Techniques for Broadband Power Line Communications: Impulsive Noise Mitigation and Adaptive Modulation

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Khalifa S. Al Mawali July 2011 This dissertation is dedicated to my parents, my wife, my daughter and to my beloved country Oman

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Power line communications (PLC), orthogonal frequency division multiplexing (OFDM), multicarrier modulation, Impulsive noise, Blanking, Clipping, bit-interleaving, convolutional coding, adaptive modulation, bit loading, power loading.

Preface

Advances in digital communications have made it possible to access the Internet by simply plugging your computer to the wall socket in your home. Power line communications (PLC) technology exploits the widespread electric power infrastructure to provide high-speed broadband multimedia services to and within the home or office. Until recently, a fundamental obstacle to the prevalent adoption of PLC technology has been the lack of an international standard issued by a globally recognized standardization body. This obstacle has been removed by the approval of the IEEE 1901 standard for Broadband over power line networks opening a new era in the PLC industry. Nonetheless, the characteristics of electrical power grids present some technical challenges for high-speed data communications. Noise at a power outlet is the sum of noises produced by different appliances connected to the line producing impulsive noise and other narrow-band interference.

This thesis presents new techniques to enhance the performance of PLC systems. This includes the mitigation of the effect of impulsive noise in PLC. It also includes introducing new schemes in adaptive power and bit loading to efficiently utilize the available frequency bandwidth. I hope that this work will help researchers and inspire further research in PLC and related topics.

Khalifa S. Al Mawali

July 2011

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List of Acronyms and Principal Symbols

σ_w	Background noise power
σ_i	Impulsive noise power
μ	Impulsive-to-Background noise power
T_{noise}	Average impulse duration
λ	Rate of impulsive noise
H(f)	Channel transfer function
T_c	Clipping threshold
T_b	Blanking threshold
N_o	PSD of Gaussian noise
N_i	PSD of impulsive noise
N_m	PSD of total noise
k	Number of bits per PSK or QAM symbol
r	Code rate
p_n	Transmit power for the \mathbf{n}^{th} subcarrier
p_{tot}	Total transmit power per OFDM symbol
b	Number of bits per subchannel
R_b	Data rate
P_n	Bit error rate for the n^{th} subchannel

List of Acronyms and Principal Symbols

P_T	Overall BER
Ν	Number of subcarriers per OFDM symbol
γ	Signal-to-noise ratio
g_{wn}	Subchannel signal-to-Gaussian noise ratio when unit power is applied
λ_L	Lagrange multiplier
γ_{mc}	Multichannel SNR
f	Frequency
PLC	Power Line Communication
$_{\rm PL}$	Power Line
HV	High voltage level
MV	Medium voltage level
LV	Low voltage level
OFDM	Orthogonal Frequency Division Multiplexing
DR	Disturbance ratio of impulsive noise
PSD	Power spectral density
WGN	White Gaussian noise
\mathbf{DFT}	Discrete Fourier Transform
IDFT	Inverse Discrete Fourier Transform
\mathbf{FFT}	Fast Fourier Transform
BER	Bit error rate
FEC	Forward error correction
\mathbf{SNR}	Signal-to-noise ratio

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Abstract

The development of power line communication systems for broadband multimedia applications requires a comprehensive knowledge of the channel characteristics and the main peculiarities that may influence the communication over this channel. PLC has the potential to become the preferred connectivity solution to homes and offices. Additionally, indoor power line networks can serve as local area networks offering high-speed data, audio, video and multimedia applications. The PLC technology eliminates the need for new wires by using an already-existing infrastructure that is much more pervasive than any other wired system.

Power line networks, however, present a hostile channel for communication signals, since their fundamental purpose is the transmission of electric power at super-low frequencies (i.e. 50 Hz or 60 Hz). Noise, multipath, selective fading and attenuation are well-known properties of power line grids and they must be considered when designing PLC systems. Particularly, random impulsive noise characterized with short durations and very high amplitudes is identified as one of the major impairments that degrade the performance of PLC systems.

Orthogonal frequency division multiplexing (OFDM) is the technique of choice for PLC and has been regarded as the modulation scheme for broadband PLC by most researchers and is used as the modulation scheme in this work. This is because OFDM minimizes the effects of multipath and pro-

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vides high robustness against selective fading. It is also powerful in impulsive noise environments and performs better than single-carrier modulation methods. If an OFDM symbol is affected by impulsive noise, the effect is spread over multiple subcarriers due to the discrete Fourier transform at the receiver. Therefore, each of the simultaneously transmitted communication symbols are only affected by a fraction of the occurring impulsive noise.

In order to achieve reliable outcomes, suitable channel and noise models must be used in the investigations. In this thesis, the power line channel transfer function is modelled using a multipath model that was proposed by Zimmermann and Dostert [1], [2]. This model is based on measurements and has been widely accepted and practically proven to well describe the signal propagation scenario and attenuation effects in power line networks. To represent the actual noise scenario in power networks, the noise is classified into two main classes: background noise and impulsive noise. Background noise is modelled as an AWGN whereas impulsive noise is modelled using a Poisson-Gaussian process. The performance of PLC is tested under three different impulsive noise scenarios that are based on practical measurements. Results show that impulsive noise can have a severe effect in the bit-error rate of OFDM-based PLC systems.

To reduce the effect of impulsive noise, conventional time domain nonlinearities are examined in this thesis under PLC environments. The threshold selection problem is studied and an adaptive-threshold selection method based on minimum bit-error rate (BER) is proposed as a solution to this problem. At the cost of additional complexity, the effect of impulsive noise is further mitigated using a novel joint time-domain/frequency-domain suppression technique. This technique uses a time-domain clip/blank nonlinearity jointly with a frequency-domain noise suppression technique found in the literature [3].

Since channel coding is essential for most telecommunication systems, we examine convolutional codes in a practically-proven PLC channel impaired

Abstract

with AWGN and impulsive noise. Random interleaving is used to combat the bursty nature of the impulsive noise present in PLC channels. The results show substantial performance gains especially in heavily-disturbed environments, where signal-to-noise ratio (SNR) gains of more than 15 dB can be achieved with a code rate of 1/3. Bit-interleaved convolutionallycoded OFDM completely eliminates the effect of impulsive noise in weaklydisturbed noise environments, while a negligible effect may remain in mediumdisturbed environments.

The adaptability feature of OFDM can be exploited by using adaptive modulation methods leading to significant improvements in the system's performance, efficiency and robustness. In later chapters of this dissertation, bit/power loading algorithms are investigated. A new power-loading algorithm that minimizes the transmission power for target BER and data rate constraints is introduced. Results indicate that, in a PLC channel impaired with impulsive noise, the algorithm achieves performance gains of more than 4 dB SNR over conventional OFDM systems. Furthermore, a novel minimum-complexity bit-loading algorithm that maximizes the data rate given BER and power level constraints is proposed in chapter 6. Results show that this bit-loading algorithm achieves almost identical performance as the incremental algorithm but with much lower complexity. The performance of both algorithms is tested under PLC channels against well-known loading methods and their superior performance is proved.

During the PhD candidature, eight refereed conference papers and one journal paper have been published.



Introduction

1.1 Power Line Communications

In the past several years, the demand for broadband multimedia applications has significantly increased and continues to grow at a rapid pace. Broadband Internet access, for instance, is being tremendously demanded and becoming a necessity for homes and businesses. A variety of technologies are currently in use for broadband connectivity to and within homes and offices.

Among those communication technologies, power line communications (PLC) is receiving a huge amount of research interest and presents a very attractive multimedia connectivity solution to the last-mile problem. PLC exploits already-existing electrical networks to deliver high-speed broadband communications. In addition to solving the last-mile connectivity issue, PLC uses the in-building electrical wiring as a local area network providing high-speed networking that includes broadband Internet access, voice over IP and home entertainment services to virtually every power socket in residential or business premises. The driving advantage of PLC is that it uses an infrastructure that is much more ubiquitous than any other wired infrastructure, hence does not require new wiring.

The concept of using power lines (PL) for communication services is not one that has just emerged. The first applications of PLC date back about hundred years ago, when analog communications were employed for remote metering and home automation. It was also important for power supply utilities to have a proper communication link to maintain the operation of high-voltage PLs. However, the attention in the past decade or so has been focussed on using PLC for fast Internet access as well as other broadband multimedia services.

PLC offers a competitive and cost-effective alternative for Internet access and LAN applications. However, large expansion and widespread adoption of this technology has so far been limited by the lack of a universally agreedon standard issued by a globally recognized standardization body. Most of the PLC products available in the market now are based on the HomePlug Standard with its variant (HomePlug 1.0, HomePlug AV and HomePlug BPL). Recently, the first IEEE standard for broadband over power line networks has been approved and the well-anticipated standard is due for publication in February 2011 [4]. It is believed that the publication of the IEEE standard 1901-2010 will constitute a significant milestone in the history of PLC and will contribute largely to the development and adoption of PLC applications.

Despite the advantages brought forward by PLC, this technology conveys communication signals through a medium that was never designed for telecommunication functions. Power lines differ significantly in their structure and physical characteristics from usual communication mediums such as fibre optic and coaxial cables [5]. Understanding those properties is essential for the design of PLC systems.

The most important factors that affect communications over power lines are attenuation, multipath fading and noise. PL cables suffer from considerable frequency-dependant attenuation that increases with high frequencies and can be severe for long-distance communications. Moreover, impedance mismatching is commonly present in PL networks causing enormous reflections of the signal, giving rise to multipath fading.

Another persistent impairment for PLC systems is the noise generated by

internal and external sources that are either connected or in close proximity to the PLC transmission medium. The noise at any power outlet is the sum of noises produced by different appliances connected to the line plus the background noise on the line. Five types of noise are often found in PL channels [6]: coloured background noise, narrowband noise, periodic impulsive noise asynchronous to the mains frequency, periodic impulsive noise synchronous to the mains frequency and asynchronous impulsive noise. The first three types are almost stationary and are classified as background noise. The last two types have a time-varying random behavior and are often classified as impulsive noise.

Impulsive noise forms one of the key challenges for PLC systems. It is generally the result of switching transients in power appliances. Typical impulses of this type have short durations ranging from some microseconds up to a few milliseconds and are characterized with very high amplitudes. During the occurrence of impulsive noise, the power spectral density (PSD) of this type of noise can be up to 50 dB higher than the background noise [6].

Due to the presence of impulsive noise and other undesirable characteristics of PL grids, it is crucial for high-speed PLC to select a modulation technique that can stand against such peculiarities. A number of modulation techniques, including single-carrier, multi-carrier and spread spectrum are of interest for PLC engineers and researchers [5], [7]. Among those, orthogonal frequency division multiplexing (OFDM) stands as an excellent candidate for PLC. The basic principle of OFDM is to split high-speed data symbols into slow data streams which then modulate multiple narrowband orthogonal subcarriers simultaneously. This reduces the effect of multipath by enlarging the symbol duration so that, depending on the channel delay spread, only a small portion of the symbol is affected. With the addition of a cyclic time guard, the problem of multipath can be completely eliminated in OFDM. Besides, the effect of impulsive noise is minimized because the received OFDM signal in addition to the added noise is divided by the number of subchannels through the discrete Fourier transform (DFT) operation in the receiver. OFDM offers robustness as well as simple implementation which make this technique a favored candidate for PLC.

OFDM can be fruitfully combined with adaptive modulation techniques that allow individual subcarriers to have different constellation sizes, transmit powers, instantaneous Bit-error rate (BER), channel code and so forth. This solves the frequency selectivity issue associated with PLC networks. Subchannels that are affected by fading or narrowband interferers can carry fewer bits or can even be zeroed in extreme cases or if the sub-bands are used by wireless operators. To enable high-speed PLC over power lines, adaptive loading algorithms that can efficiently exploit the available spectrum and optimize the performance have to be introduced.

Under harsh channel conditions, the reliability of PLC systems can be improved by the utilization of forward error correction (FEC) methods. Due to the occurrence of bursty impulsive noise in PL channels, interleaving needs to be employed to reduce the channel memory and help coding schemes, that are designed to combat single errors, to tackle errors caused by burst disturbances.

1.2 Thesis Objectives

Nowadays, there is an increased interest in the PLC technology as a means to provide homes and offices with Internet access in addition to local area networking using the in-building wiring. PLC technology has the potential to provide high-speed broadband communications through the most ubiquitous wired network without the need for new wirings. However, power line networks were only designed for the transmission and distribution of energy signals at 50 or 60 Hz and they present a hostile environment for high-speed data communications. The most undesirable characteristics of power line channels include high attenuation, multipath fading and noise with random time-varying impulsive behavior.

OFDM is the method of choice for PLC systems. Due to the long symbol duration in OFDM, inter-symbol interference caused by multipath propagation is minimized and can be entirely eliminated using a cyclic time guard. OFDM deals effectively with impulsive noise by dividing noise impulses among all the OFDM subcarriers due to the discrete Fourier transform (DFT) operation in the receiver.

Practical measurements show that, in PLC environments, the power of impulsive noise is much greater than other kinds of noise. In an OFDMbased PLC, high-power impulsive noise can lead to significant performance degradation. It is then crucial to investigate its effect in data communications and introduce ways of limiting its damage and optimizing the performance of PLC in such a harsh environment.

This thesis is aimed at enhancing the performance of current and future OFDM-based broadband PLC systems. This objective is achieved by first tackling the problem of impulsive noise and presenting new ways of limiting its effect on communication signals. Second, new methods of adaptive modulation striving to increase the power efficiency of PLC systems as well as maximizing the data rate are introduced in this thesis.

1.2.1 Research Questions

The proposed PhD program attempts to answer the following research questions:

- 1. Can OFDM systems cope with the hostile conditions in power line channels and achieve the desired performance?
- What are the suitable models to describe the propagation characteristics of power line channels and the noise they contain?
 A number of channel models exist in the literature. In addition,

Impulsive noise can not be assumed as additive white Gaussian noise (AWGN) and should be modelled properly to achieve reliable results.

- 3. How can we reduce the effect of impulsive noise in power line communications?
- 4. How good are conventional nonlinear techniques in reducing the effect of impulsive noise in PLC systems with different noise scenarios? And how can their performance be improved? Time-domain nonlinear techniques are often used in practical wireless

applications, but their performance in PLC needs to be investigated.

- 5. What is the performance gain than can be achieved when using bitinterleaved convolutional coding in OFDM-based power line communications affected by impulsive noise.
- 6. How does adaptive modulation improve the transmission performance and efficiency of OFDM-based PLC systems?
- 7. Is it possible to minimize the transmit power of OFDM-based PLC and yet maintain high data rate and low error rate specifications? How can this be achieved?
- 8. How can we maximize the data rate in PLC and achieve high-speed broadband communications in a simple and efficient way?

1.2.2 Research Aims

The specific objectives arising from these questions have been addressed. These can be summarized as follows:

- 1. Researching and investigating the performance of OFDM in an appropriate power line channel model with the addition of a properly modelled noise environment.
- 2. Investigating the existing methods for impulsive noise reduction in PLC and other communication systems.
- 3. Developing new or improved techniques for the mitigation of the

effect of impulsive noise in PLC systems.

- 4. Examining the performance of channel coding schemes in PLC environments impaired with impulsive noise.
- Investigating adaptive modulation techniques and testing them for PLC applications.
- 6. Developing new adaptive modulation algorithms that can efficiently exploit the limited spectrum in PLC in simple and cost-effective way.

1.3 Original Contributions

This thesis makes many original contributions to the body of knowledge in the field of digital communications, with focus on broadband OFDM-based power line communications. A number of novel techniques and algorithms to mitigate the effect of impulsive noise and optimize bit and power loading in PLC systems have been presented.

The main contributions of this dissertation are summarized below:

- Analysis and results of the effect of impulsive noise in OFDM-based PLC systems are presented in this thesis. The channel model used is widely-accepted and its accuracy to describe the propagation scenario in power line channels has been proved by practical measurements.
- Analysis of the performance of time-domain nonlinearities (Clipping, Blanking and Clipping/Blanking) in reducing the effect of impulsive noise has been carried out during the PhD program.
- 3. An adaptive-threshold nonlinear technique to reduce the effect of impulsive noise in PLC systems is proposed. The technique is based on minimizing the BER at the receiver.
- A joint Time-domain/Frequency-domain technique for impulsive noise suppression in OFDM-based PLC systems is introduced in this thesis. The technique is based on clip/blank nonlinearity joint with

a frequency-domain impulsive noise reduction technique. The technique is studied under practically-proven power line channel model with suitably-modelled impulsive noise with different conditions.

- 5. Examined the performance of bit-interleaved convolutionally-coded OFDM in PLC in the presence of impulsive noise. Results have been obtained for a 4-path and a 15-path echo model with different conditions of impulsive noise.
- 6. Proposed a new power-loading algorithm for OFDM-based PLC systems impaired with impulsive noise. The algorithm minimizes the transmit power given specific target BER and data rate constraints.
- 7. A new bit-loading algorithm for OFDM-based PLC systems is introduced. The algorithm aims at maximizing the data rate given specific transmit power and BER constraints. At the same time, the algorithm maintains minimum computational complexity.

1.4 Thesis Organization

This thesis is comprised of seven chapters. The first chapter serves as an introduction to the thesis whereas the second chapter presents a literature survey of the field of power line communications and related topics. The rest of the thesis can be divided into two parts. The first part, including chapters 3 and 4, focuses on the mitigation of the effect of impulsive noise in OFDM-based PLC systems. The second part consisting of chapters 5 and 6 focuses on adaptive modulation techniques for PLC systems. The dissertation is organized as follows:

Chapter 2: Literature Review

Literature survey on power line communications is made in this chapter. As power lines were not originally designed for communication purposes, the chapter starts by outlining the structures and physical properties of power line networks and the historical development of communications over power lines. A review of the previous work done in the field of modelling the PLC channel and the existing impulsive noise is given in this chapter. The use of OFDM and adaptive modulation in PLC applications is also explained. The chapter finishes by presenting some of the common applications of OFDMbased broadband PLC technology.

Chapter 3: Nonlinear Techniques for Impulsive Noise Reduction

In this chapter, different techniques striving to mitigate the adverse effect of impulsive noise in PLC are tested under a power line environment using a widely-accepted and practically proven model. The performance of nonlinear time-domain techniques in OFDM-based PLC systems at different impulsive noise environments is evaluated and the results are presented in this chapter. Next, new adaptive-threshold techniques for impulsive noise reduction are introduced and validated. A novel joint timedomain/frequency-domain technique for impulsive noise suppression is also introduced in this chapter.

Chapter 4: Performance of Bit-Interleaved Coded OFDM in PLC Systems

In this chapter, an OFDM system employing interleaving and convolutional coding is examined in a power line channel in the presence of impulsive noise. Different noise environments and code rates are used to verify the performance gain achieved by convolutional coding combined with interleaving and its ability to mitigate the effect of impulsive noise.

Chapter 5: Adaptive Power Loading for OFDM-Based PLC Systems

This chapter deals with adaptive power allocations for PLC systems employing OFDM transmission. A new power loading algorithm that minimizes the total transmit power in the presence of impulsive noise and guarantees a target bit error rate (BER) and a target data rate is introduced in this chapter. Closed-form expressions for the BER and power allocations among the subchannels are derived. The algorithm is tested in a power line channel in the presence of impulsive noise and the results are presented.

Chapter 6: Adaptive Bit Loading for OFDM-Based PLC Systems

This chapter also deals with adaptive modulation in OFDM-based PLC systems, yet from a different perspective. The focus here is on the maximization of the data rate given BER and transmit power constraints. A simple non-iterative bit-loading algorithm that can achieve high data rates, yet maintain a very low computational complexity is proposed in this chapter. The algorithm is also examined using the same PLC channel model and the results are illustrated.

Chapter 7: Conclusions and Future Work

This chapter summarizes the main conclusions of this dissertation and presents possible future directions.
Chapter 2

Literature Review

2.1 Introduction

The basic principle of power line communications (PLC) is to use the existing electrical power line networks for telecommunication purposes. Over the years, power line networks have served as a medium of transmission and distribution of electricity signals. Until recently, communication over power lines was restricted to low-speed functions such as remote metering and operations management that serve the needs of power supply utilities. This limited scope of power line functions changed recently, on account of the tremendous demand for high-speed broadband multimedia communications.

A survey of the literature surrounding PLC is provided in this chapter. Undoubtedly, knowledge of the structure and properties of power line networks is essential for the examination and development of new PLC techniques and products. The historical development and the current advances in the PLC technology are outlined. Details about the contending modulation techniques and channel modelling methods are also provided. This chapter serves as a knowledge basis that will be used in later sections of the dissertation to investigate existing techniques and develop new ones to serve the aim of enhancing the performance of PLC systems.

2.2 Electrical Networks and Their Properties

Power line communication (PLC) technologies make use of the existing infrastructure of the electrical grids to transmit communication signals delivering various broadband services. The fundamental purpose of electric power lines is, however, the transmission and distribution of AC power signals at 50 Hz or 60 Hz (typically 60 Hz in North America and 50 Hz in Europe and other parts of the world) from the power plants to the end consumer. Therefore, power line networks differ significantly in topology, structure and physical characteristics from conventional communication channels like twisted pair, Ethernet cables, coaxial cables, optical fibres and so forth. It is important to first study and understand the structure and properties of power lines to verify their viability as a medium of high-speed data communications.

Electrical networks are classified based on voltage levels into three sectors [5]: the high-voltage (HV) level (110 - 330 kV), the medium voltage (MV) level (10 - 30 kV) and the low voltage (LV) level (0.4 kV). These three segments of the electrical network are interconnected by transformers. If data signals are transmitted at higher frequencies through power lines, the transformer acts as a barrier and allows only low frequency electric signals to pass. Fig. 2.1 shows a typical structure of an electric power system.

2.2.1 High-Voltage Level

High-voltage power lines are used for the transmission of electrical power generated at the power plant to multiple substations, crossing long geographical distances of up to several hundred kilometers. High-voltage power networks form the electric power backbone for the electric utility. Three phase structures implemented in the form of overhead conductors are used for HV power transmission.



Figure 2.1: Simplified structure of the electrical network.

Electric power is transported at high voltage levels to essentially minimize the energy loss in long distance transmission. The main losses present in high-voltage lines are the heat loss caused by the resistance of the power line material and leakage losses [5]. Heat losses can be minimized by increasing the nominal voltage. However, increasing the voltage results in an increase of the leakage losses. A good selection of the wire material and appropriate dimensioning of power lines can control heat losses at acceptable levels. Due to the high electric field strength at the high-voltage level, discharge activities in the surrounding ambience are stimulated causing additional corona losses. This discharge effect is stronger if thinner wires are used for high-voltage energy transmission. In addition to the energy losses, corona discharge can generate intensive high-frequency impulses interfering with radio communications using the low and medium frequency bands. Corona losses and associated interference can be minimized by a proper geometric arrangement of the high-voltage wires.

Interference at high frequencies constitutes another obstacle for reliable communication over high-voltage lines. Two main types of high-frequency interference are present in high-voltage overhead lines [5]: the first type is the periodic short-duration impulsive interference which is caused by switching events and atmospheric discharges. This type of interference has a broadband spectra in the frequency domain. Due to the high voltage levels, the resulting impulses are characterized with very high amplitudes causing dangerous peaks at the receiving end. The second type of interference that occurs in high-voltage electric lines is a permanently present broadband interference with fairly high power spectral density. This interference is caused by discharge activities and can be modelled as White Gaussian Noise (WGN) with a PSD that is strongly dependant on weather conditions increasing dramatically during rain, frost or fog.

Due to the severe interference and attenuation at high voltages, HV power lines are not suitable for data transmission [8]. Instead, fibre optic cables are often installed along high-voltage routes for monitoring and control purposes and can be utilized for data transmission taking advantage of their high capacity.

2.2.2 Medium-Voltage Level

Medium-voltage networks are generally used to supply electrical power to rural areas, small towns and individual industrial companies. Typically, medium-voltage power lines carry voltage levels ranging between 10 kV and 30 kV and have lengths of about 5 - 25 km [5]. Overhead lines and underground cables are both used in the medium-voltage level for power transmission and distribution. However, in densely-populated urban areas, only underground cables are used. Medium-voltage overhead wires require relatively small poles and smaller wire cross sections when compared to highvoltage transmission lines. This is due to the smaller voltage levels carried in medium-voltage power lines. Regarding the physical structure, mediumvoltage wires are mainly made of copper and aluminium with various cross section shapes including round, sector-shaped and oval [5]. Polyvinyl chloride (PVC) and vulcanized polyethylene (VPE) are usually used for the insulation material in medium-voltage wires. With regards to data transmission, medium-voltage lines form the backbone of electric utility data communications over power lines [8].

2.2.3 Low-Voltage Level

The low-voltage level is the last portion of the electrical network supplying power at 100 - 400 volts to the end consumer. In Europe, underground cables are mainly used in this voltage level [5], [9]. However, in Australia LV overhead lines can still be seen in urban areas. The physical structure of lowvoltage lines is similar to that of medium-voltage lines and are composed of copper or aluminum with PVC or VPE insulation. The length of LV power lines normally extends up to 500 m from the MV/LV transformer station to the consumer's meter . PLC technologies make use of the low-voltage power networks to deliver communications services to the home or office as well as establishing in-building networking via power lines.

2.2.4 Characteristics of Power Lines

Power lines form the medium of transmission in PLC systems. The original purpose of these lines is the transportation of electric signals at 50 or 60 Hz and their design did not take into consideration the potential use for data transport at higher frequencies. This section provides an overview of the technical characteristics of electrical wiring to gain an insight about their usability for data communication.

Capacitance and Inductance

The power line network distributes electrical power to various devices connected to the network. Each of these devices is characterized with certain inductance (L) and capacitance (C) depending on the current running through its circuits.

The inductance of an electric circuit is a value expressing the magnetic flux caused by the current running through the circuit. Depending on the value of the inductance, it can be limited within the circuit or may interfere with other circuits. If an electric current (I) induces a magnetic flux (ϕ) , the inductance (L) can be defined [10] by:

$$L = \frac{\phi}{I} \tag{2.1}$$

If the current operating the circuit is an alternating current (AC) with

voltage (V) at a frequency (f), the following expression can be used:

$$L = \frac{V}{j2\pi fI} \tag{2.2}$$

The capacitance of an electric circuit represents a measure of the amount of electrical energy stored for a given potential created between two adjacent conductive surfaces with opposite charges [10]. The capacitance is defined in terms of the electric charge (Q) and the voltage (V) between the two surfaces according to the following:

$$C = \frac{Q}{V} \tag{2.3}$$

For the AC voltage supplied by the power line network, the capacitance (C) can be defined by the following:

$$C = \frac{I}{j2\pi fV} \tag{2.4}$$

Impedance

The overall opposition to the flow of current in alternating current (AC) circuits is measured by the impedance. The impedance (Z) of a cable is made of resistive, capacitive and inductive components and can be expressed in complex form by [10]:

$$Z = R + jL2\pi f + \frac{1}{jC2\pi f} \tag{2.5}$$

If a direct current (DC) runs trough the circuit, the impedance is equivalent to a pure resistance. In electrical networks, devices are continuously connected to or disconnected from the network. Therefore, the input impedance seen by a PLC device connected to the network my be variable. This variation makes it difficult to model the power network for the transmission of communication signals. If the loads in the electrical network are not properly matched to the cable's characteristic impedance, reflections from the loads back to the cable can occur. Depending on the output impedances of the loads, the reflections may be significant and can limit the distance that can be traveled by the communication signal through the power cable. The channel variation due to the plugging/unplugging of electrical appliances necessitates the need for adaptive techniques to optimize the performance of PLC systems which will be discussed in details in chapters 5 and 6.

2.2.5 Noise in Power Lines

An important feature of electric networks, particularly in the "last mile" area (see Fig. 2.1) and in-building wiring, is the susceptibility to a variety of signals. In order to use power lines for reliable high-speed PLC data transmission, it is vital to study and understand the different interference scenarios that exist in the electric network. Interference in power lines usually originates from electrical devices connected to the network or in its proximity. Interference can occur due to the normal operation of some electrical machinery and devices. In addition, switching electrical appliances (on and off) causes impulsive current and voltage peaks propagating along the electrical wiring. Typical noise-generating electrical devices include light dimmers, fluorescent and halogen lamps, universal motors and so forth [11], [12].

Another kind of interference affecting broadband power line communications (BPL) is related to electromagnetic interference (EMI) and electromagnetic compatibility (EMC) of power lines. Electric wiring is vulnerable to irradiation from radio services operating in the same radio frequency (RF) band. BPL devices typically use the frequency band (2 – 30 MHz). An example of radio services occupying frequencies within this band is the amateur radio that has been using portions of the medium-frequency (MF) and high-frequency (HF) bands for decades.



Figure 2.2: Noise scenario in the power line channel.

Therefore, unlike most other communication channels, noise in the power line cannot be described by the classical approach of additive white Gaussian noise (AWGN). The noise present in power lines is often categorized into classes. In [5], the noise at a wall outlet is summarized into three main categories: colored background noise, narrowband interference and impulsive noise. According to [6], there are five types of noise: colored background noise, narrowband noise, periodic impulsive noise asynchronous to the mains frequency, periodic impulsive noise synchronous to the mains frequency and asynchronous impulsive noise. Fig. 2.2 depicts the noise scenario encountered during PLC transmission. The transmitted signal x(t) passes through a PLC channel expressed by a channel transfer function H(f). Then, different types of noise are added to x(t) before arriving at the receiver. In the following, the different types of noise that are depicted in Fig. 2.2 are explained in more detail.

• Colored background noise: this type of noise is assumed to be the summation result of numerous sources of white noise with different noise amplitudes at different portions of the frequency band [13]. Colored background noise is generally characterized by a reasonably low power spectral density (PSD). This PSD level decreases with the increase in frequency. Its highest value is in the frequency band near the electrical signal frequency (50 Hz or 60 Hz) up to about 20 kHz [5].

- Narrow-band noise: this type of noise occurs at narrow fractions of the frequency band but with high PSD. Narrowband interference appears as sharp peaks of noise amplitudes in the frequency domain. It is generally the result of radio stations broadcasting their signals in frequencies typically within the 1 22 MHz range. However, narrowband interference may take place at lower frequencies. The cause of interference at such low frequencies is the switching of electrical devices like television sets, power supplies, fluorescent lamps or computer screens [5].
- Periodic impulsive noise synchronous to the mains frequency: the main cause of periodic impulsive noise is the switching of rectifiers in DC power supplies [13] and phase control in electric devices such as light dimmers, which happens synchronously with the electric signal frequency. Periodic voltage peaks of impulsive nature are generated at every zero-crossing of the mains signal leading to repetition rates of multiples of the mains frequency (i.e. 50 or 100 Hz for 50 Hz power grids). Impulses of this type are characterized by short durations and a PSD that decreases with frequency.
- Periodic impulsive noise asynchronous to the mains frequency: this periodic interference occurs with repetition rates in the range of 50 - 200 kHz. Impulses of this kind occur due to the switching of power supplies.
- Asynchronous impulsive noise: the main cause of asynchronous impulsive noise is the switching transients that occur in different parts

of the electric network. Experiments in [6] show that typical impulses of this type have durations ranging from some microseconds to a few milliseconds. The fact that this type of noise has a random behaviour and can appear in bursts signifies the severe effect it can have in highspeed communications using the PLC technology. It also highlights the need for robust modulation techniques, as will be discussed in section 2.7 of this chapter, as well as powerful channel coding schemes which will be investigated in chapter 4.

The first three noise types listed above usually remain stationary over long periods of time (i.e. seconds, minutes or hours) and can be summarized as background noise [5],[6],[14]. The last two types have a random timevarying nature and can be summarized as impulsive noise. A review of the different approaches to modelling impulsive noise will be given in section 2.5.

2.3 Historical Development of Communications Over Power Lines

Electrical power networks were originally designed for the transmission and distribution of power from power plants to end users. However, the use of this infrastructure for data communication purposes began soon after fullcoverage electrification [5]. The driving force behind the initial development of communication systems that use the electric network was the need for a communication link to maintain the function of HV transmission networks. Power supply utilities (PSUs) had to establish a fast bidirectional flow of information between power plants, transformer stations, switching gears and coupling points for tasks such as operations management, monitoring and fault finding and removal. It was rational to use the HV lines to fulfil the communication task in addition to the transmission of electric energy, since telephone lines were not available in all points where communication is required. Moreover, telephone lines were found unreliable and often caused serious interruptions during necessary communications [5], [15]. Among the first applications involving data transmission over power line networks were also the applications related to remote meter readings [16], [17]. This section provides an overview of the historical development and some of the classical applications of power line communications. The main technique using HV power lines for data transmission has been CTP (Carrier Transmission over Power lines), whereas in the MV and LV networks the RCS (Ripple Carrier Signalling) was used.

2.3.1 Carrier Transmission over Power lines (CTP)

The development of carrier transmission over telephone lines started in 1914 [15]. Four years later, the technique was available commercially in the US under the name "wired wireless". The application of this technique in power lines first appeared in Japan in the same year of 1918 [18]. The rapid expansion of high-voltage lines supplying electric power to new areas made it necessary for power companies to use CTP for their operations management to optimize the distribution of power. At the beginning, communications between the different parts of electric networks were mainly made using voice transmission (often referred to as "carrier-wave telephony over power lines"). Later, automatic tele-metering and remote monitoring became increasingly important and necessitated non-voice data transmission. For PSUs, the use of CTP achieved many advantages over the use of telephone lines for their communications purposes. Among these advantages are the following:

- Expenses related to the installation and maintenance of private telephone lines are removed.
- High rental costs of leased lines are avoided.

- Communication through power lines is more reliable since no interference from electric lines is experienced.
- Audibility is higher than with ordinary telephone lines.

One of the main tasks conducted by the data communications network of power companies is to ensure that the energy is distributed in an optimum way. Therefore, it is important to reserve sufficient energy for peak loads and at the same time making sure that no redundant energy is left over. Another important task achieved by data links in power networks is monitoring, which provides information about energy requirements, voltage levels and frequency. In addition to these two tasks, data communications over HV power lines is an important tool in the case of failures. In such cases, a fast and reliable communication channel must be available between power plants, transformer stations and coupling points. HV power lines represent a suitable data communication channel. Due to their good transmission characteristics, HV power lines provide a relatively wide spectrum and only low transmit powers are needed for reliable data transmission through HV lines [5].

Using a low transmit power of only 10 Watts, CTP can cross very long distances reaching up to 900 km under good conditions [5]. Under unfavorable conditions, it can cross about 300 km. CTP uses a frequency band from 15 kHz up to 500 kHz. Frequencies below 15 kHz are not suitable mainly due to the cost of the required capacitors. On the other hand, severe attenuation at frequencies above 500 kHz makes it difficult for communication signals to travel long distances. Portions of this frequency band may also be occupied by radio operators in the long-wave and medium-wave bands. Because power lines are designed mainly for power transmission at low frequencies (50 or 60 Hz), they are not well protected against interference from radio operators at higher frequencies. On the contrary, transmission of higher frequency communication signals through HV lines causes limited interference to radio receivers operating in the neighborhood. For frequency allocation of CTP, it is essential to avoid any frequency bands used by radio stations that may be transmitting their signals from neighboring locations.

Since communications over HV lines started as voice communications using the carrier-wave telephony, amplitude modulation (AM) was used to carry the voice signal through power lines. AM with its variants represented a reliable and cost-effective signal modulation scheme for both the transmitting and the receiving sides.

2.3.2 Ripple Carrier Signalling (RCS)

The idea of using power lines for data transmission was not only limited to high-voltage power lines. Medium-voltage and low-voltage levels of the power network needed to be equipped with communication links too. The task of the communication link in the MV and LV networks is primarily the management of energy distribution to ensure optimum exploitation of the power capacities delivered by HV power lines. When compared to HV power lines, MV and LV lines have poor data transmission properties, which requires high transmit power levels for communication signals [5]. This is due to the large number of junctions, relative to HV networks, that exist in the MV and LV electric networks. Ripple carrier signalling (RCS) has used MV and LV power grids for communication purposes since about 1930. To enable communication signals to pass through the transformers between the MV and LV levels and avoid additional costly coupling equipment, only very low frequencies near the power signal frequency are used in RCS. This, however, results in low data rates that are not sufficient for bidirectional flow of information. For this reason, only unidirectional communications from the PSU to the power consumer are possible using RCS. Furthermore, due to the restriction to a single directional communication flow, remote metering can not be achieved by this technique.

In its early applications, RCS used time division multiplexing (TDM)

for the transmission of its information signals, where the mains voltage was modulated based on amplitude modulation. Later in 1935, systems using single-frequency employing TDM were introduced. The information transmitted using RCS have mainly been on/off commands from the power company to the consumer, which is basically digital information. Today, digital modulation techniques such as on-off keying (amplitude shift keying (ASK)) is the obvious choice for RCS and is widely used in practice [5]. Owing to the simplicity of its receivers, ASK is the dominant modulation scheme for RCS communications.

2.4 Power Line Channel Modelling

The development of new communication systems requires a comprehensive knowledge of the characteristics of the transmission medium. The choice of the transmission technique and other design parameters is based on the channel transfer properties and the capacity offered by the channel. This calls for suitable models that can describe, with sufficient precision, the transmission behaviour over the communication channel. The power line channel was not designed for high-speed data transmission communications, hence modelling this channel is a very difficult task and forms one of the major technical challenges [7], [9], [13], [19]. In addition to the impulsive noise problem that was discussed in the previous section, power lines demonstrate strong branching due to their complicated distribution structures, leading to a significant degradation of transmission quality. Signal propagation along power lines does not only take a single path from the transmitter to the receiver. Reflections from load points lead to the reception of multiple delayed versions (echoes) of the transmitted signal. Several attempts to model the power line can be found in the literature (e.g. [2], [20]-[22]). Nevertheless, existing models for the transfer function of power lines are based on two fundamental approaches: time domain and frequency domain [9]. Time domain models are generally based on measurement trials and averaging of the obtained results. Frequency domain models, on the other hand, are based on a deterministic approach. The two approaches are briefly reviewed in the following two sections.

2.4.1 Time Domain Approach: The Multipath Model

The topology and structure of power line grids are different from telecommunications networks. In power line networks, the link between a substation and the customer's premises is not presented by a point-to-point connection as in the case of communications networks such as telephone local loops. As shown previously in Fig. 2.1, the link from a transformer substation consists of a distribution link forming a bus topology and house connections with various lengths representing branches from the distributor cable. The house connection is terminated at a house connection box followed by numerous branches in the in-house wiring. Branching and impedance mismatches in the power line network cause numerous reflections leading to a multipath propagation scenario with frequency selectivity. Moreover, frequency-dependant attenuation has to be considered when modelling the power line channel. Signal attenuation in power lines is the result of coupling losses which depend on the PLC transmitter design and line losses depending on the length of the cable [7]. In addition to the frequency-dependent attenuation, the channel transfer function is also time-varying and depends on the location of the receiver since different appliances are constantly being switched on or off causing changes in the transfer function. Models of the power line channel transfer function that describe the multipath propagation effects have been proposed by Philipps [20] and Zimmermann and Dostert [1], [2]. According to [2], the channel transfer function H(f) that describes the signal propagation in power lines in the frequency range from 500 kHz to 20 MHz is given by the following:

$$H(f) = \sum_{i=1}^{N_p} \underbrace{c_i}_{\text{weight}} \cdot \underbrace{e^{-(a_0 + a_1 f^k)d_i}}_{\text{attenuation}} \cdot \underbrace{e^{-j2\pi f\tau_i}}_{\text{delay}}$$
(2.6)

where N_p is the number of relevant propagation paths, c_i and d_i are the weighting factor and length of the *i*th path respectively. In this model, the echo scenario is represented by the superposition of signals arriving from N_p different paths. Frequency-dependent attenuation is defined by the parameters a_0 , a_1 and the exponent k. In the model, the first exponential presents attenuation factor, whereas the second exponential describes the echo scenario where τ_i is the path delay and is given by the following:

$$\tau_i = \frac{d_i \sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \tag{2.7}$$

where ε_r is the dielectric constant of the insulating material, c_0 is the speed of light and v_p is the propagation speed.

To demonstrate the multipath signal propagation in power lines, a simple example from [2] is illustrated in Fig. 2.3. The link consists of a power line with a single branch represented by the line from point B to point D in the figure. The three segments of the link (i.e (1), (2) and (3)) are assumed to have different length and different characteristic impedances. If points A and C are matched to their line characteristic impedances, then only points B and D can cause reflections in the network. Reflections caused by the points B and D lead to an infinite number of propagation paths from point A to point C (e.g A-B-C or A-B-D-B-D-B-...-C). Depending on the transmission and reflection factors in each branch, each propagation path will have a different weighting factor, which is denoted by g_i in the transfer function given in equation (2.6).

The parameters of the model in equation (2.6) can be obtained from measurements of the complex transfer function of the power line channel.



Figure 2.3: Example of a simple power line link with one branch causing multipath propagation.

The magnitude of the frequency response can be used to determine the values of the attenuation parameters (i.e. a_0 , a_1 and k). The path parameters $(g_i, d_i \text{ and } \tau_i)$ can be obtained using the impulse response of the channel. The number of paths is typically in the range 5 – 50 paths [13].

2.4.2 Frequency Domain Approach: Transmission Line Models

The power line channel can be modelled using a deterministic approach given a detailed knowledge of the communication link between the transmitter and the receiver. This includes knowledge of the topology, physical properties of the cable, load impedances and so forth. In the following, models based on the two-conductor and multi-conductor transmission line (MTL) theory are briefly reviewed.

Two-conductor transmission line models

Several attempts to utilize the two-conductor transmission line theory in modelling the power line channel can be found in the literature (e.g. [21] and [22]). These models use either scattering or transmission matrices [9]. A two-conductor transmission line, with ground being the second conductor, supports four modes of signal propagation. The signal travels along the line in two spatial modes each having two directions of propagation [9]. The two spatial modes are the differential and common modes. The dominant mode carrying the data signal in the desired direction along the transmission line is the differential mode. Differential signalling can be used to excite the propagation in the differential mode only, and minimize the propagation in the common mode which is normally induced by external noise. To achieve good rejection of unwanted external signals, the two conductors must be well balanced as any imbalance between them excites common mode propagation. The two-conductor model did not address the effects of wiring and grounding practices in the transmission behaviour. In addition, the model neglected the effect of electromagnetic compatibility issues in the estimation of the common mode currents. Moreover, the two-conductor model does not explain the propagation in the presence of a third conductor as appears in single-phase power lines, leading to a MTL situation. Therefore, the attempts to model the power line channel based on a two-conductor transmission line approach did not fully explain the propagation behaviour along power lines [9].

Multi-conductor transmission line (MTL) models

Power cable used in single-phase connections consist of three or four conductors, which limits the applicability of the two-conductor transmission line model in explaining the propagation scenario. Therefore, the modelling of the power line channel in the presence of a third or fourth conductor should rather utilize MTL theory. In MTL, a transmission line consisting of N conductors and a ground is partitioned into N simple TL's, each representing a single propagation mode [23]. Accordingly, the signal at the input of an MTL is broken into N modal components, each of which travels along the corresponding modal TL. The modal components of the signal are recombined at the output ports. The coupling between each port and each modal TL is obtained using the weighting factors in the voltage and current transformation matrices.

If a three-conductor power cable is used, then six propagation modes exist in the line resulting from three spatial modes (i.e. differential, pair and common). Each of the three spatial modes has two directions of propagation. The desired signal current generally travels in the differential mode. The signal in the pair-mode corresponds to the current flowing from the ground wire and the other two wires, whereas the signal in the common mode of propagation corresponds to the overall imbalance between the modes and is directly related to the cable installation practices [19]. In indoor PLC systems, there is often an imbalance between the propagation modes which results in coupling between the modes [19].

Frequency-domain channel models based on TL theory offer the advantage of low computational complexity that is almost independent of the power line link topology [9]. However, full and detailed knowledge of the transmission link must be available *a priori*. The model requires details about the topology, properties of the cables used and impedance values at the end of every branch involved. The accuracy of the model can be significantly affected if perfect knowledge of such parameters is not available. In a practical scenario, such knowledge of the power line network is nearly impossible, which makes modelling the power line channel using frequencydomain models based on TL theory unrealistic. The time-domain approach described in section 2.4.1, however, does not require such details about the network. For this reason, the time-domain multipath model is preferred over frequency-domain models and it is utilized in this thesis to simulate the communication scenario in power lines.

2.5 Impulsive Noise Modelling

Asynchronous impulsive noise forms one of the main challenges for highspeed communications over power lines. Practice shows that this type of noise can have large energy leading to a significant degradation in the performance of PLC systems [13], [24]. The fact that impulsive noise may frequently sweep complete data symbols concerns researchers and designers of PLC devices and systems. In [25], practical measurements in power lines found that the typical strength of a single impulse is more than 10 dB above the background noise level and can exceed 40 dB. Measurement results in [6] indicate that the PSD of impulsive noise generally exceeds the PSD of background noise by a minimum of 10-15 dB in most parts of the frequency band 0.2 - 20 MHz. According to their measurements, this difference may rise to more than 50 dB at certain portions of the band.

Fig. 2.4 shows a sample impulse having a duration of approximately 50 μ sec. In the time domain, three random variables characterize the impulsive noise that occurs in power lines and other communication mediums. These are: impulse width, amplitude and inter-arrival time (IAT). Several attempts to derive the probability distribution statistics of these three parameters based on practical measurements in power line networks can be found in the literature (e.g. [25] and [26]). The impulse width and amplitude both identify the energy of a single impulse. The frequency of the impulses (the reciprocal of the IAT) along with the impulse energy describe the power of impulsive noise. Different statistical approaches attempting to model impulsive noise can be found in the literature. Background noise on the other hand is usually modelled as white Gaussian noise (WGN) [25]. In this section, we look at some of these models to gain more understanding of the characteristics of impulsive noise.



Figure 2.4: Sample impulse.

2.5.1 Middleton Class A Noise

Middleton in [27]-[29] classifies the electromagnetic (EM) noise or interference into three main classes: Class A, Class B and Class C (the sum of Class A and Class B). Many researchers consider the Middleton Class A noise model suitable for describing the statistical characteristics of impulsive noise in PLC environments (e.g. [24], [30]-[32]) as well as other communication environments (e.g. [33]). The model incorporates both background and impulsive noises. According to the Middleton Class A model, the overall noise is a sequence of independent and identically distributed (i.i.d.) complex random variables with the probability density function (PDF):

$$p(z) = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{2\pi\sigma_m^2} \exp\left(-\frac{z^2}{2\sigma_m^2}\right)$$
(2.8)

2.5 Impulsive Noise Modelling

with the variance σ_m^2 defined as:

$$\sigma_m^2 = (\sigma_g^2 + \sigma_i^2) \frac{\left(\frac{m}{A}\right) + \Gamma}{1 + \Gamma}$$

where the parameter A is called the impulsive index and is given by the product of the average rate of impulses per unit time and average impulse duration. The variances σ_g^2 and σ_i^2 denote the power of background noise and impulsive noise respectively. The ratio between background noise and impulsive noise power is given by the parameter Γ . Therefore:

$$\Gamma = \frac{\sigma_g^2}{\sigma_i^2} \tag{2.9}$$

It can be noticed from (2.8) that the PDF of Middleton Class A noise is in fact a weighted sum of Gaussian PDF with mean equal to zero. Therefore the mean and variance of this process can be obtained by the following [24]:

$$\mu_{z} = E\{z\} = \int z.p(z).dz$$

= $\sum_{m=0}^{\infty} e^{-A} \frac{A^{m}}{m!} \frac{1}{2\pi\sigma_{m}^{2}} \int z.\exp\left(-\frac{z^{2}}{2\sigma_{m}^{2}}\right) = 0$ (2.10)

$$\sigma_m^2 = E\{z^2\} = \sum_{m=0}^{\infty} e^{-A} \frac{A^m}{m!} \frac{1}{2\pi\sigma_m^2} \int z^2 \cdot \exp\left(-\frac{z^2}{2\sigma_m^2}\right)$$
$$= \frac{e^{-A}\sigma_g^2}{\Gamma} \sum_{m=0}^{\infty} \frac{A^m}{m!} \left(\frac{m}{A} + \Gamma\right)$$
(2.11)

The Middleton Class A noise model was originally developed to describe the man-made EM interference with impulsive behaviour. Despite the fact that this model has been considered by many researchers to depict impulsive noise, its applicability to model impulsive noise in power line networks is inconclusive.

2.5.2 Binary-State Model

Impulsive noise can be modelled by a binary-state model [34]. The model has two states as illustrated in Fig. 2.5. The first state S_0 is the state when Impulsive noise is absent. At this state, the model generates samples with zero value. The second state S_1 , on the other hand, represents the "on" state which corresponds to the occurrence of impulsive noise. The model produces bursts of impulses with random amplitude and duration at this state. The probability of a transition from state S_i to state S_j is indicated by a_{ij} . Fig. 2.5 shows a simple memoryless structure of the binary-state model; in which the transition probability is independent of the current state. In the case of modelling impulsive noise, this means that the occurrence of an impulse (i.e. S_1 state) at time t + 1 is independent of the occurrence or absence of impulses at time t. This probability is given by the following:

$$P[s(t+1) = S_1|s(t) = S_0] = P[s(t+1) = S_1|s(t) = S_1] = \alpha \qquad (2.12)$$

where s(t) is the state at time t. Similarly, the probability that the model is in state S_0 at time t + 1 is independent of the state at t; it is given by:

$$P[s(t+1) = S_0|s(t) = S_0] = P[s(t+1) = S_0|s(t) = S_1] = 1 - \alpha \quad (2.13)$$



Figure 2.5: A binary-state model for impulsive noise. Reproduced from [34].

The binary-state model can be extended to a three-state model in order to improve the accuracy of modelling impulsive noise. Fig. 2.6 illustrates a three-state model for impulsive noise including a state representing the oscillations that might follow the impulses in an impulsive noise process. State S_0 corresponds to the state when there is no impulsive noise present. States S_1 and S_2 in this model represent, respectively, the occurrence of impulses and the oscillations that trail the impulses.



Figure 2.6: Three-state model for impulsive noise including a state for the oscillations that might trail the impulses. Reproduced from [34].

A more general extended form of the binary-state model is the Markov chain model. The Markov chain model uses a variable number of states with the property that the future behaviour depends only on the current state of the process. A special form of the Markov chain is the partitioned Markov chain, where the number of states is partitioned into two groups. The partitioned Markov chain model was proposed by Zimmermann and Dostert [6] to model the duration and IAT of impulsive noise in power line networks. The model was then used in several studies of impulsive noise in power line communications (e.g. [13] and [24]). The partitioned Markov model can have a variable number of states, n, partitioned into two clusters: *impulse* (A) including v states and *impulse-free* (B) including w states. The former cluster corresponds to the occurrence of impulsive noise, whereas the later cluster corresponds to the case when no impulses are present in the channel. The two groups (A and B) can be expressed using two different transition probability matrices. The following two matrices (X and Y) illustrate the transition probabilities for the *impulse* group of states and *impulse-free* group, respectively.

$$X = \begin{bmatrix} x_{1,1} & 0 & \dots & 0 & x_{1,v+1} \\ 0 & x_{2,2} & \ddots & \vdots & x_{2,v+1} \\ \vdots & \ddots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & x_{v,v} & x_{v,v+1} \\ x_{v+1,1} & x_{v+1,2} & \dots & x_{v+1,v} & 0 \end{bmatrix}$$
(2.14)
$$Y = \begin{bmatrix} y_{1,1} & 0 & \dots & 0 & y_{1,w+1} \\ 0 & y_{2,2} & \ddots & \vdots & y_{2,w+1} \\ \vdots & \ddots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & y_{w,w} & y_{w,w+1} \\ y_{w+1,1} & y_{w+1,2} & \dots & y_{w+1,w} & 0 \end{bmatrix}$$
(2.15)

where v and w indicate the number of states in groups A and B respectively. The elements of the two matrices can be found using measurements [6].

2.5.3 Bernoulli-Gaussian Model

Due to its simplicity, the Bernoulli-Gaussian model is often used to model impulsive noise in power line networks and other communication channels [35]-[39]. In a Bernoulli-Gaussian model of impulsive noise, the occurrence of impulses is modelled according to the Bernoulli process b(m), whereas the amplitude of the impulses is modelled according to the Gaussian distribution n(m) [34]. A Bernoulli process is an i.i.d. sequence of ones and zeros with a probability that the process takes a value of '1' $(p(b(m) = 1) = \alpha)$; consequently, the process takes a value of '0' with a probability of $1 - \alpha$. The probability mass function (pmf) of a Bernoulli process is given by:

$$P_b[b(m)] = \begin{cases} \alpha & \text{for } b(m) = 1\\ 1 - \alpha & \text{for } b(m) = 0 \end{cases}$$
(2.16)

The mean and variance of the Bernoulli process are:

$$\mu_b = E\left[b(m)\right] = \alpha \tag{2.17}$$

$$\sigma_b^2 = E\left\{ [b(m) - \mu_b]^2 \right\} = \alpha (1 - \alpha)$$
(2.18)

The amplitudes of impulses are obtained from a Gaussian distribution with zero mean and variance σ_n^2 , which has the following probability density function (pdf):

$$G[n(m)] = \frac{1}{\sigma_n \sqrt{2\pi}} exp(-\frac{n^2(m)}{2\sigma_n^2})$$
(2.19)

2.5.4 Poisson-Gaussian Model

A simple and efficient way that is often used to model impulsive noise is the Poisson-Gaussian model [33], [36], [37]. In [37], Measurement results in residential power line networks show that the arrival of impulsive noise follows a Poisson distribution. In the Poisson-Gaussian model, the arrival of impulses is modelled according to the Poisson process and the impulsive noise amplitudes are modelled based on the Gaussian process with a mean of zero and variance σ_n^2 . This means that impulsive noise will occur according to a Poisson distribution with a rate λ units per second, so that the probability of an event of m arrivals in unit time is:

$$P_p(m) = P_p(M = m) = e^{-\lambda} \frac{\lambda^m}{m!}, \quad m = 0, 1, 2, \dots$$
 (2.20)

On the other hand, the amplitude of impulsive noise follows a Gaussian distribution with a mean of zero and variance σ_n^2 as in the previous section.

To model the total noise that occurs in PLC transmission in the discretetime domain, the background noise w_k is usually assumed to be an AWGN [21], [36]. The impulsive noise i_k can be defined using the Poisson-Gaussian model as:

$$i_k = b_k g_k \tag{2.21}$$

where b_k represents the arrival of impulses according to the Poisson process and g_k is a white Gaussian process representing the amplitudes of the impulses. This model can be physically thought of as each transmitted symbol being independently struck by an impulse with a probability of b_k having a random Gaussian amplitude of g_k [35].

If the signal a_k is transmitted over power lines impaired by impulsive noise, the received signal can be represented by:

$$r_k = a_k + w_k + i_k \tag{2.22}$$

The probability density function of the total noise n_k is given by [35]:

$$p(n_{kR}, n_{kI}) = (1 - \alpha) G(n_{kR}, 0, \sigma_w^2) G(n_{kI}, 0, \sigma_w^2) + \alpha G(n_{kR}, 0, \sigma_w^2 + \sigma_i^2) G(n_{kI}, 0, \sigma_w^2 + \sigma_i^2)$$
(2.23)

where α is the probability of occurrence of impulsive noise and $G(x, \mu, \sigma^2)$ is the Gaussian pdf with mean μ and variance σ^2 and is defined in equation (2.19). Due to its simplicity and efficient representation of impulsive noise in practical power line networks [37], the Poisson-Gaussian model is adopted as the impulsive noise model in all the experiments studied in this thesis. The total noise that exist in power lines includes, in addition to impulsive noise, background noises that are simply modelled as an AWGN.

2.6 Mitigation of the Effect of Impulsive Noise

Several types of noise can be encountered in power line networks. Section 2.2.5 provided details about some of the characteristics and the common causes of each type of noise. Among those types, impulsive noise is the most damaging type of noise and represents a significant limiting factor for high-speed communication over power lines [13], [36]. This type of noise is also a major cause of impairments in other high-speed communication systems as well, including digital subscriber line (DSL) [41]-[43] and digital video broadcasting (DVB) 44. In DSL systems, impulsive noise is usually caused by various sources such as lightning surges, vehicles' ignition and engine noise, electromagnetic discharge and transmission and switching gear [45], [46]. A study of the effect of impulsive noise in ADSL was presented in [43]. In DVB systems, similar sources as in ADSL are the cause of noise with impulsive noise sources including home electrical appliances, light switches, ignition systems and central heating thermostats [44], [47]. Measurements and statistical analysis of impulsive noise in terrestrial DVB systems can be found in [44].

In power line networks, the presence of impulsive noise makes it difficult to model the noise scenario in this channel, since the commonly used AWGN model is not applicable. Impulsive noise can have a PSD that is 50 dB higher than the background noises [6].

A good selection of the modulation technique is crucial for high-speed PLC systems. As will be discussed in section 2.7, OFDM and multicarrier modulation schemes in general perform better than single-carrier schemes in the presence of impulsive noise [36], [48]. This is due to the discrete Fourier transform (DFT) operation at the receiver, where the effect of impulsive noise gets spread among multiple subcarriers. However, if the power of impulsive noise exceeds a certain value, it will affect all the OFDM subcarriers leading to poorer performance than in the case of single-carrier modulation [35]. This signifies the importance of employing suitable techniques to reduce the adverse effect of impulsive noise in high-speed PLC applications.

Different studies on impulsive noise and methods to mitigate its effect in communication systems are found in the literature [38]-[65]. A simple method that is often used in practice to reduce the effect of impulsive noise is the time domain memoryless nonlinearity [38]. This technique is implemented on the received time-domain signal before the DFT operation in OFDM systems. Samples exceeding a certain threshold are clipped or blanked (nulled).

Some researchers proposed the use of frequency domain-based techniques to mitigate impulsive noise [3], [49], [50]. In these techniques the effect of impulsive noise is countered in the frequency domain after the DFT block at the OFDM receiver.

Another way of mitigating impulsive noise in communication systems is by implementing powerful error correcting codes that account for impulsive noise [56]-[65]. In this section of the dissertation, an overview of the existing methods used to mitigate the effect of impulsive noise in communication systems and PLC systems in particular is presented.

2.6.1 Time-domain Methods

The effect of impulsive noise in multicarrier signals can be reduced by preprocessing the time-domain signal at the front end of the receiver using a memoryless nonlinearity [38]-[40], [46]. Owing to their simplicity, nonlinear techniques including clipping, blanking and clipping/blanking are often used in practical applications [38], [40]. The function of this kind of techniques is based on the assumption that the amplitudes of impulsive noise are often distinguishably greater than the signal amplitudes [49]. Therefore, a threshold is defined and the signal samples that have amplitudes greater than the threshold are assumed to be affected by impulsive noise and hence modified according to the used nonlinearity. Fig. 2.7 illustrates a simplified block diagram of an OFDM system implementing a nonlinear technique to mitigate impulsive noise. The figure shows that the memory nonlinearity identifies both the amplitude and phase of the received signal, but only modifies the amplitude while the phase of the signal is kept unchanged [38]. The operation of the three nonlinearities is defined by the following:



Figure 2.7: Simplified block diagram of an OFDM system employing a memoryless nonlinearity for impulsive noise reduction.

1. Clipping

$$y_k = \begin{cases} r_k, & |r_k| \le T_c \\ T_c e^{j \arg(r_k)}, & |r_k| > T_c \end{cases}, \quad k = 0, 1, ..., N - 1$$
(2.24)

where T_c is the Clipping Threshold. The received OFDM signal is first processed using a clipping circuit, where any signal sample with amplitude higher than T_c is assumed to be affected by impulsive noise. The amplitude of the affected samples is then modified to (T_c) . The clipping circuit detects the amplitude and phase of the received sample, but only modifies the amplitude without changing the phase.

2. Blanking

$$y_k = \begin{cases} r_k, & |r_k| \le T_b \\ 0, & |r_k| > T_b \end{cases}, \quad k = 0, 1, ..., N - 1$$
(2.25)

where T_b is the blanking threshold. Blanking is also based on the assumption that any signal sample with amplitude greater than the threshold is the result of impulsive noise. However, while clipping assigns the threshold value T_c as amplitude to the affected samples, blanking gives a zero value to those samples. As will be shown in chapter 3, the blanking threshold is usually greater than the clipping threshold for the same system under the same noise conditions.

3. Clipping/Blanking

$$y_{k} = \begin{cases} r_{k}, & |r_{k}| \leq T_{c} \\ T_{c}e^{jarg(r_{k})}, & T_{c} < |r_{k}| \leq T_{b} , k = 0, 1, ..., N - 1 \\ 0, & |r_{k}| > T_{b} \end{cases}$$
(2.26)

where the clipping threshold (T_c) is smaller than the blanking threshold (T_b) . Clipping/blanking technique is a combination of clipping

and blanking nonlinearities, where two thresholds are defined. If the amplitude of a received sample exceeds the blanking threshold T_b , the sample is replaced with zero. If the amplitude is below the blanking threshold T_b yet above the clipping threshold, the sample is clipped and given an amplitude equal to T_c . The remaining samples with amplitudes below the clipping threshold are assumed to be the correct OFDM signal and hence are not modified by the nonlinear circuit.

The above mentioned time-domain nonlinearities will be studied thoroughly in chapter 3, where a PLC channel is used to investigate their performance in reducing the adverse effect of impulsive noise in PLC environments. Strategies to enhance the performance of these time-domain nonlinearities and optimize the threshold selection will also be described.

2.6.2 Frequency-domain Methods

The impulsive noise mitigation techniques discussed in the previous section operate on the received OFDM signal in the time domain prior to demodulation using the discrete Fourier transform. A different approach is to treat the effect of impulsive noise in the frequency domain [3], [49], [50]. Such techniques are employed at the OFDM receiver after the signal demodulation using the DFT. Zhidkov [3] proposed a frequency-domain method to suppress impulsive noise after demodulation and channel equalization of the received signal based on preliminary estimates of the transmitted signal that are then used to estimate the noise in the received signal. The obtained estimation of the impulsive noise term is subtracted from the original received signal prior to final demodulation using the DFT operation. Frequency-domain techniques can work well in reducing the impulsive noise effect, because impulsive noise appears random in the frequency domain while the signal is well-structured, whereas the opposite is true in the time domain [50].

If an OFDM signal s_k is transmitted over a channel that is impaired with impulsive noise, the received frequency-domain signal which is obtained after channel equalization and discrete Fourier transform can be given by the following expression:

$$R_k^{(eq)} = S_k + W_k \hat{H}_k^{-1} + I_k \hat{H}_k^{-1}, \quad k = 0, 1, ..., N - 1$$
 (2.27)

where H is the channel transfer function, W and I are the DFT forms of the AWGN and impulsive noise respectively. Based on the algorithm in [3], if an estimate of the transmitted signal s_k is available, then the total noise term can be calculated using (2.27). Therefore the received and equalized signal $R_k^{(eq)}$ is demapped according to the used constellation after replacing any pilot subcarrier with its known value. Silent subcarriers should be set to zero. This provides an estimate \hat{s}_k and its DFT \hat{S}_k of the transmitted signal s_k . Using this value of \hat{S}_k , the total noise term $D_k = W_k + I_k$ can be estimated according to the following:

$$\hat{D}_k = \hat{H}_k (R_k^{(eq)} - \hat{S}_k), \quad k = 0, 1, ..., N - 1$$
(2.28)

The total noise term D_k is then transformed into the time domain by means of the IDFT and a peak detector is used to obtain the estimated impulsive noise signal \hat{i}_k in the time domain. In a final step, the DFT of \hat{i}_k is computed and divided by the channel transfer function. The signal after impulsive noise reduction can be attained according to the following:

$$R_k^{(comp)} = R_k^{(eq)} - \hat{I}_k \hat{H}_k^{-1}, \quad k = 0, 1, ..., N - 1$$
(2.29)

Fig. 2.8 has been reproduced from [3] and shows the operation of the frequency-domain suppression technique proposed to mitigate the effect of impulsive noise in multicarrier systems.



Figure 2.8: Basic block diagram of frequency-domain impulsive noise mitigation technique. Reproduced from [3].

2.6.3 Error Correcting Codes

The power line channel is considered a hostile medium for high-speed data communications suffering mainly from multipath fading, attenuation and various kinds of noise including high-amplitude impulsive noise. Despite that, studies on the capacity of this channel promise very high data rates [24]. The use of OFDM as a transmission technique not only tackles impulsive noise, but also copes with some of the impairments of this channel such as frequency selectivity. In fact, the immunity against impulsive noise was one of the fundamental motives behind the renewed interest in using multicarrier modulations for digital communications [33], [66]. As will be explained in 2.7.3, OFDM is suitable for broadband applications because it uses numerous narrowband subcarriers that can be assumed to have a flat frequency response. In the case of impulsive noise, OFDM splits its effect between all the subcarriers during the demodulation process at the receiver.

Even with OFDM, in order for the PLC channel to exploit its capacity in full and provide broadband high-speed data rates, it is necessary to make use of effective channel coding schemes that are capable of combating impulsive noise and other channel impairments. Forward error correction (FEC) is implemented by adding redundancy bits to the useful data bits. The receiver can then use these redundancy bits to detect and possibly correct errors occurring during data transmission at the cost of lowering the useful data rate.

Different coding methods can be suitable for PLC systems. One of the well-known classes of coding is block coding, in which the data is divided into blocks of k data bits and each block is attached with the required redundant bits resulting in larger blocks of n bits. The code is then denoted (n, k). The code rate defines the ratio k/n between the data bits and the total number of bits per block.

A well-known simple class of block codes are Hamming codes. Such codes are very suitable for low-speed indoor PLC [5]. Hamming codes are capable of correcting all single errors and detecting combinations of two or less errors in a single block [67]. Hamming codes can be decoded using Syndrome decoding.

Another well-known class of block codes is the BCH code. BCH codes are basically a generalization of the Hamming codes where multiple error corrections can be achieved. They are more powerful and have a large variety of block lengths, code rates, alphabet sizes and error correcting capabilities. BCH codes perform better than all other block codes with the same block length and code rate when using a block length of a few hundred [67].

Coding for impulsive noise reduction has been addressed in a number of publications (e.g. [32]-[33] and [54]-[65]). In [32] and [33], the fundamental performance limits, in terms of achievable information rates, of single-carrier and multicarrier communication systems in the presence of impulsive noise were investigated. Low-density parity-check (LDPC) coding and decoding for impulsive noise correction was considered in [54] and [55]. The authors in [54] propose a coding system that uses irregular LDPC codes and bitinterleaved coded modulation for PLC systems impaired with both AWGN and impulsive noise. The BER performance of LDPC-coded OFDM in
channels impaired with impulsive noise was studied in [58]. Other coding schemes were designed to combat impulsive noise in OFDM systems based on the fact that OFDM as a multicarrier system can be viewed in the complex field as a Reed-Solomon code [56], [57]. In [65], a decoding strategy of block codes over complex numbers for channels affected by impulsive noise is introduced. The authors show that an OFDM system can be interpreted as a complex number code that uses the discrete Fourier transform (DFT) as the generator matrix. Therefore, a suboptimal iterative decoding algorithm was proposed for OFDM systems impaired with impulsive noise [65].

Many studies of impulsive noise in power line networks assume that impulsive noise arrives as independent and identically distributed (i.i.d.) complex random variables. However, impulsive noise can occur in bursts with durations that may be longer than the length of communication symbols [13]. This burstiness of impulsive noise should be considered for a proper design of PLC systems, since coding schemes that are designed for individual errors do not appropriately correct burst errors. This problem can be solved by the use of interleaving. By rearranging the data bits, the interleaver distributes the errors among the transmitted data and reduces the channel memory [13]. Consequently, the decoder sees the errors caused by bursts of impulsive noise as independent errors that are easier to control. The use of interleaving in combination with convolutional codes in power line channels affected by impulsive noise will be investigated in chapter 4 of this dissertation. Different coding rates and impulsive noise conditions will be used to study the performance of a bit-interleaved convolutionally coded OFDM system.

2.7 Modulation Schemes for PLC Systems

In previous sections of this chapter, the characteristics of the power line as a communication channel for broadband applications were outlined. We saw that PLC technologies have to combat hostile channel conditions seldom found in other well-known communication channels. The properties of power line networks and the vulnerability to various types of noise calls for a proper selection of modulation schemes to be used in PLC systems. Three major issues must be taken into account when selecting a modulation scheme for PLC [7]:

- The susceptibility to different types of noise including impulsive noise with relatively high noise power leading to lower SNR.
- The PLC channel is a time varying channel with frequency selectivity.
- Due to electromagnetic compatibility issues, the transmit power in PLC systems is limited to relatively low levels.

In this section of the thesis, some of the candidate modulation schemes for PLC systems are discussed.



Figure 2.9: Modulation methods for power line communications [69].

2.7.1 Single-Carrier Modulation

In single-carrier modulation, the data signal modulates a single carrier with frequency f_0 . The information is encoded in amplitude, phase or frequency of the carrier. In ASK (Amplitude-shift keying), the message signal modulates the amplitude of the carrier signal without affecting its frequency and phase, whereas in FSK (Frequency-shift keying) the frequency of the carrier is modulated. PSK (Phase-shift keying) is achieved by changing the phase of the carrier signal according to the information bits. A combination between PSK and ASK produces QAM (Quadrature-amplitude modulation). An example of QAM modulation with Gray coding in depicted in Fig. 2.10. The top figure shows the constellation diagram of rectangular 4-QAM, while the middle and bottom plots illustrate the rectangular 16-QAM and 32-QAM respectively. Single-carrier modulation schemes are attractive candidates for PLC systems mainly due to their simplicity. For narrowband applications of PLC, single-carrier modulation is a convenient option and has been adopted in practical applications [9], [68]. For broadband PLC, however, these schemes have been found to be insufficient for high-speed communications through power line channels [48]. This is attributable to several factors related to the transmission characteristics of the power line channel. First, the multipath effect in this channel causes significant inter-symbol interference (ISI) and introduces deep notches in the frequency domain of the transfer function representing frequency-selective fading. The affected frequencies may vary with time and location according to the properties and structure of the used power line network. In the presence of such unpredictable frequency-selective fading, the performance of single-carrier modulation can be very poor [48]. To elevate the performance and minimize the effect of ISI, powerful detection and equalization techniques have to be employed, which cancels out the simplicity feature associated with single-carrier schemes. Secondly, the channel attenuation usually increases with frequency and wide bands cannot be assumed to be sufficiently flat for high-data rate communications. Thirdly, in a noisy environment like power lines, broadband PLC technologies need to achieve high spectral efficiency. Unfortunately, basic single carrier modulation techniques can only achieve a spectral efficiency of up to 1 bit/s per 1 Hz [69].

2.7.2 Spread Spectrum Techniques

Spread spectrum techniques (SST) were initially developed for military applications with the aim of achieving robustness against intentional interference by spreading a narrowband signal over a wide frequency spectrum. For PLC applications, the interest in SST is due to its ability to combat frequency-selective fading introduced by the multipath effect as well as its robustness against all kinds of narrowband interference [48], [69]. In addition, SST is an attractive option for PLC because of the low power spectral density (PSD) of the transmitted signal, which concurs with the constraints related to EMC. There are several variants of SST including direct-sequence spread spectrum (DSSS), frequency hopping, time hopping, chirp and hybrid techniques. The media access in SST can be achieved by code division multiple access (CDMA) without the need for global coordination and synchronization [69].

In SST, a single carrier with frequency f_0 is first modulated with the information using conventional modulation methods producing a bandwidth that is approximately double the message bandwidth. Then a second stage of modulation is performed using a high-speed pseudo-random sequence as illustrated in the middle diagram of Fig. 2.9. After this modulation, a bandwidth of about twice the clock frequency of the pseudo-random sequence is obtained. At the receiver side, the same sequence used in the transmitter must be known and synchronized with the received signal. After that the resulting signal is demodulated conventionally to obtain the message signal.



(a) Constellation for Gray-coded 4-QAM



(b) Constellation for Gray-coded 16-QAM



(c) Constellation for Gray-coded 32-QAM

Figure 2.10: Constellation diagrams for QAM modulation with different sizes.

A fundamental element of SST that enables it to combat narrowband interference is the very wide bandwidth. For a given transmission bandwidth, the high redundancy needed for SST may significantly limit the data rate through the transmission channel. Therefore, for SST to provide high-speed communications over power lines, it needs a very large bandwidth that may not be available in the power line channel. Spectral efficiency in PLC can be achieved by employing multicarrier modulation methods such as orthogonal frequency division multiplexing (OFDM) that will be discussed in the following section.

2.7.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a mature multicarrier technique that has been well-proven in several high-speed wired and wireless applications. Examples of its applications include digital audio broadcasting (DAB), digital video broadcasting (DVB), asymmetric digital subscriber line (ADSL) and Wi-Max. OFDM offers added spectral efficiency as well as robustness against selective fading, narrowband interference and impulsive noise which makes it an attractive contender for high-speed communication systems [70]-[73]. Frequency selective attenuation and interference can severely affect single-carrier systems, where a single fade or interferer may result in the failure of the whole link [74]. In contrast, the same interference or attenuation may damage only a few subcarriers in the case of OFDM. The efficiency of OFDM is reached by allowing the subcarriers to partially overlap without causing interference to each other because of the orthogonality property. Fig. 2.11 gives an illustration of the spectral efficiency of OFDM as compared to the conventional frequency-division multiplexing (FDM).

The basic principal of OFDM is to segment a high-speed serial data stream into numerous parallel low-speed streams that are carried simulta-



Figure 2.11: Spectral efficiency of OFDM compared to conventional FDM [74].

neously over multiple orthogonal subchannels. The idea of parallel transmission is not new. In fact, early developments of this technique date back to the fifties and sixties of the last century [75]-[77]. The first patent was filed in 1970 [78]. The first applications of OFDM were in military communication systems [79]. Using parallel transmission, the increase in the time length of each low-speed symbol allows it to combat the intersymbol interference (ISI) caused by multipath delay. To eliminate ISI completely, a cyclically extended time guard is appended at the beginning of every OFDM symbol. Moreover, when a sufficiently large number of subcarriers are used, the narrowband subcarriers exhibit approximately flat frequency response, which simplifies the equalization process in the receiver where a single-tap equalizer can be used.

In OFDM, the parallel data streams are first mapped into PSK or QAM symbols which then modulate a number of subcarriers using discrete Fourier transform (DFT) producing an OFDM signal. An OFDM symbol starting at $t = t_s$, carrying a sequence d_i of QAM symbols in N subcarriers can be expressed by the following complex baseband representation [74]:

$$s(t) = \sum_{i=-\frac{N}{2}}^{\frac{N}{2}-1} s_{i+N/2} \exp\left\{j2\pi \frac{i}{T}(t-t_s)\right\} , \quad t_s \le t \le t_s + T$$

$$s(t) = 0 , \quad t < t_s \land \quad t > t_s + T \qquad (2.30)$$

where T is the symbol duration. Fig 2.12 shows the basic operation of OFDM.



Figure 2.12: The modulation of multiple subcarriers in OFDM [74].

To explain the orthogonality property of OFDM, Fig. 2.13 shows an example of four subcarriers that could form an OFDM signal. It can be noted from this figure that all four subcarriers have an integer number of cycles in the time interval and that adjacent subcarriers are separated by a full cycle. Due to this orthogonality property, when demodulating for a specific subcarrier the integration over T results in the QAM symbols that were used to modulate that specific subcarrier. For all other subcarriers, the integration gives a zero result.

Fig. 2.14 depicts the spectrum of individual subcarriers in an OFDM



Figure 2.13: Example of four orthogonal subcarriers used in an OFDM symbol.

signal. Note that at the peak of each subcarrier, all other subcarriers have a zero value. Therefore, if the subcarriers are detected precisely in their peak points, any intercarrier interference (ICI) that may be caused by adjacent subcarriers is eliminated. In the literature, the OFDM signal is often defined in the discrete-time domain where the time is represented by discrete samples n in the time domain as given in (2.31). This representation implies that OFDM modulation is in fact nothing more than an inverse discrete Fourier transform (IDFT) of the QAM symbols fed into the OFDM modulator. At the receiver side of the system, the inverse happens where the discrete Fourier transform (DFT) is used to demodulate the OFDM signal. Both DFT and its inverse, IDFT, are efficiently implemented in practice using the fast Fourier transform (FFT/IFFT) algorithm. The simple and efficient implementation of OFDM gives it an advantage over other multicarrier modulation schemes.

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi \frac{k}{N}n}, \quad n = 0, 1, 2, ..., N-1$$
(2.31)

Another important advantage of OFDM is it strength against multipath delay spread and resulting ISI. OFDM divides a data stream into N



Figure 2.14: Frequency spectra of individual subcarriers in one OFDM symbol.

parallel streams each having a time length that can be N times larger. Consequently, the delay spread of the channel is made much smaller relative to the symbol duration. This minimizes the effect of ISI in the receiver. To eliminate ISI completely, a time guard that is slightly longer than the expected delay spread of the channel is attached to every OFDM symbol. It is important that the time guard does not damage the orthogonality between the subcarriers, which implies that the time guard has to be filled with a cyclic extension of the same OFDM symbol. This so-called cyclic prefix (CP) ensures that, on one hand, the delay spread does not affect the information bits and on the other hand that orthogonality is preserved resulting in a signal that is clear of ISI and ICI. The CP is removed at the receiver before demodulating using FFT. If the CP is shorter than the multipath delay spread, the channel dispersion in the delayed path will be present in the FFT interval causing loss of orthogonality and resulting in ISI and ICI.

An important task in the design of OFDM systems is the choice of

the different parameters and the tradeoffs between them. Three requirements are of major importance: bandwidth, bit rate and delay spread [74]. Knowledge of the delay spread is important for the choice of the CP length. According to Nee *et al.* [74], a good length of the CP should be around two to four times the root-mean-squared delay spread. The choice of this value depends on the modulation and coding techniques employed since higher order modulation (M-QAM) is more sensitive to ISI and ICI. The longer the symbol duration relative to the CP length, the less loss in SNR due to the CP. At the same time, this means a bigger number of subcarriers with less spacing given a specific bandwidth, adding extra implementation complexity and leading to problems related to frequency and phase offset. An additional problem arises concerning the high peak-to-average power ratio of the OFDM signal when a higher number of subcarriers are used.

Fig. 2.15 demonstrates a block diagram of a typical OFDM system suitable for PLC applications. At the transmitter side, the information bits first undergo channel coding and interleaving before mapping into PSK or QAM symbols. Pilots are inserted in the data to detect the channel transfer characteristics. Then the data stream is split into N parallel streams that modulate N subcarriers using IFFT. The CP is inserted in all OFDM symbols before preparing the signal for transmission. At the receiver side, more or less the opposite happens in addition to the required synchronization and channel equalization using the information delivered by the pilot symbols.

OFDM is considered the main candidate for high-speed broadband PLC systems. The key advantages offered by this technique can be summarized in the following:

- OFDM offers a great spectral efficiency which is necessary for broadband communications through a channel with very limited spectral resources like the power line channel.
- The long symbol period in OFDM gives the technique extra strength against multipath propagation and ISI. Although the insertion of a



Figure 2.15: Block diagram of an OFDM system consisting of a transmitter, a PLC channel and a receiver.

cyclic prefix reduces the useful data rate of the system, it gets rid of any ISI or ICI that can result from multipath when designed to have a longer duration than the delay spread of the PLC channel.

- The core element of OFDM is the IDFT/DFT process. This can be implemented in practice using the FFT algorithm in a very efficient and cost-effective way.
- When a large number of subcarriers is used in OFDM, the subcarriers occupy narrow portions of the frequency band. Therefore, the channel can be assumed flat for each subcarrier. This leads to a very simple equalization procedure using a single-tap equalizer.
- The power line network is a hostile channel when considering broadband high-speed communications. One of the most crucial properties of this channel affecting high-speed communications is the presence of random time-varying impulsive noise. OFDM performs better than single-carrier modulation techniques in the presence of impulsive noise [36], [48]. In the receiver part of OFDM, the received signal including impulsive noise is divided by the number of subcarriers through the DFT operation, which results in a significant reduction of the effect of impulsive noise.
- A significant property of OFDM is its adaptability. According to the PLC channel conditions, each of the multiple subchannels in an OFDM signal can have different data rates, code rates, constellation sizes and transmit power. These parameters can be adjusted to optimize the system performance based on the channel fading conditions using adaptive modulation algorithms. In addition, frequency bands banned from use in PLC systems due to regulations can be easily excluded by zeroing the subcarriers that fall in these bands.

2.8 Adaptive Modulation

A key benefit of using OFDM in PLC and various wired and wireless systems is its capability to effectively convert a broadband frequency-selective channel into narrowband flat-fading subchannels. Thus, the channel equalization complexity at the receiver can be minimized. PLC systems are vulnerable to narrowband interferences generated by AM broadcasters and other sources in addition to the frequency-selectivity characteristic introduced by branching and impedance mismatches. In conventional OFDM systems, all subcarriers are assigned the same constellation size and transmit power level. Therefore, if a subchannel or a group of subchannels are severely faded, they would dominate the overall bit error rate (BER) of the system resulting in a significant performance degradation.



Figure 2.16: Basic concept of adaptive modulation by adjusting the constellation size according to the channel conditions.

To improve the performance of high-speed OFDM-based PLC systems, adaptive modulation methods can be employed so that each subchannel can have a different constellation size and/or a different transmit power depending on its fading conditions. Fig. 2.16 shows the basic concept of adaptive modulation, where each subchannel carries a different number of bits depending on its gain and noise conditions. Adaptive modulation has been proven to improve the performance of multicarrier systems significantly [80], [81]. In adaptive modulation, several parameters can be controlled and adjusted to the subchannel signal-to-noise ratio (SNR). These include:

- data rate
- transmit power
- instantaneous BER
- constellation size
- channel code or scheme

Subcarriers that are excluded from the usable bandwidth due to regulations or interference with other wireless applications can be nulled by assigning zero power and distributing the data among the usable subcarriers. To ensure a significant improvement using adaptive modulation, a reliable feedback channel supplying up-to-date channel state information from the receiver end to the transmitter end can be utilized. This can be accomplished by inserting know pilot symbols in time or assigning particular subcarriers for channel estimation.

In the literature, a number of bit/power loading algorithms generally aiming at optimizing the system capacity can be found (e.g. [81]-[93]). Based on their objective function, the algorithms can be classified in two main categories:

- Margin-adaptive (MA) algorithms (e.g. [86], [87]) that endeavor to minimize the overall transmit power level. MA algorithms often have data rate and BER constraints that they have to maintain.
- Rate-adaptive (RA) algorithms (e.g. [88], [89]) that strive to maximize the overall data rate given transmit power and BER constraints.

Some loading algorithms aiming at minimizing the BER of a system where reliability is of major priority can also be found in the literature. An example of this is the algorithm proposed by Goldfeld *et al.* [90] that guarantees minimal aggregate BER, where the constellation size is assumed constant among all the subcarriers.

In terms of their basic operation, most loading algorithms can be classified into three categories [91]:

- 1. Incremental algorithms that incrementally allocate an integer number of bits to the subcarrier that has the lowest penalty in terms of the constraints until the maximum capacity is achieved without violating the power and/or BER constraints. This kind of algorithm is often called a *greedy* algorithm due to the fact that it chooses the allocation that is best for the current step without regarding the global effect of its choice [91]. An early example of incremental loading is the algorithm proposed by Hough-Hartog [92] which starts with zero bits for all the subcarriers. Then bits are incrementally loaded to the subcarriers requiring the minimum incremental energy until the BER or power constraints are violated. Another form of incremental loading is the algorithm that starts off with all subcarriers allocated the highest constellation size. Then, bits are incrementally removed from the subcarriers that have the worst BER performance until the constraints are reached.
- 2. Channel capacity-based algorithms where a closed form expression of the channel capacity is used to approximate a non-integer bit allocation for the subcarriers. Non-integer numbers of bits have to be rounded to the nearest integer causing some deviation from the optimum solution. If the subchannel SNR (γ_i) is known at the transmitter side, The number of bits per subchannel b_i can be calculated using the following expression [93]:

$$b_i = \log_2\left(1 + \frac{\gamma_i}{\Gamma}\right) \tag{2.32}$$

where Γ is the SNR gap which represents how far the system is from

achieving its maximum capacity.

3. BER expression-based algorithms that also use closed-form expressions to find the bit allocation and then round any non-integer values. For example, if subchannel *i* is modulated by an M_i -QAM signal, then the probability of error in this subchannel when its SNR is γ_i can be approximated using the expression [95]:

$$P_{M_{i},i}(\gamma_{i}) = 4\left(1 - \frac{1}{\sqrt{M_{i}}}\right) Q\left(\frac{3\gamma_{i}}{M_{i} - 1}\right)$$
$$\cdot \left[1 - \left(1 - \frac{1}{\sqrt{M_{i}}}\right) Q\left(\frac{3\gamma_{i}}{M_{i} - 1}\right)\right]$$
(2.33)

where Q(.) is the Q-function defined by the following:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{\frac{-t^{2}}{2}} dt$$
 (2.34)

Using the expression in (2.33), the BER for each subcarrier with all possible constellation sizes can be obtained given their SNR values, hence the constellation size that meets the subchannel BER constraints can be selected.

2.9 Security of PLC systems

Security is a major issue in all telecommunication systems, especially those that use a shared medium like wireless and power line systems. PLC systems are, however, naturally more secure than wireless communication systems. This is due to the fact that the physical medium of PLC is not easily accessible. In contrast, Wi-Fi systems, for instance, use a shared medium that can be accessed by anyone in the network coverage area. With suitable tools, the network traffic can be intercepted and the network device can even be reconfigured by the interceptor. An additional security advantage of PLC networks is the potential danger involved due to the presence of the AC electrical signal [10]. Furthermore, the differences in the SNR and channel frequency response between different nodes in the network makes it more difficult to retrieve the information from intercepted signals [96]. When using OFDM with adaptive modulation, different subcarriers may be modulated or even channel-coded differently. Therefore, to retrieve the information, one needs to have full knowledge of the modulation parameters of the signal.

Although power line networks are naturally more resistant to attacks, they are not fully protected and software security is essential to provide acceptable security levels. The main possible types of attacks that PLC networks are susceptible to are eavesdropping, attacks aiming at damaging the network communications and preventing its operation, and attacks aiming at obtaining access to the network devices and reconfiguring them at will [10]. Such security threats can be countered using the following:

- **Cryptography** is used to deny intruders access to the information exchanged in the network. The information is encoded using an encryption key before transmission through the medium. This makes the signals incomprehensible to the intruder. At the receiver side, a deciphering key is used to retrieve the information carried in the signal.
- Authentication is another security measure used in PLC and other wired and wireless networks. Using authentication, access to the network is only gained after identification of the user. Only then will authorization to access the network be granted.
- **Integrity control** is used to identify if the data sent through the network has been modified during transmission.

There are two main cryptography techniques: symmetric-key cryptography and asymmetric-key cryptography, which is often referred to as publickey cryptography. In the symmetric-key technique, a single key is used to encrypt and decrypt the information. This key has to be available to both the transmitter and receiver, which introduces the problem of securely transmitting the key to the receiver. This problem is solved using the public-key technique which involves the use of two different encryption keys. The first one is the private key which is used for the decryption of data and must stay confidential. The second is a public key that is sent to the users in plain text and used for data encryption. The two keys are linked using a mathematical function, which make it very difficult to find the value of one key using the other one.

Regarding authentication and integrity control, electronic signatures can be used to identify and authenticate the sender. Electronic signatures are also used to check if the received data has been modified or changed during the transmission over the network.

2.10 Standardization of the PLC Technology

Through the previous sections of this dissertation, it was proven with no doubt that the PLC technology has what it takes to become a widespread technology that can easily compete with the available wired and wireless technologies. PLC is now a mature technology and devices providing Physical layer (PHY) speeds of up to 200 Mbps are already available in the market. This technology eliminated the need for new wire installations and has superb coverage for indoor networking. The question here is what is stopping PLC from greatly penetrating the telecommunication systems market?

The limited expansion and partial adoption of PLC technologies around the world is often attributed to the lack of a globally accepted standard that is agreed-on by all parties in the PLC industry. The standard must take into account the coexistence with the various wired and wireless telecommunication systems by assigning the specific resources in the electromagnetic spectrum. Interoperability between the PLC devices that are based on different industrial standards is another important task. Until now, PLC standards have been developed by individual companies and groups of companies to help promote the widespread acceptance of the PLC technologies manufactured and sponsored by those companies. The three main parties involved in pre-standardization and standardization of PLC are HomePlug [97], IEEE [98] and the OPERA consortium [99]. In this section, we review some of the past, current and future standards in the high-speed PLC field.

It should be noted that there are some slow data rate PLC standards that have existed for quite some time and have gained global acceptance. A good example of such standards is the X-10 standard [100] that has been used for command and control applications. X-10 technology exploits the electric power signal and inserts one or two bits using Binary Phase Shift Keying (BPSK) at every zero crossing of the electrical signal. Therefore, a very slow data rate of only 100 bps can be achieved in power lines that use 50 Hz line cycles.

2.10.1 HomePlug Specifications

With the emergence of high-speed PLC technologies around the year 2000, a group of companies decided to form the HomePlug Power Line Alliance with the objective of setting the technical specifications for the in-home power line networking technology and promoting its availability and adoption around the world. The HomePlug Alliance was founded in March 2000 and currently consists of over 65 member companies. The Board of Directors of the Alliance includes representatives from Cisco, Comcast, GE Energy, Gigle, Intel, Intellon, Motorola, NEC, Sharp, and Texas Instruments [97].

The first specification developed by the HomePlug Alliance was Home-Plug 1.0 [101] which was aimed at providing broadband communications between devices in the home network. The HomePlug 1.0 industry standard was released in June 2001 and provided a PHY speed of up to 14 Mbps and used a Media Access Control (MAC) that is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The Home-Plug 1.0 specification was then slightly modified and updated to create the HomePlug 1.0.1 specification.

In 2005 the HomePlug AV (HPAV) industry standard was released with the objective to provide high-quality, multi-stream networking using the existing power line in-home networks. HPAV provides PHY data rates of about 200 Mbps for data, audio and video enabling entertainment oriented networking with applications like High-Definition TV (HDTV) and Voice over Internet Protocol (VoIP). The HomePlug Alliance is also working on the development of non-LAN specifications including HomePlug BPL and HomePlug Command and Control. In the following, a review of some of the HomePlug specifications is given.

HomePlug 1.0

This standard uses orthogonal frequency division multiplexing (OFDM), which was explained in section 2.7.3, with 84 equally spaced subcarriers to provide 14 Mbps PHY layer data rate. HomePlug 1.0 utilizes the frequency band 4.5 MHz to 21 MHz. To eliminate the inter-symbol interference caused by multipath propagations, the standard employs a cyclic prefix (CP) that is attached to each OFDM symbol. It also employs differential modulation techniques (DBPSK, and DQPSK) to cancel the need for equalization in the receiver. HomePlug 1.0 tackles the channel variations and selective fading by utilizing an adaptive tone allocation approach, in which subcarriers with very low SNR can be turned off. Impulsive noise events are combated by using FEC in addition to data interleaving. A robust modulation (ROBO) mode that uses stronger error correction codes as well as time diversity leading to slower data rate is defined in HomePlug 1.0. The ROBO mode is used for the transmission of important management messages. The CSMA/CA scheme with four levels of priority is used for the MAC layer in HomePlug 1.0. In this access scheme, the nodes are required to sense the medium before transmitting data. If the medium is busy then the transmission is delayed until the medium becomes idle. At this stage, the node can start transmitting after a randomly chosen duration to avoid collisions with packets coming from other waiting nodes. In addition, HomePlug 1.0 uses an adaptive window size management technique. The security of information in HomePlug 1.0 specification is achieved using data encryption based on the 56-bit data encryption standard (56-bit DES).

In the application level, the overall theoretical data rate achieved by HomePlug 1.0 is around 8 Mbps [9], whereas practical measurements in typical home power line networks showed actual data rates of about 4-7Mbps [102].

The HomePlug 1.0 standard was then updated to generate HomePlug 1.0.1 which was used as a basis for HomePlug Turbo that was released by Intellon [9] providing speeds of up to 80 Mbps. The boost in data rates in HomePlug Turbo, as compared to 14 Mbps in the original HomePlug 1.0 specification, was achieved by using higher order modulation schemes.

HomePlug AV

Following the success of its first specification, in 2005 HomePlug Alliance released a much more advanced technology specification; HomePlug AV (Audio/Video) [103]. HPAV represents the second generation PLC technology made available by the HomePlug Alliance. It utilizes advanced PHY and MAC technologies to achieve its aim of creating home networks using the AC power lines with PHY data rates of up to 200 Mbps suitable for high-quality broadband services including high-speed data, audio, video and other multimedia applications. HPAV aims to be the favored network technology for data multi-stream entertainment applications such as HDTV, SDTV and VoIP. HPAV utilizes the frequency band 2 - 28 MHz, which is rather wider than the frequency band used by HomePlug 1.0.

The PHY layer provides 150 Mbps information rate from the total channel rate of 200 Mbps. This rate is achieved by using windowed OFDM with 917 subcarriers in conjunction with adaptive bit-loading. Constellation sizes ranging from 1 bit (using BPSK modulation) to 10 bits (using 1024-QAM modulation) can be allocated to each subcarrier individually depending on the subchannel fading conditions. This, as explained in section 2.8 and will be studied in chapter 6, greatly improves the overall BER performance since the heavily-faded subcarriers that would otherwise dominate the BER are turned off. Moreover, the subcarriers that have high SNR values can be assigned to carry up to 10 bits per QAM symbol resulting in significant improvements in the system data rate. The PHY layer also employs a flexible cyclic prefix to account for the variation in the channel delay spread and eliminate any ISI. To mitigate the effect of impulsive noise, HPAV employs FEC using powerful turbo convolutional coding with different code rates.

In the MAC layer, HPAV has a great efficiency realized by using timedivision multiple access (TDMA) and CSMA based schemes synchronized with the AC line cycle. TDMA provides guarantees of quality-of-service (QoS) in the form of high reliability and guaranteed bandwidth reservation. Furthermore, the efficiency is enhanced using CSMA with four levels of priority. The synchronization with the AC cycle provides increased robustness in the face of the usually-present periodic impulsive noise synchronous with the mains frequency that was discussed in section 2.2.5 of this dissertation.

In terms of network management, HPAV incorporates advanced network management capable of providing plug-and-play configurations as well as service provider configurations. The security of data traffic in PLC networks based on the HPAV specification is guaranteed using 128 - bit Advanced Encryption Standard (AES). HPAV is compatible with the older version HomePlug 1.0 and has optional and mandatory modes to enable coexistence with other network types. A summary of the architecture of the HPAV system is obtained from [103] and illustrated in diagram in Fig. 2.17.



Figure 2.17: Architecture of the HomePlug AV specification [103].

HomePlug Access BPL

Using the AC power lines as a broadband communication link to the home or office is usually referred to as broadband over power lines (BPL). In addition to the in-home networking standards, the HomePlug Power line Alliance formed a working group to address the access BPL side of the PLC system. The HomePlug BPL working group was formed in 2004 with the purpose of developing the market requirements for the HomePlug BPL specification. A market requirement document was finalized in June 2005. Later in March 2007, the Access BPL working group completed the initial draft of the HomePlug Access BPL standard. The draft standard was integrated into the IEEE Standard for Broadband over Power Line Networks through the IEEE 1901 working group. In the following section, we will review the main aspects of the IEEE Standard for Broadband over Power Line Networks.

The HomePlug Alliance also released the HomePlug Green PHY standard with the objective of becoming the leading standard for implementing the Smart Grid applications which work to optimize the energy usage.

2.10.2 The IEEE 1901 Standard

Broadband PLC technologies have been available in the market place for several years. The technology received a reasonable acceptance from users in different parts of the world owing to the increased demand for highspeed broadband applications. Despite the moderate success of current PLC solutions, there has not been a unified standard as a basis for those technologies. For this reason, the IEEE established the IEEE P1901 Corporate Standard Working Group with the objective of developing a unified standard for high-speed (100 Mbps) PLC devices using frequencies below 100 MHz [104]. The standard addresses both the in-home networking cluster using low voltage in-home wiring as well as the access cluster concerned with delivery of broadband communications through the LV and MV power grids to the consumer's premises.

The IEEE P1901 Working Group was formed in June 2005. On the 30th of September 2010, the *I*EEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications was approved by the Standards Board of the IEEE Standards Association and is expected to be released in February 2011.

The IEEE 1901 Standard provides a solution with a common MAC layer and is capable of supporting two PHY layers [105]. The two PHY layers include one that is based on FFT-OFDM and another one that is based on wavelet-OFDM. The reason behind having two PHY layers is the compatibility with the current PLC devices that are based on the two transmission techniques. HomePlug specifications are based on FFT-OFDM, while devices based on HD-PLC Alliance industry specification employ wavelet-OFDM [106]. The MAC layer interacts with the two PHY layers via a transitional layer called the Physical Layer Convergence Protocol (PLCP). According to [105], the proposed FFT-OFDM based PHY uses a maximum number of subcarriers of 1893 and exploits the frequency band 1.8 - 48MHz to provide substantial data rates of up to 400 Mbps. This PHY layer features flexible frequency notching to account for regional and applications requirements. It employs flexible guard interval and bit-loading with the capability of carrying 1, 2, 3, 4, 6, 8 or 10 bits per data symbol through the use of QAM modulation. The FEC scheme used in this PHY is the turbo convolutional code. Periodic impulsive noise that is synchronous with the AC cycle is accounted for by synchronizing with the mains cycle.

The second PHY layer in the proposed IEEE 1901 Standard is based on wavelet-OFDM [107], [108]. The main feature of wavelet-OFDM is its superior spectral containment and its ability to combat ISI without the addition of a cyclic extension which may degrade the system throughput. The proposed wavelet-OFDM for IEEE 1901 uses 512 subcarriers (only 338 of them are used to carry information) equally spaced among the 2-28 MHz frequency band. An optional band of up to 60 Hz can be occupied boosting the achievable data rate to above 500 Mbps. The modulation used is pulse amplitude modulation (M-PAM) with real constellations M = 2, 4, 8, 16or 32 bits per data symbol. FEC is achieved using concatenated Reed-Solomon/convolutional code schemes and an optional low-density parity check (LDPC) code.

The MAC layer in the proposed IEEE 1901 Standard incorporates a hybrid access control employing both CSMA/CA and TDMA schemes. To efficiently control traffic with different transmission requirements, the MAC defines a contention-free and a contention period [105].

2.11 Applications of PLC

In the early days of the PLC technology, the use of electric grids for communication purposes was motivated by the need for a convenient communication link to maintain the function of power networks. The tasks of this link included mainly operations management, monitoring and troubleshooting [5]. Then, other narrowband applications using PLC emerged including single-directional communications, like remote switching of public lights, and bidirectional communications such as meter reading and various home automation applications (e.g. intruder alarm, fire detection and so forth). Nowadays, PLC technologies span a wide range of applications including voice, video, multimedia, networking and so forth; thanks to the increased demand for high data rate broadband applications. This section provides an overview of the current and prospective applications of PLC.

2.11.1 PLC-based Local Area Networks

A common and widespread application of PLC is to create a local area network (LAN) in the home or office using the indoor electric wiring. The driving advantage of PLC for this application is the availability of power sockets everywhere in the house or office which makes it easy to network various computers in one LAN using the already existing power lines. Similar to other LAN technologies, PLC-based LAN networks allow the sharing of files and printers, yet without the need for new wires. File and printer sharing is particularly important in professional computer networks.

Computers connected to one PLC network can share a single Internet connection. Regardless of the technology used to provide the Internet to the customer premises, a PLC device can reroute the data flow into the electrical network. This way, Internet access is made available to every outlet in the home or office. Fig. 2.18 illustrates a PLC-based local area network including file and printer sharing as well as an Internet connection shared by the network users. Broadcasting of data from different sources is another



Figure 2.18: LAN network including file, printer and Internet sharing based on PLC.

application of LANs based on the PLC technology. An example of this is broadcasting audio signals in different formats from an audio files server to all the computers connected to the electrical network at the home or office [10]. In addition, audio devices can be interconnected with each other and to speakers using the PLC network. Other recreational applications like network games, which can be played between different stations in the network, can also use the PLC connection.

PLC can be integrated with other LAN technologies in different ways. PLC can play the role of a backbone to the widely-used Wi-Fi networks as shown in Fig. 2.19. Although Wi-Fi networks provide mobility and flexibility to the users within a building, full coverage of large buildings may not be guaranteed without using multiple wireless routers interconnected via a wired backbone. The electric wiring can provide this backbone link between Wi-Fi routers using PLC devices.



Figure 2.19: PLC used as a backbone for a Wi-Fi network.

2.11.2 Voice, Video and Multimedia

The high data rates offered by PLC can support applications like voice, video and multimedia. For example, telephony over PLC is one of the first applications using PLC and was first tested in 1918 [15]. The transmission of telephone speech requires a bit rate that can be as low as 5.6 Kbps, which can very easily be supported by PLC. However, the data rate is not the only concern for conveying telephone conversations over PLC. For a reliable application with human interaction, the maximum time allowed between the transmission of information and the reception of the same information is 300 ms. This means that the round trip of speech bits in a telephone conversation over PLC must not take more than 300 ms. In addition, synchronization at the receiver is another issue for voice communications over PLC. The transmitted information has to arrive at the receiver at precise synchronization times.

Voice can be transmitted through PLC as IP packets using VoIP (voice over IP) technique. Using this technique, the speech is partitioned into IP packets, which then travel over PLC and other networks. Access to the network is often managed using the CSMA/CA (Carrier sense multiple access with collision avoidance) protocol.

PLC can also support higher data rates suitable for video applications such as video streaming, video surveillance, cable TV and videoconferencing. If the application requires only single-directional flow of information, as in the case of video streaming, the time delay constraint can be relaxed. The waiting time for the time when the source starts sending information and the time when the video is played at the receiving end can reach several seconds [10]. This time allows the receiver to have sufficient packets in memory before viewing the video, hence avoiding interruptions during the video playing time. Another uni-directional application is video surveillance using power lines. The use of PLC for this application offers a great flexibility in relation to the location of the camera, since a power outlet has to be in close proximity to power up the camera. Another advantage achieved by PLC in this context is that there is no need for extra wires as in other wired technologies often used in video surveillance.

Video are often encoded using the MPEG standards. Depending on the employed compression technique and ratio, the quality of images constituting the video may vary. Generally, the lower the compression, the higher the image quality. Another important parameter affecting the quality of images is the achievable data rate that can be used to convey video image frames. For PLC based on recent standards like HomePlug AV and IEEE 1901, no difficulties should exist in terms of the data rate requirements for video transmission with television quality, so long as the PLC network is not excessively used. HDDTV (high-definition digital television) can also be supported by these PLC standards. However, due to the high bit rate required for HDDTV (5 - 10 Mbps), the number of users in a network is very limited. Earlier PLC standards like HomePlug 1.0 have limited data rate capabilities and can not support HDDTV.

Videoconferencing is another function that can be employed using PLC

systems. In order to have a quality as good as television, high data rates of several megabits per second are required. For cinema quality videoconferencing, the required data rate can be as high as 50 Mbps [10]. As in the case of telephony over PLC, videoconferencing includes human interactivity, which imposes the time delay constraint (300 ms for a round-trip). Synchronization is another concern for videoconferencing and has to be controlled effectively. The PLC technology also supports the transmission of multimedia files incorporating speech, video and other data types. Multimedia applications normally need high bit rates depending on the types of data included. High data rates can be provided using PLC devices based on the recent standards. However, when transmitting multimedia files, it is necessary to synchronize the simultaneous applications that comprise a multimedia process.

2.11.3 Internet Access

The PLC technology can use the LV power grids as an access network providing Internet and other IP services to customers in the last-mile area. This is achieved by injecting the PLC signal into the LV power grid using a PLC device (Master). Fig. 2.20 illustrates this scenario. In the subscriber end, another PLC device (Slave) retrieves the Internet signal and distributes it into the in-building electric network, where different communication devices can use the power sockets to gain access to the network. The communication is controlled by the master PLC device which is located near the MV/LV transformer. This master PLC equipment acts as a base station for the subscribers' PLC devices. The communication between this base station and the wide area network (WAN) can be achieved by conventional communication methods such as optical fibres, radio links and so forth or by the use of MV power grids.



Figure 2.20: PLC used to provide Internet access to the subscriber in the LV network.

2.12 Summary

A literature survey covering all the aspects of power line communications was conducted in this chapter. The structures of power line networks and their physical properties were explained and a brief overview about the historical developments of PLC systems was provided. In addition, the chapter outlined the available models in the literature that describe the PL channel and the existing noise. The advantages and drawbacks of each model were also determined and explained. The chapter provided a survey of the existing impulsive noise mitigation techniques that were found in the literature. Those methods were categorized into three main classes including: time-domain, frequency-domain and FEC-based methods. Different modulation techniques and their applicability in PLC were also reviewed to enable the reader to identify which technique is more suitable. The superiority of OFDM and the need for adaptive modulation have been described. A review of the existing types and algorithms of adaptive modulation was given in this chapter. A short overview about the security of the PLC technology was provide in addition to a survey of the past, current and future PLC standards. The chapter ends by demonstrating some of the current 2.12 Summary

applications of PLC.



Nonlinear Techniques for Impulsive Noise Reduction

3.1 Introduction

Interest in using PLC technology to deliver high-speed communication signals over electric power lines continues to grow at a rapid pace. However, power line networks were not originally designed for data transmission and they differ significantly in topology, structure, and physical properties from conventional communication channels such as twisted pair, coaxial, or fiberoptic cables [2]. Power lines were only designed to transport electric signals at 50/60 Hz and they provide a harsh environment for higher frequency communication signals [11]. The most influential channel properties degrading the performance of high-speed communications are noise, attenuation and multipath propagation [36]. Unlike many other communication channels, noise in power line channels can not be described by Additive white Gaussian Noise (AWGN) due to the presence of impulsive noise. This type of noise has a random time-varying behaviour and its duration varies from a few microseconds to milliseconds. Practical experiments in power lines [6] show that, during the occurrence of an impulse, the power spectral density (PSD) of impulsive noise exceeds the PSD of background noise by a minimum of 10-15 dB and may sometimes reach 50 dB. It is, therefore, necessary to employ mitigation techniques in order to combat its effect on data transmission.

A simple technique of impulsive noise mitigation is to precede the receiver with a memoryless nonlinearity. Assuming low SNR values, locally optimal detection of arbitrary signals in impulsive noise environments is achieved by a conventional detector preceded with a memoryless nonlinearity [109]. Suboptimal clipping or blanking methods are used in modern OFDM receivers to reduce the effect of impulsive noise [38]. This method has been addressed by Zhidkov [38] for conventional OFDM receivers in wireless applications. Therefore, it is important to study the performance and applicability of such techniques for PLC systems.

In this chapter, we first investigate the performance of three nonlinear techniques (i.e. Clipping, Blanking and joint Clipping/Blanking) in reducing the effect of impulsive noise in OFDM-based PLC systems. The analysis and results of the three techniques led to the publication of [110].

To tackle the threshold selection dilemma in these nonlinearities, an adaptive threshold that minimizes the BER is proposed. The study and results of the adaptive threshold for both clipping and blanking nonlinearities as a technique to reduce the effect of impulsive noise in PLC systems led to the publications [111] and [112], respectively.

Next, a joint time-domain/frequency-domain impulsive noise suppression technique is proposed. Results are obtained by computer simulations using a widely accepted and practically proven PLC multipath channel model [2]. Three different scenarios of impulsive noise, namely "Heavily disturbed", "medium disturbed" and "weakly disturbed" are considered. The results were published in the proceedings of the 2008 Australian Telecommunication Networks and Applications Conference [113].

3.2 System Model

3.2.1 OFDM System

The transmission system employed to study the performance of nonlinear techniques to mitigate the effect of impulsive noise is OFDM. The OFDM transmission system was discussed in detail in section 2.7.3. In the presence of impulsive noise, OFDM performs better than single carrier modulation schemes [36], [48]. This is due to the fact that OFDM spreads the effect of impulsive noise over multiple symbols during the discrete Fourier transform (DFT) operation at the receiver. In addition to its robustness against impulsive noise, OFDM offers a great spectral efficiency and capability to combat multipath and narrowband interference. The discrete time OFDM signal can be expressed as:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{j2\pi \frac{k}{N}n}, \quad n = 0, 1, 2, ..., N-1$$
(3.1)

where N is the number of sub-carriers and S_k is a sequence of QAM symbols. In order to eliminate inter-channel interference (ICI) and inter-symbol interference (ISI), OFDM uses a cyclic prefix (CP) that is appended at the start of OFDM symbols.

3.2.2 Channel Model

Power line networks differ significantly in topology, structure, and physical properties from conventional communication channels such as twisted pair, coaxial, or fiber-optic cables [2]. Because they were not specifically designed for data transmission, power lines provide a harsh environment for higher frequency communication signals. The most influential properties of this hostile medium in the performance of high speed communications are signal distortion due to frequency-dependent cable losses, multi-path propagation
and noise [6]. Zimmermann and Dostert [2] introduced a practical multipath channel model that is suitable for describing the transmission behavior of power line channels. The model is based on practical measurements of actual power line networks and is given by the channel transfer function:

$$H(f) = \sum_{i=1}^{N_p} \underbrace{c_i}_{\text{weighting}} \cdot \underbrace{e^{-(a_0 + a_1 f^k)d_i}}_{\text{attenuation}} \cdot \underbrace{e^{-j2\pi f(d_i/v_p)}}_{\text{delay}}$$
(3.2)
factor portion portion

where N_p is the number of multipaths, c_i and d_i are the weighting factor and length of the *i*th path respectively. Frequency-dependent attenuation is modelled by the parameters a_0 , a_1 and k. In the model, the first exponential presents attenuation in the PLC channel, whereas the second exponential, with the propagation speed v_p , describes the echo scenario. The attenuation parameters for a 4-path model and a 15-path model were obtained using physical measurements in [2] and are summarized in Tables 3.1 and 3.2 respectively. The simple four-path model covers only the dominant paths of the impulse response while the 15-path model assumes 15 propagation paths and provides more detail and accuracy to the channel transfer function given by (3.2). For this reason, the 15-path model is utilized in the simulation experiments conducted in this chapter.

attenuation parameters								
k = 1	$= 1 a_0 = 0 a_1 = 7.8 \cdot 10^{-10} \text{ m/s}$							
path parameters								
i	g_i	$d_i/{ m m}$	i	g_i	$d_i/{ m m}$			
1	0.64	200	3	-0.15	411			
2	0.38	222.4	4	0.05	490			

Table 3.1: Parameters of the 4-path PLC channel model.

attenuation parameters									
k = 1	$a_0 = 0$	$a_1 = 7.8 \cdot 10^{-10} \text{ m/s}$							
path parameters									
i	g_i	$d_i/{ m m}$	i	g_i	$d_i/{ m m}$				
1	0.029	90	9	0.071	411				
2	0.043	102	10	-0.035	490				
3	0.103	113	11	0.065	567				
4	-0.058	143	12	-0.055	740				
5	-0.045	148	13	0.042	960				
6	-0.040	200	14	-0.059	1130				
7	0.038	260	15	0.049	1250				
8	-0.038	322							

Table 3.2: Parameters of the 15-path PLC channel model.

3.2.3 Noise Model

In PLC environments, data transmission may encounter different types of noise. Noise in power lines can be classified into five categories [6]. These are:

- 1. coloured background noise
- 2. narrow-band noise
- 3. periodic impulsive noise asynchronous to the mains frequency
- 4. periodic impulsive noise synchronous to the mains frequency
- 5. asynchronous impulsive noise

Details about the noise types that occur in power line channels and their characteristics and causes were provided in section 2.2.5. The first three noise types listed above usually remain stationary over long periods of time (i.e. seconds, minutes or hours) and can be summarized as background noise (w_k) . The last two types have a time-varying nature and can be summarized as impulsive noise (i_k) . Impulsive noise is mainly caused by power supplies (synchronous to mains frequency) or by switching transients in the network (Asynchronous to the mains power). The received signal after down-conversion, analog-to-digital conversion assuming perfect synchronization is thus represented as:

$$r_k = s_k * h + w_k + i_k \quad k = 0, 1, 2, \dots, N - 1$$
(3.3)

where s_k is the transmitted OFDM signal as in (3.1), h is the PLC channel impulse response which is the Inverse Fourier Transform of the transfer function defined in (3.2). The symbol * denotes convolution.

To analyze the effect of noise in OFDM-based PLC systems, the background noise (w_k) is modelled as an AWGN with mean zero and variance σ_w^2 [21], [36]. Impulsive noise (i_k) is modelled using the Poisson-Gaussian noise model described in section 2.5 of this dissertation. This model offers a simple and efficient representation of impulsive noise in power line channels and has been utilized in several studies (e.g. [33], [36] and [37]). According to the Poisson-Gaussian model, impulsive noise is given by the following:

$$i_k = b_k g_k \tag{3.4}$$

where b_k is the Poisson Process which corresponds to the arrival of impulsive noise, and g_k is white Gaussian process with zero mean and variance σ_i^2 . This means that the arrival of impulsive noise follows a Poisson distribution with a rate λ units per second, so that the probability of event of x arrivals in unit time is:

$$P(x) = P(X = x) = e^{-\lambda} \frac{\lambda^x}{x!}, \quad x = 0, 1, 2, \dots$$
(3.5)

The amplitude of impulsive noise, on the other hand, follows a Gaussian distribution with mean zero and variance σ_i^2 . Since impulses can have random durations in practical situations [6], the impulse width is assumed to follow a Gaussian distribution with a mean that is equal to the average impulse width. The probability density function of the total noise n_k is given by the



Figure 3.1: Example of a single impulse mixed with AWGN.

following [35]:

$$p(n_{kR}, n_{kI}) = (1 - p) G(n_{kR}, 0, \sigma_w^2) G(n_{kI}, 0, \sigma_w^2) + p G(n_{kR}, 0, \sigma_w^2 + \sigma_i^2) G(n_{kI}, 0, \sigma_w^2 + \sigma_i^2)$$
(3.6)

where p is the probability of occurrence of impulsive noise and $G(x, \eta, \sigma^2)$ is the Gaussian pdf with mean η and variance σ^2 and is defined as:

$$G(x,\eta,\sigma^{2}) = \frac{1}{\sigma\sqrt{2\pi}} exp(-\frac{(x-\eta)^{2}}{2\sigma^{2}})$$
(3.7)

Let T_{noise} be the average impulse duration. We define the average disturbance ratio DR which indicates the actual disturbed time fraction and is given by:

$$DR = \frac{\sum_{i=1}^{N_{imp}} t_{w,i}}{T_{tot}} = \lambda T_{noise}$$
(3.8)



Figure 3.2: Example of impulsive noise mixed with AWGN.

where $N_{\rm imp}$ is the total number of impulses occurring in time $T_{\rm tot}$ and $t_{\rm w,i}$ is the width of the *i*th impulse. A ratio μ between impulsive noise and background noise powers can be defined as:

$$\mu = \frac{\text{DR.}\sigma_i^2}{\sigma_w^2} \tag{3.9}$$

Fig. 3.1 shows the time domain representation of a sample impulse with an overall duration of 50 μ s surrounded by background noise. In Fig. 3.2, a number of impulses with average impulse rate (λ) 5 s⁻¹ and average inter-arrival time (1/ λ) of 200 ms are illustrated.

Scenarioaverage DR (%)average λ (s^{-1})1) Heavily disturbed0.32751.12) Medium disturbed0.006321.043) Weakly disturbed0.001350.122

Table 3.3: Characteristic Parameters of The Three Impulsive Scenarios



Figure 3.3: Illustration of the three noise scenarios used in the simulations. (a)Heavily-disturbed, (b) Medium-disturbed and (c) Weakly-disturbed.

Three impulsive noise scenarios are considered to observe how different nonlinearities perform at different noise conditions. The characteristics for all three scenarios are obtained from practical measurements in [6] and listed in Table 3.3. They are characterized by the average impulse rate λ which is the number of impulse occurrences in a second and the average disturbance ratio DR in the channel. The first scenario is named as "heavily disturbed" and it was measured during the evening hours in a transformer substation in an industrial area. The less disturbed scenario is the "medium disturbed" where measurements were recorded in a transformer substation in a residential area with detached and terraced houses. The third scenario is named as "weakly disturbed" and was recorded during nighttime in an apartment located in a large building. Fig. 3.3 depicts the total noise for all the three noise conditions including both background and impulsive noises according to the parameters in Table 3.3. Impulsive noise is produced using the Poisson-Gaussian model. Fig. 3.3 (a) shows the noise in a heavilydisturbed environment. Due to the very large number of impulses that occur every second in this condition, a lower scale in the x-axis is used for this figure so that the impulsive noise is distinguished from the background noise given as AWGN. Fig. 3.3 (b) shows the noise in a medium disturbed environment, while Fig. 3.3 (c) shows that in 10 seconds, only a single short-duration impulse appeared, which is the case in a weakly-disturbed environment. In this noise scenario, the average inter-arrival time (IAT) between impulses which is given by the reciprocal of the impulse rate is about 8.2 seconds.

3.3 Time-domain Nonlinearities for impulsive noise mitigation

In OFDM systems, the long symbol duration increases the signal robustness to impulsive noise, since the impulse noise energy is spread over the simultaneously transmitted OFDM subcarriers. Nevertheless, if mitigation techniques are not employed, impulsive noise can have a significant effect on the performance of OFDM systems, especially in a channel like power lines where the presence of impulsive noise is a typical scenario. In fact, if the impulse energy exceeds a certain level, the spreading of its energy among OFDM subcarriers will rather be a disadvantage [35]. In this case, all subcarriers can be severely affected by impulsive noise.



Figure 3.4: Simplified block diagram of OFDM-based PLC system with memoryless nonlinearity.

Different techniques for impulsive noise mitigation have been discussed in the literature [38]-[65]. An overview of some of these techniques was given in section 2.6. Due to their simplicity, memoryless nonlinearity techniques are often used in practical applications in order to reduce the adverse effect of impulsive noise in data communications [38]. They are employed



Figure 3.5: Illustration of the three nonlinearities.

at the front-end of an OFDM receiver before demodulating using the fast Fourier transform (FFT). Fig. 3.4 depicts a block diagram of OFDM with a memoryless nonlinearity block for impulsive noise reduction preceding demodulation using the FFT. These techniques change only the amplitude of the signal according to a specific threshold without changing its phase. The three time-domain nonlinearities were discussed in section 2.6 in the previous chapter. For the convenience of the reader, a brief overview of these techniques is given here. The function of each of the three nonlinearities is illustrated in Fig. 3.5. 1. Clipping

$$y_k = \begin{cases} r_k, & |r_k| \le T_c \\ T_c e^{j \arg(r_k)}, & |r_k| > T_c \end{cases}, \quad k = 0, 1, ..., N - 1$$
(3.10)

where T_c is the clipping threshold.

2. Blanking

$$y_k = \begin{cases} r_k, & |r_k| \le T_b \\ 0, & |r_k| > T_b \end{cases}, \quad k = 0, 1, ..., N - 1$$
(3.11)

where T_b is the blanking threshold.

3. Clipping/Blanking

$$y_{k} = \begin{cases} r_{k}, & |r_{k}| \leq T_{c} \\ T_{c}e^{jarg(r_{k})}, & T_{c} < |r_{k}| \leq T_{b} \\ 0, & |r_{k}| > T_{b} \end{cases}$$
(3.12)

where the clipping threshold (T_c) is smaller than the blanking threshold (T_b) . It will be shown in the following sections that the optimum clipping threshold is always smaller than the blanking threshold for the same signal and under the same conditions. This allows a combinational technique, in which two threshold values are selected. If a sample has a magnitude that exceeds the higher threshold T_b , the sample is blanked (i.e. replaced with zero). If a sample has a magnitude that is below the blanking threshold T_b but above the lower threshold, the sample is clipped according to T_c . If the signal amplitude is below the clipping threshold, it is assumed to be the correct OFDM signal sample and hence passed through unchanged.

3.3.1 Threshold Selection

The function of any nonlinearity is highly dependent on the selection of a certain threshold value beyond which a signal sample will be modified. If the amplitude of a signal sample exceeds this threshold, it will be either clipped or blanked (i.e. set equal to zero). To minimize the BER at the receiver, this threshold has to be carefully selected so that the nonlinearity unit only modifies the samples affected by impulsive noise and avoids modifying the original non-affected signal samples. When T_c or T_b is very small, most of the received samples of the OFDM signal are clipped or replaced with zeroes. This introduces more errors in the output signal and hence increases the BER. In contrast, for very large values of T_c or T_b , it is more likely that the nonlinear preprocessor will bypass the received samples including the ones affected by impulsive noise. Therefore the system performance may be influenced significantly by impulsive noise and the nonlinearity may not introduce any improvement. A properly selected threshold reduces the probability of false detection of impulsive noise and improves the function of the nonlinear clipping or blanking nonlinearities.

Fig. 3.6 illustrates how the BER changes with different threshold values. It can be observed from the figure that there exists an optimal threshold for clipping, blanking and the combined clipping/blanking nonlinearities. The results are for the "heavily disturbed" scenario with SNR equal to 30 dB. The figure also demonstrates clearly that, under these conditions, blanking nonlinearity performs significantly better than clipping nonlinearity. Clipping with optimum threshold achieves a minimum BER of approximately 10×10^{-3} , whereas optimum-threshold blanking can achieve a BER that is below 10×10^{-4} . The clipping/blanking nonlinearity performs slightly better than blanking as shown in Fig. 3.6. These results were obtained using simulations based on the PLC multipath channel model discussed in Section 2.4.1. The performance differences between the three nonlinearities match



Figure 3.6: BER performance at the output of OFDM (QPSK) receiver in heavily disturbed PLC channel as a function of threshold value for three different types of nonlinearities. $T_b = 1.6T_c$ for clipping/blanking.

well with the analytical and simulation results demonstrated by Zhidkov [38].

3.3.2 Performance results for fixed-threshold Nonlinearities

The performances of the three time-domain nonlinearities (3.10)-(3.12) in OFDM-based PLC receivers were studied by computer simulations under the three different impulsive noise scenarios outlined in Table 3.3. The threshold values used in the nonlinearities were optimized by simulations of different threshold values according to the discussion in the previous section at a specific SNR of 30 dB and the selected values were fixed for all other SNR values. This work has been published by the author [110]. In the transmitter side, a randomly generated binary stream is mapped into QPSK symbols and modulated using OFDM with 128 subcarriers. This signal is then passed through a PLC multipath channel given by equation (3.2) with 15 paths with parameters given in Table 3.2. The arrival of impulsive noise is assumed to follow a Poisson distribution as given by (3.4) while the background noise is assumed to be AWGN. The total noise resulting from impulsive and background noises is added to the OFDM signal. At the receiver side, the received signal r_k is first passed through the memoryless nonlinearity then demodulated using a DFT unit. The signal is then demapped and the BER performance is obtained. To achieve reliable results the simulation is repeated 100 times and every time a random bit stream with a length of 1600000 bits is generated and transmitted through the channel based on the described system. The signal-to-noise ratio (SNR) in all figures is defined according to the following.

Let p_n be the total noise power resulting from AWGN and impulsive noise, and p_x is the average PSK or QAM symbol power. The SNR can be defined as:

$$SNR = \frac{p_x}{p_n} = \frac{p_x}{p_w + p_i}$$
(3.13)

where p_w and p_i are the mean AWGN and impulsive noise powers, respectively. The average disturbance ratio DR given in equation (3.8) can be used to calculate the average impulsive noise duration in unit time. Since impulsive noise arrival is modelled by a Poisson process with λ impulses per second, the following expression for the average disturbance ratio can be obtained:

$$DR = \lambda T_{noise} \tag{3.14}$$

where T_{noise} is the average impulse duration. The following expression for

(SNR) is used in this study:

$$SNR = \frac{p_x}{\sigma_w^2 + DR.\sigma_i^2}$$
(3.15)

where σ_i^2 is the mean power of a single impulse over its duration T_{noise} and is modelled by a Gaussian process as given by (3.7). A ratio μ between impulsive noise power and background noise power (AWGN) is defined by the following:

$$\mu = \frac{p_i}{p_w} = \frac{\text{DR.}\sigma_i^2}{\sigma_w^2} \tag{3.16}$$

In the simulations performed $\mu = 3$ was used.

Fig. 3.7-Fig. 3.9 illustrate a comparison between the three simple nonlinearity techniques used for impulsive noise suppression in OFDM-Based PLC systems. Results in these figures are obtained for "heavily disturbed", "medium disturbed" and "weakly disturbed" impulsive noise environments, respectively. It can be noticed from Fig. 3.7 that for such PLC channel conditions, although blanking nonlinearity performs better than clipping for SNR values between 25 dB and 35 dB, the latter technique outperforms the former by approximately 2 decibels for high SNR values (SNR > 35dB) for fixed threshold values. For the same impulsive noise characteristics, simulations show that the best nonlinearity solution to impulsive noise in this case is the combined clipping/blanking. This technique can sometimes improve the performance over Clipping and blanking by more than 5 dB. Note that for this environment, all three techniques provide negligible improvement for very high SNR values (SNR > 40 dB).

In the "medium disturbed" environment, depicted in Fig. 3.8, blanking nonlinearity performs the best of the three techniques using the same threshold values. In this impulsive noise environment, all three techniques reduce the effect of impulsive noise significantly. Blanking nonlinearity can



Figure 3.7: Performance of fixed-threshold nonlinearities for impulsive noise reduction (heavily disturbed PLC channel).



Figure 3.8: Performance of fixed-threshold nonlinearities for impulsive noise reduction (medium disturbed PLC channel).



Figure 3.9: Performance of fixed-threshold nonlinearities for impulsive noise reduction (weakly disturbed PLC channel).

lessen the BER of OFDM based PLC receiver from 7×10^{-3} to 10^{-5} when the SNR is equal to 45 dB in a medium disturbed environment. Blanking and Clipping techniques provide comparable results in the case of "weakly disturbed" power lines for fixed threshold values as can be observed from Fig. 3.9. Clipping/blanking achieved the worst performance under this impulsive noise environment.

Due to the multipath effect in power line channels, there exists an error floor in the BER performance of the OFDM system. This error floor is caused by the inter-symbol interference (ISI) and inter-carrier interference (ICI) and it is affected by the occurring impulsive noise. Increasing the signal power increases the power of the ISI and ICI effects [36], and hence does not improve the BER. A number of factors determine the level of the error floor including the channel impulse response, the symbol duration and the number of OFDM subcarriers [36].

3.4 Adaptive-threshold Nonlinearities

In PLC networks, communication signals do not only propagate through a direct path from the transmitter to the receiver. Branching in power lines causes numerous reflections in the network leading to the reception of multiple delayed versions of the original signal. These multipath and frequency selectivity features of power line channels can be different from one network to another. In addition, depending on the length of the propagation path, the received signal is attenuated differently. In such conditions and when time domain nonlinearities (3.10) and (3.11) are employed at the front-end of the receiver, selecting the optimum threshold value becomes a very crucial task. Fig. 3.10 shows that, even under the same channel conditions, the optimum threshold may slightly vary depending on the SNR of the received signal. In the following we describe how the threshold value can adapt to the channel state and the condition of the received signal based on a minimum BER approach. The adaptive-threshold technique is then examined in a power line channel impaired with impulsive noise. Results are obtained for different threshold levels at different noise conditions to show the enhancements achieved by the adaptive technique.

3.4.1 System Description

In order to optimize the performance of clipping and blanking in mitigating the effect of impulsive noise at variable channel conditions, an adaptive threshold selection is described in this section. The objective of this technique is to minimize the output BER by adjusting the nonlinearity threshold value to the optimum level. In this technique, a predetermined threshold having a very small value is first set. This threshold is then incremented by a small amount and after every increment the new BER is measured. A feedback link from the BER estimation delivers the new BER values to the adaptive threshold clipping or blanking block. BER estimation can be



Figure 3.10: BER performance at the output of OFDM (QPSK) receiver in heavily disturbed PLC channel as a function of threshold value for clipping and blanking at different SNR values.

achieved using training sequences and pilot subcarriers. However, it is assumed in this section that knowledge of the BER is available in the receiver. After a number of iterations the BER starts to increase indicating the optimum threshold has been achieved. The obtained value is then set as the clipping or blanking threshold.



Figure 3.11: Simplified block diagram of OFDM-based PLC system with Adaptive-threshold nonlinearity.

Fig. 3.11 depicts a simplified block diagram of OFDM system including adaptive-threshold nonlinearity. The PLC channel in this diagram is represented by the channel transfer function of the power line channel outlined in section 3.2.2. The BER can be measured using pilot symbols during the initialization stage.

3.4.2 Results

The performance of clipping and blanking nonlinearities based on the adaptivethreshold selection in an OFDM-based PLC environment is presented in this section. The power line channel is modelled by the transfer function described in section 3.2.2 using the parameters for the 15-path case. Results are obtained at all three different impulsive noise scenarios presented in Table 3.2, where each noise scenario is defined by the rate and disturbance ratio of the occurring impulsive noise. Three different threshold values are used for the fixed threshold case to indicate low, medium and high threshold values and their effect on the error performance of the system. The results for the different thresholds are compared with the adaptive technique. In every realization of the simulation code, a random bit stream of 1,600,000 bits are mapped into QPSK symbols and transmitted using a 128 -subcarrier OFDM with a cyclic prefix of 16 subcarriers through a PLC channel. The parameters of the 15-path PLC channel model in Table 3.2 are used in the simulations. Background and impulsive noises are produced according to the noise model described in section 3.2.3 and then added to the OFDM signal. At the receiver, after the removal of the cyclic extension, the channel is equalized and the OFDM symbols are demodulated and demapped to retrieve the transmitted bits. Equalization is implemented in the frequency domain assuming perfect knowledge of the channel transfer parameters. The simulation is repeated 100 times to increase the reliability of the simulations and the results are averaged over all the realizations.

Clipping nonlinearity

Fig. 3.12-Fig. 3.14 illustrate the BER performance of the proposed adaptivethreshold clipping technique for impulsive noise reduction in OFDM-based PLC systems. Results in these figures are obtained for "heavily disturbed", "medium disturbed" and "weakly disturbed" impulsive noise environments, respectively. The same 15-path channel was used to represent the power line channel. This work has been published by the author in [111]. The adaptive-threshold is compared against fixed-threshold using three different threshold values (i.e. $T_c = 0.15, 0.20, 0.25$). When a small threshold value is used, clipping degrades the BER performance of the OFDM system introducing more errors by clipping some signal samples which are not affected by impulsive noise. This is clearly seen in the weakly-disturbed scenario in Fig 3.14, where the error performance of the OFDM system employing a clipping device is worse than the case when no impulsive noise mitigation is employed. This effect is also seen in the heavily-disturbed and weaklydisturbed environments depicted in Fig. 3.10 and Fig. 3.11, respectively. This highlights the need for an adaptive threshold selection since a bad threshold value can worsen the system performance instead of mitigating the effect of impulsive noise.



Figure 3.12: Performance of OFDM-based PLC system with Adaptive-threshold clipping in a heavily-disturbed PLC channel.

For a higher threshold value $T_c = 0.2$, the performance of the fixedthreshold is close to the adaptive-threshold which indicates that the threshold selected by the adaptive technique has a value close to 0.20. Higher threshold values reduce the improvement achieved by the clipping nonlinearity. It can be noticed from Fig. 3.12-Fig. 3.14 that, in all the three studied noise scenarios, the proposed adaptive-threshold clipping guaran-



Figure 3.13: Performance of OFDM-based PLC system with Adaptive-threshold clipping in a medium-disturbed PLC channel.



Figure 3.14: Performance of OFDM-based PLC system with Adaptive-threshold clipping in a weakly-disturbed PLC channel.

tees the maximum performance of the clipping nonlinearity and achieves significant improvements over fixed-threshold clipping.

Blanking nonlinearity

The BER performance of the proposed adaptive-threshold blanking technique for impulsive noise mitigation is illustrated in Fig. 3.15-Fig. 3.17. Results in these figures are obtained for the same three noise conditions, namely "heavily disturbed", "medium disturbed" and "weakly disturbed" respectively. The same as for clipping nonlinearity, three threshold values are used (i.e. $T_b = 0.27, 0.36, 0.45$) to indicate small, medium, large threshold levels respectively. It should be noted that the properly-selected blanking threshold is larger than the clipping threshold for the same signal under the same channel conditions. This result was outlined in the literature (e.g. [38]) and has been verified in this work as shown in Fig. 3.6. It can be noticed that the proposed thresholding technique outperforms blanking nonlinearity with fixed threshold for all fixed threshold values in all three noise scenarios. For instance, in a weakly-disturbed environment with SNR equal to 40 dB, the proposed adaptive-threshold blanking lessens the BER from 7×10^{-5} down to less than 6×10^{-7} . Under the same conditions and the same SNR, blanking with fixed threshold can only reduce the BER to a minimum of about 1.8×10^{-6} , which is only achieved if a carefully selected threshold T_b of about 0.36 is used. As can be seen in Fig. 3.17, the adaptive-threshold technique almost eliminates the effect of impulsive noise completely and achieves a performance that is very similar to the case when the PLC channel is only affected by AWGN. As in clipping nonlinearity, the adaptive technique guarantees the best performance of the blanking circuit and offers a great improvement over blanking with a fixed threshold.



Figure 3.15: Performance of OFDM-based PLC system with adaptive-threshold blanking in a heavily-disturbed PLC channel.



Figure 3.16: Performance of OFDM-based PLC system with adaptive-threshold blanking in a medium-disturbed PLC channel.



Figure 3.17: Performance of OFDM-based PLC system with adaptive-threshold blanking in a weakly-disturbed PLC channel.

3.5 Frequency-domain Impulsive Noise Suppression

A suppression technique of impulsive noise in OFDM receivers was proposed in [3]. The technique is based on a frequency-domain approach where impulsive noise is compensated for after OFDM demodulation using FFT. In this section we provide a brief overview about this technique. More details about the technique are available in [3]. At the receiver side of an OFDM system, the signal in (3.3) can be expressed, after channel equalization and DFT demodulation, as:

$$R_k^{(eq)} = S_k + W_k \hat{H}_k^{-1} + I_k \hat{H}_k^{-1}, \quad k = 0, 1, \dots, N - 1$$
(3.17)

where H is the channel transfer function, W and U are the DFT of the AWGN and impulsive noise respectively. The main idea of the algorithm

is to get an estimation of the impulsive noise term $I_k \hat{H}_k^{-1}$ and subtract it from the equalizer output. To do this, a preliminary estimate of the transmitted baseband symbol has to be obtained. This is achieved through demapping the data subcarriers to the nearest constellation points, setting silent subcarriers to zero and replacing the pilot subcarriers by their known values. By rearranging (3.17), estimation of the total noise term $D_k =$ $W_k + I_k$ can be found by the following expression:

$$\hat{D}_k = \hat{H}_k (R_k^{(eq)} - \hat{S}_k), \quad k = 0, 1, ..., N - 1$$
 (3.18)

The total noise term D_k is then transformed into the time domain by means of IDFT and a peak detector is used to obtain the estimated impulsive noise signal \hat{i}_k in the time domain. In a final step, the DFT of \hat{i}_k is computed and divided by the channel transfer function. The frequency-domain signal after impulsive noise reduction can be attained according to the following:

$$R_k^{(comp)} = R_k^{(eq)} - \hat{I}_k \hat{H}_k^{-1}, \quad k = 0, 1, ..., N - 1$$
(3.19)

3.6 Joint TD/FD Impulsive Noise Suppression

The adverse effect of impulsive noise in communication systems generally and in power line communications in particular has been studied and illustrated in previous sections of the thesis. For high data rate communications over PLC mediums, mitigation of the effect of impulsive noise is inevitable, due to the high power and random behavior of this type of noise. In this part of the chapter we introduce a joint time-domain/frequency-domain (TD/FD) technique for impulsive noise reduction in OFDM-based PLC systems [113].

3.6.1 System Description

In this section we describe a joint time-domain/frequency-domain technique for impulsive noise reduction in OFDM-based PLC systems. The technique combines the time-domain nonlinearities that were studied in previous parts of this chapter with the frequency-domain suppression technique described in section 3.5. Fig. 3.18 shows how this technique is implemented in OFDM systems. The impulsive noise in the received OFDM symbols r_k is first reduced using combined clipping/blanking nonlinear preprocessors described in section 3.3. Clipping/blanking nonlinearity, in particular, is known to perform better than the individual clipping and blanking nonlinearities [38]. This result was verified in PLC channel environments using simulations and is illustrated in Fig. 3.7. Next and in order to further improve the impulsive noise mitigation, the frequency-domain suppression technique described in section 3.5 is applied to the OFDM signal after channel equalization and DFT demodulation. The technique is tested under power line conditions with impulsive noise. In the following section, simulation results are presented where a significant improvement in Bit Error Rate as compared to conventional OFDM systems and also OFDM-systems with nonlinearitybased impulsive noise reduction is shown.

3.6.2 Results

MATLAB software was utilized to study the performance of the proposed joint time-domain/frequency-domain impulsive noise mitigation technique. A random bit stream is mapped into QPSK symbols and modulated using OFDM with 128 subcarriers and passed through a PLC multipath channel with 15 paths. Noise, including background as well as impulsive noise, is then added to the OFDM signal. The background noise is modelled as an AWGN noise, whereas the impulsive noise is modelled according to the Poisson-Gaussian noise model. In this model, impulses with Gaussian



Figure 3.18: Block diagram of the OFDM-based PLC system with Joint TD/FD impulsive noise reduction

amplitudes arrive according to a Poisson distribution. The simulation is run 100 times and in every iteration 200,000 bytes of data are transmitted and received.



Figure 3.19: Performance comparison of time-domain techniques, frequencydomain technique and the Joint TD/FD technique for OFDM-Based PLC in a heavily-disturbed environment

The superior performance of the proposed joint TD/FD impulsive noise suppression technique over the frequency-domain technique and the three time-domain nonlinear techniques can be observed from Fig. 3.19. The curves in this figure depict the BER performance of the proposed joint TD/FD technique in addition to the frequency-domain suppression discussed in section 3.5 and all three time-domain nonlinearities discussed in section 3.3. Fig. 3.19 is the result of simulation in a multipath power line channel with 15 propagation paths. The channel is heavily disturbed with impulsive noise. In this noise scenario, the frequency-domain suppression method provides significant improvements over time-domain nonlinearities only at high SNR values. The proposed TD/FD technique, however, outperforms all the other techniques including the FD technique at all SNR values. For example, at BER of 10^{-4} the joint TD/FD provides an improvement of more than 5 dB over all the other methods. In a heavily-disturbed environment and with SNR values below 35 dB, the proposed technique achieves a BER performance close to that of the signal with only AWGN, which means that the effect of impulsive noise is almost eliminated.

Fig. 3.20 depicts the BER performance of all the studied noise reduction techniques in a power line channel that is moderately affected with impulsive noise. In this noise environment, the FD noise reduction method does not provide any advantage over TD techniques with properly selected thresholds. It should be noted here that the impulsive-to-background power ratio μ defined in (3.16) is maintained at a value of 3 for all three noise scenarios, while the disturbance ratio and impulse rate are defined for each noise scenario according to Table 3.3. With reference to (3.16) and for fixed μ , the power of impulsive noise will be much higher in the mediumdisturbed scenario than in the heavily-disturbed and is even higher in the weakly-disturbed scenario. The reason for this is the smaller disturbance ratio in the medium and weakly disturbed environments when compared to the heavily-disturbed environment. As outlined in [3], the FD technique



Figure 3.20: Performance comparison of time-domain techniques, frequencydomain technique and the Joint TD/FD technique for OFDM-Based PLC in a medium-disturbed environment

does not work as well when the encountered impulsive noise has high amplitudes, because the preliminary estimation of the transmitted signal becomes unreliable. This leads to erroneous estimation of the impulsive noise vector I_k and degrades the performance of the FD suppression technique. The curve for the joint TD/FD technique in Fig. 3.20 shows that this technique reduces the effect of impulsive noise significantly and outperforms the other studied techniques.

The performance of the joint TD/FD technique in a power line channel that is weakly affected with impulsive noise is illustrated in Fig. 3.21. As explained above, the FD technique performs worse than the simple TD nonlinearities, due to the high peaks impulsive noise. On the other hand, the joint TD/FD performs the best in reducing the effect of impulsive noise among all the studied methods.



Figure 3.21: Performance comparison of time-domain techniques, frequencydomain technique and the Joint TD/FD technique for OFDM-Based PLC in a weakly-disturbed environment

3.7 Summary

In this chapter the performance of nonlinear techniques for impulsive noise mitigation in OFDM under practical PLC channel characteristics was considered. Three different nonlinearities, namely clipping, blanking and clipping/blanking, were compared by means of computer simulations. Three noise scenarios based on practical measurements in [6] were used to simulate the impulsive noise in PLC channels. An adaptive-threshold technique for nonlinear impulsive noise mitigation based on minimum BER was introduced in this chapter. The BER performance of OFDM with adaptivethreshold nonlinearities was compared with fixed-threshold nonlinearities. The obtained results show that the adaptive-threshold technique improves the performance of OFDM-based PLC receivers as compared to clipping with fixed threshold value. The joint Time-domain/Frequency-domain impulsive noise suppression technique was also introduced. The performance of this technique is studied against well known time-domain nonlinearities by means of computer simulations. The obtained results show that the Combined TD/FD technique performs better than practically used nonlinearities and can reduce the adverse effect of impulsive noise significantly. Using the TD/FD technique and at SNR values below 35, the effect of impulsive noise can be approximately eliminated in a channel that is heavily-disturbed with impulsive noise.



Performance of Bit-Interleaved Coded OFDM in PLC Systems

4.1 Introduction

Power line channels suffer from the adverse effects of impulsive noise and other narrow-band interferences. Impulsive noise, in particular, can degrade the performance of OFDM-based PLC systems significantly. Channel coding is therefore essential to improve the reliability of communication over PLC channels. Examples of such channel coding schemes include BCH, Reed-Solomon (RS), Low Density Parity Check (LDPC) and convolutional codes. In addition to coding, Interleaving needs to be used in order to account for the bursty behavior of impulsive noise in PLC channels. The performance of coded OFDM in PLC channels was investigated in [114]. However, no interleaving was used and no details about the amount of impulsive noise used in the simulations is given. Interleaving reduces the channel memory and disperses the errors caused by the channel. This leads to a better exploitation of the capabilities of a coding scheme that is designed to control independent errors [7]. In this chapter the same PLC multipath channel model that was described in previous chapters of this thesis is used to simulate the Bit Error Rate performance of bit-interleaved convolutionally coded OFDM in the presence of impulsive noise. Three different scenarios of impulsive noise depicted in Table 3.3 in chapter 3 are considered.

4.2 System Description

OFDM is considered as the transmission scheme for conveying coded data bits through the PLC channel. OFDM copes well with multipath and frequency-selectivity of PLC channels. It also achieves a great efficiency by distributing the data into multiple orthogonal subcarriers through the use of the inverse discrete Fourier transform (IDFT). Moreover, OFDM performs better than single-carrier modulations in the presence of impulsive noise, because it spreads the effect of impulsive noise throughout multiple subcarriers using the discrete Fourier transform (DFT) in the receiver. Convolutional coding is used for forward error correction (FEC) and combined with interleaving to combat the bursty impulsive noise. This coding scheme is briefly reviewed in the following subsection below. To produce reliable results, the PLC multipath channel model that was described in section 3.2.2 of chapter 3 is used. This model has been practically proven to emulate the transmission channel behavior in the frequency range from a few hundred kHz up to 20 MHz. Noise in power lines is a mixture of five different types: coloured background noise, narrow-band noise, periodic impulsive noise asynchronous to the mains frequency, impulsive noise synchronous to the mains frequency and asynchronous impulsive noise. These five types of noise can be summarized into two major types: background noise and impulsive noise. Background noise (w_k) is modelled as AWGN with mean zero and variance σ_w^2 . Impulsive noise (i_k) , on the other hand, is assumed to follow a Poisson-Gaussian model where impulses with Gaussian amplitudes arrive according to Poisson process.

4.2.1 Convolutional Coding

In convolutional coding, a coded bit sequence is produced by passing the information bits through a linear finite-state register consisting of K stages [95]. When a binary sequence of k bits is the input to a convolutional encoder, n bits are generated at the output. The ratio between k and n defines the code rate r = k/n. Another important parameter of convolutional codes is the *constraint length* which is given by the number of stages in the shift register K. To decode a convolutionally coded bit stream, Viterbi decoding is often used in practice. To obtain the simulation results demonstrated in this chapter, convolutional coding with constraint length K = 8 and code rates r = 1/2 and r = 1/3 is used to encode the information data. The encoder employs generator polynomials of [10011111,11100101] and [11101111, 10011011] for code rates 1/2 and 1/3 respectively as these are of the most commonly used convolutional encoders [67].

It is often assumed in the literature that impulsive noise in power line networks arrive as independent and identically distributed (i.i.d.) complex random variables. In fact, impulsive noise often appears in bursts of highpeak impulses that can sometimes be long enough to overshadow complete communication symbols [13]. This fact should be considered for a good design of PLC systems, since coding schemes that are designed for individual errors do not appropriately correct burst errors. The utilization of an interleaver can solve the burstiness problem of impulsive noise. The interleaver distributes the errors among the transmitted data and reduces the channel memory [13] by rearranging the data bits. Consequently, the decoder sees the errors caused by bursts of impulsive noise as independent errors that can easily be corrected.



Figure 4.1: Block diagram of bit-interleaved convolutionally coded OFDM-based PLC system.

4.2.2 Simulation Set-up

Fig. 4.1 depicts a simplified block diagram of the simulated coded OFDM system. At the transmitter side, a random sequence of bits is first generated and encoded using convolutional coding with code rates 1/2 and 1/3. To combat the bursty impulses and allow the capabilities of convolutional codes to be exploited in full, the encoded bits are interleaved using a random interleaver. The interleaved coded bit sequences are then mapped into QPSK symbols before modulation using Inverse Discrete Fourier Transform (IDFT). At the receiver side, the opposite is done where the signal is demodulated by means of Discrete Fourier Transform (DFT) then demapped, deinterleaved and finally decoded using Viterbi decoding. To study the BER performance of coded OFDM in PLC channels, three impulsive noise scenarios, explained in chapter 3, based on practical measurements of impulsive noise in real power line networks are considered. These are "heavily disturbed", "medium disturbed" and "weakly disturbed" and are listed in Table 3.3. The performance of the coded system is measured in terms of
$4.3 \; Results$

BER versus E_b/N_m , where E_b is the energy per bit and N_m is the total noise PSD given by:

$$N_m = N_o + \text{DR.}N_i \tag{4.1}$$

where N_o and N_i are the PSD of background noise and impulsive noise respectively and DR is the average disturbance ratio caused by impulsive noise during measurement time. For all the results illustrated in the following section of this chapter, the following expression for E_b/N_m is used in the simulations:

$$\frac{E_b}{N_m} = (\frac{1}{k.r}).\text{SNR}$$
(4.2)

where k is the number of bits per PSK or QAM symbol and is equal to 2 for QPSK and r is the code rate. SNR is defined according to the following equation:

$$SNR = \frac{p_x}{\sigma_w^2 + DR.\sigma_i^2}$$
(4.3)

where σ_i^2 is the mean power of a single impulse over its duration T_{noise} and is modelled by Gaussian process. The ratio μ between impulsive noise power and background noise power (AWGN) is defined in equation (4.4) as:

$$\mu = \frac{\mathrm{DR.}\sigma_{\mathrm{i}}^2}{\sigma_w^2} \tag{4.4}$$

4.3 Results

Matlab was used to simulate the system depicted in Fig. 4.1 and study its BER performance in three different impulsive noise conditions. The study and results presented in this chapter have been published by the author in [115]. 128 subcarriers are used for the IFFT and FFT operations at the transmitter and receiver respectively. The OFDM signal produced at the output of the transmitter is passed through a PLC multipath channel (refer to section 3.2.2). First, a four-path model representing the most significant propagation paths with parameters given in Table 3.1 is used to represent the PLC channel transfer function. Then for a detailed channel response, the model uses 15 propagation paths with parameters given in Table 3.2. Impulsive noise is modelled using a Poisson-Gaussian model, in which the arrival of impulsive noise follows a Poisson distribution with rate λ per second, while the impulse amplitudes follow the Gaussian process. The background noise is assumed to be AWGN. The total noise term resulting from impulsive and background noises is added to the OFDM signal. At the receiver side, the signal is demodulated using the DFT, demapped and deinterleaved before decoding using a Viterbi decoder with traceback depth of 5K = 40. The simulation is repeated 100 times and the BER results are averaged over all the realizations. A value of $\mu = 3$ was used to obtain the following simulation results.



Figure 4.2: Performance of OFDM-based PLC system in the presence of impulsive noise in three different noise environments using the 4-path model.

Fig. 4.2 and Fig. 4.3 illustrate the BER performance of uncoded OFDM in a typical PLC channel corrupted with background and impulsive noise in three impulsive noise scenarios. The results in Fig. 4.2 are obtained us-



Figure 4.3: Performance of OFDM-based PLC system in the presence of impulsive noise in three different noise environments using the 15-path model.

ing the simplified 4-path model whereas the results in Fig. 4.3 are obtained using the parameters for the 15-path model. The severe effect of impulsive noise in OFDM-based PLC systems is obvious for both channels. In a power line channel heavily impaired with impulsive noise, the performance of uncoded OFDM is degraded due to impulsive noise by more than 15 dB in terms of E_b/N_m at BER below 10^{-4} . Impulsive noise in medium and weakly-disturbed environments can produce BER floors at reasonably high levels of BER. This introduces a significant problem for applications that require very low BER levels, which necessitates the implementation of coding schemes that can help in reducing the effect of impulsive noise.

It should be noted that, in an average weakly-disturbed scenario, only a single impulse occurs every 8 seconds of transmission. The average disturbance ratio in this environment is only 0.0000135. In order to achieve reliable simulation results, a large number of impulses are required during the simulation time. However, for the weakly-disturbed environment this is limited by the very small impulse rate and disturbance ratio given limited memory resources when an average computer is used for the simulations.



Figure 4.4: Performance of bit-interleaved coded OFDM-based PLC system in a heavily-disturbed PLC channel using the 4-path model.

Figures 4.4-4.9 present the BER performance of bit-interleaved coded OFDM in the same three impulsive noise conditions (heavily-disturbed, medium-disturbed and weakly-disturbed) using both the simple 4-path and detailed 15-path echo models. The performance improvement achieved by convolutional coding and interleaving over uncoded OFDM in the presence of impulsive noise is indeed very significant, especially in the heavilydisturbed environment.

As shown in Fig. 4.4 and Fig. 4.5, in a heavily-disturbed medium, a gain of more than 15 dB can be achieved at BER less than 10^{-3} for both code rates 1/2 and 1/3. In the same channel with the same noise conditions, the results for a code rate of 1/3 have a slight improvement of a few decibels over a code rate of 1/2. When the 15-path channel model is used, the residual effect of impulsive noise for both code rates is small (< 1.2 dB). This is



Figure 4.5: Performance of bit-interleaved coded OFDM-based PLC system in a heavily-disturbed PLC channel using the 15-path model.



Figure 4.6: Performance of bit-interleaved coded OFDM-based PLC system in a medium-disturbed PLC channel using the 4-path model.

4.3 Results



Figure 4.7: Performance of bit-interleaved coded OFDM-based PLC system in a medium-disturbed PLC channel using the 15-path model.



Figure 4.8: Performance of bit-interleaved coded OFDM-based PLC system in a weakly-disturbed PLC channel using the 4-path model.



Figure 4.9: Performance of bit-interleaved coded OFDM-based PLC system in a weakly-disturbed PLC channel using the 15-path model.

shown in Fig 4.5, where the BER curves for the heavily-disturbed case and the case when no impulsive noise is present are close to each other for both code rates.

In the medium and weakly disturbed environments, interleaving and coding approximately eliminates the effect of impulsive noise completely. This can clearly be observed from the graphs in Fig. 4.6-Fig. 4.9 where BER curves in the presence and absence of impulsive noise are identical for both code rates. It can also be noticed that, under the same transmission environment, using convolutional coding with rate 1/3 provides a gain of about 1 dB over the same code with rate 1/2.

4.4 Summary

In this chapter, the BER performance of bit-interleaved convolutionally coded OFDM under practical PLC channel characteristics and impulsive noise was investigated. Three noise scenarios based on practical measurements were used in the simulations. Convolutional coding with constraint length of 8 and two code rates (1/2 and 1/3) was used as the forward error-correction scheme. To distribute the errors caused by bursts of impulsive noise, a random interleaver was employed in the transmitter. The obtained simulation results show that, in the presence of impulsive noise convolutional coding combined with interleaving improves the performance of OFDM-based PLC systems significantly. A gain of more than 15 dB may be achieved by convolutional coding and interleaving when the channel is heavily affected by impulsive noise. In addition, this combination of convolutional coding and interleaving completely eliminates the effect of impulsive noise in the medium and weakly disturbed environments.



Adaptive Power Loading for OFDM-Based PLC Systems

5.1 Introduction

OFDM is a key feature for present and future PLC systems. It is wellknown for its robustness to multipath, selective fading and different types of interference. The performance of OFDM and other multicarrier systems can be significantly enhanced when combined with adaptive modulation [80]. In adaptive modulation, different parameters including data rate, transmit power, instantaneous BER, constellation size and channel code or scheme can be adjusted according to the channel fading conditions. In order to optimize one or more of these parameters, a feedback channel must provide channel state information (CSI) at the transmitter.

Several bit/power loading algorithms can be found in the literature [81]-[93]. Most of these algorithms can be classified, based on their objective function, into two categories: margin-adaptive (MA) algorithms (e.g. [86], [87]), that strive to minimize the transmitted power subject to data rate and BER constraints, and rate-adaptive (RA) algorithms (e.g. [88]-[92]) that strive to maximize the data rate subject to power and BER constraints. The optimal bit/power loading can be achieved by the well-known waterfilling approach but at the cost of excessive complexity. In this chapter, the MA loading strategy is investigated. A solution to the power minimization problem for OFDM with uniform bit allocation and nonuniform BER distribution is introduced. The power allocation is optimized subject to fixed data rate and target BER. This leads to the derivation of closed form expressions for BER and power distribution in the presence of impulsive noise. Based on these expressions, a simple adaptive power loading algorithm is presented and tested by computer simulations in a widely-accepted power line channel model impaired with impulsive noise. The power of impulsive noise is varied to observe the performance of the presented algorithm at different noise conditions. The work presented in this chapter has been published in the proceedings of the IEEE International Symposium on Power Line Communications and its Applications (ISPLC 2010) [94].

5.2 Adaptive Power Loading

5.2.1 Problem Formulation

The problem that we try to solve here is finding a margin-adaptive strategy in the presence of impulsive noise, in which we try to minimize the transmit power p_{Tot} subject to a fixed bit rate R_b per OFDM symbol and a maximum target bit-error rate P_T . A similar approach to the one adopted in this chapter was presented by Lui *et al.* [87]. However, the work presented in this chapter focuses on PLC systems and studies the effect of impulsive noise with variable impulsiveness levels using a well-accepted power line channel model. Bits are allocated equally among subcarriers. The problem can be summarized by the following:

Minimize
$$p_{Tot} = \sum_{n=1}^{N} p_n$$
 (5.1)

subject to

$$\sum_{n=1}^{N} \frac{b \cdot P_n}{R_b} \le P_T \quad \text{and} \quad b = \frac{R_b}{N}$$
(5.2)

where N is the number of subcarriers, b is the number of bits per subcarrier, p_n and P_n are the transmit power and the BER of the *n*th subcarrier, respectively. The PLC channel usually contains various kinds of noise including colored background noise, narrowband interference and impulsive noise of different characteristics. To simplify the noise situation in power lines, the noise is often summarized as background noise and impulsive noise. As explained in earlier chapters, the studies conducted in this thesis model the background noise as an AWGN with power σ_w^2 . Impulsive noise is modelled using a Poisson-Gaussian model. In this model, the arrival of noise impulses is modelled using Gaussian distribution with variance σ_i^2 .

When the channel is affected by background and impulsive noise and assuming that impulsive noise affects all subchannels equally, then the total noise per subchannel σ_n^2 becomes:

$$\sigma_n^2 = \sigma_{wn}^2 + \text{DR.}\sigma_i^2, \quad n = 1, 2, ..., N$$
 (5.3)

Using the following expression for the disturbance ratio (DR) that was derived in section 3.3

$$\mathrm{DR} = \frac{\mu . \sigma_w^2}{\sigma_i^2} \tag{5.4}$$

and substituting in (5.3) the following expression for the total subchannel noise is obtained:

$$\sigma_n^2 = \sigma_{wn}^2 (1+\mu), \quad n = 1, 2, ..., N$$
(5.5)

5.2.2 Optimization of Power Loading

The BER of square MQAM with Gray bit mapping can be approximated by [80]:

$$P_n = 0.2. \exp\left\{-\frac{1.6.\gamma_n}{2^b - 1}\right\}, \quad n = 1, 2, ..., N$$
(5.6)

where $\gamma_n = \frac{p_n \cdot |H_n|^2}{\sigma_n^2}$ is the *n*th subchannel signal-to-noise ratio, with H_n being the channel gain of the *n*th subcarrier. This approximation is tight within 1 dB for $b \ge 2$ and BER $\le 10^{-3}$ [80]. In the presence of impulsive noise, this approximation becomes

$$P_n = 0.2 \exp\left\{-\frac{1.6.p_n g_{wn}}{(1+\mu)(2^b-1)}\right\}, \quad n = 1, 2, ..., N$$
(5.7)

where g_{wn} represents the *n*th subchannel signal-to-Gaussian noise ratio when a unit energy is applied to it and is defined as $g_{wn} = |H_n|^2 / \sigma_{wn}^2$. From this expression, the transmit power required to transmit *b* bits per symbol on the *n*th subcarrier with P_n is calculated by

$$p_n = -\frac{1}{1.6.g_{wn}} \cdot (1+\mu)(2^b - 1) \cdot \ln(5.P_n), \quad n = 1, 2, ..., N$$
 (5.8)

Using Lagrange multipliers, the cost function to minimize (5.1) subject to the constraint (5.2) is

$$J = \sum_{n=1}^{N} p_n - \lambda_L \frac{b}{R_b} \sum_{n=1}^{N} P_n - \lambda_L P_T$$
(5.9)

where λ_L is the Lagrange multiplier. Substituting (5.8) into (5.9), the following is obtained

$$J = -\sum_{n=1}^{N} \left\{ \frac{1}{1.6.g_{wn}} \cdot (1+\mu)(2^{b}-1) \cdot \ln(5.P_{n}) \right\} -\lambda_{L} \left(\frac{b.P_{n}}{R_{b}} - P_{T} \right)$$
(5.10)

The optimum P_n vector is found when the derivative of the cost function in (5.10) with respect to P_n equals zero (i.e. $\frac{\partial J}{\partial P_n} = 0$). This yields

$$P_n = -\frac{R_b}{1.6.g_{wn}.b.\lambda_L} \cdot (1+\mu)(2^b - 1), \quad n = 1, 2, ..., N$$
(5.11)

Substituting this expression for P_n into the constraint (5.2) of the optimization problem yields the following term for λ_L

$$\lambda_L = -\frac{R_b \cdot (1+\mu)(2^b - 1)}{1.6.b.N.P_T} \cdot \sum_{n=1}^N \frac{1}{g_{wn}}$$
(5.12)

From (5.12) and (5.11), the P_n vector is attained

$$P_n = N.P_T.\frac{\frac{1}{g_{wn}}}{\sum_{n=1}^N \frac{1}{g_{wn}}}, \quad n = 1, 2, ..., N$$
(5.13)

The optimized power distribution is then calculated using (5.13) and (5.8)

$$p_n = -\frac{(2^b - 1)}{1.6.g_{wn}} \cdot (1 + \mu) \cdot \ln(5.N.P_T \cdot \frac{\frac{1}{g_{wn}}}{\sum_{n=1}^N \frac{1}{g_{wn}}})$$
(5.14)

where n = 1, 2, ..., N. Obviously, a practical transmit power p_n can not be negative and from (5.14) we can see that the allocated power to the *n*th subchannel will only be negative if

$$5.N.P_T.\frac{\frac{1}{g_{wn}}}{\sum_{n=1}^N \frac{1}{g_{wn}}} > 1$$
 (5.15)

This leads to the following simple criterion for g_{wn} in order to avoid assigning negative power to the subcarrier.

$$g_{wn} \ge \frac{5.P_T}{\left(\frac{1}{g_{wn}}\right)} \tag{5.16}$$

since $\sum_{n=1}^{N} \frac{1}{g_{wn}} = N.(\frac{1}{g_{wn}})$ where $(\frac{1}{g_{wn}})$ is the mean value of the $\frac{1}{g_{wn}}$ vector. It can be proved from (5.15) that to guarantee the use of all OFDM subcarriers without violating the condition in (5.16), the target bit error rate (P_T) would have to be equal or lower than 0.2/N since the fraction in (5.15) never exceeds 1. On the other hand, if $P_T \ge 0.2/N$, the subcarriers affected by the deep notches in the channel transfer function will not meet the criterion (5.16). Therefore, the corresponding subcarriers should be allocated zero power.

5.2.3 Power Loading Algorithm

Based on the findings described in the previous section, a power loading algorithm suitable for OFDM-based PLC systems impaired with impulsive noise is introduced in this section. The algorithm takes the following steps:

- 1. Calculate $g_{wn} = |H_n|^2 / \sigma_{wn}^2$ for all N data subchannels and find $(\overline{\frac{1}{g_{wn}}})$.
- 2. Compare g_{wn} with the criterion (5.16), find the subchannels that violate it and set their transmit power to zero. Count their number k and update the number of used subchannels $N^* = N - k$.
- 3. If no impulsive noise is present in the channel, set μ = 0. Otherwise, if impulsive noise is present, calculate μ according to the detected impulses. Impulsive noise can be detected in the frequency domain [3] or in the time domain using a simple threshold detection circuit.
- 4. Calculate the number of bits per QAM symbol $b = R_b/N^*$
- 5. Allocate power to the remaining subcarriers according to (5.14).

It should be noted that this algorithm can be used even if no impulsive noise detection circuit is employed or if impulsive noise effect is mitigated using some technique or by means of powerful channel coding (e.g. [32]-[33] and [54]-[65]). This is done by setting $\mu = 0$.

5.3 Simulation Results

The performance of the proposed algorithm in OFDM-based PLC systems is evaluated under different impulsive noise scenarios by computer simulations. This algorithm is compared with the conventional OFDM system where all subcarriers are allocated equal transmit powers ($p_n = p_{Tot}/N$ for all n = 1, 2, ..., N). The number of subcarriers used is 512. A PLC multipath channel model (3.2.2) with 15 paths with parameters given in Table 3.2 was used in the simulations. We use equations (5.13) and (5.14) to calculate the subcarrier BER and power, respectively. The performance is presented in terms of E_b/N_o for various target bit-error rate (BER) with different impulsive noise scenarios.



Figure 5.1: Channel gain against subcarrier index for the 15-path power line channel.



Figure 5.2: BER distribution among subcarriers for the 15-path power line channel. $P_T = 10^{-2}$

The magnitude of the channel transfer function is depicted in Fig. 5.1 as a channel gain versus subcarrier index. The OFDM system used in the simulations occupies the transmission bandwidth 0.2 - 30 MHz. Fig. 5.2 shows the BER distribution among OFDM subcarriers in the 15-path power line channel. The BER for each subcarrier P_n is calculated using (5.13) for target bit-error rate ($P_T = 10^{-2}$). The relationship between the channel gain in Fig. 5.1 and the calculated BER allocation in Fig. 5.2 is clearly visible. The subcarriers that suffer from deep fades in the channel transfer function produce high error rates.

For the same channel and P_T , Fig. 5.3 illustrates the normalized power distribution (p_n) calculated using (5.14) after allocating zero power to subcarriers violating (5.16). The zoomed in snapshots show examples of the



Figure 5.3: Power distribution among subcarriers for the 15-path power line channel after nulling the subchannels violating criterion (5.16). $P_T = 10^{-2}$

nulled subcarriers.

The performance of the proposed simple power loading algorithm in a PLC channel with impulsive noise is depicted in Fig. 5.4 in terms of E_b/N_o versus BER and compared to the conventional OFDM system where bits and powers are distributed equally between subcarriers. Different impulsive noise scenarios (i.e. $\mu = 0$ (no impulsive), 100, 200, 500) are used to observe the effect of impulsive noise with different powers in the OFDM system performance. It can be easily observed from Fig. 5.4 that, in a power line channel, the proposed algorithm can achieve a performance gain of more than 4 dB over conventional OFDM for high P_T . Table 5.1 summarizes some of the obtained E_b/N_o results for specific values of P_T using both conventional OFDM and OFDM with the proposed power loading.



Figure 5.4: Performance of proposed power loading algorithm as compared to conventional OFDM (equal power distribution) in the 15-path power line channel for different impulsive noise scenarios.

Table 5.1: A comparison of E_b/N_o between conventional OFDM and OFDM with the proposed power loading at specific P_T .

P_T	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Proposed	34.6	38.8	41.2	42.7
Conv. OFDM	38.6	41.1	42.6	43.8

5.4 Summary

In this chapter the effect of impulsive noise in adaptive power loading in OFDM-based PLC systems was studied. The multipath model that was described in previous parts of the dissertation was used to represent the power line channel. 15 significant echo paths were assumed in order to improve the accuracy of the simulations. Closed form expressions for BER and power allocation in the presence of impulsive noise were presented. We presented a simple power loading algorithm to minimize the transmitted power under fixed data rate and target BER constraints. The proposed algorithm was tested in a widely-accepted power line channel model impaired with impulsive noise using computer simulations. Results show that the proposed algorithm can achieve a significant improvement over conventional OFDM with uniform power allocation.



Adaptive Bit Loading for OFDM-Based PLC Systems

6.1 Introduction

In a conventional OFDM system, all subcarriers use a fixed constellation size. Therefore, the overall error probability is dominated by the subcarriers that have the worst signal-to-noise ratios (SNR). When channel state information is available, the performance of OFDM can be significantly improved by using adaptive modulation [80]. Different parameters including data rate, transmit power, instantaneous bit-error-rate (BER), constellation size and channel code or scheme can be adjusted according to the subchannel fading conditions.

Different loading algorithm have been published in the literature [82]-[92]. Based on the objective function that they try to optimize, most of those loading algorithms are either margin-adaptive algorithms that strive to minimize the transmitted power subject to data rate and BER constraints such as the power loading algorithm presented in chapter 5, or rate-adaptive algorithms (e.g. [88]-[92]) that strive to maximize the data rate subject to power and BER constraints. In addition, some algorithms that have different objectives can also be found in the literature. For example, the algorithm proposed by Goldfeld *et al.* [90] is aimed at minimizing the probability of error. Such algorithms are useful for systems that require maximum reliability or have fixed power levels and require fixed data rates. In all these algorithms, there is generally a tradeoff between algorithm performance and computational complexity. Optimum bit/power loading can be achieved by the well-known water-filling approach [116]. Some loading algorithms can also achieve near-optimal solutions using incremental allocation (e.g. [89], [92]). However, the cost in terms of computational complexity associated with both approaches is excessive. To reduce the complexity of bit allocation, closed-form expressions for BER or channel capacity approximations can be exploited. This method, however, requires rounding of the constellation size to integer numbers which deviates the allocation from optimality. Wyglinski et al. [89] proposed an optimum bit-loading with reduced complexity. However, the method is still rather computationally complex especially when the number of subcarriers is large, because it includes an extra iterative algorithm to find the initial peak BER in addition to the main algorithm.

In this chapter, we attempt to solve the rate maximization problem with target overall BER constraint and uniform power allocation. A simple discrete bit-loading algorithm that approaches the maximum throughput with minimal complexity is presented. The algorithm performance is verified in a widely-accepted power line channel model [2].

6.2 Adaptive Bit Loading

In this section, the optimization problem is first described and formulated. A solution to the problem is sought and the results are used to create a simple loading algorithm suitable for PLC systems.

6.2.1 Problem Formulation

The proposed loading algorithm aims to solve the following rate-adaptive problem with minimal complexity given a target mean BER P_T and a fixed energy distribution across all subcarriers:

Maximize
$$\sum_{n=1}^{N} b_n$$
 (6.1)

subject to

$$\bar{P} = \frac{\sum_{n=1}^{N} b_n P n}{\sum_{n=1}^{N} b_n} \le P_T \tag{6.2}$$

where b_n and P_n are the number of bits and BER of the *n*th subcarrier respectively. N and \bar{P} are the number of used subcarriers and their mean BER respectively. As in other studies, it is assumed that perfect knowledge of the channel gains is available to both the transmitter and the receiver. Different loading algorithms trying to solve this problem have been discussed in the previous section. These algorithms, however, are either too complex or do not achieve maximum throughput. Therefore, an algorithm that can maximize the throughput and at the same time maintain low computational complexity is needed. In the following, an algorithm with such properties is developed and explained.

6.2.2 Proposed Bit Loading Algorithm

The BER of square MQAM with Gray bit mapping can be approximated by [80]:

$$P_n = 0.2 \exp\left\{-\frac{1.6\gamma_n}{2^{b_n} - 1}\right\}, \quad n = 1, 2, ..., N$$
(6.3)

where $\gamma_n = \frac{p_n |H_n|^2}{\sigma_n^2}$ is the *n*th subchannel SNR, with p_n , H_n and σ_n^2 being the signal power, channel gain and noise power of the *n*th subcarrier respectively. Accordingly, the number of bits that can be carried in subchannel *n* is given by:

$$b_n = \log_2\left\{1 + \frac{\gamma_n}{\Gamma_n}\right\}, \quad n = 1, 2, ..., N$$
(6.4)

where Γ_n is the SNR gap representing how far the system is from achieving capacity and can be defined from (6.3) and (6.4) as:

$$\Gamma_n = -\frac{\ln(5.P_n)}{1.6}, \quad n = 1, 2, ..., N$$
(6.5)

The average number of bits per subcarrier in one OFDM symbol can then be written as:

$$\bar{b} = \left(\frac{1}{N}\right) \sum_{n=1}^{N} b_n
= \left(\frac{1}{N}\right) \sum_{n=1}^{N} \log_2 \left\{ 1 - \frac{1.6.\gamma_n}{\ln(5.P_n)} \right\}
= \left(\frac{1}{N}\right) \log_2 \left\{ \prod_{n=1}^{N} \left[1 - \frac{1.6.\gamma_n}{\ln(5.P_n)} \right] \right\}
= \log_2 \left\{ 1 - \frac{1.6.\gamma_{mc}}{\ln(5.\bar{P})} \right\}$$
(6.6)

where γ_{mc} is the multichannel SNR which characterizes the set of N subchannels by an equivalent single AWGN that achieves the same data rate with the same error probability [116]. The concept of the multichannel SNR is illustrated in Fig. 6.1. From (6.6), the multichannel SNR can be defined by:

$$\gamma_{mc} = \frac{\ln (5.\bar{P})}{1.6} \cdot \left(1 - \left(\prod_{n=1}^{N} \left[1 - \frac{1.6.\gamma_n}{\ln (5.P_n)} \right] \right)^{(1/N)} \right)$$
(6.7)

The proposed algorithm initially computes for each subcarrier the maximum number of bits b_n that gives a value of P_n below P_T . The resulting overall BER \overline{P} will generally be below P_T by a large margin. To exploit this margin, the algorithm then computes the number of extra bits that can be added to the OFDM symbol without violating the BER constraint P_T . The



Figure 6.1: The concept of the multichannel SNR [116].

extra bits are added to the subcarriers that will have the minimum effect in the overall BER. This is done by evaluating ΔP_n for each subcarrier where

$$\Delta P_n = b_n \left(P_n^+ - P_n \right) \tag{6.8}$$

and P_n^+ is the BER of the *n*th subchannel when the constellation size is shifted to the immediately higher constellation. The proposed algorithm takes the following steps:

- 1. Given SNR values γ_n , find the largest signal constellation b_n for each subcarrier for which P_n is below P_T .
- 2. Calculate the current values of \bar{b} and \bar{P} and compute the multichannel SNR γ_{mc} using (6.7).
- 3. Use γ_{mc} to find the maximum average number of bits \bar{b}_{max} per subcarrier that satisfies P_T :

$$\bar{b}_{max} = \log_2 \left\{ 1 - \frac{1.6.\gamma_{mc}}{\ln(5.P_T)} \right\}$$
(6.9)

- 4. Find the number of extra bits $I = N. (\bar{b}_{max} \bar{b})$ that can be added to the OFDM symbol.
- 5. Calculate $\triangle P_n$ for all subchannels that have b_n below the maximum constellation size. Sort subchannels according to their $\triangle P_n$ in increasing order.
- 6. Add I extra bits to the subchannels that have the lowest $\triangle P_n$ by shifting their constellation to the immediately higher size.

6.3 Simulation Results

3.7

6.3.1 Channel Model

To examine the performance of the discrete bit loading algorithm in a PLC environment, the same PLC multipath channel model that was described earlier in this dissertation (refer to section 3.2.2) is used here. The model is based on practical measurements of actual power line networks and it is the most accepted model for power line channels. As it was explained in earlier sections of this dissertation, the multipath model is preferred over transmission line models due to various reasons. The fact that TL models require a complete and precise knowledge of the topology and physical properties of the PLC network renders such models hardly practical in real situations. In contrast, the time-domain multipath model that is used here does not require detailed information about the topology of the channel. For the convenience of the reader, we restate the channel transfer function in this section:

$$H(f) = \sum_{i=1}^{N_p} \underbrace{c_i}_{\text{weighting}} \cdot \underbrace{e^{-(a_0 + a_1 f^k)d_i}}_{\text{attenuation}} \cdot \underbrace{e^{-j2\pi f(d_i/vp)}}_{\text{delay}}$$
(6.10)
factor portion portion

where N_p is the number of multipaths, c_i and d_i are the weighting factor and length of the *i*th path respectively. The channel gains of this PLC channel model against subcarrier index is illustrated in Fig. 6.2 for 1024 subcarriers. The deep notches representing frequency selective fading can be clearly observed from the figure. The frequency-dependant attenuation is also obviously illustrated in the same graph, where larger attenuation generally appears at higher frequencies. The model involves parameters a_0 , a_1 and k that describe the frequency-dependant attenuation in the propagation channel. The echo scenario is accounted for by the second exponential in the transfer function H(f). To provide sufficient accuracy, the number of significant paths is assumed to be 15. The parameters of the 15-path model are taken from [2] and illustrated in Table 3.2.



Figure 6.2: Channel gain for the 15-path power line channel.

6.3.2 Results

The performance of the proposed bit-loading algorithm is evaluated by computer simulations against two different loading methods based on the achieved average number of bits per subchannel. The two algorithms are the incremental algorithm and the equal-BER loading algorithms.

In incremental loading that was used here, all subcarriers are initially allocated the maximum signal constellation. Then depending on the channel feedback, bits are incrementally removed from the subcarrier with the worst BER until the overall BER satisfies P_T . This way, optimum bit allocation can be achieved. Nevertheless, the computation of this algorithm greatly depends on the channel gain conditions and the number of OFDM subcarriers. For low SNR values and if a large number of subcarriers is employed the computational complexity of the incremental loading can be excessive.

On the other hand, in equal-BER allocation, a constant BER threshold (i.e. P_T) is set for all subcarriers and each subcarrier is allocated the maximum number of bits for which its P_n is below P_T . For this method, the number of bits in each subchannel can be evaluated using (6.4) and rounding down to the nearest smaller integer. This rounding procedure degrades the overall bit rate and generally results in large margin from the achievable bit rate. In the following simulation results all the algorithms are used with OFDM with 1024 subcarriers in the frequency band 1.8 – 30 MHz and the approximation (6.3) is used. Each subchannel can be assigned to carry a maximum number of 10 bits.

Fig. 6.3 shows the number of bits allocated to each subcarrier using the proposed algorithm when the target BER constraint P_T is equal to 10^{-5} . The performance of the proposed algorithm, measured in average number of bits per subchannel, is depicted in Fig. 6.4 and compared to incremental and equal-BER loading algorithms for two different values of target BER $(P_T = 10^{-3}, 10^{-5})$. The figure shows that the proposed algorithm and incre-



Figure 6.3: Bit allocation based on the proposed algorithm

mental loading have similar performances, whereas the equal-BER loading achieves lower rates. To compare the computational complexity of these algorithms, the computation time (in milliseconds) taken by each algorithm to reach the final allocation is measured. To insure fairness, each of those algorithms was implemented using Matlab and executed 1000 times in the same workstation. Table 6.1 illustrates the mean computation times for a 1024-subcarrier OFDM system with P_T of 10^{-5} for different values of SNR. It should be noted that the proposed algorithm is non-iterative, which results in a significant reduction in algorithm computational complexity as compared to the iterative incremental loading. Although the computation time of the proposed algorithm is less than a quarter of that of the incremental loading, both of these algorithms have indistinguishable performances in terms of average number of bits per subchannel. The proposed method



Figure 6.4: Performance of the proposed loading algorithm as compared to incremental and default loading methods in the 15-path power line channel.

takes about twice the time taken by the equal-BER to reach the final allocation. However, it achieves a considerable improvement of more than 300 bits per OFDM symbol over the equal-BER loading method.

Algorithm	40 dB	50 dB	60 dB	70 dB
Incremental	2.80	2.90	3.30	3.10
Equal-BER	0.30	0.33	0.38	0.40
Proposed	0.60	0.65	0.74	0.76

Table 6.1: Mean Computation times (ms) for different values of SNR, $P_T = 10^{-5}$, (CPU: Intel(R) Core(TM)2 Duo 3 GHz)

6.4 Summary

This chapter presented a simple non-iterative discrete bit-loading algorithm striving to maximize the data rate subject to target BER constraint and uniform power distribution. The algorithm was tested in a practically-proven power line communication channel model using computer simulations. Results show that the proposed algorithm improves the data rates achieved by the equal-BER loading with a small cost in complexity. When compared to the incremental loading, the proposed algorithm achieves similar rates, but with much lower computational complexity.

l Chapter

Conclusions and Future Directions

Power line communication systems employing orthogonal frequency division multiplexing and the effect of impulsive noise have been considered in this dissertation. Despite the potential to become a successful and widespread technology enabling high-speed broadband Internet and network applications, PLC technology suffers from serious challenges and channel impairments. In this dissertation, the problem of impulsive noise was investigated and proper mitigation techniques were examined and developed. In later parts, methods of enhancing the speed and efficiency of OFDM-based PLC systems using adaptive modulation were introduced and examined. The studies conducted during the author's PhD candidature resulted in the publication of eight internationally refereed conference papers in addition to the submission of a journal paper.

7.1 Summary of Results

• First, the theoretical aspects of the PLC technology have been reviewed in chapter 2. The topologies, structures and physical properties of power line grids were outlined. It was shown that this technology, on one hand, has a great potential to compete against well-know broadband Internet access techniques such as ADSL as well as local area network implementation techniques such as Ethernet and Wi-Fi. A unique advantage of PLC is the global ubiquity of the transmission medium (i.e. power line networks). On the other hand, power lines suffer from major drawbacks including high attenuation and susceptibility to high-amplitude impulsive noise. The problem of impulsive noise, in particular, has been discussed thoroughly and the existing techniques to reduce its effect in communication systems have also been studied.

The available power line channel models in the literature have also been discussed. There are two fundamental approaches for modelling the power line channel: time-domain and frequency-domain. It was found that the multipath model that is based on a time-domain approach is the most suitable model for describing the transmission behaviour and the attenuation characteristics of PLC systems. Unlike frequency-domain-based transmission line models, the multipath model can accurately express the channel by a transfer function without the need for a detailed knowledge of the network topology.

The possible modulation techniques for PLC including single carrier, spread-spectrum techniques and OFDM were also described and compared in chapter 2. Due to its outstanding advantages, OFDM was considered as the modulation technique for the work presented in this dissertation. In addition to robustness against multipath and frequency selectivity, OFDM reduces the effect of impulsive noise by spreading its effect over multiple symbols. When combined with adaptive modulation techniques, the performance and efficiency of OFDMbased systems can be significantly improved.

The effect of impulsive noise with different magnitudes and occurrence rates in OFDM-based PLC was studied in chapter 3. Simulation results were obtained for three noise environments: "heavily-disturbed", "medium disturbed" and "weakly-disturbed". The severe effect of impulsive noise in PLC systems was clearly demonstrated by the drastic changes in BER curves. Furthermore, time-domain nonlinearities including clipping, blanking and the combined clipping/blanking were employed in the OFDM receiver to combat impulsive noise and the issue of threshold selection was investigated. It has been found that, with proper threshold selection, nonlinear techniques can reduce the effect of impulsive noise in OFDM-based PLC systems considerably. As a treatment to the threshold selection dilemma, a BERbased adaptive threshold selection technique has been proposed and the performance was verified by simulations. To further improve the receiver's ability to reduce the effect of impulsive noise, a technique that combines time domain nonlinearities with a frequency-domain approach has been proposed. The technique can reduce the effect of impulsive noise to an acceptable level. The work presented in this chapter led to the publication of four refereed conference papers [110]-[113].

- In chapter 4, an OFDM system employing a convolutional encoder in addition to a random interleaver was examined in a PLC environment. The performance of the system was studied in the presence of impulsive noise with different conditions. Two code rates (¹/₂ and ¹/₃) were used to observe the achieved performance gains. The PLC channel was represented by the multipath channel model described in section 3.2.2. Both the simplified four-path and the detailed 15path models were used in the simulations. A Viterbi decoder is used to decode the received data. The obtained results showed that a very significant gain can be achieved especially in environments that are heavily-affected by impulsive noise. These results were published in the proceedings of the 209 International Conference on Advanced Technologies for Communications [113]
- To enhance the performance and efficiency of PLC systems, adaptive modulation techniques were investigated in chapters 5 and 6. A

power loading algorithm that minimizes the power cost to achieve certain data rates and target BER has been developed and published in the proceedings of the 2010 IEEE International Symposium on Power Line Communications and its Applications [94]. Closed-form expressions of BER allocation and power loading have been derived. The performance of the proposed algorithm was compared against conventional OFDM. Results showed that with very low complexity, significant power savings can be achieved using the proposed algorithm.

• A novel bit-loading algorithm has been developed and explained in chapter 6 of this dissertation. Verified by simulation results, the algorithm maximizes the data rate and achieves rates similar to those achieved by very computationally-complex incremental loading. Yet, the complexity of the algorithm is kept at a very low level by using closed-form expressions and minimizing the number of algorithm iterations to a single iteration. This novel algorithm has been accepted for oral presentation and publication in the proceedings of the 2011 IEEE International Symposium on Power Line Communications and its Applications.

7.2 Future Directions

There are several areas in this dissertation that can be extended through further research as follows:

• The results obtained in this work are based on computer simulations using widely-accepted models to represent the power line channel and the existing noise. The following step is to conduct practical measurements in actual power line networks. This will add an additional tool to verify the practicality of existing and new PLC techniques. Channel and noise measurements in Australian power line grids should be conducted since the differences in topologies, structures and types of wire can affect the transmission behaviour.

- A threshold selection method that is based on the achieved BER at different threshold values was presented in chapter 3 of the dissertation. Although the results can be superior especially in a timevarying channel influenced by frequent impulsive noise like the power line channel, the computational complexity should be reduced if the technique is to be implemented in practical applications. This issue can be further researched.
- In chapter 4 of this dissertation, the study investigated the utilization of convolutional coding in power line communications under the effect of impulsive noise. The work can be extended to other coding schemes such as turbo codes, low-density parity check (LDPC) and Reed-solomon codes. The use of combined codes in the form of outer and inner codes in PLC environments affected by impulsive noise can also be examined.
- In addition to the bit/power loading methods developed in this work, other adaptive modulation criteria can be investigated. This may include adaptively adjusting the code rate or scheme among subcarriers, where the subcarriers that have poor channel conditions can use more robust coding methods.
- In the study and development of bit and power loading algorithms described in this dissertation, it was assumed that perfect channel knowledge is available to both the transmitter and the receiver. This implies that perfect channel estimation is achieved in the receiver. In addition, a very reliable feedback link providing error-free channel state information (CSI) from the receiver to the transmitter must exist. This may not be the situation in practical PLC systems since channel information may also be affected by AWG noise and impulsive noise. The studies conducted in chapters 5 and 6 can be extended by

assuming imperfect channel state information. This adds an error term to the CSI that is sometimes modelled using AWGN.
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