature of this idea is the presence of a vast infrastructure for power distribution, enabling penetration of the services that could be much higher than any other wired alternative.

Access to the internet is becoming as indispensable as access to electrical power. Since devices that access the internet are normally plugged into an electrical outlet, the unification of these two networks seems to be a good option. The power distribution grid represents an omnipresent, widely branched hierarchical structure. Moreover, the structure of the whole low-voltage distribution grid including outdoor supply cables is most appropriate for internet access, offering both ‘last mile’ and ‘last feet’ solutions [6]. Within the ‘last mile’ domain, the telecom monopolists are still owners of the communication wires, but the ‘last feet’ is still a bottle neck, and a strong competition in the form of alternative links is most desirable. For high speed indoor networking, power lines exhibit the unique feature to connect any point of interest with no need for new wires. A simple diagrammatic representation of a typical PLC in the ‘last feet’ is shown in Figure 1.1

The advantages of power line communication (PLC) are

(a) Broadband access availability at all power points in a house,

(b) Guaranteed rates unlike loss of rate due to shadowing effects, and

(c) No concerns about long term effects of Electromagnetic radiation inside a house.
Figure 1.1: PLC at ‘last feet’

Power line networks were designed for distribution of power at 50Hz or 60Hz. The use of this medium for data communication at higher frequencies presents several technical challenges. The structure of the mains grid, as well as indoor wiring and grounding practices differ from country to country and even within a country. The barrier to a widespread adoption of broadband PLC is the lack of an international accepted technical standard issued by a credible and globally recognized standards-setting body. However there is bound to be a progress with establishment of IEEE P1901 Corporate Standards Working Group. This group was created in June 2005 [11, 12], and commenced developing a set of unified functional and technical requirements (FTRs). With technical assistance from members of IEEE ComSoc Technical Committee on Power Line Communications developments commenced on channel and noise models, as well as topology descriptions and were approved for insertion into an informative annex. In 2010 ITU-T started a new standardization called G.hn for a unified next generation networking technology, operating over all types of in-home wiring (phone line, power line, coaxial cable and Cat-5 cable)[10]. G.hn specifies network architecture, most of the PHY and some aspect of MAC.

Use of power lines for data communication at higher frequencies presents several technical challenges. Power line channel is a harsh, noisy and time varying transmission medium that is difficult to model [13-30]. It is frequency selective, and affected by colored background noise, impulse noise [38] and RF noise. The channel transfer function of the power line channel may vary abruptly when the topology
changes, that is when devices are plugged in and out. Intersymbol interference (ISI), due to multipath effect caused by impedance mismatch, result in deep signal fades. Such channel impairments make reliable high-speed data transmission difficult over power lines. However improvements in ASIC density and speed, along with advancement in signal processing and development of powerful error detection and correction techniques have helped in making PLC a strong contender for home networks. Different communication systems have been proposed for broadband PLCs. In particular, Discrete MultiTone techniques have proved to be an appropriate solution due to their capabilities in facing channel impairments, while affording high capacity [52, 56, 58].

In this thesis multicarrier modulation over power lines is employed for broadband communication. Unlike telephone lines where standard test cases are described for validation of performance, in power lines there are no defined set of test cases. Here we have projected a set of test cases which represent a typical indoor residential power line network, with straight line sections and distribution lines with open ends and with residential inductive loads. The performance of an indoor power line (AWG14) up to 10 inductively loaded bridge taps over 600mts is analysed using ABCD matrix channel model based on two-port network theory [18,19]. The SNR is obtained by considering the signal PSD as per the ITU standards 992.3 for VDSL2 upstream and downstream [49] along with noise profiles and channel transfer function H (f). The channel is further analysed without and with impulse noise that is predominant over power lines. Finally channel capacity is obtained by summing up the tone loading profile obtained from SNR profile for upto 30MHz.

Loop topology estimation which is very much essential in analysing power lines with loads, and therefore the performance capability of the line determined by SNR. Hence the loop topology estimation algorithm with the combined Correlation Time Domain Reflectometry-Frequency Domain Reflectometry (CTDR-FDR) method is extended to power line applications employing a multi-point measurement technique [67].

As a build up to the performance results presented in this thesis, it is important to understand Discrete Multi Tone (DMT) which is a line modulation scheme used
over the power lines and discussed in the next section. Also power line have to be mathematically modelled for simulation, apart from understanding various noises in the line. These are introduced in the sections that follow.

1.2 Discrete Multi-Tone Modulation

Discrete Multi-Tone (DMT) modulation, a form of Multi-Carrier Modulation with dynamic bit-loading for subchannels, provides a robust transmission scheme against multipath reflections, radio frequency interference and impulse noise due to house hold appliances in a power line channel. DMT essentially divides a communication channel into a number of equally spaced frequency bands [56]. A subcarrier carrying a portion of the user information is transmitted in each band. The process of tone-loading assigns different number of bits to different sub-channels, depending on their individual Signal-to-Noise Ratios (SNRs), for efficient transmission. A sub-channel or a tone with high SNR will carry more bits as compared to a sub-channel with low SNR. Each tone in DMT supports a constellation size that is determined by SNR.

DMT is employed in Digital Subscriber Line (DSL), which is a robust, interoperable and easy to use multi-vendor access solution for economical high-speed data networks in the last mile. DSL collectively refers to a group of technologies that utilize the unused bandwidth in the existing copper access network to deliver high-speed data services from the distribution centre to end user over an bandwidth up to 30 MHz. A data rate up to 100Mbps is possible with this high bandwidth over the wire line. There are different variants of DSL technologies available, depending on the geographical location and bandwidth needs [32, 33]. Asymmetrical DSL (ADSL) and very high speed DSL (VDSL) are the two types of DSL technologies, whose standards have evolved.

- ADSL/ADSL2+ employs two different transmission speeds [51], with the downstream (from distribution centre to subscriber) speed usually being much higher than the upstream (from subscriber to distribution centre) speed. ADSL can achieve downstream data rates up to 8 Mbps and 1Mbps, while ADSL2+
achieves rates up to 20Mbps in downstream.

- VDSL2 promises higher speeds than ADSL over much shorter distances. VDSL2 can run with either symmetric or asymmetric rates[49, 50]. The highest rate proposed for VDSL is in the range of 50Mbps.

The allocation of the frequency bands for upstream and downstream for various DSL services is defined in the band plan specified by International Telecommunication Union (ITU) standards. ADSL uses the frequency range up to 1.1MHz and VDSL2 utilizes the frequency ranges up to 30MHz. The maximum frequency used by a modem to transmit data depends on the selected band plan and the profile.

1.3 Loop Topology Estimation

Performance estimation of DSL is critical for an operator to meet the quality of service (QoS) requirements to a subscriber. The performance of the subscriber line depends on the line conditions. Line conditions include the transfer function of the line which depends on the line topology and the noise power spectral density (PSD). Line conditions needs to be independently estimated as exchange equipments and cable plants are typically owned by different companies. A service provider’s ability to easily and accurately predict these line conditions is important to predict the performance. Single ended loop testing (SELT) allows lines to be qualified in bulk without human intervention [63, 64] and hence essential to achieve low cost deployment of DSL. SELT works on the principle of reflection and consists of three major phases [65,66]

i) Measurement phase - This is done in the physical layer of the modem. A probe signal is transmitted and reflected signals (echoes) are collected in this phase.

ii) Analysis phase – The received echo signals are processed and interpreted to arrive at the loop topology.

iii) Performance estimation phase – Capacity of the line is computed for the estimated loop conditions by applying PSD guidelines as per the ITU.
Measurement and analysis of the reflection in time domain called Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) are two techniques that have been investigated in the line topology estimation. A variant of FDR and Correlation TDR (CTDR) for topology estimation are developed here which uses the existing DSL modem in the measurement phase.

### 1.4 Power Line Modeling

The power line network has been designed for distribution and delivery of electrical energy, not for communication. The power line thus poses a unique challenge in channel modeling that has only been partially addressed in literature [13-30]. Apart from a thicker gauge (typically 14 AWG) the power lines are fundamentally shorter in length (as compared to telephone lines) but have a large number of parallel bridge taps with predominantly inductive load terminations that are often switched in and out of circuit. Further unlike telephone lines that are terminated by modems that meet low, medium and long line length impedances, power lines are not terminated with anything that is even close to their characteristic impedance.

Several techniques have been introduced to model the transfer characteristics of power lines. Basically there are two essential facets to these models viz the model parameters and modeling algorithms. These two facets determine the reliability and accuracy of the model. In this thesis we examine the methods to characterize such time varying frequency dependent channel transfer function of power lines, and analyse the effect of these two parameters to obtain variable rates in a modem.

### 1.5 Power Line Noise

Unlike telephone lines, power lines are a single pair of wires where there is no need to consider Near End Cross Talk (NEXT) and Far end Cross Talk (FEXT). In contrast to many other communication channels, the noise in a powerline network cannot be described by Additive White Gaussian Noise (AWGN) model alone. Hence a thorough analysis of interference is an inevitable prerequisite for noise modelling.
The interference in PLC can be classified into three categories viz, background noise, periodic impulsive noise synchronous or asynchronous to the mains frequency, and asynchronous aperiodic impulsive noise [38-48]. The power line noise can thus be regarded as a combined sum of AWGN and the impulsive noise from all online appliances as shown in figure 1.2.

![Figure 1.2: Noise Scenario in PLC](image)

Among the different types of noise found on power lines, the most unfavourable is asynchronous impulse noise, caused by switching transients in the network [6]. This impulse noise causes bit or burst errors in high-speed data transmission [14, 15], that is mitigated by interleaving and forward error correction. The SNR profile obtained from the received signal and noise is used to find the channel capacity.

### 1.6 Tone Loading Algorithms and Channel Capacity:

The performance of a DMT system strongly depends on the effectiveness of the tone-loading technique that is adopted. The tone-loading algorithms aim to assign bits to the sub-carriers in such a way that the transmission signal minimizes
the bit error rate (BER) and thereby maximize the bit-rate (BR) [20]. Channel capacity estimation is based on a Modified version of Shannon’s theorem [52-62]. The number of bits per tone is linked to the SNR through a modified version of Shannon’s theorem. The SNR however is determined by the channel and applied to the tones in a DMT symbol. Bridge taps with inductive loads result in severe shortfall in data rates due to mismatch between line impedance and receiver impedance. Data rates are shown to be considerably improved by adopting settable values of conjugate impedances in the hybrid of the modem that match with the line look in impedance. We thus recommend a combination of settable hybrid impedances and a capability to nominally increase Transmit PSD to achieve desired rates, apart from providing a marginal over capacity with free tones to cater the rate drawbacks.

1.7 Research Motivation and Objectives

Increasing demand for broadband signal in different media viz audio, video/image and internet has led to the development of wireless/wireline technology processing with a high growth rate. However, last feet connectivity at the end user’s premises still remains a bottleneck for the telecom service providers. Out of several options for broadband service over wider geographical locations, broadband over power line (BPL) is emerging as a viable contender for its advantage of less infrastructure investment and better quality of service.

At present the power lines are been used to carry only the power, wherein the vast infrastructure of the power lines can be utilized for broadband communication, so that the internet is available at every socket in the residence. The ways to achieve this is analysed in this thesis.

The general notion of using electric power lines as a transmission medium for communication has been around for almost a century, but until the past decade or so only relatively narrow bandwidth (<100 KHz) have been feasible. Advances in signal processing techniques now enable, megabits per second to be carried over this extremely hostile channel, viz residential power wiring.
The objective of this thesis is to analyse the performance of power media for communication and estimate the quality of service (QOS) over the last mile (local area) and in last feet (in premises). Towards this thesis dwells on

i) Different power line topologies with different load terminations

ii) Power line impulse noise

iii) Computation of SNR profiles and capacity

iv) A simulation test bed to test DMT transmission under a variety of conditions.

1.8 Organization of the thesis:

*Chapter 1* introduces the concept of broadband power line communication (PLC) and outlines the importance of PLC. The research objectives and the methodology are discussed in this chapter.

*Chapter 2* a literature survey of different types of power line modeling, noise modelling existing and different modulation schemes for data transmission has been discussed. A brief introduction to the rates achieved over a typical home power line is also discussed.

*Chapter 3* consists of power line modelling for plain line, lines with open and short taps and lines with inductive loads connected to the bridge taps. Two-port network model has been developed for the mainline, distribution line or the bridge taps with open and load connected. Distribution matrix has been derived for the inductive load terminations. Transfer function is obtained for the test cases with and without inductive loads connected to the bridge taps which is the novelty of the chapter.

*Chapter 4* deals with adaptive bit- loading of the multicarrier profile considering only AWGN noise. To perform the bit-loading, SNR is obtained by considering the transmit signal PSD as per the ITU standards 992.3 for VDSL2 upstream and downstream which is new idea and not seen in literature. Considering AWGN of -140dBm/Hz and the channel transfer function H (f) which has been obtained in chapter 3. Channel capacity is hence computed for all the test cases. There is a fall
in the channel capacity with the bridge taps but very much higher than the required, hence the reduction in signal PSD is recommended.

Chapter 5 deals with the adaptive bit-loading with AWGN and impulse noise. Impulse noise, which is predominant type of noise in power lines and is significant contributor to SNR degradation is analysed. Spectral spread of impulse noise is obtained by considering the noise as repetitive pulses with damped sinusoids. Considering this impulse noise PSD also, channel capacity is obtained which is the novelty of this chapter. SNR and hence the channel capacity gets reduced with number of bridge taps and gets worse with impulse noise. It is shown here that with impulse noise the channel capacity can be improved by increasing the signal PSD by 10 to 20 dB.

Chapter 6 deals with obtaining adaptive bit-loading with AWGN, impulse noise and different terminations viz inductive loads connected to the bridge tap. In chapter 4 & 5 simulations are performed for only open termination. Compared to the simulation results of the previous chapters, SNR and hence the channel capacity significantly declines with inductive load connected to the bridge tap. A three part procedure to improve the SNR is suggested in this chapter: (i) initial provision with over capacity that allows fall back to required rate, (ii) in an line with few taps the signal PSD is increased for the improvement in the capacity and (iii) the worst case condition with more number of taps is dealt with suggesting provision of matched impedance and also with the new signal PSD with one more transmit band which is a new idea implemented in this chapter. Two algorithms are developed for fixed-rate bit-loading that caters to customer requirements.

Chapter 7 discusses a complete test bed that has been created to emulate the blocks of the modem. In the previous chapters the algorithms are simulated in the MATLAB. In this chapter a test bed is created which is close to the real operating conditions. The signal conditioning blocks are emulated and brought to the stage of direct implementing on the DSP kit.

Chapter 8 discusses the conclusion driven from this research and the possible future work.